PHYSICS TODAY

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A new view of the MOON

A new zoo of hidden particles

The secret search for Moroccan uranium

Project-based learning takes off

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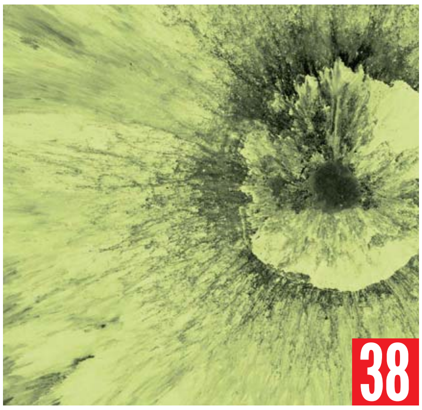
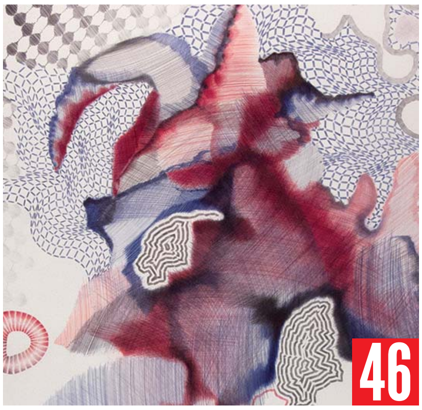
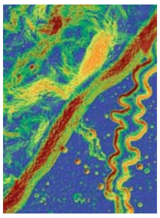
FEATURES







ON THE COVER: This slope map of the northwestern rim of the Moon's Posidonius Crater reveals an intricate topography, including a meandering channel likely carved by ancient lava flows. Warmer colors indicate steeper slopes. The map was captured by NASA's *Lunar Reconnaissance Orbiter*, one in a flurry of lunar missions launched since 2007. On **page 38**, Brett Denevi explains how those missions are helping planetary scientists rewrite the history of Earth's nearest neighbor. (Image courtesy of NASA/GSFC/Arizona State University.)

Recently on PHYSICS TODAY ONLINE

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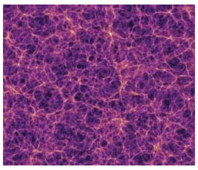
NATIONAL GEOGRAPHIC

▶ Witnessing *Genius*

The new National Geographic TV series on Albert Einstein's life begins with sex and murder. But from there, the show compellingly—and for the most part, accurately—examines Einstein's intellectual and personal journeys, say historians Daniel Kennefick and Alberto Martínez.



MPI FOR ASTROPHYSICS

▶ Negative mass

Recently physicists reported the creation of a Bose–Einstein condensate that behaved as if it had negative mass. Though many scientists scoff at the idea of truly negative-mass matter, it could help physicists unravel the mysteries of the early universe, argues theoretical physicist Manu Paranjape.

ISHAI PARASOL, CC BY-SA 2.0

▶ Mental health

About half of PhD students have symptoms consistent with depression, and physics graduate students are no exception. Georgia Tech graduate student Andrea Welsh explains why the physics community urgently needs a serious discussion about mental health.

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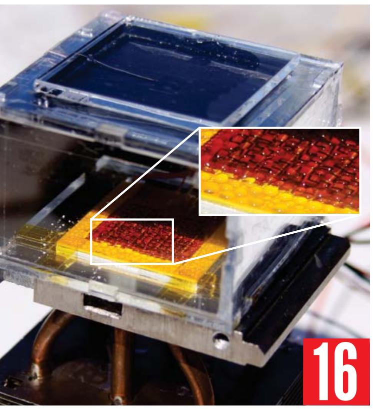

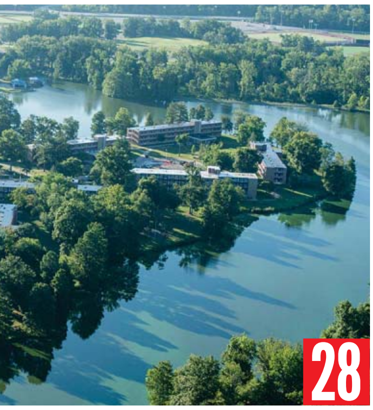

DEPARTMENTS

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FROM THE EDITOR

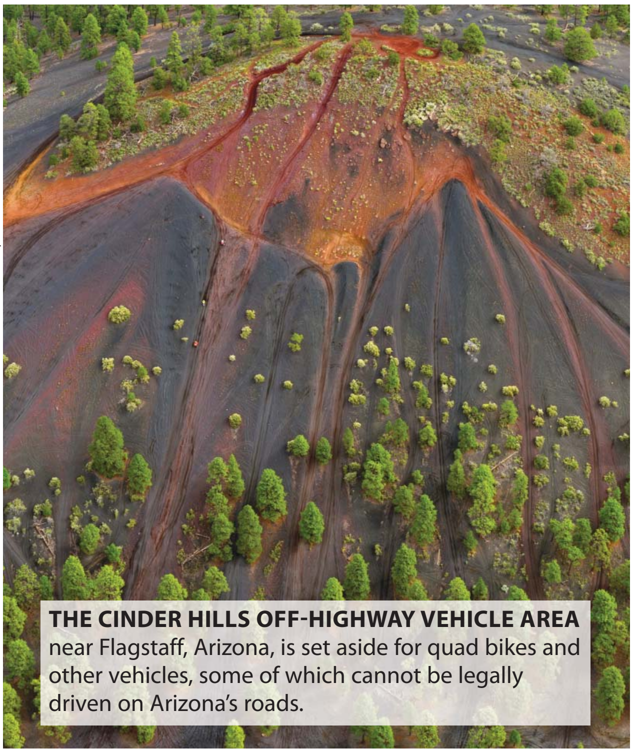
Where's my flying car?

Charles Day

"Silicon Valley is full of very smart people, but they don't always get the laws of physics. Gravity is a formidable adversary." The quote comes from John Leonard, a mechanical engineer from MIT. His remarks closed a recent news story in the *New York Times* about Kitty Hawk, a startup based in Mountain View, California. The company makes ultralight electric-powered flying machines.

The Flyer, as the machine is known, is designed to take off from and land on water. Equipped with two pontoons, it resembles a Jet Ski in that the operator mounts and straddles the fuselage like a motorbike. It also resembles a drone. Arrayed around the rider are eight propellers that provide lift and propulsion.

A sleek promotional video for the Flyer shows a woman who hops on the machine to fly across a lake to join her friend for dinner in much less time than it would take her to drive around the lakeshore. Judging by the video, Leonard's skepticism could be misplaced. The Kitty Hawk Flyer has overcome gravity triumphantly. But whether it has done so efficiently remains to be seen. Although the company has released the Flyer's top speed, 40 km/h, it has not disclosed how far it can fly on one charge of its battery.



MICHAEL COLLIER, WWW.MICHAELCOLLIERPHOTO.COM

THE CINDER HILLS OFF-HIGHWAY VEHICLE AREA near Flagstaff, Arizona, is set aside for quad bikes and other vehicles, some of which cannot be legally driven on Arizona's roads.

The question Where's my flying car? has become a shorthand for the failure of science and technology to deliver an advanced future as promised. "When we were kids, they made it seem like it was just around the corner," complained George Costanza in "The Dealership," an episode of *Seinfeld* that first aired in 1998. Jerry Seinfeld voiced his own disappointment at the absence of flying cars and underwater bubble cities: "It's like we're living in the fifties here."

To be fair, the technical challenges of building a practical flying car are formidable. Given the tight topography of urban landscapes, a flying car should be able to take off and land vertically like a helicopter, but more quietly.

Besides the laws of physics, flying cars must also obey the laws of the land. According to Kitty Hawk's FAQ webpage, "the Flyer operates in the FAR 103 Ultralight Category of US FAA regulations. It does not require registration or a pilot's license and may be flown in uncongested areas for recreational purposes." Worries about noise and crashes could relegate flying cars to designated areas, as is the case for quad bikes and some other off-highway vehicles.

Scientists are expected to tout the future technological benefits of their research. That's fair. The general public, which ultimately funds research through taxes, can reasonably expect payoffs. But scientists should be careful not to overpromise. In their August 2007 PHYSICS TODAY article, "Graphene: Exploring carbon flatland," Andrey Geim and Allan MacDonald managed expectations deftly when they asked,

> What kind of mind-boggling technology might emerge from graphene? Before we proffer an answer, imagine you are on a boat trip watching a school of dolphins. Everyone is mesmerized by the magnificent animals until someone spoils the moment by voicing the unromantic question, "But can we eat them?" One-atom-thick materials have only recently been spotted in our universe and most researchers are happy, for the moment, to expand our understanding of this new and captivating type of matter. PT

READERS' FORUM

Commentary

Pursuing science across nationalities and disciplines

At our home base at the Okinawa Institute of Science and Technology (OIST) Graduate University, my wife, Anya Dani, works as an art conservator in collaboration with local museum personnel to preserve Okinawan artifacts, and I run a physics research unit specializing in femtosecond spectroscopy. In December 2014 we took the long journey to Buffalo State College (BSC) in New York, where Anya's mother, Katherine Conway-Turner, had recently become president.

Barely off the plane, we headed to BSC for a tour of the art conservation and physics departments to find out about their latest projects.

Sipping tea in the art conservation department, I spoke with scientist Aaron Shugar and conservator James Hamm, who explained to me the importance of taking cross sections of paintings to analyze the layers of paint and other decorative coatings. Such analysis enables art conservators to uncover critical information about the history and authenticity of a piece of art and to aid in its restoration.

According to Aaron, the conventional approach of using a scalpel to remove a small cross section of the artwork is not ideal and could damage the painting further. Curious about my research, Aaron asked if a femtosecond laser could be used to create a clean cross section of a painting. In theory it could, but I had certainly never tried it. I had used femtosecond lasers to engineer optoelectric devices, image electrons in motion in a solar cell device, and study photocarrier dynamics in novel materials.[1] But never had I fired laser beams at a painting.

Anya immediately appreciated the value of the idea and saw it as a good opportunity for my research unit to partner with the art conservation programs at both OIST and BSC.

Many physicists might have left it there. But having just begun my career at OIST, a new international research institute that prides itself on interdisciplinary research, I saw the collaboration as a great opportunity to dip my toes in unfamiliar waters. By using femtosecond lasers to solve an art conservation problem, I could break down barriers between the two seemingly distinct disciplines and potentially make an important contribution to the study of cultural heritage. And it certainly helped my wife working alongside me professionally; after all, we make a good team in our personal lives.

I made no promises to Anya, Aaron, or James. If I could find time to work on the project, I would do so with enthusiasm. Before our tour was over, Aaron handed me a package of paintings to work on, if time ever permitted. Anya and I returned to Okinawa with the precious cargo safely stowed in our luggage.

KESHAV DANI, leader of the femtosecond spectroscopy unit at the Okinawa Institute of Science and Technology and author of this Commentary, standing outside one of the university's skywalks.

Paintings and lasers

The paintings sat in my office collecting dust for several months. In the summer of 2015, Anya gave the project a nudge by hiring an intern from the art conservation department at BSC to pursue, among other things, our interdisciplinary idea. After many months of collaboration between OIST's femtosecond spectroscopy unit and the OIST and BSC art conservation programs, we successfully demonstrated that femtosecond lasers could cut a tiny cross section from the corner of a painting with minimal damage to the surrounding area.

Unlike normal lasers that produce a continuous light beam, femtosecond lasers produce extremely short pulses that last just a few millionths of a billionth of a second. During that seemingly insignificant amount of time, the pulses can deliver more power than that needed to launch a shuttle into space. Moreover, femtosecond lasers deliver their energy so quickly that damage from heat transfer is avoided.

Culminating in a recent publication,[2] our interdisciplinary and international collaboration provided a safe and nondamaging new technique for analyzing and sampling artwork.

Although such collaborations between scientists and art conservators aren't widespread, that sort of research is commonplace at OIST. Since I joined the institute in late 2011, I have witnessed mathematicians working with ecologists, chemists with engineers, and physicists with biologists to solve big scientific problems that no one discipline could solve alone and to innovate at the boundaries of academic disciplines.

Femtosecond light

Thanks to the close-knit community at OIST, I get exposed to worlds outside my own, including that of neurobiologists. In a collaboration that grew out of a conversation at a weekly OIST tea in 2012, we learned with Takashi Nakano and Jeff Wickens of the neurobiology unit that it might be possible to manipulate brain activity using femtosecond lasers. Together with chemists at the University of Otago in New Zealand, we attached gold nanoparticles to liposomes (spherical vesicles made of a lipid bilayer), preloaded them with dopamine—a key neurotransmitter in the central nervous system—and used femtosecond lasers to repeatedly release precise pulses of dopamine and other chemicals.[3]

In that truly interdisciplinary research, chemists, neurobiologists, and physicists worked together to design an experiment that capitalized on our various areas of expertise. Our latest results[3] demonstrate the applicability of the technique to interface with neural functioning, with implications for future brain and behavior research.

Using powerful femtosecond lasers to nondestructively release chemicals in a brain slice may be an unexpected application. But in general, neuroscientists are no strangers to femtosecond lasers: The devices are used ubiquitously in two-photon microscopes to image neurons.

At a swing dance class at OIST in the fall of 2014, graduate student Viktoras Lisicovas, who worked in the information processing biology unit, approached me about building a novel type of two-photon microscope that would allow him to image multiple neurons simultaneously in a live *Caenorhabditis elegans* roundworm. A traditional two-photon microscope, in which a tightly focused optical beam is scanned across the field of view, was too slow to record such an event.

So we embarked on a project to build a novel two-photon microscope demonstrated by Yaron Silberberg and colleagues at the Weizmann Institute of Science[4] and independently by Chris Xu and colleagues at Cornell University.[5] Instead of focusing the light beams tightly in space, as conventional techniques do, we focused them in time, which allowed us to image simultaneously a larger field of view and thus multiple neurons in *C. elegans*. With the first images just now coming out of our microscope, we hope that this work between physicists and neuroscientists will lead to a deeper understanding of the collective behavior of neurons in live *C. elegans*, and fruitful future collaborations between physicists and neuroscientists in general in the years to come.

A new model

Interdisciplinary and international research embodies OIST's core values. By actively discouraging the separation of scientific disciplines—both metaphorically and physically—and by having more than 50 countries and regions represented in the university community, the institute is at the forefront of a new model of research and education. In my unit alone, our 13 people represent 8 nationalities and speak more than 15 languages, including French, Lithuanian, Cantonese, Mandarin, Filipino, Hindi, and, of course, Japanese and English.

Without the support and administrative structure of OIST, the breadth and depth of collaborations I've described between physicists and people from other disciplines would probably never have happened. The sense of trust and teamwork that has developed among the faculty across disciplines, the willingness of researchers to try innovative ideas, and the flexibility in funding, personnel, and experimental setup all help in developing successful interdisciplinary projects that further our shared pursuit of knowledge.

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LETTERS

More details on Israel's water story

In a letter in the January 2017 issue of PHYSICS TODAY (page 12), Gabriel Antonius takes offense at a report in the June 2016 issue (page 24) that covers Israel's innovative water technology. He claims that "a key policy explaining the effectiveness of Israel's water management" is "monopolizing water in occupied Palestinian territories" by denying Palestinians the right to drill wells or repair existing ones and by destroying wells, irrigation systems, and water lines. The source for that claim is one report from 2009 by Amnesty International, an organization known for anti-Israel incitement[1] but certainly not known for its expertise on water use and maintenance. That eight-year-old, biased report has been widely debunked in several detailed documents.[2]

Since the signing of the Oslo agreements between Israel and the Palestinian Liberation Organization, the amount of fresh water available to the Palestinian Authority (PA) has increased considerably. In fact, if one takes as starting point the year 1967 when Israel gained control over the West Bank, per capita freshwater consumption in the Palestinian-controlled regions of the West Bank increased by more than 30% over the ensuing 40 years, despite a threefold increase in population. In 1967 only 10% of the Palestinian households were connected to the water infrastructure, whereas by 2012 that figure had risen[2] to 95%. Furthermore, the joint water committee established in the Oslo accords in 1995 has approved approximately 100 new wells and 55 upgrade requests in the areas under jurisdiction of the PA in the West Bank. The approvals resulted in a 50% increase in annual freshwater availability, to more than 250 million cubic meters—about 10% beyond that called for in the accords.

Careful consideration of the historical, political, and cultural context offers a much clearer insight into the regional water issues than impressions gleaned from a superficial view of the situation. One such study is a scholarly thesis that analyzed the water issue in the context of the political failings on both sides, including internal Palestinian politics that undermined the water agreements.[3]

Examples of politically motivated impediments to water supply abound.[2] For instance, Palestinians refused to accept a donation from foreign donors of a seawater desalination plant on the Israeli coast for their exclusive use.[2] They also have refused donations to set up sewage treatment plants, and as a result less than 8% of the sewage from Palestinian towns and cities is treated. Some 30% of the remaining 92% effluents are treated by Israel after flowing into Israel by way of polluted streams; infusion of untreated sewage water—some 33 million cubic meters per year—into the Mountain Aquifer endangers the viability of that important water source. Furthermore, 250 illegal wells dug by Palestinians were documented[2,4] from 1995 to 2005, accounting for 10 million cubic meters of water per year. Because the flow of aquifer water is from east to west in the region where those wells were dug, the illegal drilling further endangers the delicate balance required in maintaining underground water quality within Israel.

Gaza is in a far worse situation than the West Bank. Immediately after Israel's withdrawal from the Gaza Strip in 2006, over 3000 unapproved wells were dug, which caused a severe drop in the aquifer level.[2] Agricultural methods in Gaza not only waste water, but they also allow fertilizer to enter the already depleted and polluted aquifer. The only solution for Gaza to avoid a true humanitarian crisis is cooperation on resource management with Israel, which looks unlikely now due to lack of political will between the ruling Hamas and Israel. Here again, political impediments have made their mark. A new sewage treatment plant funded by the World Bank is ready for operation in Gaza, but there is no electricity to run it: PA president Mahmoud Abbas has cut off payments for electricity to the Hamas-controlled Gaza Strip.[5]

In short, without belittling the very real water problems faced by the PA, particularly in Gaza, the picture is much more complex than Israel monopolizing this precious resource. Efforts to improve the situation are taking place, but there are many political obstacles. In fact, rather than, as Antonius says, "tacitly endorsing the brutal oppression of the Palestinian people" by publishing the June 2016 article (as stated by Antonius), the American Institute of Physics has shown the important role scientists can play in improving regional quality of life. Many of the technologies showcased in that article could go a long way toward alleviating the problems.

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Magnetic monopole search, past and present

For a longtime magnetic-monopole aficionado like me, it was thrilling to learn from Arttu Rajantie's article (PHYSICS TODAY, October 2016, page 40) that we soon shall have data from the highest available energies at the Large Hadron Collider on whether magnetic monopoles with mass up to a few TeV have been detected.

Such an observation would be an even bigger shock to the standard model than would have been *non*-observation of the Higgs boson at mass 125 GeV. As Charles Goebel concluded in 1970, a consistent description of photon–monopole scattering requires the monopole to have a radius much larger than its Compton wavelength.[1]

Sometime later I developed another argument for the same conclusion.[2] The reasoning used simple energy considerations. In principle, a monopole could be confined in a region not much larger than its Compton wavelength, with only a modest addition to its energy. However, the magnetic Coulomb field outside that region would carry an energy much greater than the rest energy. To avoid that contradiction, the monopole radius should be at least an order of magnitude bigger than the Compton wavelength.

Dirac's quantization condition on the product of electric and magnetic charge holds in quantum electrodynamics and in the standard model. Thus in either of those theories the monopole charge cannot be spread out because little bits of magnetic charge would violate the quantization condition. As Rajantie notes, there are models, such as the 't Hooft–Polyakov model,[3] which give a very good classical-field approximation, in terms of $SU(2)$ gauge fields, for the interior structure of a monopole.

Another possible dynamic would be a confinement mechanism for fractional monopoles, analogous to quark confinement in quantum chromodynamics. Therefore, finding a monopole with mass of a few TeV would imply the existence of new objects on scales of several hundred GeV or less to account for the fact that the magnetic charge is spread out. At the moment, we have no evidence for such objects. Thus discovery of a monopole would motivate searches for new phenomena at lower energies, which in turn would require dramatic supplementation of the standard model.

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In the article by Arttu Rajantie on the search for magnetic monopoles, I noticed there was no mention of other monopole searches that had negative results. The most significant of those is the work by Luis Alvarez and his coauthors.[1,2,3] The references to Rajantie's figure 4, the plot of monopole flux versus monopole mass, cite experiments by Alvarez and his colleagues. A description of the implications of their work would have been helpful.

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The feature article by Arttu Rajantie describes the various hypotheses concerning the existence of magnetic monopoles and attempts to discover them. However, it did not cover some of the earlier efforts—in particular, those by Henry Kolm and by Luis Alvarez. Both men thought that a search for magnetic monopoles in deep-sea sediments might be productive because in deeper parts of the oceans, the sedimentation rate is about 1 millimeter per millennium. With a constant supply of extraterrestrial material, the slow sedimentation rate would help in finding monopoles because they would be more concentrated than in other sediments.

I was involved in both of those

attempts because of my interest in deep-sea sediments and their ability to record polarity changes in Earth's magnetic field.[1] Alvarez's method at the University of California, Berkeley, was to take a sample of sediment and pass it through a circular solenoid; the current in the solenoid would have increased each time a monopole passed by. I do not believe Alvarez had any positive results.

Kolm was a staff member at the Francis Bitter National Magnet Laboratory at MIT, and his method was to move the sediment across a strong magnetic field,[2] which would cause a monopole to be dragged out from within a magnetic particle, pulled through the magnetic field, and then trapped in an emulsion. He received barrels full of sediment off a vessel from the Scripps Institution of Oceanography working in the Pacific Ocean and one from the University of Miami working in the Atlantic, but he saw nothing in them that was very promising. He then designed a magnetic rake to be towed behind a vessel and dragged through the sediment. The idea was to gather magnetic particles that might have collected monopoles and to sample a much greater volume of sediment than could be provided with barrel dredges. I do not believe he obtained any positive results.

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▶ **Rajantie replies:** Alfred Goldhaber raises an interesting point that the radius of a magnetic monopole has to be larger than its Compton wavelength. As with the 't Hooft–Polyakov monopole, the nonzero size could be due to some new particles whose mass would have to be around 10–100 GeV for a TeV-scale monopole. So far the Large Hadron Collider (LHC) has produced no evidence of new particles beyond the standard model, but that does not necessarily rule out the existence of magnetic monopoles because we currently do not have a good enough theoretical understanding of the properties those particles would need to have.

The requirement for a finite monopole size is a consequence of the monopole's strong magnetic charge, and the electromagnetic duality means that the same conclusion would also apply to particles that have a strong electric charge. The strong charge means that the classical picture of a field around a static source may not apply, and hence the nonzero size could also be due to quantum mechanical effects without any new particles.

Our theoretical understanding of strongly coupled quantum field theories is limited, but lattice field theory simulations[1] show that in its simplest form, quantum electrodynamics allows relatively strong charges, although not as strong as the Dirac charge of a magnetic monopole. The maximum charge allowed for a magnetic monopole in the standard model without any new particles is an interesting and still open theoretical question.

Either way, the argument implies that if magnetic monopoles exist, they would have a nontrivial size and shape, which could be studied in future experiments.

Because of space limitations, I could not do justice to the wide range of fascinating ways people have been trying to find magnetic monopoles. Christopher Harrison and Ken Frankel highlight some of the pioneering attempts. Although those searches did not produce positive results, they paved the way for future experiments, and their method of using a SQUID (superconducting quantum interference device) to search for monopoles is still being used in the MoEDAL experiment at the LHC.

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LIGO backstory delights and displeases

Robert Garisto tells us (PHYSICS TODAY, August 2016, page 10) of the secrecy he maintained at *Physical Review Letters* prior to the announcement that a "chirp" had been detected at the Laser Interferometer Gravitational-Wave Observatory (LIGO). On sabbatical at Caltech, I had the pleasure of joining local astronomers to watch the press conference from the astronomy and astrophysics auditorium (whose street number, 1216, is the Lyman-alpha wavelength in angstroms). But as we left after the dazzling announcement, with music in our ears, they gave out coffee cups and bumper stickers each with the data already emblazoned on it. I should have hung out in the print shop days before!

Further, if I had a name that began with the letters Aa, I should have joined the LIGO collaboration, which published as "B. P. Abbot et al." with more than 1000 coauthors.[1]

Reference

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I was unpleasantly surprised by the tone of Robert Garisto's Commentary in the August 2016 issue. There are two principal reasons for my displeasure.

First, cheerleading of any form in scientific reporting is entirely inappropriate. It brings several issues into question. Were the referees preferentially chosen so as to guarantee a positive outcome? Was the discovery truly momentous? With regard to the second question, I doubt that many relativists would have thought that gravitational waves didn't exist. Entirely different is the truly momentous experimental observation of the Higgs particle, for example. The self-aggrandizing posture of the editor of *Physical Review Letters* would make us think that even he was a fully involved partner in the discovery.

Second, it's fine to use nicknames in private or in a group. But referring to Gabriela González as "Gaby" is, in a sense, demeaning to her, and it is inappropriate in a larger context. The practice is reminiscent of the overly enthusiastic reporting of the early space missions as if they were great athletic events, of early spaceflights, and of often unfortunate political postures—for example, referring to former secretary of defense Donald Rumsfeld as "Rummy."

I look for more dignity and less personality in scientific reporting.

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Guns on campus: Is that physics?

The report "Texas law sets off debate about guns at universities" (PHYSICS TODAY, July 2016, page 26) seemed out of place in your magazine. The subject is not scientific, and the discussion was not handled in a scientific manner.

I see the scientific process as basically an endless loop of five steps:

1. Eliminate all emotions and preconceived notions related to the topic.
2. Take as much data as possible, as randomly and nonjudgmentally as possible.
3. Analyze the data for anomalies and patterns. Test to see if they correlate with any theories.
4. Subject any findings to an open and intensive peer review.
5. Cycle through the steps again based on responses and findings, and look for data in other new directions.

For example, as a physicist, even if I am strongly religious, data showing the possibility of purely mechanical random creation should not be discarded or ignored simply because it threatens my beliefs.

The only concrete data in the article were the laws themselves, the legal reactions to those laws, and two self-inflicted gunshot wounds. All other statements were either emotional conjectures about scary things that might happen or someone's beliefs about possible events. No actual case histories were presented of concealed-carry-permit holders doing any of those scary things. To the contrary, according to the article, Utah and Idaho have seen no change in attitudes or behaviors on campus as a result of the new law.

One possible source of data about the effect of concealed carry on campus is the seemingly infinite supply of statistical studies floating around. How many were truly scientific studies with useful data? What do they say?

Another source might be a study of the individuals on campus to determine, for example, any influence their backgrounds and training might have on their current attitudes. Have they had gun training or endured gun-related trauma? Another source of data might be an examination of the requirements to obtain a concealed-carry permit. Would they inherently make someone a safer person with a gun? Another might be a study of police records to see if the good guy–bad guy issue is a real problem.

I don't claim to be on any side of the issue, except to want to believe the statements made about Utah and Idaho. Gun control is much more a political issue than a scientific one. But shouldn't we as scientists conduct a proper, nonjudgmental data analysis?

By the way, campuses have never been gun free. Many holders of concealed-carry permits ignore the signs and carry all the time, except when faced with metal detectors.

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The article about guns on college campuses has me puzzled. Because technical physics content is completely absent, a peer reviewer would be hard-pressed to explain how the article aligns with PHYSICS TODAY's mission statement. Further, it does not address the main issue, namely, the inherent conflict between publicly funded institutions and the exercise of individual rights. Instead, it reports mainly on the expressed fears of various individuals.

A discussion of political policy requires something other than expertise in physics and knowledge of current events. For that discussion, I recommend two written works by economist and historian Murray Rothbard. His essay "The Mantle of Science" and his book *Science, Technology, and Government*, both available online, are important for understanding the role of deductive logic as it applies to human action generally and to public funding of universities and scientific research specifically.

Christopher Barsi
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Metal–organic framework extracts water from thin air

Until now, atmospheric water at low humidity could be condensed only at great energetic expense. A new material overcomes that challenge.

An average-sized living room of 90 m^3 in a temperate climate—25 °C and 60% relative humidity—contains about a kilogram of water vapor dispersed in the air. Even in the desert, where liquid water is scarce, relative humidity typically hovers around 20%, so there's still plenty of water in the air. Because it's constantly refreshed by evaporation from the ocean and atmospheric circulation, the water in the atmosphere can be considered a limitless renewable resource.

Now Omar Yaghi of the University of California, Berkeley, Evelyn Wang of MIT, and their colleagues have taken a step toward tapping that resource by creating a water-collecting device that works at relative humidity as low as 20% and requires no external energy source.[1]

Their concept is based on a metal–organic framework (MOF), a highly porous material whose properties can be tuned by varying the metal and organic components and how they're put together. With their MOF-based devices, such as the one in figure 1, they performed two proof-of-principle demonstrations: one in a humidity-controlled lab and another on the roof of a building on the MIT campus.

Any drop to drink

Hot air can hold many times as much water vapor as cold air can. When a volume of air holding a given amount of moisture is cooled, therefore, there comes a temperature—the dew point—at which the water has no choice but to condense. The phenomenon is exemplified by the dewdrops that cling to blades of grass on a cool morning—or by the fogging of eyeglasses when one enters a warm room.

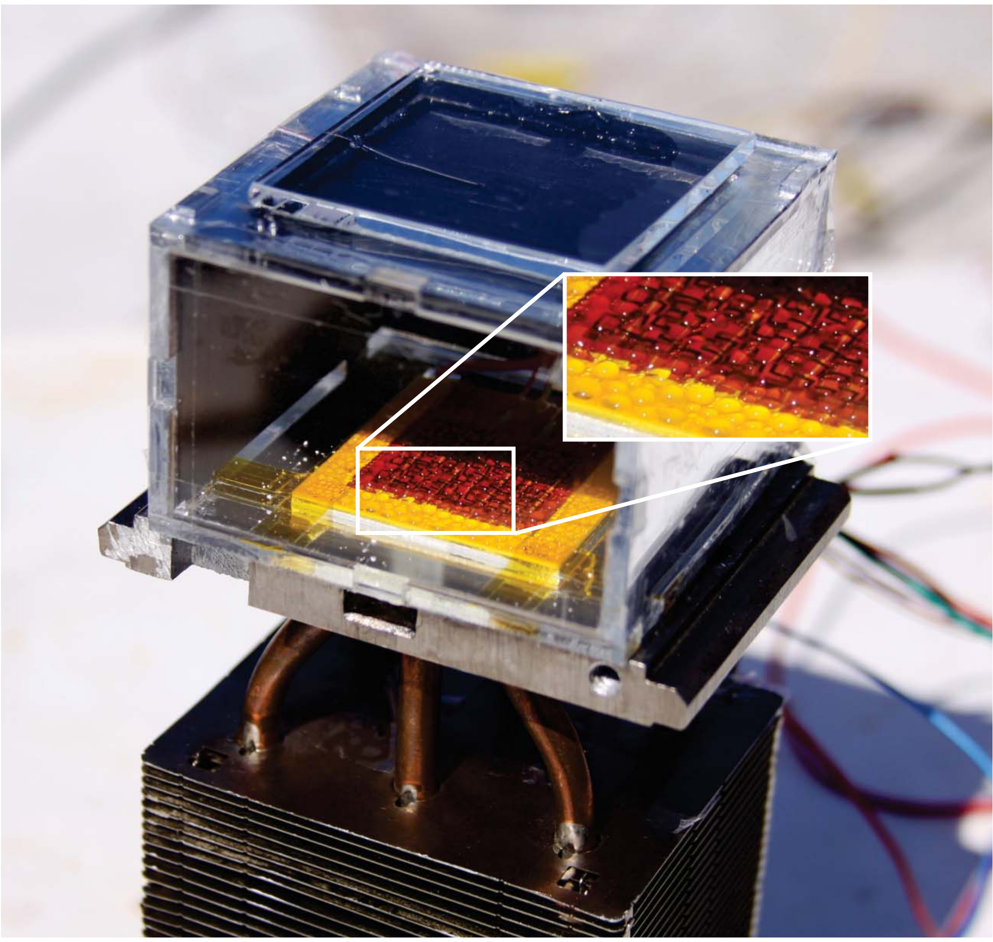

FIGURE 1. A WATER HARVESTER on an MIT rooftop consists of a small sealable chamber containing a temperature-controlled condenser (the yellow and orange square, 5 cm on a side) and a layer of humidity-attracting metal–organic framework (not visible). As shown in the inset, drops of water collect on the condenser even though its temperature is the same as that of the outside air. (Courtesy of Evelyn Wang.)

Schemes for harvesting the water that nature obligingly condenses into dew are nothing new.[2] In arid regions, however, the daytime relative humidity may be so low that the nighttime temperature never drops below the dew point.

Happily, many so-called hygroscopic materials exist that, by virtue of their surface or bulk properties, can extract water from the air even above the dew point. Sugar is a familiar example: Dry hard candies become sticky when exposed to humid air for too long. Another example is silica gel, a porous form of silicon dioxide commonly used as a desiccant. Because silica gel has both a strong surface affinity for water molecules and a high surface area, it can hold up to 40% of its own weight in water.

The water held by a hygroscopic material is not yet in liquid form, but it can be made so; designs for desiccant-based water harvesting systems[2] have been proposed and patented since at least the 1940s. Their basic operating principle is as follows: Cool, moist air circulates over the desiccant, usually at night. When the desiccant has captured enough moisture, it's sealed in a small space and heated to force the water to re-evaporate. The moisture-laden air is cooled to the ambient temperature to condense the water, and the desiccant is ready to be used again.

The problem is that conventional desiccants stop working at low relative humidity, require an impractically high regeneration temperature, or both. For example, silica gel no longer takes in water at around 40% humidity, and it must be heated to around 120 °C to extract the water it's holding. Other conventional materials can improve on one of those limitations or the other, but not both at the same time. The dilemma can be understood as a simple trade-off: Materials with lower affinity for water have higher cutoff humidities, and those with higher affinity for water must be heated to higher temperatures to get that water out.

MOF-801

A growing class of designer porous materials, MOFs are built out of metal-based nodes and carbon-based links arrayed in a regular crystalline structure. The first stable MOFs were reported in 1999 by two groups, including Yaghi's.[3] Tens of thousands of MOFs are now known, and they're being explored for applications such as catalysis and gas storage.[4] Their appeal stems from their customizability: By choosing the right metal and organic units, one can independently tune the pores' size, shape, topology, and surface chemistry.

The new water harvester uses a material called MOF-801; shown in figure 2a, it's made of zirconium oxide and fumaric acid. A few years ago, Yaghi and his group identified it as having advantageous water-adsorption properties.[5] At extremely low humidity, MOF-801 takes in little water, but as the relative humidity is increased to around 10%, the water uptake shoots up sharply, then levels off. As shown in figure 2b, the shape of the uptake curve changes little with temperature. At 25 °C and 20% relative humidity, the MOF is mostly saturated with water. Then, because 20% relative humidity at 25 °C corresponds to less than 3% relative humidity at 65 °C, the MOF can be made to release that water with a temperature swing of just 40 degrees.

X-ray and neutron diffraction of water-saturated MOF-801 helped reveal how the material can overcome the trade-off between high regeneration temperature and high operation humidity. The MOF's interconnected pores have structurally distinct shapes: tetrahedral (orange and green in figure 2a) and octahedral (yellow, though mostly obscured). As the material starts to take in water, H_2O molecules attach via hydrogen bonds to the zirconium clusters—but only in the tetrahedral pores. The octahedral pores remain empty until the tetrahedral ones are full, at which point newly arrived water molecules cling not to the MOF but to other water molecules. The shapes of the pores are just right to allow adsorbed water molecules to form hydrogen bonds with one another.

That strong network of interactions among stored molecules, with fairly few bonds between the water and the MOF, is presumed to be why MOF-801 takes in water so readily but also releases it easily. Furthermore, Yaghi and colleagues found that the material can endure many adsorption–desorption cycles with no structural damage.

Heat and water

Having created the new MOF, Yaghi struck up a collaboration with Wang, an engineer with an interest in thermal systems, to make use of it. At first, the application they had in mind was a so-called thermal battery. When water (or anything else) is adsorbed onto a surface, heat is released; conversely, when water returns to the gas phase, heat is consumed. A device that can harness that heat of adsorption and desorption, using water from a self-contained reservoir, could be a more efficient means of climate control in electric cars than running an electric heater or air conditioner off the car battery.[6] The water-harvesting idea grew out of the thermal battery project. "It operates based on the same physics," says Wang.

The proof-of-principle water collector, designed and built by Wang's student Hyunho Kim, is conceptually similar to other desiccant-based systems. Air is passed over the MOF in an open chamber to saturate it with water. Then the chamber is closed and the MOF is heated. Water is released and quickly liquefies on an ambient-temperature condenser.

Importantly, though, the 65 °C needed to regenerate MOF-801 is much easier to achieve than the 120 °C required to extract the water from silica gel. Direct but unconcentrated sunlight can heat a

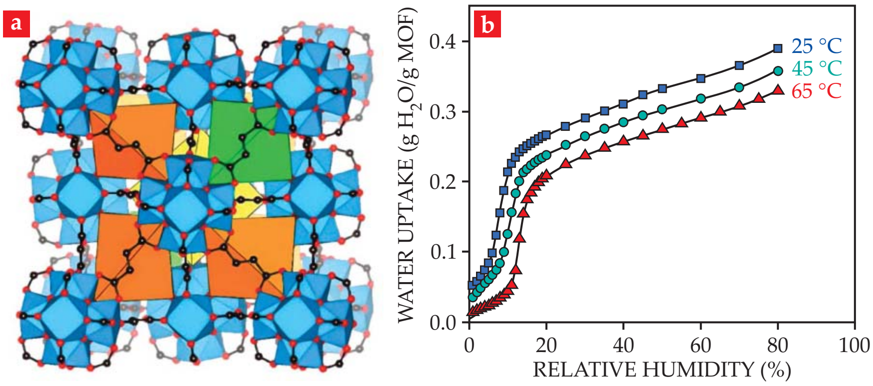

FIGURE 2. THE METAL–ORGANIC FRAMEWORK MOF-801 (a) is made of zirconium oxide clusters (blue polyhedra) and fumaric acid molecules (whose atoms are indicated by black and red dots). The size, shape, and surface chemistry of its internal pores (yellow, orange, and green) make it an ideal water collector. Because its isothermal water-uptake curves **(b)** feature a sharp upswing at low relative humidity, it can capture water even in dry air and release it under modest heating. (Adapted from refs. 1 and 5.)

dark-colored surface to a considerably higher temperature than the ambient air. On a 25 °C day, such simple solar heating can easily reach 65 °C.

Wang and colleagues used a heating panel darkened with graphite, which can be seen on the top of the demonstration chamber in figure 1. "One of the challenges we faced is that MOFs have low thermal conductivity and need mechanical support," says Wang. "So we infiltrated the MOF material into a porous copper foam, which is readily available." The MOF-imbued foam, not visible in the photo, was affixed to the inside of the top wall of the chamber.

The condenser at the bottom of the chamber was held at the ambient temperature even as the graphite and MOF were heated by the Sun. Sure enough, drops of water—visible in the inset—began to accumulate. For simplicity in their demonstration, the researchers chose to use active refrigeration to maintain the condenser's temperature. But for off-the-grid operation, they could just as easily have cooled it passively by connecting it to a heat sink.

Because the demonstration used less than 2 g of MOF, the collected water amounted to just a fraction of a milliliter. Wang and colleagues estimate that a larger device could harvest more than 200 mL of water per kilogram of MOF-801 under 20% relative humidity. Furthermore, if the MOF layer were made sufficiently thin, it could adsorb and desorb water quickly enough to perform up to 12 heating and cooling cycles per day. (Cooling the MOF from its 65 °C high is as simple as shading the graphite panel from sunlight.) In that case, a device could produce up to 2.8 L of water per kilogram of MOF per day.

Dust and other airborne particles can condense along with the water vapor. "We expect a filter would be needed, as it is with other atmospheric water generators," says Wang. "But we don't anticipate any other issues with the cleanliness of the water."

What may be an issue, however, is cost. Although zirconium, the metal component of MOF-801, is not among the rarest elements, it costs around $150 per kilogram. Yaghi and his group are working on replicating MOF-801's properties with cheaper metals such as aluminum. Still, says Wang, "We don't anticipate that this technology will ever compete with other nontraditional water systems such as desalination. It's more suitable for isolated regions where there's no water infrastructure, or no water at all."

Johanna Miller

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Biological tissue can behave like a liquid crystal

Topological defects trigger the death and removal of cells.

Consisting of a small number of cell layers, an epithelium is the protective membrane that lines animal organs and embryos. The epithelium must continually renew itself, and its cells form a dense colony whose local tension fluctuates during morphogenesis, growth, and tissue repair as some cells are born and others die. Despite the ubiquity of those processes, however, the mechanical and biochemical mechanisms that regulate tensional homeostasis and determine which cells are targeted for removal have long been obscure. Dying or injured cells are not the only ones extruded. As biologists discovered in 2012, so are healthy cells whose migration or proliferation overcrowds the tissue.[1]

Intercellular signaling, adhesive junctions, and dynamic stresses generated by the motion of cells are all thought to influence the targeting. But their interplay has made it difficult to disentangle relative contributions. Researchers from the Mechanobiology Institute (MBI) at the National University of Singapore, the Jacques Monod Institute at CNRS and Paris Diderot University, the University of Oxford, and the Curie Institute have now discovered that the arrangement of cells in the membrane may be the primary factor behind the mechanics and location of cell removal.[2]

The discovery builds on earlier efforts in soft-matter physics to model biological tissue as a liquid crystal. Like collagen-producing fibroblasts, smooth muscle, lipids, and other biological cells, certain types of epithelial cells are rod shaped—longer than they are wide. When isolated, the cells move randomly but persistently, powered by their internal hydrolysis of adenosine triphosphate. But in dense colonies, the anisotropic shape prompts them to align into domains, much like rod-shaped nematic liquid crystals, whose orientational order lowers their collective free energy. Also like liquid crystals, the cellular packing contains defects—misalignments in the long-range orientation—that punctuate the separate domains.

When the MBI researchers and their colleagues cultured epithelial cells from a canine kidney into monolayer sheets and imaged them under a microscope, they were not surprised to find pervasive misalignments. The surprise was the defects' profound influence on cell behavior. An analysis of the microscopic snapshots of the cultures revealed that the vast majority of cells extruded from the tissue came from lattice sites that hosted a comet-shaped defect—a misalignment in which cells in the "head" lie

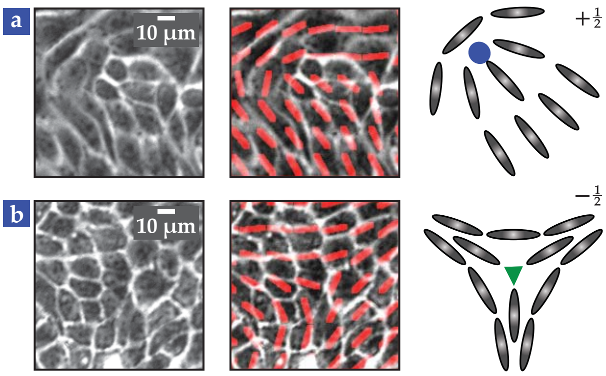


FIGURE 1. MISALIGNMENTS BETWEEN ROWS of elongated cells in epithelial tissue take on the same structure as topological defects in nematic (orientationally ordered) liquid crystals. The top and bottom sequences show microscope images of two types of defects: **(a)** a comet-shaped (+½) defect, in which a row of cells in the "head" is oriented perpendicular to a row in the "tail," and **(b)** a triradius (−½) defect, in which different rows diverge from each other. The cells' calculated orientations (red, middle) reveal the resemblance to liquid-crystal defects (right), whose cores (blue and green) represent points of maximum misalignment. (Adapted from ref. 2.)

perpendicular to those in the "tail." According to Benoit Ladoux, one of the principal investigators in the collaboration, the implication was immediately clear: "The positions of those defects represent a powerful predictor of where cells are likely to die."

The usual suspects

Orientational defects in a collection of motile cells emerge spontaneously as the cells flow en masse. Created in pairs, the defects can migrate apart and annihilate each other on recombining. Epithelia host comet-shaped and triradius varieties, shown in figure 1 and known more formally as +½ and −½ topological defects, respectively. (The classifications refer to the $\pm\pi$ rotations traced by the cell orientations as you go around the defect.) Both types have been observed in elongated biological cells for nearly two decades, ever since the University of Ulm's Hans Gruler and his colleagues noticed them in the pigment cells of human skin and used the framework of liquid-crystal theory to explain the cells' elastic properties.[3]

In some cases, the defects can self-organize into an ordered configuration.[4] In others, they can channel a one-dimensional flow of cells between themselves. This past month Harvard Medical School's Kyogo Kawaguchi and his colleagues at the University of Tokyo and Kyoto University found that ±½ defects control the collective flow of neural stem cells cultured on a glass slide: The neural cells become depleted in the vicinity of a triradius and flow toward a comet-shaped defect.[5] An apparent logjam at the head of the comet causes cells flowing from the tail to accumulate into ever-denser 3D mounds. According to Kawaguchi, the channeled flow covers several millimeters and mimics the migration of cells in part of an adult mammal's brain.

Defects kill

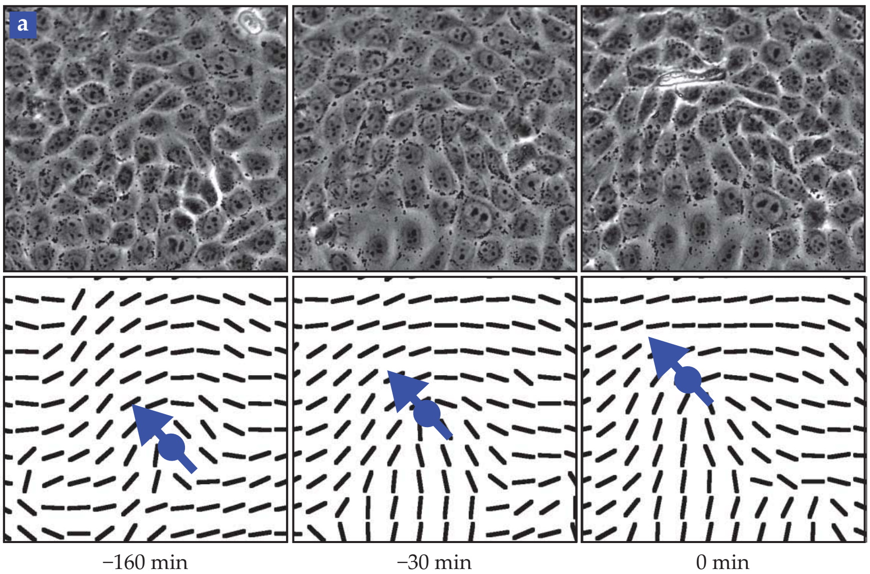
Although epithelial cells are packed more densely than neural stem cells and are more subtly rod shaped, they still migrate toward comet-shaped defects at about the same velocity—tens of microns per hour. To look for a causal role in the correlation found between defect sites and cell-extrusion events, Ladoux and his colleagues scanned relevant areas of the epithelial sheet using traction force microscopy. In that technique, fluorescent particles are embedded in a substrate under the sheet. The forces generated by the cells are determined from the measured displacement of the particles. Having measured those forces, the researchers were able to infer the compressive stress acting on cells near a defect.

The measurements and simulations made by the researchers offered a consistent picture: The distortion on a cell caused by a misalignment with neighbors builds up for hours prior to an extrusion event, as cells in the tail of the comet overcrowd those in the head. And if the compression is high enough, it triggers an extrusion. The phase-contrast images shown in figure 2 illustrate the time evolution, with an extruded cell in white at time zero.

Further corroboration for that extrusion mechanism came from monitoring the activation of YAP, a stress-triggered protein in the cells' cytoplasm, that the researchers observed in the vicinity of a defect. They also observed greater-than-normal levels of caspase 3, an enzyme that signals a cell's impending death.

A complex choreography commences between a dying cell and its neighbors. A contractile cable forms around the cell and acts as a purse string to draw in surrounding cells to gently pinch off the dying piece. The cable is made of the scaffolding protein actin and the motor protein myosin; their coordinated motion provides the force behind the pinching.

The relative force contributions from actin–myosin and the defect compression that triggers cell death are not clear. Compression squeezes the cell, but that alone is unlikely to launch it outward



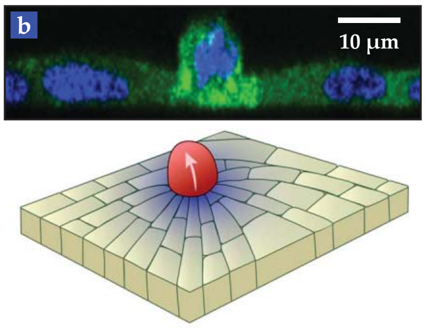


FIGURE 2. TIME EVOLUTION OF A COMET-SHAPED DEFECT. (a) The top panels show a series of microscope images that capture dynamical changes to epithelial cells of a canine kidney in the same 100 μm by 100 μm scene. Bottom panels represent the calculated orientations (black lines) of the cells, modeled as components of a liquid-crystal lattice. The core (blue dot) of the defect migrates upward in the direction of the arrow. Cells in the comet tail become compressed against cells in the head. At a modest threshold stress of about 70 Pa, a cell located in front of the defect core is extruded (white). (A movie is available in the online version of this report.) **(b)** A side-view fluorescence image of an extruding cell is shown above a schematic of the scene. (Adapted from ref. 2.)

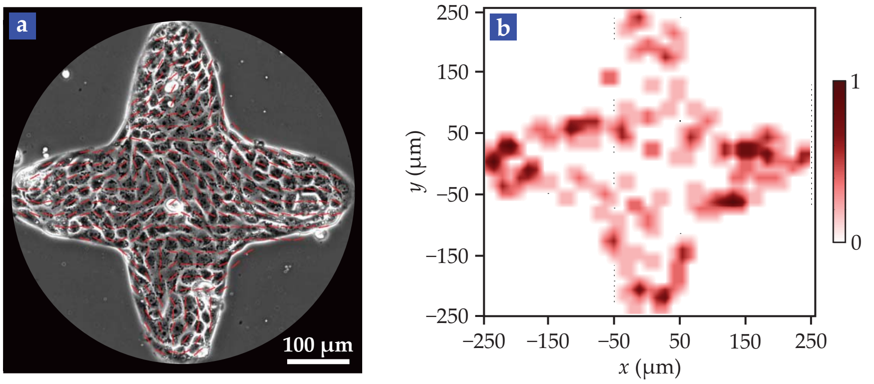


FIGURE 3. GEOMETRY-INDUCED DEFECT PRODUCTION. (a) A star-shaped monolayer of cells produces comet-shaped topological defects predominantly at the tips of its four arms. **(b)** With their higher density of defects, those regions extrude a greater number of cells (red). The color denotes the normalized extrusion number. (Adapted from ref. 2.)

like a tiddlywinks disk. The compression also activates enzymes that degrade cellular proteins, fragment the nucleus, and weaken the cell's adhesive bonds with its neighbors. Those processes lead to the detachment of the dying cell from the tissue. As the purse string tightens, the neighboring cells stretch to prevent a gap.

Intriguingly, a phenomenon akin to extrusion also happens at defects in a generic liquid crystal. Any elongated object, whether an inanimate particle or a biological cell, becomes geometrically frustrated at the core of a topological defect (the blue and green shapes in figure 1). The particle is unable to align with all neighbors simultaneously, so the best way for it to reduce the large elastic energy it experiences near the core is to orient itself out of the plane. In liquid-crystal theory, the maneuver is known as "escape in the third dimension."[6]

Defect control

Although defects emerge spontaneously in biological tissue, it's possible to control their density—and thus the density of extrusion hot spots. Canine kidney cells prefer to align tangentially to the boundary of a substrate, and the researchers cultured their cells in one experiment atop a star-shaped substrate, as shown in figure 3. That geometry forces comet-like defects to predominantly form around the star's four tips.

By contrast, the triradius defect density was higher near the center of the star, but without a commensurate increase in extrusion events there. The experiment further corroborates the causal link: The emergence of comet defects provides hot spots of compressive stress, which lead to a higher probability of cell death.

The demonstrated control over defect density may chart a path for scientists trying to suppress the invasion of cancerous tumors and other pathological tissue in which the process of cell death has gone awry. To influence the process, one can imagine inserting implants surgically to guide cell orientations in a way that produces topological defects.

Could such an approach work? "Why not?" quipped biophysicist Guillaume Charras at the London Centre for Nanotechnology. "I wonder about its practicality as a therapy, though. The usual problem is detection. And if you can detect a cancerous lesion, the most effective strategy is often to just cut it out with a scalpel."

Mark Wilson

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The many dimensions of Earth's landscapes

An airborne imaging-spectroscopy campaign portends the wealth of information to come from future orbital instruments.

Humans are born with built-in remote sensing equipment: With our eyes, ears, and noses, we gather information about far-away objects. When we look at a tree and judge its health based on the number and colors of its leaves, we are performing a sort of spectral analysis. The three types of cone cells in the human eye sense light in three spectral bands; the mantis shrimp, with its 16 types of cones, sees, in principle, much more.

Similarly, a digital camera senses three bands, whereas NASA's *Terra* and *Aqua* satellites each carry an instrument called MODIS (Moderate Resolution Imaging Spectroradiometer) that views Earth in 36 bands. The bands sample a spectral region (405 nm–14.4 μm) that ranges from the visible well into the long-wavelength IR. Data from those instruments help researchers to monitor the oceans and land and categorize Earth's surface into 17 broad classes—for example, savannahs, croplands, and water—frequently called the MODIS land-cover types.

However, multiband instruments leave gaps in the spectrum. Imaging spectrometers fill in those gaps by spanning the wavelength range of interest with hundreds of contiguous bands. The amount of information that can be extracted from an image taken by such an instrument depends on both the spectral diversity of the light coming from a scene and the spectral sensitivity of the instrument.

Several space-based imaging spectrometers are in the works, including one proposed by the Jet Propulsion Laboratory (JPL) called the Hyperspectral Infrared Imager (HyspIRI).[1] In 2013 NASA and JPL launched the HyspIRI Preparatory Airborne Campaign to demonstrate the capability of such instruments. For the job, they turned to the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), which has a similar bandwidth and spectral resolution as the instrument planned for HyspIRI. The aim was to take multiple images of large and diverse areas of California that represent all 17 MODIS land-cover types.

To examine the spectral diversity seen in the HyspIRI-preparatory data, JPL's David Thompson and his colleagues have carried out a statistical analysis of the 2013–14 data set.[2] The results portray a California of high spectral diversity that is distributed in distinct ways for different land-cover types.

How much does a camera see?

The spectral diversity captured by an image can be quantified by a value called the intrinsic dimensionality. In essence, it is the number of independent variables necessary to describe a given data set. Digital photographs taken with an RGB camera, for instance, carry at most three dimensions. The number is not always equal to the number of colors; a scene with many colors could have a dimensionality of 1 if all the colors involve a particular linear combination of red, green, and blue.

The AVIRIS detector measures visible to short-wavelength IR spectra (400 nm–2.5 μm) in 224 contiguous, 10-nm-wide spectral bands. In flight, the instrument sweeps a scanning mirror back and forth perpendicular to the direction of the aircraft's path.[3] When flown at an altitude of 20 km, it has a spatial resolution of about 20 m.

As is the case with other imaging spectrometers, the raw data from AVIRIS come as a data cube; each spatial x–y pixel has a full spectrum along the z-axis. The data that the JPL group used for their analysis included more than 600 flight lines, which they broke into 20 km segments. Each of the more than 4000 segments contains somewhere in the neighborhood of 700 000 spectra. That adds up to nearly 3×10^9 spectra for the entire campaign.

To estimate the dimensionality of a scene, the group used principal-component analysis, a venerable statistical technique that aims to recast a set of possibly correlated independent variables into a new set of uncorrelated variables. Those uncorrelated variables, or principal components, are linear combinations of the wavelength bands ranked in order of their degree of spatial correlation.

The dimensionality is the number of resulting principal components for which the signal is greater than the noise. Consequently, one has to decide what is signal and what is noise. To automate the decision making, Thompson and his colleagues came up with an algorithm that smooths the segment image for each principal component. The signal is taken to be the smoothed data and the noise to be the difference between the smoothed and unsmoothed data.

With that procedure the team obtained the same dimensionality estimates from multiple images—taken months apart under varying illumination—of Ivanpah Playa, a barren, visually unchanging location on the California–Nevada border. That consistency confirmed that the noise-estimation procedure worked as it should and gave the team confidence that seasonal variability seen in croplands, on mountaintops, and for other more mercurial scenes was being correctly determined.

Colorful California

With one of the largest imaging spectroscopy data sets ever collected to hand,

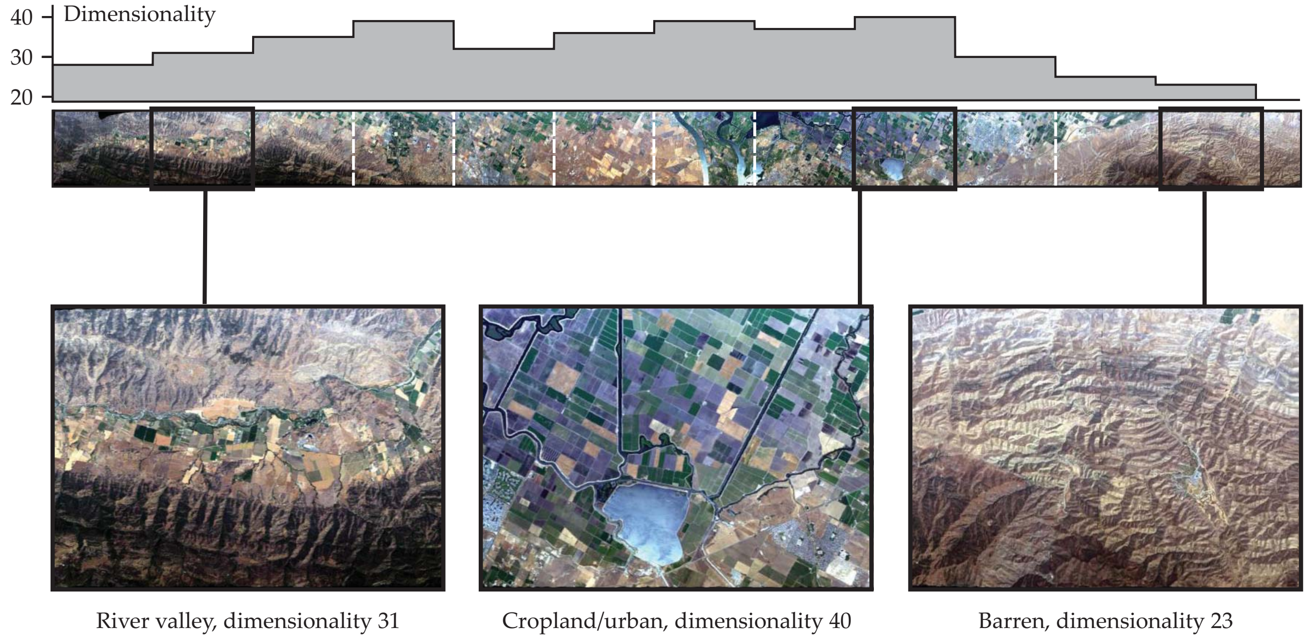

FIGURE 1. IMAGE FROM A FLIGHT LINE running roughly northwest near the San Francisco Bay area in California. The bar chart at the top shows dimensionality estimates for each 20 km segment. Three segments representing different types of land cover are shown magnified at the bottom. (Adapted from ref. 2.)

Thompson and his colleagues set out to evaluate how dimensionality was distributed for the different land-cover types and to look at its stability over time. In addition, they wanted to check the seemingly intuitive notion that spectral diversity should increase as one goes from scenes of open water to natural environments on land to urban scenes.

The average dimensionalities in individual 20 km segments ranged from single digits to the high 40s. For the complete data set, Thompson and his colleagues estimate a dimensionality of about 50. Geographer Dar Roberts of the University of California, Santa Barbara, says that the HyspIRI Preparatory Airborne Campaign provides a good preview of future satellite-borne missions that will look at the entire surface of Earth. "As diverse as California is, it probably still only represents a fraction of the global diversity," he says.

Figure 1 shows a portion of a flight line taken in May 2014 and highlights some representative land-cover types. For some perspective on the dimensionality estimates, consider an RGB digital photograph, which can have at most a dimensionality of 3. In the so-called true-color scheme, those three dimensions, each carrying an integer value between 0 and 255, can encode 256^3 or 16 777 216 different colors. The number of distinguishable things grows exponentially with the dimensionality. "Anything raised to the 20th power is already mind-bogglingly high," Thompson notes. "To the 50th power is even more so."

A 224-band instrument might therefore seem like overkill for scenes with 50 spectral dimensions. But having more bands than strictly necessary could prove crucial. For a case in point, Thompson uses the normalized difference vegetation index (NDVI). The index is calculated as the ratio of the difference and sum of reflectances measured by two spectral bands—one in the visible and one in the near-IR. It rates the relative greenness of vegetation and is often used as a proxy for plant health. But haze from atmospheric aerosols, surface material near the vegetation, the variety of plants present, and many other factors can affect the ratio. The effects of those factors, explains Thompson, end up as assumptions in models designed to infer meaning from the NDVI. By dint of having so many bands, an imaging spectrometer can measure those confounding details and validate or falsify the models.

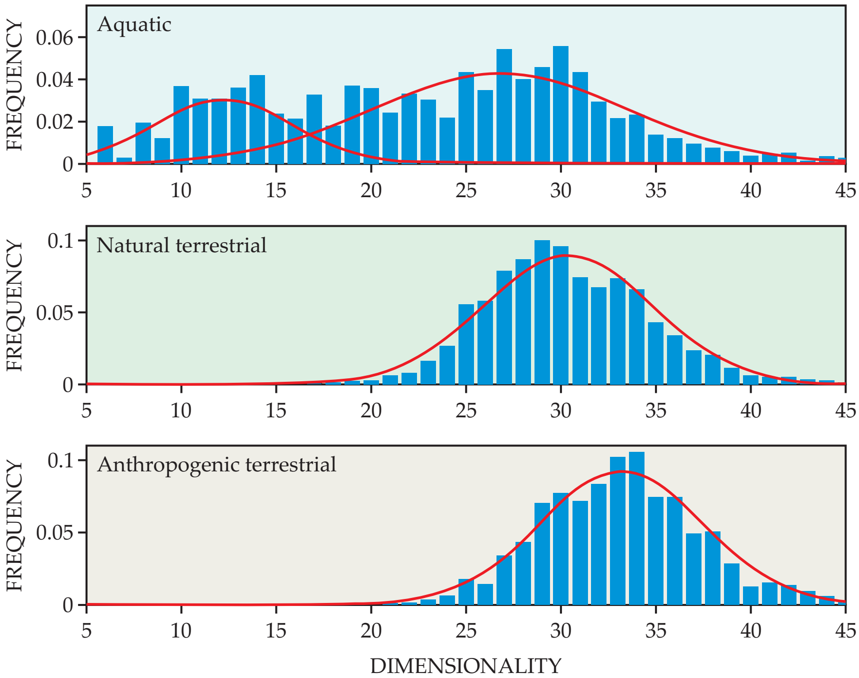

FIGURE 2. DISTRIBUTION OF DIMENSIONALITY for aquatic (top), natural terrestrial (middle), and anthropogenic terrestrial (bottom) environments. The terrestrial scenes are well described by single Gaussian distributions. The broader distribution of the aquatic scenes, better described by two Gaussians, may stem from some segments that contain both water and terrain features. (Adapted from ref. 2.)

Figure 2 shows the dimensionality distribution for three types of scenes. As expected, aquatic scenes, on average, are the least spectrally diverse and urban areas are the most diverse. "When we dig minerals out of the ground and paint them on our cars, that tends to increase the dimensionality," remarks Thompson. Surprisingly, he says, the segments with the greatest spectral diversity were not in a city but in an agricultural area in southern California's Imperial Valley. The heavily irrigated region turns out to produce more than a hundred different commodities, including grains, garden vegetables, livestock, and flowers. That variety gives the area a high spectral diversity.

Terrestrial scenes follow a simple Gaussian distribution, with urban areas and croplands having a significantly higher mean dimensionality than forests and other natural settings. Aquatic scenes, however, are better described by a bimodal distribution. Thompson and his colleagues conjecture that the higher dimensional mode may come from segments that contain land features in addition to water.

Colorful future

Imaging spectrometers have been around since the 1980s. The AVIRIS instrument captured its first images in 1987. However, the inherent complexity of the data has presented difficulties. "We're just now reaching a point where we've matured our algorithm savvy and our computer capabilities so that imaging spectroscopy is really becoming accessible in a meaningful way," says Thompson. He cites the increasing availability of imaging spectroscopy data that have been precorrected for atmospheric effects. With multiple international projects planned to send imaging spectrometers into orbit, says Thompson, "It's really starting to come into its own and will continue to do so."

Sung Chang

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PHYSICS UPDATE

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

HOW STARS VISIT THE SOLAR NEIGHBORHOOD

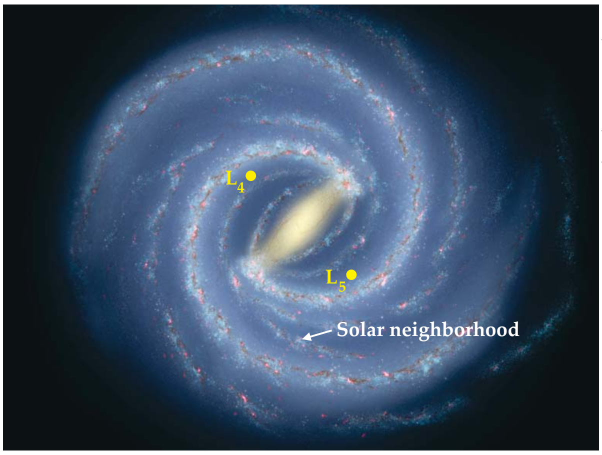
About 10% of the stars in the solar neighborhood belong to a large group that exhibits an oddly distinctive collective motion. Known as the Hercules stream, the group includes stars that are moving away from the center of the galaxy while falling behind the galaxy's general rotation. The cause of that motion is the subject of a new study by Angeles Pérez-Villegas and her colleagues at the Max Planck Institute for Extraterrestrial Physics in Garching, Germany.

New stars typically condense with other new stars out of the same dense cool region of gas and dust. Because stars are born more or less around the same time, they inherit the motion around the galaxy of their birthplace. The Hercules stream is different. Spectroscopic observations have revealed that it's made up of stars of widely different ages. Whatever is causing the streaming motion operates across large scales of time and space.

One candidate is the dense central bar of stars from which two of the galaxy's spiral arms sprout (see accompanying figure). The solar neighborhood lies beyond the orbit of the ends of the bar, but the Sun and the stars of the Hercules stream are close enough to feel the bar's gravitational influence. Generally speaking, as stars orbit the galaxy, they oscillate toward and away from the galactic center. If a star's radial oscillation resonates with the bar's rotation, the star can end up with an extra kick away from the galactic center.

That resonance, the outer Lindblad resonance (OLR), has been invoked to explain the Hercules stream, but new observations have identified a flaw in the explanation. The bar rotates more slowly than originally thought. Consequently, the OLR is too far away from the solar neighborhood to be the stream's prime mover.

Pérez-Villegas and her colleagues used those new observations to test a detailed dynamical model of the stars in and around the bar. The model not only re-created the positions and velocities of the Hercules stream, it also revealed what causes its unusual motion: The stream's stars are orbiting two local maxima—the L_4 and L_5 Lagrange points—in the bar's effective gravitational potential. The maxima are situated on the bar's perpendicular bisector close to the distance where stars corotate with the bar. In the model, most of the stars in the Hercules stream originate from the inner part of the galaxy, where the stars tend to be older than the Sun. Their looping orbits around L_4 and L_5 take them all the way into the solar neighborhood, but not much beyond it. (A. Pérez-Villegas et al., *Astrophys. J. Lett.* **840**, L2, 2017.) —CD



NASA/JPL-CALTECH/ESO/R. HURT

PRINTING GLASS IN 3D


NEPTUNLAB/KIT

These days it seems you can make anything with 3D printers—but not if you want to make it out of glass. The main complication is that the printers create structures that are rather coarse, at least at the millimeter scale and smaller. For glass, such a rough surface hinders the transmission of light.

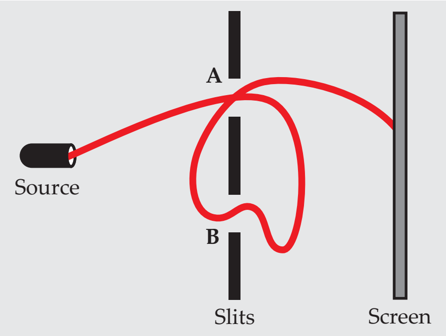
Now Bastian Rapp at the Karlsruhe Institute of Technology in Germany and colleagues have used off-the-shelf chemicals and a commercially available 3D printer to create transparent structures out of glass that is nearly indistinguishable from pure fused silica glass. The team's big advance was dissolving large amounts of silicon dioxide nanoparticles—between 30% and 45% by volume—in their polymer "ink." A $7500 stereolithography printer composed the desired structure layer by layer using the silica-infused polymer. After burning off the polymer, Rapp's team sintered together the enduring nanoparticles at 1300 °C to create the final solid product (such as the one shown here). Both Raman spectroscopy and x-ray photoelectron spectroscopy confirmed that the printed glass, which was highly transparent for wavelengths above 350 nm or so, had nearly identical optical properties to fused silica.

Printed optical-grade glass could prove useful for lenses, fiber-optic cables, and photonic applications. And because the technique doesn't require a custom printer, the properties of printed glass should become even more finely tunable as 3D printing technology improves. Rapp hopes to devise a similar nanoparticle–polymer mix for soda-lime glass, which is used for everyday items like windows, windshields, and drinking glasses. (F. Kotz et al., *Nature* **544**, 337, 2017.) —AG

SHEDDING LIGHT (AND DARK) ON QUANTUM PROBABILITIES

For more than a century, Thomas Young's seminal double-slit experiment was seen as a convincing demonstration that light is a wave phenomenon. The modern interpretation provided by quantum mechanics is radically different: Light comprises discrete entities called photons, and the photon wavefunction at a given location on a detector screen receives contributions from all paths that pass from the photon source through the slits (call them A and B) and on to the screen. The intensity at any location on the screen is proportional to the probability that the photon arrives at that location. According to the Born rule, that probability is given by the absolute square of the wavefunction. Interference was famously observed with light, but it is not a phenomenon limited to light. Any particle can, in theory, exhibit an interference pattern determined by the absolute square of its wavefunction.

You can destroy the characteristic double-slit interference by determining which slit the particle passes through. As textbooks typically describe it, when you check, paths passing through slit A are distinguishable from paths passing through slit B, and the slit-A intensity adds to the slit-B intensity. But as emphasized in a new theoretical paper by James Quach, a postdoc at the Institute of Photonic Sciences in Barcelona, Spain, if a detector registers a particle traversing slit A, it could be that the particle followed a classically nonsensical path that passed through both slits in succession. Such paths typically have only a small effect on the intensity pattern, but their contribution can become significant when the light's wavelength is commensurate with or larger than the slit separation.



Observations of interference patterns can serve as a direct test of the Born rule. In particular, as observed by the Perimeter Institute's Rafael Sorkin, the Born rule implies that a cleverly chosen combination of three-slit-experiment intensities will vanish. Last year Urbasi Sinha and colleagues from the Raman Research Institute implemented Sorkin's intensity combination with microwaves and found a nonzero value. The Sorkin observation, however, assumes that classically nonsensical paths may be ignored.

Theoretically, the Sorkin prescription can be corrected to account for those neglected paths, but the exact calculation is currently beyond theorists' reach. The classically nonsensical paths mean that the Sorkin approach cannot be simply implemented. But in return they generate a new simplicity: As Quach demonstrates, the strange paths mean that the Born rule can be tested with an appropriate combination of intensities observed in two-slit experiments in which zero, one, or both slits are monitored. Quach's suite of observations requires two kinds of experiment in which a detector monitors both slits. In one, the detector can tell whether the particle passes through slit A, slit B, or both. In the other, the detector can tell whether the particle passes through one slit or both, but cannot distinguish passage through A from passage through B. Before experimenters can carry out Quach's suggested test, however, they'll need to meet the challenge of fabricating reliable detectors that don't destroy the particles they register. (J. Q. Quach, *Phys. Rev. A* **95**, 042129, 2017.)

—SKB

THE OCELLATED LIZARD IS A COMPUTER GAME COME TO LIFE

Timon lepidus, known familiarly as the ocellated lizard, wears the signs of aging on its scaly back. As the lizard matures, the spots that adorn its youthful skin break up and rearrange into a labyrinthine design that marks adulthood. Michel Milinkovitch of the University of Geneva and his colleagues don't know why the lizard transforms that way—perhaps to camouflage itself, perhaps to signal potential mates—but they now know how.

COLD PERIODS ACCELERATE EVOLUTION

When Charles Darwin visited the Galápagos Islands in 1835, he was struck by the diversity in bill size exhibited by the local finches. Evolutionary biologists attribute such divergences of species to adaptive radiation, which arises when organisms mitigate competition for resources by branching out into ecological niches. Those niches change when Earth's climate warms or cools, thereby affecting evolution. But shifts in temperature also influence metabolism and, potentially, evolution too. Julien Clavel and Hélène Morlon of the École Normale Supérieure set out to untangle those two temperature-dependent effects. Their starting point was a family tree of 6100 bird species and 3550 mammal species from the Cenozoic era, which began 66 million years ago with the extinction of the dinosaurs and continues, through periods of advancing and retreating glaciation, to the present. Besides ancestries, the database also contained the


KEVIN COLE

species' body size. Clavel and Morlon developed a statistical model for the rate of evolution that incorporated an adjustable temperature dependence. When they fed their model with Cenozoic climate data and compared it with the body sizes in their family tree, they found the best match occurred with a strong negative dependence of evolution on temperature. That is, body size changed fastest when the climate was coldest. Given that the metabolism of birds and mammals slows when the ambient temperature drops, Clavel and Morlon conclude that climate influences evolution primarily through its effect on the environment. (J. Clavel, H. Morlon, *Proc. Natl. Acad. Sci. USA* **114**, 4183, 2017.)

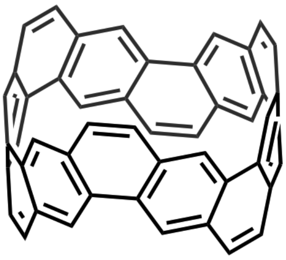
—CD

By monitoring three lizards over several years, the researchers deduced that the patterns on the animals' backs were updating according to a well-defined algorithm: Over a period of a month or so, a given scale will change color—from green to black or black to green—with a probability *p* that depends on the colors of the scales around it. For, say, a green scale surrounded by green neighbors, *p* is around 50%. For a green scale with two or fewer green neighbors, *p* drops effectively to zero. The researchers confirmed the algorithm by modeling the reaction–diffusion equations that govern the evolving distribution of the lizard's various color-generating cells.

MICHEL MILINKOVITCH

In essence, the reptile is the embodiment of a cellular automaton, a type of discretized model made popular by John Conway's Game of Life and used to simulate the spread of wildfires, the firing of neurons, and other phenomena. Although some cellular automata evolve indefinitely, the rules governing the ocellated lizard eventually steer it to a static pattern. Around the time the lizard turns four, its pixelated look becomes permanent. (L. Manukyan et al., *Nature* **544**, 173, 2017.) —AGS

FORGING A CARBON NANOBELT



Rings of carbon atoms can be fashioned into balls, tunnels, and sheets. Yet before the discoveries of fullerenes, carbon nanotubes, and graphene, chemists dreamed of building a different carbon-ringed structure: a loop of edge-sharing benzene molecules. Now, more than six decades after it was proposed, Guillaume Povie and colleagues at Nagoya University in Japan have created the elusive carbon nanobelt.

The researchers started by combining an aldehyde and a benzylic bromide. Using a series of creative chemical reactions, some of which had rarely been employed before, Povie and colleagues assembled building blocks, joined them together to form a ring, and then introduced additional bonds that solidified the belt configuration. X-ray crystallography measurements confirmed a roughly 8-Å-diameter nanobelt structure made up of a single strand of 12 benzene rings, as shown here. The hexagonal panels stand perpendicular to the cross-sectional plane of the belt, like the slats of a fence surrounding a garden.

The researchers performed fluorescence, light-absorption, and Raman spectroscopy measurements on their creation and found similarities to a metallic, single-walled nanotube that has the same diameter and orientation of benzene rings. The resemblances are especially notable because of the new nanobelt's potential to serve as a template from which to grow those (6,6) nanotubes. Current fabrication methods tend to produce a hodgepodge of nanotube species, each with different electronic and thermal properties. The new nanobelt, which is, in effect, an ultrashort nanotube open on both ends, could form the basis of a production method that yields uniform tubes. Povie and colleagues are working on ways to stack nanobelts to build lengthy nanotubes. (G. Povie et al., *Science* **356**, 172, 2017.) —AG

SEDIMENT SUPPLY PREDICTS RIVER GEOMETRY

Gravel-bedded rivers, such as the one pictured here in Yellowstone National Park, are major features of some of the world's most diverse ecosystems. Understanding rivers' bankfull geometry—the shape of a river during the stage just before flooding—is an important key to flood management in these regions.

Typical models for predicting a gravel-bedded river's geometry rely on a simple assumption: that the flowing water does not generate enough shear stress to move average-sized sediment until the river reaches its bankfull stage. If that assumption holds true, the stable "armor" layer of gravel that makes up the riverbed only shifts once every few years. However, a new paper by Allison Pfeiffer, a graduate student at the University of California, Santa Cruz, shows that many rivers generate much larger amounts of shear stress than standard models predict. Pfeiffer concludes that the amount of sediment being fed into a river is a major and previously unrecognized factor that influences the geometry and mobility of gravel-bedded rivers.

Sediment supply depends on the erosion rate of the surrounding landscape; a high erosion rate means that more rock is eroding from the land's surface and entering the river. Pfeiffer and coauthors Noah Finnegan and Jane Willenbring compiled data on nearly 350 gravel-bedded rivers in North America and found that rivers with a large sediment supply also experienced large amounts of shear stress. Because high-sediment rivers move gravel more forcefully than the models predict, they probably never form an armoring layer of coarse gravel like their low-sediment counterparts. Instead, their beds are constantly shifting and made of relatively fine-grained gravel.

NEAL HERBERT

Significantly, most of the high-sediment, high-shear-stress rivers were located in western North America. Pfeiffer concludes that those rivers, which are often the major channels that carry water from areas prone to landslides, have developed geometries and bed structures that enable them to move a large amount of sediment quickly without becoming blocked. Once the findings are incorporated into geologists' models, they could have significant implications for civil engineering and ecological preservation. (A. Pfeiffer et al., *Proc. Natl. Acad. Sci. USA* **114**, 3346, 2017.) —MB PT

ISSUES & EVENTS

College-level project-based learning gains popularity

The approach can develop undergraduates' skills in teamwork, communications, entrepreneurship, and tackling real-life problems.

When Haley Jane Hancock enrolled at Quest University Canada, she planned to focus on creative writing. But she switched to physics after taking "Energy and Matter," a required first-semester course. Students were challenged to independently devise methods to measure the speed of sound and to show that energy is conserved in a pendulum. "A new problem was thrown at you every day or so," she says. "You had to figure it out. I wanted more problems and longer-term problems. I got addicted to the lab."

Quest, in Squamish, British Columbia, is marking its 10th year this fall. It is among a small but growing number of institutions that are embracing project-based learning. Implementation varies, but the crosscutting aims are to motivate students and prepare them for the changing needs of the modern world and workplace. Learning by doing is a common thread. In the process, students are to develop into team players and effective communicators.

"Instruction tends to be faculty-as-coach more than faculty-as-expert," says Mark Somerville of Olin College of Engineering. The 15-year-old institution in Needham, Massachusetts, serves as a model to other places interested in moving in the direction of project-based learning. Because students seek information as they need it, he says, instruction tends to be "just-in-time, as opposed to just-in-case," as is more traditional in higher education.

The hands-on, interdisciplinary, socially conscious approach common to project-based learning seems to make engineering and other traditionally male-dominated fields more appealing to women. For example, when Harvey Mudd College revamped required courses in computer science a decade ago and in engineering this year, the classes went from "being the most hated to the most loved," says college president Maria Klawe. For the engineering course, she says, "we have 20 years of data showing males outperforming females." But once it had real-life context and was more project-based, "both males and females performed better, and there was no gender difference in performance."

TONY MARTIN

AS A QUEST UNIVERSITY CANADA STUDENT, Kyle Martin built subsurface ocean drifters to measure the relationship between surface and subsurface water body currents. The project was the culmination of the upperclass curriculum he designed to answer a question he posed, How are design elements transformed into mechanical systems?

Real-life problems

From the start, Olin College's mission was to transform engineering education. During the planning stages, "a bunch of us sat around and asked ourselves what we remembered from college," recalls the college's president, Rick Miller. "We

QUEST UNIVERSITY CANADA was started a decade ago to a bring liberal arts college to the country. Located 70 km north of Vancouver in Squamish, British Columbia, the school emphasizes learning by doing.

QUEST UNIVERSITY CANADA

could all remember in stunning detail our senior projects. I can even remember what I was eating! Why did we wait to do them until the senior year? And why only do one project?"

The planners decided to test whether they could build a curriculum based on solving real-life problems. A pilot group of fresh high school graduates was split into teams and given a challenge: In the next five weeks, design and build a pulse oximeter to measure a person's blood oxygen level. "We didn't know what would happen," says Miller. The students blew a lot of transistors and their device was clunky, but it—and the test—worked.

"We learned two things," he says. "You don't need two years of calculus and physics to make things work. And, more important, the impact of the experience was profound. It was as if [the students] were two feet taller. Their attitude was 'anything I can dream up, I can do.' " The Olin planners repeated the experiment and decided that they had been underestimating what students are capable of. "It's about adventure, as a team. The teamwork is hugely important," Miller says.

Today, an Olin graduate will have done two to three dozen projects, ranging from building mechatronics devices to starting a business to identifying and designing a solution for a societal challenge. Recent projects have led to products and services for stay-at-home dads, doulas, the elderly, homeless people, and winter surfers. Says Somerville, "It's about understanding the group of people and their needs, and then proposing a product that will solve a problem." The students, he says, come out of such projects with empathy.

Incomparable depth

Quest, a liberal arts and sciences college, shares a pedagogical philosophy with Olin (see the Q&A with Quest founder David Strangway on PHYSICS TODAY's website). Like Olin, it takes a project-based, interdisciplinary approach that bestows trust and responsibility on students. Both schools are small and private with tuition coming to about $25 000 (for Olin, that's after merit-based scholarships are factored in); Quest accepts 200 students a year and Olin takes 84. One difference is that Quest divides the academic year into eight three-and-a-half-week blocks, with one course per block. And there are no majors; students graduate with a bachelor of arts and sciences degree.

The first two years consist of 16 required courses, with some flexibility, such as a choice among humanities, social sciences, and math topics. Early on, everyone takes rhetoric to learn writing and communication skills. At the end of the second year, students formulate a question and a related plan of study for their final two years.

Hancock built a gas chromatograph from scratch as part of addressing her question, How does experimentation advance understanding of the physical universe? She used her project to show what one can build with off-the-shelf supplies. Another student delved into philosophy, quantum mechanics, and societal implications to analyze her question, How is the universe different from what we see? Other recent questions include How does science fiction inform scientific progress? What is the physical and chemical nature of olive oil? What forces shape Earth's surface?

Students work many more hours total on each class when they take sequential blocks than when they take several classes concurrently, says David Helfand, the Columbia University astronomer who served as Quest president for most of the university's first eight years. "And you have no time constraints," so if an instructor wants to take students on a field trip, they can. Classes at Quest have flown to Belize to look at economic development, spent days outside studying the local geology, and traveled to study a language or attend a conference.

"I was a typical academic and said the block system won't work in physics," says Helfand. "My English colleagues say it won't work in their field." It requires throwing out most of what you have done in your teaching career, he warns, but "when you see the depth the students can get to, it's incomparable."

He cites exoplanets as an example. "At Columbia, I go to the board and write down equations and diagrams. Everyone copies it down in their notes. At Quest, I gave them a computer simulation with some variables—telescope size, inclination of orbit, masses, distances. Then I let them go." After a few hours, someone got up and wrote Kepler's three laws on the board. "That's what I call constructing knowledge instead of transferring knowledge."

Hybrid programs

Some campuses have introduced project-based learning on a smaller scale. The

LEISE JONES PHOTOGRAPHY

STUDENTS AT OLIN COLLEGE OF ENGINEERING designed an LED-covered cube that lights up to music.

engineering school at the University of Illinois at Urbana-Champaign, for example, started with a single course that met twice a week within the established educational environment. "It was a pea shooter relative to Olin's full curriculum," says David Goldberg, an emeritus professor of engineering from Illinois. "We've had a paradigm of obedience-based education. We wanted to balance that with an unleashing of possibilities. I never imagined that with the variables we could adjust we would get the 'Olin effect' at Illinois. But we did. It's about culture and emotions."

More recently, the engineering schools at the University of Texas at El Paso (UTEP) and York University in Toronto have injected elements of learning-by-doing in the context of a traditional university environment. In May UTEP's Engineering Leadership program graduated its first class. Olin was a model for the program on a pedagogical level, "but we are as different from them as you can imagine," says founding chair Roger Gonzalez. "They get the crème de la crème and have a small student–teacher ratio," says Gonzalez. "UTEP is about access. The students self-select. We are showing that you can effect change in the culture without having to change every course in the curriculum." (See the Q&A with Gonzalez on PHYSICS TODAY's website.)

At UTEP, students in the engineering leadership program take one project-based class each semester and are otherwise integrated in the broader campus. The new program has attracted a higher proportion of women—some 40–45%, compared with 15–20% in UTEP engineering overall. "We are getting people who are not geeks," says Gonzalez. "They may want to do music or political science or business along with engineering."

Janusz Kozinski and colleagues reinvented engineering at York University a few years ago. "We wanted to change the curriculum so people would learn in a horizontal way rather than in silos," he says. "And we wanted to attract more women to engineering." Engineering, business, and law were linked to form the Lassonde School of Engineering. In just three years, enrollment increased nearly 10-fold, says Kozinski. Still, the program is limited by having inherited the departmental structure and the people in it. "We advanced it, it is progressive," he says, "but what we are doing in the UK is the ultimate frontier."

A UK startup

Kozinski is referring to the New Model in Technology & Engineering (NMiTE), a university that this spring got government funding to get started on an industrial estate outside Hereford, near the Welsh border. "Unlike with Lassonde," says Kozinski, NMiTE's founding president, "here we are creating the university from the outset, so we have carte blanche and are not constrained by preexisting mechanisms."

Like Olin, NMiTE will be a "liberal engineering" school, and like Quest it will use the block system. As at both of those schools, faculty will work on renewable contracts without tenure, and their responsibilities will include teaching, service, and intellectual activity that does not have to be original research. Courses will be in session 46 weeks out of the year, so students experience a workplace schedule and will be able to complete their degrees faster. A partner, Warwick University, will monitor academic performance and collaborate with NMiTE to develop new teaching approaches that could be difficult to introduce into more traditional environments.

Students entering NMiTE will start

with a “passion project,” whose goal is to get them to see that they need to learn more about materials science, math, physics, and chemistry. Once they do, “they will realize these subjects are not abstract,” says Kozinski. “Young people want to study engineering because they want to change the world. They see engineering through successful companies—Apple and so on—and they want to do something extraordinary.”

The university will have four focus areas within engineering: manufacturing, green renewables and smart cities, agricultural engineering, and big data and resource security. Instruction in other skills—leadership, communications, conflict resolution, political context, finance, marketing, and so on—will be peppered throughout the engineering courses.

NMiTE will start up in fall 2018 with a pilot group of tuition-free students to test the courses and methods. The first official class will enter in fall 2019.

Is physics a good fit?

Carl Wieman, physics Nobel laureate and education researcher at Stanford University, says that “most instructional labs courses would be much improved” in a project-based format. But he worries that it is impractical to apply the approach across the full physics curriculum. Besides, he says, as of now there are glowing, anecdotal testimonies but not much hard data about project-based learning in physics.

Rutgers University’s Eugenia Etkina specializes in physics and astronomy education. “In complex subjects such as physics and math,” she says, “the fact that ideas build on each other prevents the real project-based approach from being implemented.” But her research on curriculum reform, like the limited versions of project-based learning at Illinois, UTEP, and York, suggests benefits for physics students even when the approach is a small part of the overall curriculum. Etkina has developed labs intended to give students more independence and more opportunity to learn from failure than is the case in traditional undergraduate laboratory exercises. Ideally, she says, the need to solve a problem or complete a project motivates students.

For his part, Helfand is sold on the learning-by-doing approach for engineering and for nonscience majors, for whom, he says, it’s “revolutionary.” For physics majors, though, he’s on the fence.

UTEP COMMUNICATIONS

THE FIRST GRADUATING CLASS to go through the project-based engineering leadership program at the University of Texas at El Paso, celebrate with program chair Roger Gonzalez (center, orange shirt).

“There is value, because it’s about asking questions and solving problems.” But the time-intensive project-based approach could be unwieldy for covering the large base of material that physicists need to command. “I have seen it work in engineering, geology, medicine, and business. I haven’t decided if it’s a good approach on its own for physics.”

Eric Mazur, a Harvard University physicist who has pioneered education reform in physics for nonmajors, is a proponent of using real-life problems in physics teaching. “For 27 years all I had done was to take something that was broken and try to patch it by making the class experience more interactive so students are not just dozing off. I hadn’t tackled the intrinsic lack of motivation.”

Inspired by Olin to switch to a project-based approach, he followed three principles from Harvard Business School: test relevant skills, make projects relevant to the real world, and incorporate a component of empathy or social good. “Initially I was limited in my imagination,” he says, “but it’s not that hard to come up with social good motivators.” And, he adds, “the students are interested because they realize that in learning physics they can do something meaningful.”

“Whatever works for nonmajors will work for majors—nonmajors are significantly harder to motivate,” says Mazur. “We need to rethink not individual courses, but the entire curriculum; then it shouldn’t be hard to restructure to yield graduates that are motivated to learn and keep learning.”

The project-based philosophies at NMiTE, Olin, and Quest aim to prepare students for the modern workplace. The depth sometimes comes at a cost of breadth of coverage found in more traditional curricula. Not surprisingly, graduates who have opted to continue their education report needing to fill gaps, but they also say they are more adept than others in their cohort at tackling open-ended problems.

Hancock, for example, admits that her nontraditional education made it harder to find a good match when she took physics courses at other institutions. Still, she believes that project-based learning “creates a student better-equipped to take on the new and ever-changing problems in the field.” After graduation, she landed a job as lab manager for a biotech startup.

Toni Feder

Illinois budget impasse damaging state universities

Declining enrollments, faculty departures, and fewer low-income tuition grants are among casualties of the long-standing dispute.

SOUTHERN ILLINOIS UNIVERSITY CARBONDALE (outside the library and in aerial view) has seen a sharp drop in enrollment and will have to cut $30 million from its $400 million annual budget next year if a two-year-old budget deadlock between the state's governor and legislature isn't resolved. (Photos courtesy of Southern Illinois University Carbondale.)

A two-year budget deadlock between the Illinois governor and legislature continues to take a heavy toll on the state's universities, with the severest effects on schools that serve a primarily lower socioeconomic population. The stalemate will enter its third year in June, and as PHYSICS TODAY went to press, there were no indications of a resolution.

States have been gradually trimming their contribution to public universities for decades, but the reductions experienced in the past two years by Illinois institutions such as Northeastern Illinois University (NEIU), Chicago State University, and Southern Illinois University have been sudden and steep. Two tranches of "stopgap" funding appropriated to those Illinois public universities during the impasse have amounted to just 41% of what they would normally see. Sudha Srinivas, a physics professor and associate dean of the College of Graduate Studies and Research at NEIU, says the school counts on state funding for 35% of its budget. "To say this is hurting us badly would be an understatement," she says.

The dispute between Republican governor Bruce Rauner and the Democratic-controlled legislature led by veteran house speaker Michael Madigan centers on Rauner's insistence that a package of proposals, including tort reform, changes to unemployment compensation, a right-to-work law, and collective bargaining reform, be enacted part and parcel with the budget. Democrats, however, have refused that demand and argued for separate consideration of the proposals.

According to the Responsible Budget Coalition, an advocacy group that comprises 300 health-care, education, social services, labor, faith-based, and other organizations, higher-education spending by the state of Illinois has been slashed by $2.3 billion, or 59%, during the past two years. In addition, the state has stopped funding tuition-assistance grants to 130 000 low-income college students, which has forced many to delay their education or drop out.

Budget standoffs aren't uncommon between states' executive and legislative branches, but the Illinois dispute stands out. "It's far and away the worst in the country. Nobody comes even close," says Thomas Harnisch, director of state relations and policy analysis for the American Association of State Colleges and Universities (AASCU). Having achieved national notoriety, the Illinois impasse "will haunt the state for years to come," he warns. "Higher education is a small community. People talk to each other and are well aware of the budget situation in some states. It makes it difficult for these institutions to attract the best-quality candidates."

The State Higher Education Executive Officers Association says that nationwide, support for higher education per full-time student would have increased 3.2% in 2016 had it not been for the plunge in Illinois, which caused US spending to decline 1.8% instead. The association also reported that full-time enrollments at Illinois universities fell by 46 000, or 11%, from 2015 to 2016.

Forced into stability

Mel Sabella, a physics professor at Chicago State University, says the lack of funding forced the layoff of more than 300 university employees, or one-third of its workforce, during the 2015–16 school year. To raise awareness of the crisis that year, about 20 Chicago State student demonstrators shut down three nearby freeways in January 2016. The drastic downsizing has helped achieve some level of financial stability this year, Sabella says, but enrollment has plunged by 25% or more in the past two years.

Chicago State serves a predominantly African American population, and last year it graduated six black physics majors, about 3% of the black physics bachelors awarded that year in the US. The university has five physics faculty members, not counting one currently detailed to NSF. Adjunct and lecturer positions have been jettisoned, and the permanent faculty have had to take on teaching more upper-level courses, some of which are sparsely attended.

Amber Wise taught chemistry at Chicago State for three years before resigning in 2016 and heading to Seattle, where she found a job in the private sector. She says she most likely would not have left had it not been for the budget deadlock. "When I started in 2013, everything seemed great. There was money for minority students in STEM [science, technology, engineering, and mathemat-

ics], there were grant applications for professors at minority-serving institutions, and it seemed like a great place to land. I loved the students, and I loved the other faculty," she says.

With the impasse, "things flipped on a dime." Wise was expected to teach four courses a semester, while operating a research lab and finding grants to fund it. "I was working until midnight, setting my alarm for 5am to get up and work again, and my salary was ridiculously low," she says.

"I felt privileged that I had options to leave and find something else. But the students? That's their lifeline to get out of the South Side and make their lives better," Wise says. "You want to talk about reducing crime in Chicago, try educating some folks on the South Side."

Although primarily an undergraduate institution, NEIU, also in Chicago, expects its faculty and students to do some research. But the university has had to severely curtail the internal funding it long provided to help start research programs, says Srinivas, and the travel budget has been zeroed. Enrollment at NEIU fell this year by 3.6%, and she says as many as 10 of the university's 250 tenured faculty have left for positions in other states since the stalemate began. Recruitment has continued, but any offers are made contingent on the availability of state funding. State universities are hopeful that at the very least, another round of stopgap funding will materialize.

Paulo Acioli, an NEIU physics professor, says employees have been forced to take eight unpaid furlough days this year, including the entire spring break. With the elevation of Srinivas to associate dean, the physics department is down to three faculty, and it's unlikely that she will be replaced, Acioli says. He now worries that the state may "flag" the physics department for possible closure due to insufficient numbers of graduating physics majors.

Sabella says he's committed to Chicago State, but he's worried about the future. "If you lose a place like Chicago State . . . you lose an institution that's helping to address diversity in the field," he says. "It's easy to destroy something fast; it's a lot harder to build it up."

Zero from the state

At the Carbondale campus of Southern Illinois University, interim chancellor Brad Colwell warned faculty and staff in late March to brace for cuts of $30 million—29% of its usual state appropriation—in the fiscal year that begins 1 July. Carbondale, the largest of Southern Illinois's three campuses, already endured a $21 million cut in the current year. In his memo, Colwell estimated that 158 of 4800 staff positions will be eliminated for the next academic year, adding to the 293 positions already lost during the budget dispute. Most of the new reductions will be attained by not filling vacancies.

Carbondale spokeswoman Rae Goldsmith says the belt-tightening is partly due to a need to start replenishing internal accounts meant for other purposes, from which money was borrowed to maintain operations during the past two years. Carbondale normally expects to receive about $100 million in state appropriations, around one-quarter of its operating budget. About $40 million was provided in the two stopgap measures, but all of that was spent during the first year of the impasse, leaving no state funding for 2016–17.

Enrollment at Carbondale declined 7.6% from 2015 to 2016. Universities in neighboring states that offer in-state tuition rates have been using the budget stalemate as a student recruiting tool, says Goldsmith. "There is doubt being planted in the minds of our students about the viability of their institutions. We spend a lot of time talking with students and parents, reassuring them we are here to stay."

The situation isn't so dire at the University of Illinois system, which includes the state's flagship Urbana-Champaign (UIUC) campus. Just 9% of that institution's $2 billion budget would normally come from state appropriations. More than one-third of revenue is from tuition, which is high relative to that of most comparable institutions in other states, says interim provost John Wilkin. UIUC's tuition for 2015–16 was $17 086, whereas the University of Wisconsin–Madison's was $10 415 and Chicago State's, $9994.

Relative to the regional universities, UIUC has larger reserves and an endowment to help tide it over through lean times. Its strong credit rating will permit borrowing, should that become necessary, Wilkin adds.

Nonetheless, institutions outside Illinois have been trying to poach UIUC faculty, Wilkin acknowledges. "We've been targeted by other universities at an unprecedented level, 50% more than a couple of years ago, both this year and last. But we've been very successful in retaining faculty. We may look vulnerable, but we're doing great, thanks."

Wilkin acknowledges some faculty departures. According to news reports, 50 of the 1900 tenure-track UIUC faculty members quit during the 2015–16 academic year and 23 the previous year. New faculty recruitments have been going fairly well, Wilkin says, although the pools of applicants for three positions currently advertised have been smaller than usual. That could be due to factors other than the state budget, he says, such as the state of the economy.

Illinois not unique

Disputes between governors and legislatures are nothing new, acknowledges Harnisch of the AASCU. "What is new is the brinkmanship . . . that has taken it to a whole new level." In the latest example, New Mexico's Republican governor Susana Martinez in April vetoed the higher-education portion of the state budget for the year that begins 1 July. The Democratic-controlled legislature has petitioned the state supreme court to overturn the veto; oral arguments were scheduled for 15 May (after PHYSICS TODAY went to press).

Nevertheless, New Mexico State University chancellor Garrey Carruthers, a former state governor, reassured students questioning whether they should register for the fall term. "I've served in government before. I've been in this arena, and these things always work themselves out," he said in a 24 April message to students, faculty, and staff.

A nine-month budget impasse in Pennsylvania ended in March 2016, when Democratic governor Tom Wolf allowed appropriations bills for education crafted by the Republican-controlled legislature to take effect. Wolf had refused to sign the bills in the absence of a balanced budget.

In Kansas, steep tax cuts initiated in 2012 have yet to produce the economic growth that Republican governor Sam Brownback had promised. Funding to the state's six public universities fell from $408 million in 2013 to $399 million last year. In February, after tax revenue forecasts fell short, Brownback ordered an additional $17 million in cuts to the universities, about 3% of their appropriation.

State funding for the University of Wisconsin system was cut $362 million from FY 2012 to FY 2017, according to UW system officials. But Republican governor Scott Walker, who was first elected in 2010, has proposed a $42.5 million increase for the fiscal year beginning 1 July in his budget request now before the legislature. If approved, the increase would be the first reinvestment by the state that the system has seen in nearly a decade, said UW system spokesperson Stephanie Marquis.

Louisiana, Oklahoma, North Dakota, and Texas, which rely heavily on revenues from oil and gas production, have trimmed their higher-education spending as prices fell in recent years. Although crude-oil prices have recovered a bit from their lows at the beginning of the year, they remain below $50 per barrel, compared with more than $100 per barrel in 2014. The oil producing states "will have a rough ride in the years ahead," says Harnisch.

"Universities are doing everything they can to protect the academic core of the institution and keep it affordable," Harnisch continues. "But it's been an incredibly difficult time for public university presidents."

David Kramer

Breakthrough battery hinged on funding from program in Trump's crosshairs

Novel nickel–zinc cells overcome long-standing limits on recharging, says industry–government development team.

Abetted by the imperiled Advanced Research Projects Agency–Energy (ARPA–E), the California startup company EnZinc is now well on the way to commercializing an innovative battery technology that its backers claim will match the performance of lithium-ion cells for as little as half the cost, with none of the safety concerns inherent to lithium-ion.

Michael Burz, president of EnZinc, says the company is two years away from manufacturing a battery for electric bicycles, the first of what he expects will be many applications. Others include electric vehicles and electricity storage for grids and microgrids. The technology breakthrough, discovered and developed at the US Naval Research Laboratory in Washington, DC, with ARPA–E financing, is an anode material composed of a three-dimensional zinc sponge. The new material, described in the 27 April issue of *Science*, makes possible repeated discharge–recharge cycles of nickel–zinc batteries, an electrochemical technology that has mostly been limited to single-use and disposable batteries.

US NAVAL RESEARCH LABORATORY

RESEARCHERS DEBRA ROLISON, JEFFREY LONG, AND JOSEPH PARKER (holding awards) of the US Naval Research Laboratory last year each received a Dr Delores M. Etter Award for developing improved zinc-based alkaline battery technology. Presenters were acting navy secretary Sean Stackley (far left) and Delores Etter (far right).

"In the classic sense of the 'valley of [technology funding] death,' ARPA–E was there for us when the venture capital community was not," Burz says. "VC's are not into basic research, and no battery company was willing to take the risk on a technology outside their product line or comfort zone."

In his budget outline for fiscal year 2018, released in March, President Trump proposed to terminate funding for ARPA–E, "because the private sector is better positioned to finance disruptive energy research and development and to commercialize innovative technologies."

Burz is alarmed that the Trump administration would zero out ARPA–E. "I completely disagree that what it does can or should be picked up by the commercial sector," he says. "ARPA–E is a critical bridge to keeping American technology innovation leadership within the energy sector. Period."

Congress, however, appropriated $306 million for ARPA–E for FY 2017, compared with $291 million last year. Apart from administrative costs, all of ARPA–E's budget is distributed in grants.

Department of Energy officials announced on 18 May that they had released funding for three ARPA–E grants totaling $11.1 million, after they had concluded that the awards "applied good governance principles consistent with the new administration's policy directives." The disbursements had been held up for several weeks while energy secretary Rick Perry and his staff conducted a department-wide review of programs, policies, and grants. Additional ARPA–E awards are expected to be approved in the coming weeks, the DOE release said.

The announcement came after Representative Eddie Bernice Johnson (D-TX), the ranking minority member of the House Committee on Science, Space, and Technology, wrote to Perry in late April complaining that up to $40 million in appropriated ARPA–E funding was being withheld from program awardees.

In a 19 May statement, Johnson welcomed DOE's release of the $11.1 million as "a step in the right direction," but added, "I still have serious concerns given that at least 20 additional competitively selected awardees are still awaiting notice that contract negotiations with ARPA–E can resume." She said she would continue to raise questions until the appropriations are fully distributed.

On 8 May, Johnson asked US comptroller general Gene Dodaro to investigate whether DOE was violating the law by not dispensing the monies as directed by appropriations measures. She noted that Dodaro has the authority to compel the executive branch to spend the funds.

"Congress has provided these monies to the Department of Energy for the expressed purpose of fulfilling ARPA–E's mission as prescribed by law," Johnson wrote. "Diversion or impoundment of this money would be contrary to law."

The Trump administration's efforts to eliminate ARPA–E without congressional authorization "would be both ill-advised and potentially illegal," she added.

Johnson quoted an 8 March tweet by Perry saying "innovators like the ones supported by our ARPA–E program are key to advancing America's energy economy."

More cycles are needed

Recharging conventional nickel–zinc cells, which have powdered zinc anodes, causes stalactite-like dendrites to form on the anodes after as few as 20–30 cycles; they cause shorts and battery failure. Joseph Parker, the NRL researcher who is lead author of the *Science* paper on the battery advance, says the sponge material's large surface area permits a more even distribution of electric currents to the anode and thus mitigates dendrite formation. The NRL–EnZinc team reported achieving more than 100 deep-discharge cycles in nickel–zinc cells using the 3D sponge. Burz says his company is working to achieve 500 cycles and is confident it can begin manufacturing batteries commercially in 2019.

According to Burz, a nickel–zinc battery for an electric vehicle using the 3D sponge will cost 30–50% less than a comparable lithium-ion battery pack. That comparison factors in the more extensive ancillary systems that lithium-ion technology requires, such as those to prevent cell overheating. The aqueous electrolyte of the zinc cells is inherently safer than the highly reactive and flammable lithium-ion electrolyte. Zinc is plentiful and cheap and is mined domestically, he adds; most lithium comes from outside the US.

EnZinc tried exhaustively to obtain

venture funding to develop the technology, Burz says, before securing a one-year, \$452 000 grant from ARPA–E's robust affordable next generation energy storage systems (RANGE) program. The company invested \$113 000. NRL performed the development work as a subcontractor, receiving \$465 000 from EnZinc.

Moving away from lithium

Venkat Srinivasan, director of Argonne National Laboratory's Collaborative Center for Energy Storage Science, says the research "provides a first step toward saying maybe there's a different way for us to think about zinc." But Srinivasan, who was not involved in the work, cautions that many more charge–discharge cycles are needed to prove the technology's worth. "If you're going to compete with lithium–ion for a Nissan Leaf, we are talking maybe 1000 cycles. Somewhere between 100 and 1000, all sorts of bad things can happen. We have beautiful pictures from the 1970s and 1980s where after a few hundred cycles you look at the electrode and all the zinc will be sitting on the edges of the electrode, with nothing in the middle."

Debra Rolison, principal investigator of the NRL team, says the zinc sponge technology offers a safe alternative to lithium-ion for both military personnel and shipboard applications. In April the US Navy banned e-cigarettes from ships after several incidents in which the devices, which are powered by lithium-ion batteries, burst into flames. NRL is also developing silver–zinc batteries using the 3D sponge for submarine applications. Silver–zinc technology has been hindered by the same recharge limitations.

EnZinc's exclusive license from NRL covers the nickel–zinc battery for electric-vehicle and electricity-storage applications. Included in the vehicle sector are so-called microhybrids, whose engines automatically shut off and restart whenever the vehicle stops. More commonly found in Europe, microhybrids require only around a 5% battery discharge, compared with the 40–60% discharge typical of fully electric vehicles. NRL's stop–start prototype batteries have attained 50 000 cycles. Today's microhybrids use a class of lead–acid batteries, which are expensive and have limited lifetimes, says Burz. Up to half of all new vehicles could be microhybrids by 2020, according to some projections.

Burz says the company has lined up investors to finance continued development once the patent for the technology has been issued. The patent application was submitted in May 2014.

David Kramer

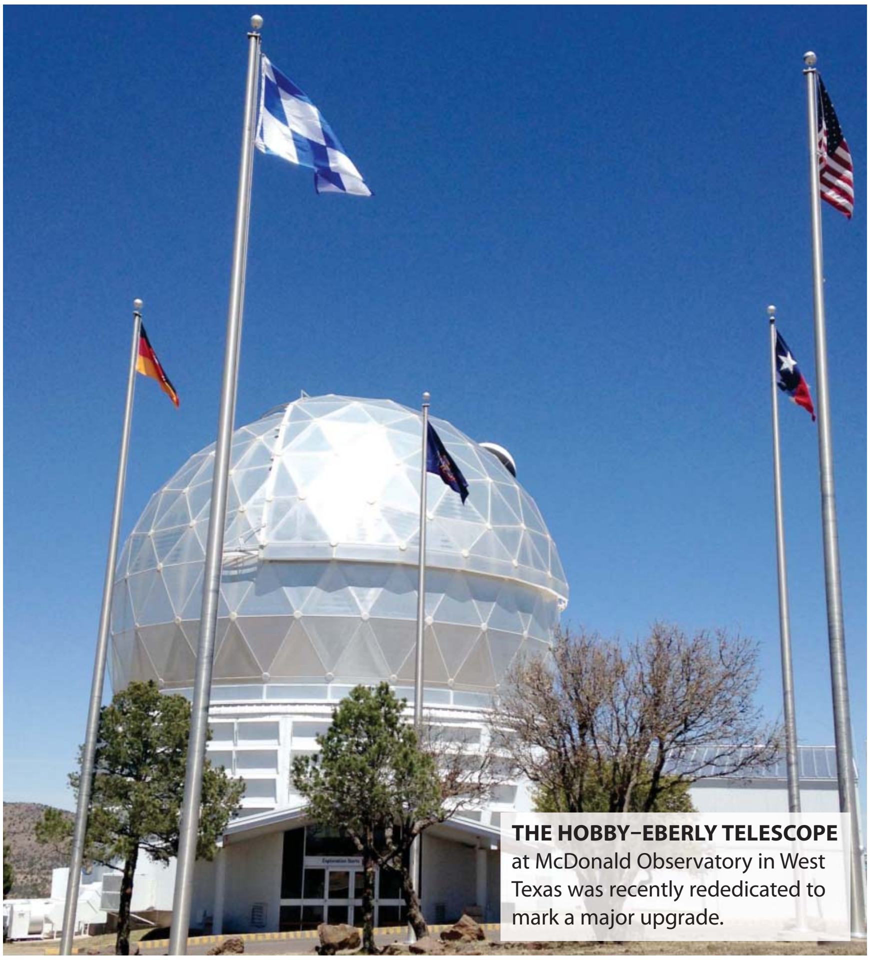
Hobby–Eberly Telescope eyes sky with new capabilities

Galaxy mapping, exoplanet searches, and more are getting started on the largest optical telescope on the US mainland.

On 9 April, McDonald Observatory in West Texas celebrated the reopening of its 10 m Hobby–Eberly Telescope (HET) after a roughly three-year shutdown for upgrades and the installation of \$40 million in instruments.

The telescope is located at an altitude of 2030 m on former mountain ranchlands some 300 km southeast of El Paso. Its primary mirror, made up of 91 hexagonal segments, is at a fixed angle and can rotate to access 70% of the visible sky. With its wide, 22-arcminute field of view, the HET is well-suited for carrying out surveys and hunting for planets.

In its new incarnation, the 20-year-old telescope hosts the Visible Integral-field Replicable Unit Spectrograph (VIRUS), the Habitable Zone Planet Finder (HPF), a low-resolution spectrograph for capturing data from weak sources over wide swaths of sky, and a high-resolution spectrograph for brighter sources. Campaigns to study dark energy and to search for potentially habitable planets



TONI FEDER

THE HOBBY–EBERLY TELESCOPE at McDonald Observatory in West Texas was recently rededicated to mark a major upgrade.

will have more than half the observing time. The remaining time is open to competition by the telescope's four partners: the University of Texas at Austin, the Pennsylvania State University, the University of Göttingen, and Ludwig-Maximillians University of Munich.

So far 16 of 78 VIRUS modules have been installed. The full spectrograph, with 35 000 optical fibers, is slated to be up and running early next year. In the HET Dark Energy Experiment (HETDEX), astronomers use VIRUS to map galaxies in three dimensions at times going back 12 billion years to when the universe was 13% of its current age.

HETDEX collects light for 20 minutes from a given patch of sky. The telescope is then pointed at an adjacent patch. After three and a half years the instrument will have scanned the visible sky with uniform tiling. The "blind blanketing of the universe" as opposed to targeting is an advantage, says Karl Gebhardt of UT Austin, a leader in the experiment. "We get whatever the universe gives us, with no bias by selection."

Processing the data is not yet automated, so each night the HETDEX team pores through reams of data in search of white dots that could be galaxies; they show up as white dots because as star-forming hot spots they emit mostly at a single hydrogen wavelength.

The aim of HETDEX is to distinguish among cosmological theories about dark energy. Two of the leading theories are that dark energy is a cosmological constant or that it follows from a modification of gravity in Einstein's theory of general relativity. If it's a cosmological constant, says Gebhardt, HETDEX will find the value, and then it will be up to theorists to explain why it's a constant. But if dark energy is the result of a modification of gravity, "we can make important measurements. The galaxies would be either more or less clustered than predicted." HETDEX could also bolster or knock out other theories, such as that dark energy is a changing cosmological constant or that it's an illusion conjured by a nonuniform universe.

Among dark-energy experiments, HETDEX's extent and sensitivity let it look back the furthest in time and put the best constraint on the universe's expansion rate, Gebhardt says. Because the density of far-away galaxies is low, only about 5% of the light collected will contribute to the galaxy mapping. "There is a wealth of information in the other 95% of data," he says, "and no one has looked at that part of the universe. We will find massive black holes, star-forming galaxies, and more."

The other main observational campaign on the HET is a search for habitable planets with the HPF, led by Suvrath Mahadevan of Penn State. It targets red dwarf stars and looks for shifts in their velocities due to the gravitational pull of a companion planet. The instrument works in the near-IR, where red dwarfs are brightest. Light from the HET is carried to the instrument, which is housed at −90 °C in a basement beneath the telescope. The environment is controlled to better than submillikelvin precision.

"We will keep going back to the same stars," says Mahadevan. "It's a time-intensive survey, and that's why HET is so fantastic for this." Having a share in the telescope is a huge boost, he notes. Getting sufficient time on a large telescope like the Keck would not be possible.

Toni Feder PT

The new MOON

Brett Denevi

Recent findings are challenging much of what we thought we knew about Earth's nearest neighbor.

NASA/GSFC/ARIZONA STATE UNIVERSITY

Brett Denevi is a planetary geologist at the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland.

With humans' initial exploration of the Moon at the dawn of the space age came the birth of modern planetary science, which seeks to understand the complex history of our solar system in enough detail to piece together the story of how we got to where we are. To what extent was Earth an inevitable outcome of planetary evolution? To what extent was it a quirk of fate?

The Moon is critical to unraveling that story. Much of Earth's history has been erased by tectonic processes and erosion; its earliest crust appears to have disappeared without a trace.[1] But the Moon has been well preserved. We have samples of its primordial crust, and its cratered surface records the history of more than 4 billion years of asteroid and comet bombardment—a barrage that also showered Earth.

The timeline etched into the Moon's face can be a startling reminder of how short our own time on Earth has been. Tycho, the bright, rayed crater that stands out sharply on the Moon's southern nearside, is among the body's newest landmarks. Yet when it formed from an impact around 100 million years ago, the dinosaurs were still around to witness what was for them a near miss. When Copernicus, another young lunar crater, formed some 800 million years ago, trees had not yet appeared on Earth and the pre-Pangaea supercontinent Rodinia was still intact.

In the past decade, the world's interest in the Moon, both as a cornerstone in our understanding of the solar system and as a stepping-stone from which to explore that system, has undergone a revival. After the last Apollo astronaut returned to Earth in 1972 and the Soviet Luna program's robotic landers returned their last lunar sample in 1976, lunar science went relatively quiet. There were no lunar missions in the 1980s and just two, the US's *Clementine* and *Lunar Prospector*, in the 1990s.

Then, starting in 2007 with Japan's *Kaguya* lunar orbiter, a new group of missions began the second era of lunar exploration. *Kaguya*'s suite of remote-sensing instruments provided new information about the Moon's composition. India's *Chandrayaan-1* obtained radar and near-IR spectra that led to new insights about volatiles—water, hydrogen, helium, and other molecules that readily vaporize under typical conditions at the lunar surface. Four NASA-operated missions—the *Lunar Reconnaissance Orbiter* (*LRO*), *Lunar Crater Observation and Sensing Satellite* (*LCROSS*), *Gravity Recovery and Interior Laboratory A* and *B*, and *Lunar Atmosphere and Dust Environment Explorer*—mapped the Moon from radio to UV wavelengths, revealed the presence of water ice, obtained highly precise gravity maps, and studied the movement of dust and volatiles at the lunar surface. Finally, on 14 December 2013, China's *Chang'e 3* and its *Yutu* rover touched down in the Imbrium basin—the first soft landing on the Moon since 1976.

Where has this burst of renewed lunar investigation left us? Last year, in a crowded room at the Lunar and Planetary Institute in Houston, Texas, the lunar science community convened to discuss what we've learned in the past decade, identify the most important outstanding questions in lunar science, and decide where our field should go next. In this article, I'll discuss some of the insights, hypotheses, and paradigm shifts that emerged from that meeting. Some ideas are new, others are fresh perspectives on old problems, and still others represent the reopening of cases that were previously considered closed. Collectively, they suggest that the Moon, an object of the human gaze since time immemorial, still guards many secrets.

Not so dry

Some parts of the lunar surface never see the Sun. Due to the minimal axial tilt of the Moon, regions in impact craters and other topographic lows near the lunar poles remain shielded from direct sunlight year-round. Figure 1 shows the permanently shadowed regions, or PSRs, of the lunar south pole. Theories dating back to the early 1960s posited that PSRs could hold trapped water ice and other volatiles. That hypothesis, together with volatiles' potential value as a resource for a lunar outpost and for deep-space exploration, provided the impetus for what is now a very active line of research: the hunt for lunar water.

In recent years, scientists have made significant advances in that pursuit. Neutron-absorption data collected by *Lunar Prospector* and the *LRO* provided definitive evidence of large amounts of hydrogen sequestered in both polar regions;[2] the depressed fluxes of cosmogenic neutrons in those regions were attributed to an abundance of hydrogen nuclei, which efficiently absorb neutrons. Although neutron-absorption data provide no information on the form of the hydrogen, radar measurements in and around the south pole's Shackleton and Cabeus Craters are suggestive of relatively pure ice: At low phase angles, the radar exhibits a coherent backscatter effect marked by a polarization that's consistent with scattering by crystalline water.[3]

The case for water isn't closed, however. Studies based on higher-resolution data from the Earth-based Arecibo Observatory and Green Bank radio telescopes showed that the radar

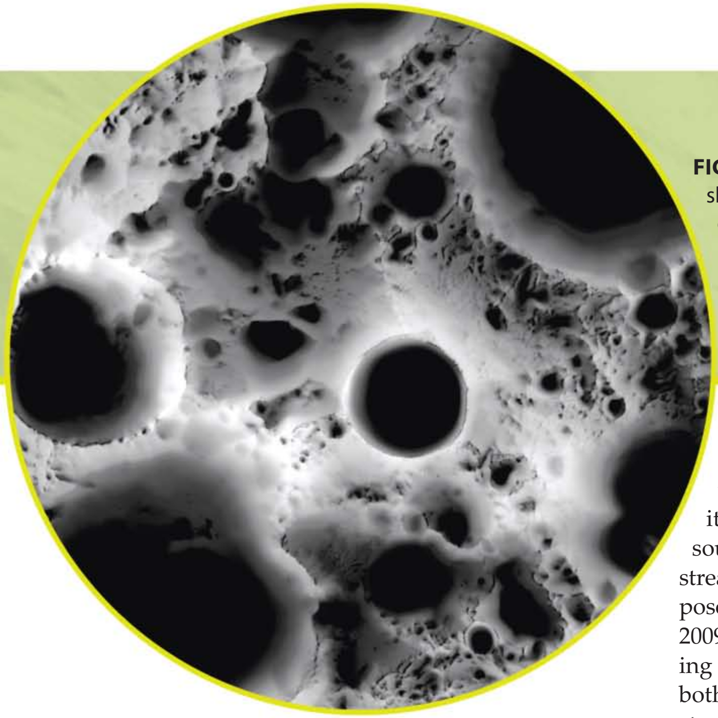


FIGURE 1. AN ILLUMINATION MAP of the lunar south pole shows permanently shadowed regions (black) that receive no direct sunlight and potentially harbor thermally stable water. Such regions are typically found in topographic lows, such as the floors of impact craters. The map covers latitudes 88°–90° S; the brightest areas receive sunlight over 90% of the time. (Image courtesy of NASA/GSFC/Arizona State University.)

signature seen in PSRs also appears in some sunlit polar regions and could plausibly be due to the presence of rock-strewn crater deposits.[4] But according to interpretations of radar measurements collected by *Chandrayaan-1* and the *LRO*, when geologic context is considered, rocky deposits alone can't explain the radar signatures produced by some PSRs.[5]

Optical measurements have helped to clarify the matter to some degree. Whereas neutron and radar measurements penetrate a meter or more into the lunar soil, optical measurements probe only the surface. Still, they can paint a rich picture. For instance, far-UV reflectance observations by the *LRO*'s Lyman Alpha Mapping Project revealed strong water-absorption features—evidence for a small amount of surface frost—restricted to locations that, according to the *LRO*'s IR radiometer, never get warmer than 110 K, the cold-trap temperature above which water-ice sublimates.[6] Likewise, the orbiter's laser altimeter indicates that PSRs have elevated albedo in the near-IR and that the albedo increases with decreasing temperature—characteristics consistent with, but not definitive of, the presence of water and other surface volatiles.[7]

But not all locales where water is thermally stable show evidence of frost. And the frosty areas suggested by the *LRO*'s UV and IR instruments are poorly correlated with the hydrogen-rich areas identified by its neutron detector data. In fact, in some regions exhibiting enhanced hydrogen, ice is not thought to be thermally stable at any depth.[8]

Although the distribution, abundance, and form of volatiles at the lunar poles remain unknown, water's presence is certain in at least one locale. On 9 October 2009, a NASA Centaur rocket crashed at nearly 9000 km/h into the Cabeus Crater, liberating a plume of dust and vapor witnessed by *LCROSS* and the *LRO*. Measurements confirmed that water made up around 5% of the mass of the ejecta plume.[9]

Whence the water?

Assuming substantial amounts of water and other volatiles are present at the poles, how did they get there? Some water deposits may have been emplaced by cometary and asteroidal impacts. A portion of that water would be expected to vaporize and eventually find its way to the poles, where it would be cold-trapped as water ice. Another possible source is the solar wind, which irradiates the lunar surface with streams of hydrogen, long known to alter the chemistry of exposed grains of soil and to darken those grains with time. In 2009 three spacecraft observed near-IR absorptions corresponding to fundamental OH vibrations.[10] The features were seen at both high and low latitudes; the low-latitude absorption was strongest at the coldest temperatures, closest to the lunar night. One possible explanation is that hydrogen from the solar wind binds loosely with mineralogically bound oxygen and then escapes when the temperature rises as either molecular hydrogen or water. The volatiles would eventually either be lost to space or become cold-trapped at the poles.

Alternatively, some water may be native to the Moon—or at least have arrived early on in lunar history. Fewer than 10 years ago, the consensus among planetary scientists was that nearly all the Moon's primordial volatiles vaporized during the impact that created it—a fiery collision between Earth and a Mars-sized planetesimal—and that those volatiles were lost to space as the Moon accreted from the impact's debris. (See the article by Dave Stevenson, PHYSICS TODAY, November 2014, page 32.) In fact, the low levels of volatiles measured in lunar samples—less than one ppb—were considered supporting evidence for the giant-impact hypothesis. But new, sensitive techniques such as ion microprobe mass spectrometry have found water concentrations of hundreds of ppm in returned lunar samples,[11] suggesting that water is about as abundant in parts of the Moon's mantle as it is in parts of Earth's.[12] Near-IR observations hint at the presence of water in recently uplifted crustal material, another clue that at least some of the Moon's water is native rather than generated by the solar wind.[11]

The new work is leading theorists to reassess the giant impact and its effect on volatiles. It has also led them to explore the idea that the Moon's water—and Earth's—could have been delivered after the fiery impact, possibly by comets. Isotopic ratios have the potential to help distinguish between various sources of early water and elucidate the origin of Earth's water, but they likely require laboratory measurements of lunar samples.

Although remote-sensing missions and sample analyses have shed light on certain properties of lunar volatiles, in other aspects we remain in the dark. We know relatively little about the processes that control the redistribution, retention, and loss of volatiles. We don't know how much ice is trapped at the poles and at what depths. And we don't know whether water ice and other volatiles could reasonably be extracted to, say,

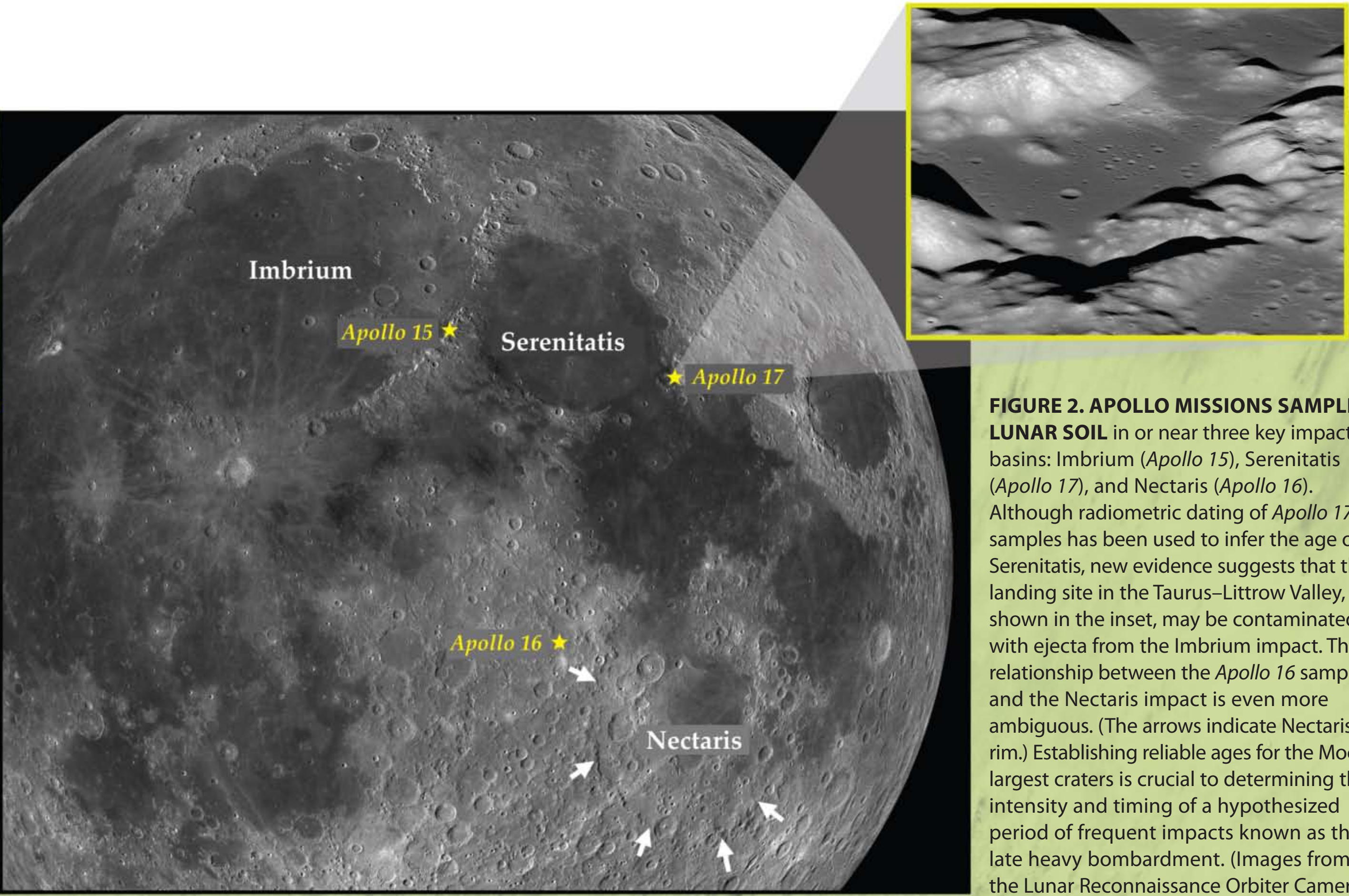


FIGURE 2. APOLLO MISSIONS SAMPLED LUNAR SOIL in or near three key impact basins: Imbrium (*Apollo 15*), Serenitatis (*Apollo 17*), and Nectaris (*Apollo 16*). Although radiometric dating of *Apollo 17* samples has been used to infer the age of Serenitatis, new evidence suggests that the landing site in the Taurus–Littrow Valley, shown in the inset, may be contaminated with ejecta from the Imbrium impact. The relationship between the *Apollo 16* samples and the Nectaris impact is even more ambiguous. (The arrows indicate Nectaris's rim.) Establishing reliable ages for the Moon's largest craters is crucial to determining the intensity and timing of a hypothesized period of frequent impacts known as the late heavy bombardment. (Images from the Lunar Reconnaissance Orbiter Camera.)

support a sustained human presence on the Moon or produce rocket fuel.

Some of those questions may soon be resolved. The *LRO* team is developing new strategies to measure lunar hydration, including monitoring PSRs that have been in darkness for many years but are now emerging into sunlight due to orbital precession. Also, NASA is building three new CubeSats: *Lunar Flashlight*, which will map surface frost; *LunaH-Map*, which will chart hydrogen to depths greater than 30 cm; and *Lunar IceCube*, which will examine the distribution of water as a function of latitude and time of day. (For more on CubeSats, see PHYSICS TODAY, November 2014, page 27.) A fourth proposed mission, the rover *Resource Prospector*, would land and extract volatiles from polar soil.

The Moon and the cataclysm

All told, the Apollo missions of the late 1960s and early 1970s returned more than 2000 moon rocks to Earth. Many of those rocks have been radiometrically dated to around 3.9 billion years ago, when they presumably formed from melts generated during impact events. Surprisingly, relatively few samples record impacts from the 600 million years of the Moon's existence before that time. Assuming early impacts were a result of debris being swept up in the end stages of planetary accretion,[13] they should have become rarer as the Moon aged. To explain the discrepancy, theorists proposed the so-called late heavy bombardment, a spike in large impacts that occurred after the first wave of accretion had died down. Some previously unexpected event would have to have caused that bombardment.

Solar-system-wide scenarios have been contrived to explain what the event might have been.[14] One scenario, known as the Nice model, posits that the outer planets were initially much closer to the Sun and that their outward migration scattered objects that had been in stable orbits. Not only would that scattering have caused the late heavy bombardment suffered by the Moon, it would have had massive effects across the whole of the inner solar system, with important implications for the emergence of life on Earth. If the Nice model is correct, many of the objects bombarding the inner solar system were from the proto-Kuiper Belt; they would have delivered water and, perhaps, prebiotic material to the terrestrial planets.

But theorists have frequently called into question just how "heavy" the late heavy bombardment really was. And in the past decade, new studies of the Moon have energized the debate.

As conventional wisdom has it, the Serenitatis basin, whose rim was sampled by *Apollo 17*, formed from an impact around 3.89 billion years ago, just 50 million years before the impact that formed the neighboring Imbrium basin, sampled during several missions (see figure 2). Based on stratigraphic relationships between craters, theorists initially concluded that three basin-forming impact events occurred in the interval between Serenitatis and Imbrium. But new examinations of those relationships and of the impact craters superposed on Serenitatis[15] have revised the number to 25. If we accept the conventional ages of Serenitatis and Imbrium, then the late heavy bombardment was even more intense than previously thought; it would have been a true cataclysm, with a basin forming every 2 million years.

But can we accept the conventional wisdom? New work has

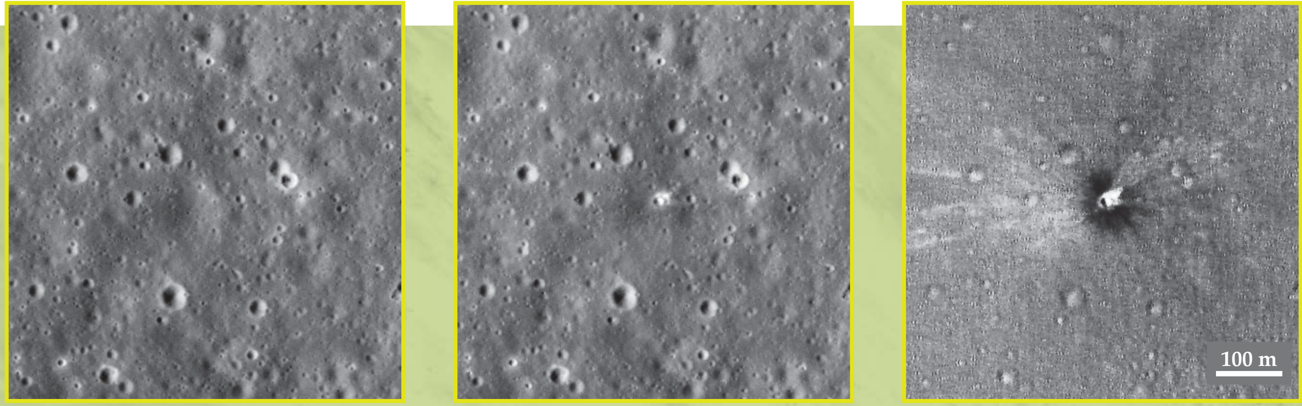


FIGURE 3. A RECENT METEOROID IMPACT was identified by comparing a "before" image from 2012 (left) with an "after" image taken under identical lighting conditions in 2013 (center). The ratio of the two images (right) clearly shows an 11 m crater. Immediately surrounding the crater are areas of high and low reflectance and faint rays that stretch farther out. The landscape changes are due to the deposition of ejecta and to the churning of the soil by impact debris. (Images from the Lunar Reconnaissance Orbiter Camera.)

shown that Imbrium ejecta likely litter the *Apollo 17* landing site, so the samples thought to date the Serenitatis impact may instead date the formation of the Imbrium basin.[15] If so, we're left with diminished evidence that the late heavy bombardment occurred at all—and increased evidence of the monumental effect that the Imbrium impact had on the nearside lunar landscape.

Serenitatis figures pivotally in our understanding of the late heavy bombardment in large part because we've collected so few samples that can be definitively linked to known crater-forming events. The *Apollo 16* landing site is not so distant from the Nectaris basin, but the evidence that samples collected there date to the actual formation of the basin is even more tenuous than it is for Serenitatis. It's possible that Imbrium is the only basin whose true age we know.

The obvious answer to the quandary is to collect samples that definitively date the formation of large impact basins such as Serenitatis, Nectaris, Crisium, South Pole–Aitken, and Orientale. But the ambiguous results from Serenitatis demonstrate the importance of careful sample-site selection. The currently available trove of orbiter data will no doubt aid in such site selection, as will future missions to collect high-resolution images of the lunar surface. Advancing our understanding of the timing of events on the Moon is critical for clarifying the timing of events on Mercury, Mars, and even early Earth: The lunar time scale is the foundation on which the others are built.

Not dead yet

Although the Moon's most intense geologic activity occurred early in its history, it is a more dynamic place than once thought. Impact events continue to reshape the surface, and we are now able to measure the rate of crater formation. By taking images of the same lunar terrain at different times and then comparing them, we can identify craters that formed in the intervening period. Most of that work has been done with images from the Lunar Reconnaissance Orbiter Camera (LROC), which can have pixel scales as small as 50 cm.

Early attempts to compare LROC images with decades-old photographs from the Apollo missions required an enormous amount of manual effort and—despite the lengthy interval in which new craters could accumulate—led to the identification of only a handful of new craters. Once LROC acquired a sizable collection of high-resolution "before" images, however, it began a dedicated campaign to reimage the surface under identical illumination conditions. Figure 3 shows an example of the subtle changes that can be detected by comparing before and after images.

It turns out that the lunar surface is changing at a remarkable pace: A new 10-m-diameter or larger crater forms about once every 23 days, about one-third faster than standard models predict. And each crater affects substantially more surface area than was previously appreciated.[16] For example, ejecta from a crater 10 m in diameter can strike and churn up soil tens of kilometers away. So far only a few hundred resolvable primary impact craters have been identified, the largest being 70 m in diameter, but images show tens of thousands of surface changes that are likely caused by secondary impacts of ejecta from those newly formed craters. That result is important for understanding how rapidly the surface overturns and exposes new material to the solar wind, but it will also inform the design of any future long-term outposts on the Moon. Furthermore, the primary impact rate has important considerations for Earth: The impact rate for objects large enough to survive passage through Earth's atmosphere is the same on Earth as it is on the Moon.

Another recent, and likely ongoing, process is tectonic deformation—the surface manifestation of billions of years of cooling and contracting. That deformation takes the form of lobate scarps, which are the surface expression of thrust faults: As the Moon's liquid outer core solidifies and contracts, its brittle overlying crust is forced to give way. LROC's high-resolution images reveal lobate scarps that cut across craters less than 10 m in diameter, too small to have survived for long on the surface. Those faults must therefore have been active recently, within the past 50 million years, and they may be active today.[17]

The orientations of thousands of newly discovered scarps indicate that Earth-induced tidal forces significantly contribute to stresses in the Moon's crust. Those forces are small compared with those of global contraction—the Moon's daily tidal swelling is only around 10–20 cm—but they add up over the course of a lifetime.

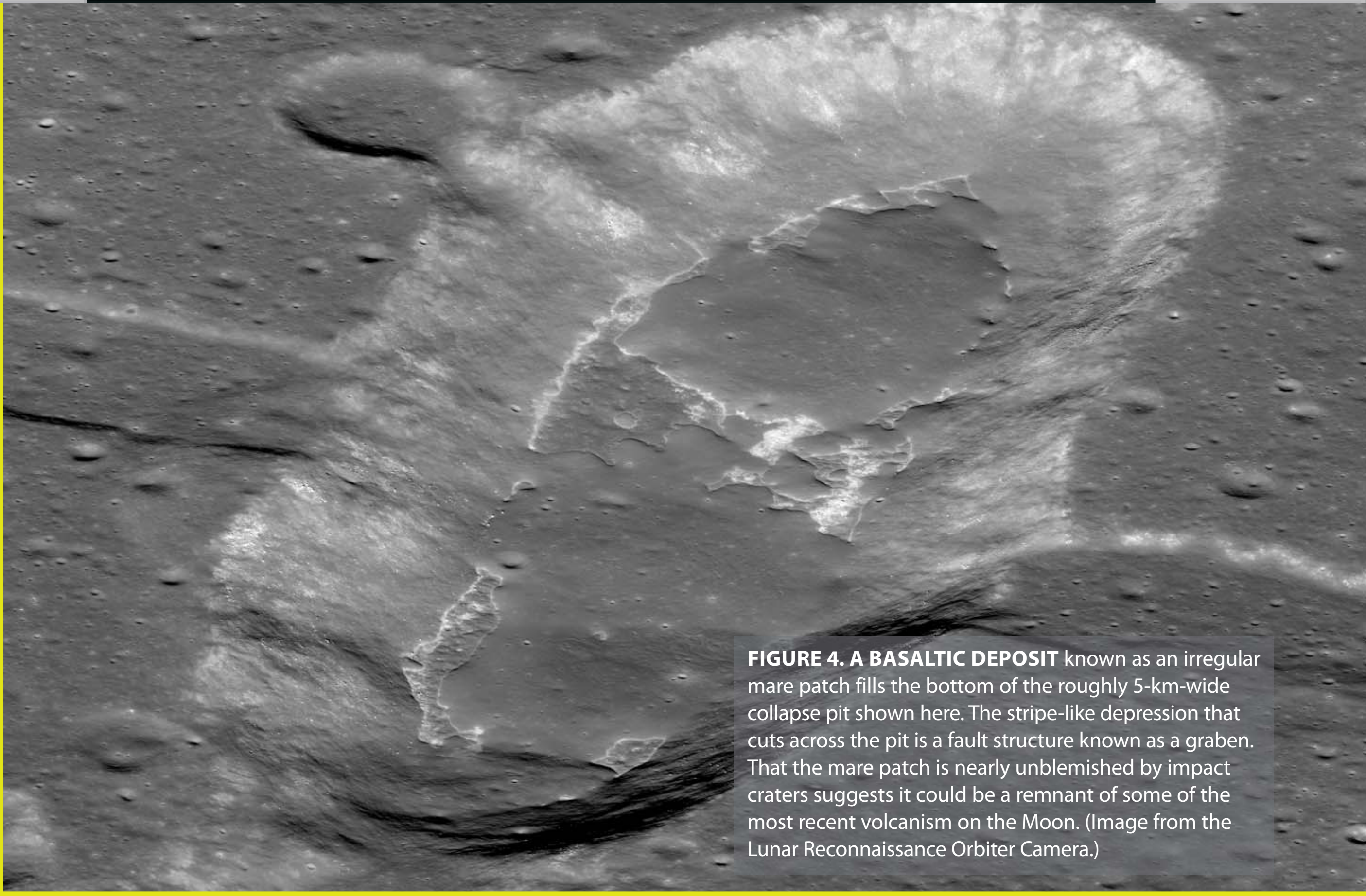


FIGURE 4. A BASALTIC DEPOSIT known as an irregular mare patch fills the bottom of the roughly 5-km-wide collapse pit shown here. The stripe-like depression that cuts across the pit is a fault structure known as a graben. That the mare patch is nearly unblemished by impact craters suggests it could be a remnant of some of the most recent volcanism on the Moon. (Image from the Lunar Reconnaissance Orbiter Camera.)

Lunar cooling is critical to another geologic process that has shaped the Moon's crust and yielded information about its interior: volcanism. Lunar volcanism was dominated by eruptions of basaltic lavas not unlike those that spill today from Earth's Hawaiian volcanoes and mid-ocean ridges. But because the Moon is smaller, it cooled faster and its eruptions largely ceased 1 billion to 2 billion years ago. (We don't know that number as precisely as we'd like.)

However, scattered across the nearside are small patches, between 100 m and 5 km across, with compositions and morphologies consistent with basaltic deposits. (See figure 4.) That those so-called irregular mare patches are largely unblemished by impact craters and have sharp, steep topographic boundaries suggests that they are very young; the steep slopes wouldn't have survived for long under the relentless rain of meteoroid impacts. The discovery raises the tantalizing prospect that the last dregs of lunar volcanism may have occurred within the past 100 million years, which is startlingly recent given what we know, or think we know, about the thermal history of the Moon.[18] But irregular mare patches also contain a host of contradictions. They aren't as rocky as one would expect for such young features, and they have no directly analogous volcanic counterparts on Earth. Now that more than 70 of those patches have been discovered, new hypotheses for their formation continue to emerge. It will be fascinating to see how the story shakes out. Confirmation or refutation of the patches' proposed young ages will likely require a sample return mission.

What's next?

Although orbital missions clearly still have a critical role, the attendees of the Houston meeting vigorously agreed that surface exploration, both human and robotic, and sample return will be necessary to address the important open questions in lunar science. The number and variety of exploration sites they proposed—easily more than 50 locations across the near and far sides—bespoke the community's excitement.

So how can we get back to the Moon? Lunar missions are likely to be proposed to NASA's Discovery Program, which funds low-cost missions that address high-priority science questions anywhere in the solar system (except the Sun and Earth). Six additional projects, including one to return samples from the Moon's largest and oldest impact event, the South Pole–Aitken basin, can be proposed to the agency's New Frontiers Program, which funds more complicated and costly missions that address specific gaps in scientific knowledge. There is no guarantee, however, that a lunar mission will be among the next round of proposals selected by Discovery and New Frontiers. And NASA currently has no dedicated exploration program for the Moon as it does for Mars.

Lunar science and human exploration enjoy a mutually beneficial relationship that dates back more than half a century. The early era of lunar exploration led in the late 1960s and early 1970s to the first geologic fieldwork conducted on another solar-system body. Lunar scientists still enthusiastically pore over that fieldwork's bounty, revisiting samples with new techniques and ideas and making new discoveries from old observations. Thirteen years ago US officials called for NASA astronauts to be back on the Moon to stay by 2020. But exploration is inextricably linked to politics, and rapidly shifting political priorities can thwart the long-term planning efforts necessary to realize a sustained program of exploration. Those efforts are even more complicated when multinational politics are involved and political "realities" are at play. For instance, US scientists are currently barred from using NASA funding for bilateral research projects with Chinese scientists. (See PHYSICS TODAY, December 2013, page 24.)

Nonetheless, the world is pressing forward with lunar exploration. South Korea, India, and Russia have plans for orbital and landed missions. In November 2017 China plans to launch *Chang'e 5*, the first lunar-sample return mission in four decades. The following year, *Chang'e 4* and its small rover will conduct the first landing on the far side of the Moon. The *Resource Prospector*, the only landed mission currently being formulated by NASA, is targeted to launch early in the 2020s.

The European Space Agency has proposed a "moon village" as a natural follow-up to the International Space Station. The international effort would use public and private partnerships to build a sustained human presence on the Moon, but so far it is more a concept than a plan. And then there are private projects, among them the Google Lunar X Prize, which will award $20 million to the first team to land and move a robot at least 500 m on the surface of the Moon. Five teams now have launch contracts in place for 2017.

For now, the *LRO* is the only dedicated lunar mission that is still fully operating. Launched as part of NASA's Exploration Systems Mission Directorate (now the Human Exploration and Operations Mission Directorate) but currently run by the Science Mission Directorate, it is exemplary of the constructive interplay between science and exploration. Its current extended mission is funded through 2018, but it has the fuel to run for years beyond that. Hopefully it will still be circling the Moon as the next generation of missions arrives at the lunar surface to make new measurements, collect new samples, and further advance our quest to understand the history of the solar system.

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HIDDEN WORLDS of fundamental particles

David Curtin and Raman Sundrum

Spectacular bursts of particles that seem to appear out of nowhere may shed light on some of nature's most profound mysteries.

Why is there something rather than nothing? It's a question so basic and so vast in scope that it seems beyond the realm of quantitative inquiry. And yet surprisingly, it is a question that can be framed and at least partially answered in the study of particle physics.

The standard model (SM) is our current theory of matter and its interactions. Written in the language of relativistic quantum field theory, it has stood up to several decades of tests at high-energy colliders. We know, however, that it cannot be the complete description of the universe, in large part because in several important regards it fails to answer the something-versus-nothing question.

Material existence is connected to three fundamental mysteries. First, why can matter clump to form a rich array of structures without collapsing into black holes? The requisite weakness of gravity arises because the particles that make up everyday matter are incredibly light. In the SM, the mass of all fundamental particles must be less than the electroweak mass, whose value of a few hundred GeV/c^2 follows from the physics of the Higgs boson. However, when the effects of gravity are taken into account, the SM electroweak scale receives quantum contributions on the order of the Planck mass, 10^{18} GeV/c^2. That puzzling discrepancy of scale is called the hierarchy problem. In the SM, a particle's lightness is recovered only thanks to an incredible cancellation among unrelated parameters. There exist more attractive solutions, including supersymmetry and the Higgs boson as a composite particle, that also predict high-energy signatures of new physics at the Large Hadron Collider (LHC).

Second, stuff exists only because at some point in the early universe, there was one extra particle of SM matter for every one billion matter–antimatter pairs. That tiny excess is all that remains today, and it must have been created dynamically in the primordial plasma of the Big Bang. In the SM, that process—baryogenesis—is too weak by many orders of magnitude; evidently, additional particles and interactions must have been present. Theorists have suggested many possibilities, including additional Higgs bosons and modified Higgs couplings that could be detected at the LHC.

Third, strong interlocking evidence from a multitude of astrophysical and cosmological observations suggests that dark matter makes up about 80% of the matter in the universe. We have no definitive knowledge of what it is or how it connects to the SM. The most popular theories predict a tiny interaction of dark matter with ordinary matter. Such a coupling would enable direct detection by nuclear recoils in sensitive detectors and indirect detection in cosmic-ray data that show evidence of dark-matter annihilation into SM particles.

The hierarchy problem, the riddle of matter–antimatter

(GHOST) RIDERS IN THE SKY
by Christopher Arabadjis, 2009.

asymmetry, and the nature of dark matter drive much of experimental and theoretical particle physics. Many experimental searches for answers to those mysteries are proceeding vigorously, but so far with null results across the board. That doesn't mean nothing is to be discovered. On the contrary, the null results may well point us toward the true nature of the universe. There could be hidden sectors—additional particles and forces—with only tiny couplings to the SM. Far from being inconsequential, those new sectors can address all three big mysteries. Their signatures are subtle and easily missed, but luckily, their hidden nature is also the key to their discovery. Invisible long-lived particles (LLPs) can be produced at colliders and decay into energetic SM particles after traveling an appreciable distance. Can we catch those revealing flashes?

A tale of two frontiers

Physicists built the LHC in part to access new physics at mass scales higher than those characteristic of the SM. However, new physics may be concealed, not by virtue of high mass, but by very small couplings to the SM. We use the term "hidden sectors" to refer to such disconnected non-SM matter and forces, which can arise robustly within the framework of quantum field theories.

Like the push for higher energy, the investigation of hidden sectors with tiny couplings to visible particles has important historical precedent. Neutrinos are almost massless, and nowadays they are understood to be related to charged leptons (electrons, muons, and taus) through their shared weak interaction. Wolfgang Pauli postulated their existence in 1930 to restore conservation of momentum to beta decay, but their direct detection via scattering off nuclei wasn't achieved until 1956, when large neutrino fluxes from nuclear reactors became available. The discovery of the ghost-like neutrino sector was only the beginning, and those elusive particles still aren't done confusing us. For example, we know that neutrinos have masses and oscillate from one type to another, which is not accounted for in the SM.

New hidden sectors can be connected to the SM by small but nonzero couplings called portals. Figure 1 illustrates the most important types. Portal couplings are small for several reasons. For example, symmetries can give rise to quantum mechanical selection rules that force interactions between the SM and a hidden sector to proceed by means of a heavy and therefore hard-to-access mediator state. The mediator is not part of the SM but interacts with both the SM and hidden sectors.

It's possible for some SM states—most importantly the photon and the Higgs boson—to function as a mediator. Although the structure of the theory makes the Higgs-portal and photon-portal couplings smaller than ordinary SM couplings, they are readily made much larger than the couplings of other types of portals. Furthermore, accelerators produce lots of Higgs bosons and photons. In rough analogy to an oscillating neutrino, a photon could transform into a hidden photon and interact with hidden states.[1] The Higgs boson, with a mass of 125 GeV/c^2, is heavy enough to sometimes decay directly into the hidden sector. Such exotic Higgs decays are one of the most promising avenues for producing hidden-sector particles.[2]

Hidden sectors typically contain massive states that would be stable in isolation but that decay into SM particles in the presence of portal couplings. Precisely because the portal is

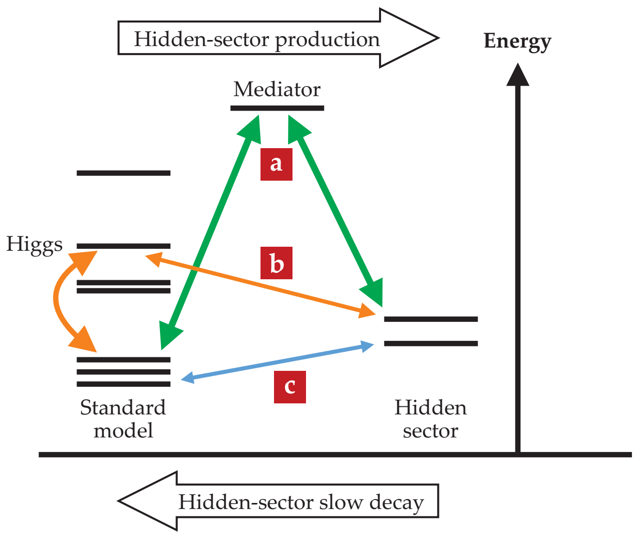

FIGURE 1. PORTALS TO HIDDEN SECTORS. The diagram represents the energies of possible hidden-sector states in relation to those of the standard model. Colored arrows indicate possible transitions between states. At the Large Hadron Collider, hidden-sector states can be created by means of the production and decay of heavy mediators **(a)**, exotic decays of the Higgs boson **(b)**, or small direct couplings **(c)**. Once produced, the states decay through the same portals. Hidden-sector states have long lifetimes because the direct couplings are small or because energy must be borrowed, courtesy of the Heisenberg uncertainty principle, to excite the intermediate mediator or Higgs boson.

such a tiny keyhole, the decay can take a relatively long time. That is what makes LLPs and their spectacular decays a hallmark of hidden sectors.

Solving mysteries

Searching for the flashes of LLP decays at the LHC and other colliders will be a major enterprise. It will require dedicated analyses and maybe new detectors, but it is well worth the effort. Here are just a few examples of how new sectors with hidden states address the three big mysteries.

Let's start with the hierarchy problem. As shown in figure 2, known solutions cancel the top quark's large quantum contribution to the Higgs (and thus electroweak) mass by introducing partners related to the top by a symmetry. In the case of supersymmetry, the top partners take part in the SM's strong interaction, so they should be produced in large numbers at the LHC.

We haven't found any sign of those partners yet, but another solution, called neutral naturalness,[3] relies on hidden valleys,[4] which are a family of theories that are essentially cousins of quantum chromodynamics (QCD), the theory of the SM's strong interactions. Hidden valleys give rise to low-energy bound states; in analogy to SM protons and pions, they are called hidden hadrons. In theories of neutral naturalness, the top partner does not interact via the SM strong force, but it does interact via those hidden cousins of QCD. A striking signature of that novel interaction involves exotic decays of Higgs bosons to hidden hadrons, which can eventually decay back to SM particles through one of several portals. The result, as shown in the figure, looks like a displaced decay.

What about dark matter? Perhaps the best-known candidate

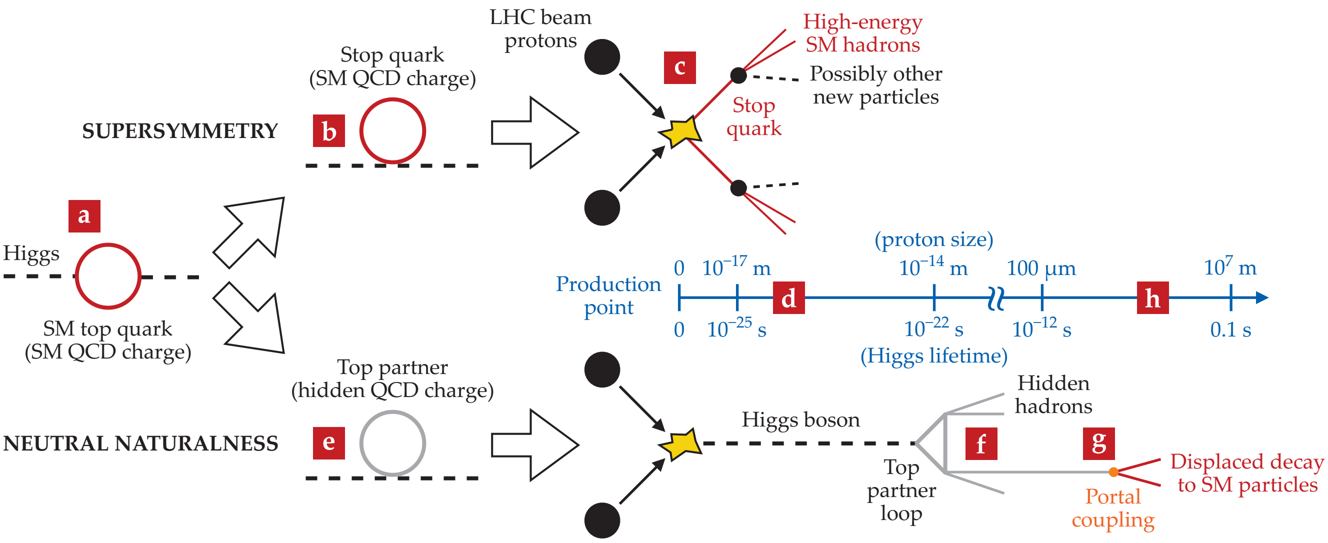

FIGURE 2. SUPERSYMMETRY VERSUS NEUTRAL NATURALNESS. The hierarchy problem in the standard model (SM) arises because quantum processes make large contributions to the Higgs boson mass and there is no natural mechanism for their cancellation. The most important contributions come from top-quark loops **(a)**, intermittent quantum mechanical fluctuations of the Higgs boson into top and antitop pairs. In supersymmetry, the top loop is canceled by a loop of top partners called stops **(b)**, which have a mass comparable to that of the top quark. The stops have the same quantum chromodynamics (QCD) charge as the top quarks—that is, they experience the strong interaction just as the tops do. As a result, they should be copiously produced **(c)** in proton–proton collisions at the Large Hadron Collider (LHC). Stops typically decay into sprays of highly energetic SM particles and possibly new invisible particles within a very short amount of time **(d)**. Neutral naturalness solves the hierarchy problem with top partners that don't have a QCD charge—that is, they don't participate in the SM strong interaction.[3] Under a discrete symmetry, the top quark is reflected by a top partner charged in a hidden QCD **(e)**. Because of the absence of SM QCD couplings, those top partners are not produced in large numbers. However, due to its coupling to the top partners, the Higgs boson acquires a new decay mode that yields hidden QCD hadrons **(f)**. Eventually those hidden hadrons can decay back to SM particles **(g)**. The decay products are well displaced in space and time **(h)** from the original proton–proton interaction point.

is the WIMP (weakly interacting massive particle). As illustrated in figure 3, it freezes out in the early universe when it becomes too diluted to annihilate any further, and its relic abundance is set by its coupling to the SM. If that coupling is the SM electroweak coupling and the mass of the dark matter is close to the electroweak mass, one finds roughly the dark-matter abundance measured today. That confluence is called the WIMP miracle. However, the direct coupling of dark matter with the SM also predicts signatures yet to be seen in direct and indirect detection experiments. Dark matter can be produced at colliders but it is invisible and only reveals itself as a momentum imbalance in a collision.

A different possibility shown in the figure is that the relic abundance of dark matter is set by the lifetime of a heavy LLP parent that produces dark matter in its decays.[5] The corresponding dark-matter particle has a much weaker coupling to the SM than a WIMP does and is called a feebly interacting massive particle (FIMP). The LLP can be produced at colliders; typical lifetimes are in the millisecond ballpark.

We turn to baryogenesis, which can proceed according to several known mechanisms. In all cases, an out-of-equilibrium process needs to create more matter than antimatter in the plasma of the early universe. A simple way to achieve that imbalance is the out-of-equilibrium decay of a heavy particle. In particular, the scenario of WIMP baryogenesis,[6] as shown in figure 4, piggybacks off the quantitative success of the WIMP miracle. Since the abundances of dark matter and SM matter in our universe are only different by a factor of five, a long-lived WIMP decaying into SM particles could easily generate the required matter asymmetry. The WIMP can be produced at colliders and possibly give rise to LLP signatures.

The above list of theories is certainly not exhaustive; it is meant to illustrate that LLPs and hidden sectors are highly motivated for a variety of fundamental reasons.

Flashes beyond the shrapnel

Long-lived particles can be reliably identified only if we know where they are produced. Unlike dark matter or cosmic rays, which occur naturally, LLPs have to be synthesized at colliders, where experimenters can hope to measure the macroscopic distance from the production point to the flash point of the decay.

If the LLPs have masses below the electroweak scale, they might be produced in high-intensity experiments with lower collision energy than at the LHC. Examples of such experiments include the BaBar search at the PEP-II electron–positron collider,[7] the APEX search at the Thomas Jefferson National Accelerator Facility,[8] and the proposed SHiP (Search for Hidden Particles) experiment at CERN.[9] The abundance of collisions in such investigations allows tiny couplings to be probed by sheer force of numbers.

The LHC, however, is unique in that it allows us to probe hidden sectors when the mediator mass or hidden-sector particle masses are at or above the electroweak scale. The high-luminosity LHC upgrade, planned for the mid 2020s, will increase the number of collisions at the facility by a factor of 10 and is projected to yield 10^8 Higgs bosons over a 10-year period. A tiny Higgs portal can easily force 0.1% of them to decay to hidden-sector states, which would produce plenty of LLPs. Just as the enormous neutrino fluxes at nuclear reactors paved the way to neutrino detection in the 1950s, the combination of high-energy and high-intensity collisions in the current era may

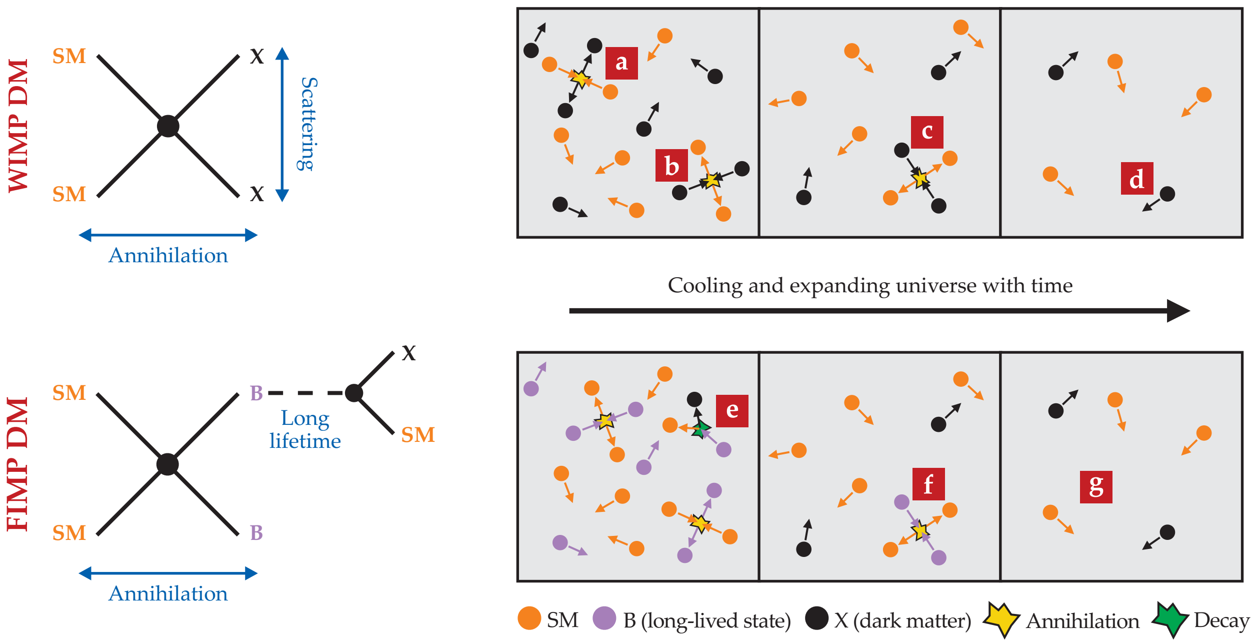

FIGURE 3. DARK-MATTER freeze-out versus dark-matter freeze-in. Early in the history of the universe, the thermal energy is much greater than the rest energy of a dark-matter (DM) particle. In that epoch, standard-model matter (SM) is in thermal equilibrium with dark matter (X); the process SM + SM → X + X **(a)** and the reverse process **(b)** occur at equal rates. As the universe cools, colliding standard-model particles no longer have the energy to create the heavy dark matter, but X still annihilates to SM **(c)**, which drastically reduces the dark-matter abundance. As the universe cools and expands even more, dark matter becomes so diluted that annihilation to SM no longer takes place. The dark-matter abundance is frozen out and survives to this day **(d)**. That relic abundance is dictated by the dark-matter coupling to the standard model, which sets both the annihilation rate in the early universe and the rate for dark matter to scatter off standard-model particles in direct detection experiments. On the other hand, the relic density of feebly interacting massive particles (FIMPs), an alternative to the popular weakly interacting massive particles (WIMPs), is set by a freeze-in mechanism, in which no FIMPs are initially present.[5] A parent particle B has sizable couplings to the standard model and is in thermal equilibrium in the early universe. However, the long-lived B decays into SM and X **(e)**. Even when the universe is much younger than the lifetime of the B, a tiny fraction of Bs still decays, so dark matter steadily accumulates. As the universe cools, the Bs annihilate almost completely away to standard-model particles **(f)**. The frozen-in dark-matter abundance **(g)** survives to the present day. In this FIMP scenario, the dark-matter relic density is set directly by the lifetime of the B, which is typically in the millisecond ballpark.

give us unparalleled access to new hidden worlds, provided we look in the right places.

The main detectors at the LHC are busy places, with lots of hadronic shrapnel flying around. Luckily, neutral LLP decays are a spectacular signature, and the bursts of energy appearing out of nowhere set them apart from the mundane rubble emanating from the collision point. Looking for LLPs represents something of a paradigm shift from the usual approach, exemplified by the top branch of figure 2, to hunting for new physics. As-yet-undiscovered particles with large coupling to the SM would have large production rates. And that ample production is necessary if the particle signals are to be observed above the SM background noise, because the large coupling also makes the particles decay immediately at the collision point. LLP production typically occurs at much lower rates, but each individual displaced decay is so spectacular that backgrounds are orders of magnitude lower than for particles that couple strongly to the SM. Far fewer observed events are needed to claim discovery.

The decay lengths of hidden-sector LLPs could be almost anything from a few hundred microns to astrophysical scales. You might find that a little discouraging: Why should we expect to see an LLP decay in the lab if it could just as well decay near Proxima Centauri? Some detailed theories suggest that LLPs should have relatively short lifetimes, but in any case, there exists a robust ceiling. If the LLP is producible at colliders, it must have been in thermal equilibrium with the SM plasma in the early universe. As the universe cooled, the first elements—hydrogen, helium, lithium, and beryllium—came into being. That formation process, Big Bang nucleosynthesis, took place when the universe was about 0.1–1 second old, and it is exquisitely sensitive to ambient conditions. With few exceptions, LLPs decaying during or after Big Bang nucleosynthesis would disrupt the process and yield inconsistencies with measurements of primordial elemental abundances.[10]

Ongoing searches

Some experiments at the LHC are already looking for LLPs, but much more needs to be done to cover the whole range of accessible masses, lifetimes, and production processes. Figure 5 provides a basic overview of the ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid) detectors at the LHC and the signatures they might observe.

Many theories, with and without hidden sectors, predict LLPs that interact electromagnetically or strongly, and those particles can show up in several detector subsystems.[11] For ex-

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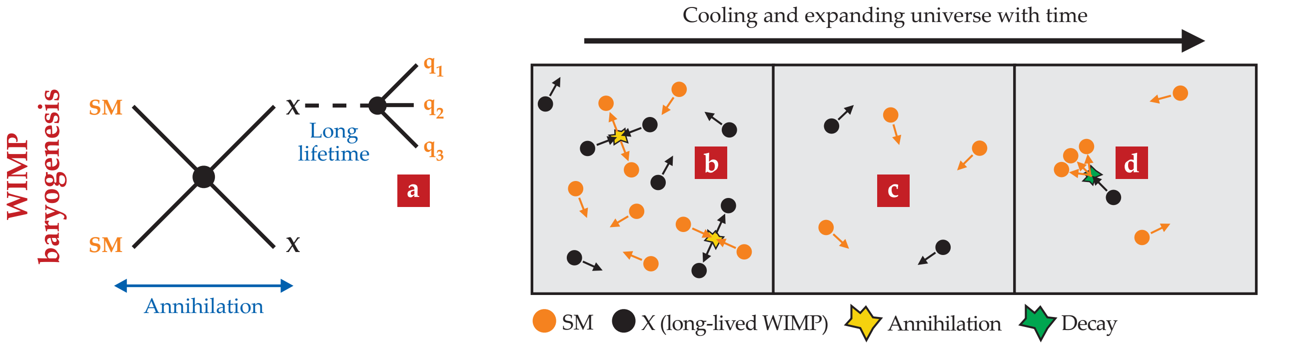

FIGURE 4. WIMP BARYOGENESIS. The creation of matter over antimatter is favored by the decay **(a)** of a metastable weakly interacting massive particle (WIMP) X into standard-model (SM) quarks (q).[6] At early times, X is in thermal equilibrium with the matter-antimatter-symmetric thermal bath **(b)**, and as with conventional WIMPs, it eventually freezes out as the universe expands and cools **(c)**. When the universe is about as old as the lifetime of the X, the particle decays out of equilibrium and creates the matter excess **(d)** that survives today.

ample, due to its high mass, the LLP could deposit a lot of energy in a calorimeter, or it could leave a kinked track if it decays while it traverses the detector.

It is also possible for stable hidden-sector particles to be electrically millicharged—that is, to have an electronic charge that's just a tiny fraction of the electron's. It happens when states interact with each other via a massless hidden photon that oscillates into the SM sector through the photon portal. Millicharged states are extremely difficult to detect because they are only weakly ionizing when they pass through matter. However, their traces could be observed with a dedicated detector like MilliQan, which would be situated in a tunnel, close to one of the main detectors.[12]

Neutral LLPs are challenging to isolate at the LHC, since the detectors there weren't primarily designed for such particles. However, if the LLPs decay to charged particles, the tracking systems can reconstruct displaced vertices,[13] such as is shown in figure 5. The signals are spectacular, but there is some SM background: Extremely rare events involving production of highly energetic SM hadrons, peculiar configurations of long-lived SM hadron decays, and detector hiccups can conspire to fake a displaced vertex. Such a chain of coincidences can be a problem only because of the enormous rate of SM strong-interaction events, which produce multitudes of hadrons at the LHC.

The obvious challenges are neutral LLPs with decay lengths much larger than the detector size; only a small fraction of those will decay in the detector. The ATLAS detector is able to look for displaced vertices in its largest subdetector, the muon system. If the LHC produces enough LLPs, the ATLAS team can afford for the large majority to escape, and their searches can have sensitivity to decay lengths in the kilometer range.[14] But for particles with longer lifetimes and hence lower chances of decaying in the main detector, strong-interaction background swamps the signal. How can we probe those especially long-lived particles?

The lifetime frontier

Big Bang nucleosynthesis limits the lifetime of an LLP to less than 0.1–1 second, but that still allows an LLP produced at an accelerator to travel all the way to the Moon. We won't catch them all. Luckily, we don't have to. Being able to observe just one in a million of those limit-testing LLPs would already allow us to probe the most important new physics scenarios.

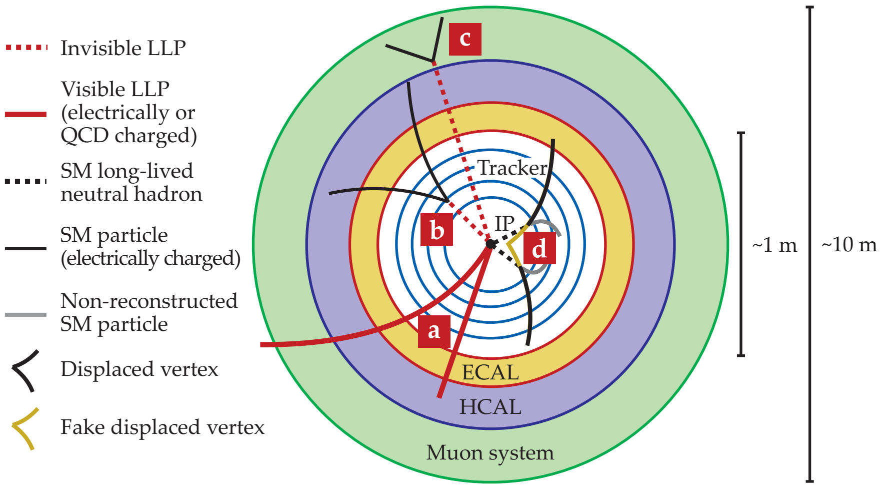

FIGURE 5. SEARCHES FOR LONG-LIVED PARTICLES (LLPs) at the Large Hadron Collider (LHC). Shown here is a schematic cross section, transverse to the beam, of the ATLAS and CMS detectors; the inner layers are enlarged to show detail. The tracker layers detect passing charged particles, and the track curvature in the magnetic field reveals a particle's momentum. The calorimeters labeled ECAL and HCAL measure energy of electrically charged particles and hadrons, respectively, and the muon system detects muons. Particles are produced in collisions at the interaction point (IP). Electrically charged LLPs or strongly interacting LLPs charged under quantum chromodynamics (QCD) leave signals **(a)** in many detector layers. Neutral LLPs are invisible but can decay to standard model (SM) particles in the tracker **(b)**. The tracks of the decay products meet at a displaced vertex. The muon system of the ATLAS detector can also reconstruct displaced vertices **(c)**. A rare but important background to neutral LLP searches consists of fake displaced vertices that occur due to various freak coincidences. For example, the tracker might fail to detect all the decay products of a few long-lived SM hadrons. Such an event is extremely rare, but it can lead to a fake displaced vertex, shown as yellow intersecting lines **(d)**.

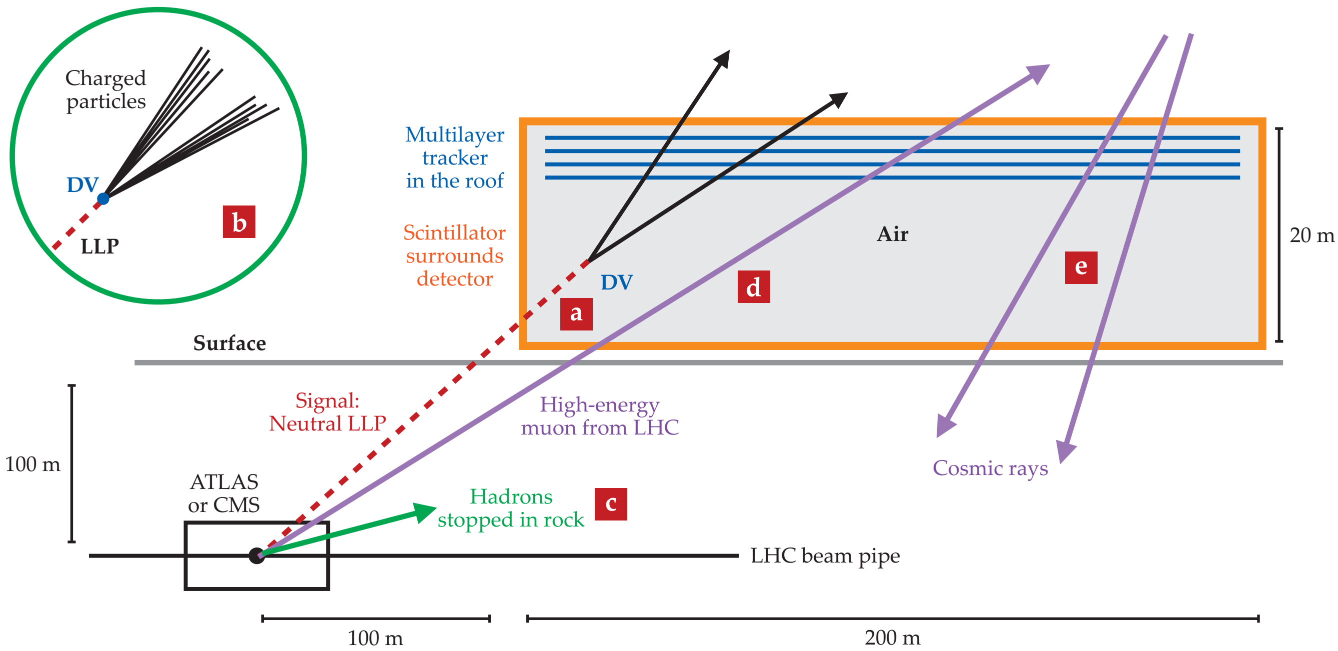

FIGURE 6. THE MATHUSLA DETECTOR for catching long-lived particles (LLPs) at the lifetime limit. The MATHUSLA concept[15] envisions a 200 m × 200 m × 20 m detector on the ground above the Large Hadron Collider (LHC), offset from the ATLAS or CMS collision points. An LLP produced at the LHC travels upwards and decays in the air-filled decay volume **(a)**. The inset **(b)** shows a simulated LLP with mass of 20 GeV decaying into a quark and an antiquark that give rise to an upward-traveling shower of about 10 charged standard-model particles. The particle shower is detected by trackers in the roof; tracker data enable the reconstruction of a displaced vertex (DV). The spectacular nature of this signal is vital for background rejection. Standard-model hadrons produced in the collision are stopped in subsurface rock **(c)**. A scintillator surrounding the detector volume ensures the DV is not falsely constructed from upward-traveling charged muons **(d)** penetrating the rock. Cosmic rays **(e)** are constantly incident on the whole detector, but they do not yield a reconstructed DV, and they can be reliably distinguished by their direction of travel. Rare backgrounds such as cosmic-ray neutrinos scattering off air (not shown) can be rejected due to the geometry and timing of their final states, which are quite different from what would be observed for the signal shown in the inset.

The main LHC detectors can't pull off such observations, but a dedicated LLP detector might; a preliminary concept has recently been proposed by one of us (Curtin), and collaborators.[15] The MATHUSLA (Massive Timing Hodoscope for Ultra-Stable Neutral Particles) detector, a gigantic tracker named after the long-lived biblical character, is shown in figure 6. Situated on Earth's surface rather than underground, it is shielded from troublesome SM hadrons produced in LHC collisions. Backgrounds, which are currently being studied in detail, can be nearly perfectly rejected. Since the instrumentation is relatively simple, MATHUSLA could be built in time for the high-luminosity LHC upgrade.

Many hidden sectors could go undiscovered at the LHC without a dedicated LLP detector, and the achievable sensitivity of MATHUSLA is remarkable. For example, if the Higgs boson decays to very long-lived particles 10% of the time, the high-luminosity LHC main experiments will be able to detect a deviation from SM predictions of its couplings, but they will not be able to determine if they had just discovered dark matter or LLPs. MATHUSLA could catch those LLPs decaying, even if their lifetimes are near the Big Bang nucleosynthesis limit. For shorter lifetimes, corresponding to decay lengths down to 100 m or so, MATHUSLA's sensitivity would enable the detection of LLPs with production rates three orders of magnitude smaller than what the ATLAS or CMS detectors could discover on their own.

We're in for an exciting ride. The LHC is the accelerator of our time, and both theoretical and experimental clues point toward new physics near its operating energy at the TeV scale. Null results to date don't invalidate those hints; they may simply be pointing us toward the brave new world of hidden sectors. Much work is needed to take advantage of the unique opportunities the LHC provides, but if the necessary searches and detector ideas are implemented now, we have every reason to hope for spectacular discoveries in the years to come.

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The secret search for URANIUM IN COLD WAR MOROCCO

Matthew Adamson

In the 1950s, as Cold War tensions rose, France and the US entered a secret alliance to search for uranium in the French protectorate of Morocco.

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This article is based on Adamson's article "*Les liaisons dangereuses*: Resource surveillance, uranium diplomacy and secret French–American collaboration in 1950s Morocco," *British Journal for the History of Science* **49**, 1, 2016.

In October 1939, President Franklin Roosevelt received a surprising letter warning him of the dangers of a recent scientific discovery: the nuclear fission of uranium. Albert Einstein and Leo Szilard were the letter's authors, though only Einstein signed his name. Known today as the Einstein letter, the missive warned of more than bombs or a new source of motive power. Its main concern was, as the authors put it, "the problem of securing a supply of uranium ore for the United States." The two physicists feared that most of the world's known supply of uranium would end up in Nazi Germany's hands, which would give the Germans a monopoly over fission's potential power.

Thus was kindled an obsession with uranium that would persist through several US administrations. The interest in uranium ore led not only to a frenzied effort to prospect the American West for radioactive minerals but to a worldwide diplomatic and geological effort to secure uranium wherever it might be found, in whatever country—even if it involved undercover agents, secret agreements with rivals, and private enterprises serving as fronts for covert prospecting operations.

One such enterprise, the Moroccan Research and Mining Company (Société Marocaine de Recherches et d'Exploitations Minières, SOMAREM), explored the soils and sands of Morocco from 1953 to 1955. Although it recovered virtually no uranium, SOMAREM served its US and French creators well. Its secret uranium exploration yielded geophysical and geopolitical lessons that are still important today.

France's Atomic Energy Commission

The atomic attacks on Hiroshima and Nagasaki made clear the new strategic centrality of uranium. As World War II came to an end, the US, along with the UK and Canada, made an attempt to find and secure the world's uranium supply.[1] At the time, geologists believed uranium to be rare and primarily found in a few high-grade deposits: The Shinkolobwe mine in the Belgian Congo, the Joachimsthal mine in Czechoslovakia, and the Eldorado mine at Port Radium in Canada. Secret wartime research had shown that coal and oil shales and monazite sands might also contain uranium. But American geologists were convinced that exploitable occurrences of uranium were rare enough to warrant an attempt to control them all.

The US was not alone in its pursuit of uranium. Not only was the USSR organizing a giant program to build nuclear weapons, friendlier rivals were also starting up nuclear programs. In October 1945, Charles de Gaulle's provisional government decreed the creation of the French Atomic Energy Commission (Commissariat à l'Énergie Atomique, CEA). France entrusted the CEA with sole responsibility for the development of nuclear energy and technologies, including the possibility of weapons.

The CEA leadership took to its mission with youthful energy. One of the commission's first tasks was to locate a source of uranium for France's new atomic program. In the CEA's first five years, nearly half the CEA's limited budget went to uranium prospection and mining, including the creation of sections devoted to exploration, borehole drilling, mineralogy, and topography. CEA officials in Paris anxiously awaited reports from their prospectors, who were exploring possible deposits in central France and the French colonies.

US agents followed the French prospectors carefully. Not only was the US Atomic Energy Commission (AEC) involved in the surveillance, but the State Department was contributing to the nuclear spy effort. Washington distributed Geiger counters to embassies and consulates worldwide. Records show that the US embassy in Paris became a way station for minerals. Samples flowed in from the abandoned wartime German program and from programs in France, Western Europe, and elsewhere. Samples that showed high levels of radioactivity were forwarded across the Atlantic Ocean to the AEC laboratory in New Brunswick, New Jersey.

Determined to control the global flow of uranium, the US proved capable of countering the ambitions of rival programs, including the French program. In 1950, with a small stock of prewar uranium and with promising deposits discovered in central France, the CEA was ready to ink a deal to provide uranium to the Norwegian atomic effort. That arrangement would have given the French access to Norway's supply of heavy water and established France as an international atomic presence. US officials got wind of the prospective deal and stepped in. They convinced their British counterparts to offer the Norwegians a stock of available Dutch uranium and kept the French out.[2]

Uranium in the protectorate of Morocco

With the high value of even a modest stock of uranium clear, Jean Orcel, the renowned mineralogist at France's National Museum of Natural History and the CEA's leading consultant on uranium, recommended sending CEA prospectors to Morocco.

Orcel knew Morocco well. In September 1945, he deposited a sealed envelope at the French Academy of Sciences in which he reported that he had spotted "a greenish-yellow mineral, immediately calling to mind a possible uranium salt" at an unspecified location in Morocco.[3] The CEA leadership was ready to act.

But Morocco presented several complications. The 1912 Treaty of Fez had declared the North African nation a French protectorate, and France controlled it much like a colony. However, Morocco's sultan was technically the ruler of a sovereign state. That semiautonomy, carefully cultivated by Sultan Mohammed V after World War II, was enough to keep the CEA from having an automatic claim to any Moroccan uranium, as it did in the French colonies. In the Moroccan protectorate, uranium fell into the category of common metals. The world's most strategically sensitive substance was, legally speaking, fair game to all prospectors. In addition, the CEA was strapped for resources: Throughout the 1940s it could send but one geologist to Morocco to explore the situation in that vast, promising land.

The CEA's inability to exploit opportunity in Morocco was apparent at the close of 1948, when the Mining Co of Bou Azzer, in cooperation with protectorate mining services, detected traces of uranium in its cobalt mine, located in the Anti-Atlas mountain range (see the map in figure 1). Shortly afterwards, lenses of pitchblende were detected in the Azegour molybdenum mine southwest of Marrakech. The CEA sent reinforcements, hoping it could scrape together the prospectors necessary for a concerted search of the entire protectorate.

Quietly, the US sent its own assets. A geologist with the Economic Cooperation Administration—the Marshall Plan's administrative arm—reported on the Bou Azzer finding. The AEC wanted to know more. It drafted metallurgist Frank McQuiston Jr, deputy director of its raw materials division and a consultant for the Newmont Mining Corp, to gather intelligence. McQuiston had seen the Shinkolobwe mine in the Belgian Congo and the uranium-laced gold fields of the Witwatersrand in South Africa; now, on the pretext of a visit to Newmont's zinc mine in eastern Morocco, he reported on traces of uranium found in cobalt and molybdenum mines and in the vast phosphate deposits at Khouribga, and on rumors of uranium elsewhere in the protectorate.[4]

A fragile diplomacy

As 1951 brought more reports of uranium in Morocco, the AEC and the US State Department agreed that it was time to make a move. But how? The diplomatic sensitivity of the situation was acute. Not only were rival French uranium prospectors

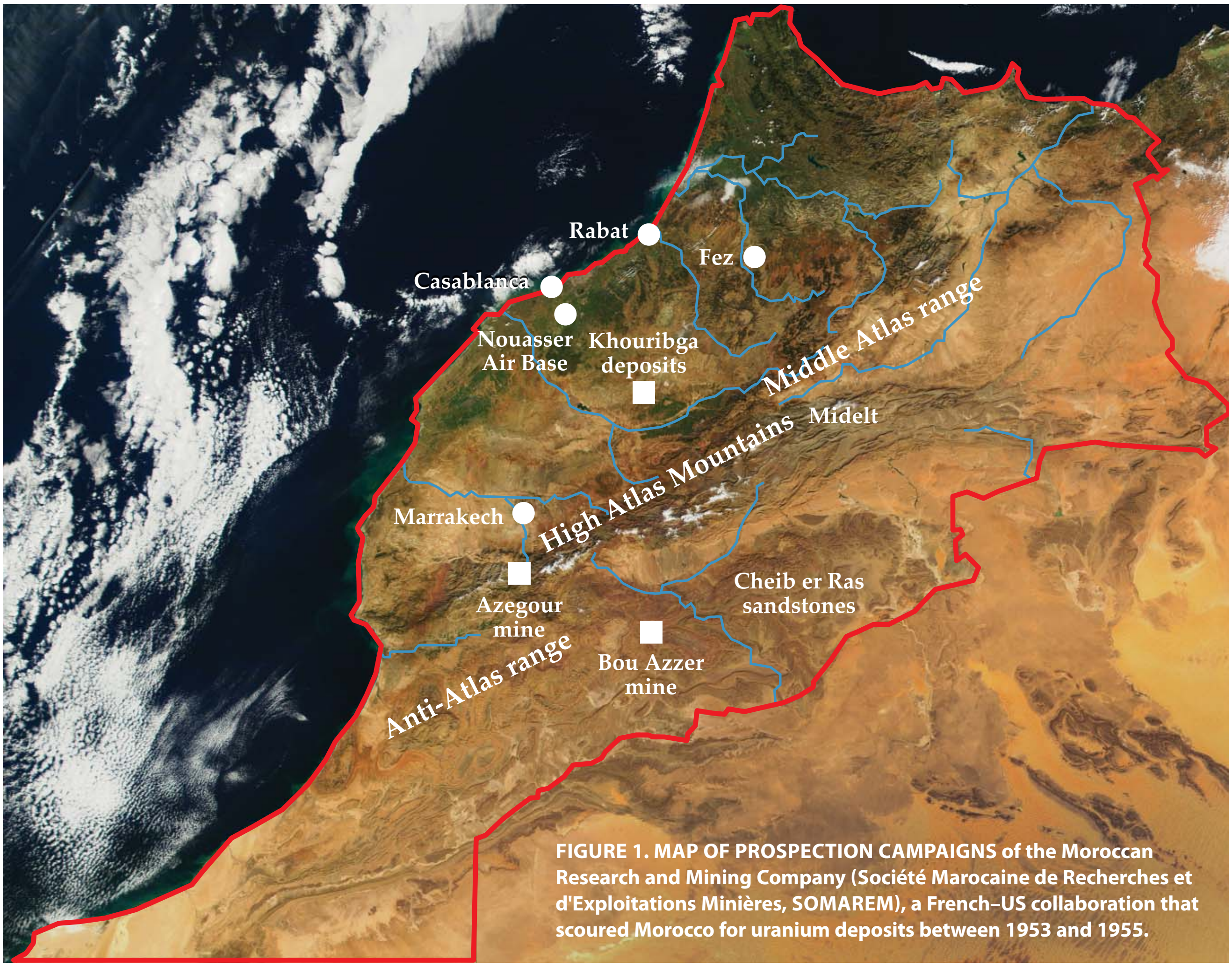


FIGURE 1. MAP OF PROSPECTION CAMPAIGNS of the Moroccan Research and Mining Company (Société Marocaine de Recherches et d'Exploitations Minières, SOMAREM), a French–US collaboration that scoured Morocco for uranium deposits between 1953 and 1955.

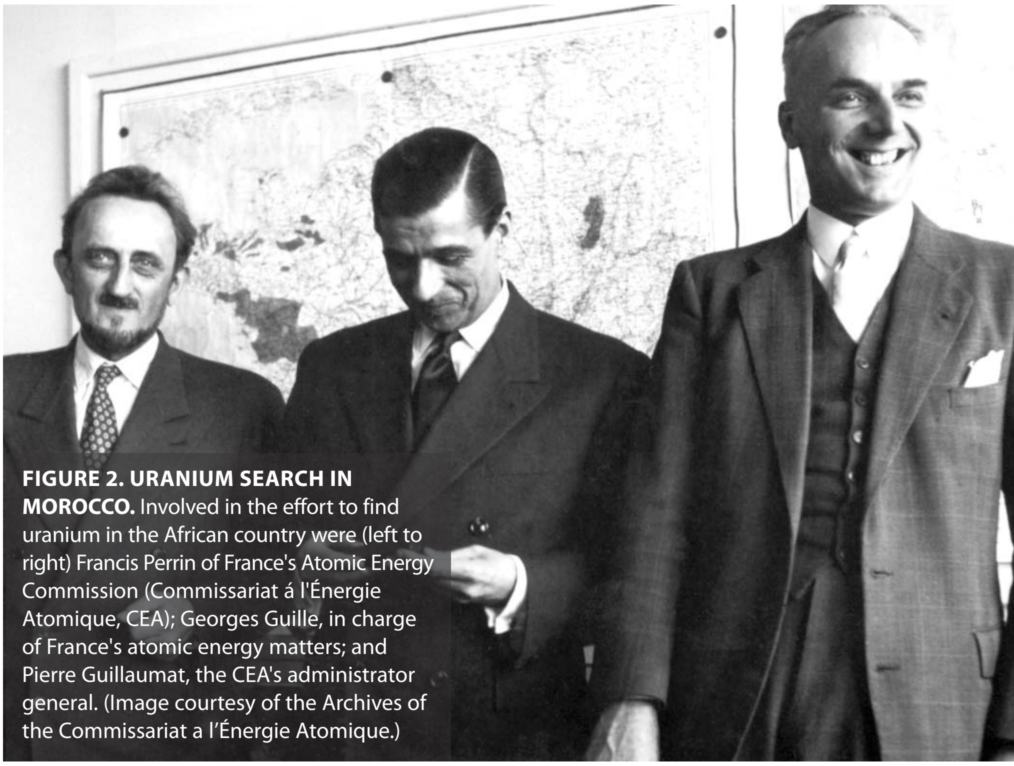


FIGURE 2. URANIUM SEARCH IN MOROCCO. Involved in the effort to find uranium in the African country were (left to right) Francis Perrin of France's Atomic Energy Commission (Commissariat á l'Énergie Atomique, CEA); Georges Guille, in charge of France's atomic energy matters; and Pierre Guillaumat, the CEA's administrator general. (Image courtesy of the Archives of the Commissariat a l'Énergie Atomique.)

on the ground in Morocco, the French protectorate was becoming increasingly important to US Cold War strategy. A December 1950 French–US agreement permitted the US Air Force to build bases for staging bombers on Moroccan soil, adding massively to its military presence there.

At the same time, with the outbreak of the Korean War in June 1950, maintenance of US alliances with Europe became an increasingly high diplomatic priority. The French mattered, and the fragile Fourth Republic, which went through 21 governments from 1946–58, was a constant cause for concern. The US desperately wanted to avoid destabilizing the French polity, which was constantly being pulled from the right by the Gaullists and from the left by the Communists. Yet sending US scientists to search for a strategic resource in a French protectorate would outrage both factions.

The good news for the US was that the French government had replaced Communist Frédéric Joliot-Curie as the CEA's top scientist with politically moderate Francis Perrin (figure 2). Perrin, along with his CEA administrative counterpart Pierre Guillaumat, was vocal about his desire to expand France's uranium production. The Americans detected a chance for cooperation.

On 11 February 1952, the US ambassador in Paris reached out to the French prime minister to open secret negotiations on a deal to hunt for uranium in Morocco. Officials from both countries were anxious to keep negotiations secret from domestic groups that might expose them for political gain, such as the Communists and Gaullists. Furthermore, the Americans had no desire to tip their hand to the British and reveal they were pursuing an arrangement outside the customary US-British-Canadian approach to monitoring and securing uranium resources.

Any partnership in Morocco would need more than just cooperation between scientists from rival atomic programs. It would also have to permit the US to navigate between the Scylla of irritating the French and upsetting the delicate Fourth Republic and the Charybdis of inflaming nationalist Moroccan sentiment against the Americans themselves at a time when the US presence in Morocco was growing daily.

What ensued was a year-long negotiation involving scientists, engineers, technocrats, and diplomats. No longer undercover, McQuiston impressed Guillaumat and other French officials with the chemical-concentration techniques the Americans were willing to share. A promise of future access to what the French Foreign Ministry reported were "jealously guarded secret American techniques" persuaded French officials that Morocco's strategic importance was increasing in American eyes. French officials expressed a belief that US interest in Morocco—secret uranium exploration efforts explicitly included—reinforced France's position in its protectorate, "the presence of France being the guarantor of order and security in this country."[5]

Not that US officials were uncritical of French rule. They voiced their displeasure during the summer of 1952, when the French administration strong-armed the sultan of Morocco into accepting "reforms" that granted French colonials civic powers in a country where they were legally foreigners. The episode humiliated the sultan, enraged Moroccans, and disappointed US hopes of gradual reforms in favor of Moroccan autonomy.

However, what mattered most to the American administration was not political reform but strategic stability—and the predictable circulation of uranium. When Thami El Glaoui, Marrakech's powerful feudal potentate and an immensely wealthy man with enormous agricultural and mining interests, got wind of uranium within his reach, he attempted to convince AEC officials to send geologists directly to him. US officials instantly refused—the last thing they wanted was a local strongman (and rival to the sultan) willing to deal uranium to the highest bidder.

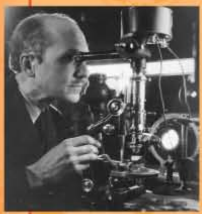
Much in terms of nuclear fuel and Moroccan geopolitics was riding on a uranium agreement with the French.

In search of uranium

US and French officials entered into a secret alliance on 2 March 1953 to prospect for uranium in Morocco. Two months later, those reading the Moroccan protectorate's *Bulletin Officiel* discovered the announcement of a new private enterprise, SOMAREM, created for the "prospection and research of all deposits of metallic mines and, more generally, all mineral deposits." The announcement contained not a word about uranium. The real arrangement behind this public facade was known to only a few officials in the US State Department and the AEC and to the French Foreign Office and the CEA.

SOMAREM's board of directors and its shareholders were officials from the CEA and various protectorate mining offices—not a genuine investor or mining entrepreneur to be found among them. A secret three-man "managing committee"—comprised of one man each from the AEC, the CEA, and the protectorate—assured US influence. The majority of funding

May 1945 World War II comes to an end in Europe.



September 1945 Jean Orcel submits secret report on a uranium mineral found in Morocco.

October 1945 Creation of the French Atomic Energy Commission (CEA).

1945

Spring 1949 Uranium (brannerite) detected in the Bou Azzer cobalt mine.

April 1950 Communist Frédéric Joliot-Curie dismissed as CEA high commissioner.

1949

December 1950 France and the US agree to build a Strategic Air Command base in Morocco.

May 1950 Frank McQuiston Jr searches undercover for evidence of uranium in Morocco.

1950

November 1951 Pierre Guillaumat becomes administrator general of the CEA.

February 1952 US and France begin negotiations to collaborate on a search for uranium in Morocco.

1951

Fall 1952 Mohammed V renews his call for a constitutional monarchy in Morocco.

1952

came from the AEC. Any uranium mined would be divided on a sliding scale, with an increasing percentage going to the AEC as more uranium was found.

The new partners were eager to get started. A preliminary survey in April took US and French geologists to Azegour, Bou Azzer, and the upper Moulouya valley immediately north of Midelt. The heat of the Moroccan summer was difficult to endure. That set a pattern: prospecting started in the autumn and lasted through winter and spring, and summer provided a moment for annual accounting and limited prospecting operations in the cooler High Atlas range.

Even in Morocco's cooler seasons, the search was not easy. There were merely indications of uranium in Morocco's granites and scheelite deposits. And although the phosphates of the eastern Khouribga region contained uranium minerals, they were hardly uranium laden: The Khouribga deposits contained just 0.03–0.05% uranium by mass, and 0.1% had become the cutoff for calculating viable reserves. Even if those grades rose as one went south, the problems of extraction and concentration would remain.

While French geologists began cooperating with their US counterparts, the French government ignored US diplomats' advice. In August 1953 they sent Mohammed V into exile and installed a more compliant relation on the throne. Moroccans were outraged. A bloody campaign pitting incensed Moroccan revolutionaries against pitiless French colonial officials ensued, all while thousands of radio sets were sold to pick up dissenting broadcasts from Cairo.

US officials did not bother to inform Moroccan leaders that they disapproved of the French actions. On the United Nations (UN) Security Council, they voted against investigation of the incident. Their primary concern was the safety of their strategic and military interests and the stability of France at yet another crisis point in the short history of the Fourth Republic.

There is every reason to think that the covert search for uranium factored into US support for the French position in Morocco. When US Secretary of State John Foster Dulles stated in November 1953 that "there is no slightest wavering in our conviction that the orderly transition from colonial to self-governing status should be carried resolutely to a completion," the French were privately assured that his words were for public consumption only.[6] After all, the French and the Americans were intimately linked in a secret geological research effort, the strategic payoff for which might be enormous.

Prospecting in Morocco

Prospecting season opened in autumn 1953 with three SOMAREM prospecting teams in Morocco: two ground-based teams equipped with jeeps and one airborne team with a Piper Super Cub (see figure 3). When not in the field, prospectors lived in the Moroccan capital of Rabat, where SOMAREM maintained headquarters, living quarters, a mineralogical laboratory, a workshop, and a garage. In that first full 1953–54 prospecting season, the teams—always including at least one US member, according to the March 1953 agreement—continued the work they had begun in the upper Moulouya valley the previous spring and also commenced exploration of the Anti-Atlas range. Although there were a number of promising leads, nothing was judged to be immediately exploitable.

The Americans present among the SOMAREM teams brought important skills that the French prospectors had to learn. Royal Stuart Foote, who not only had published on airborne exploration for uranium but had invented a gamma-ray-detection device particularly suited to sedimentary formations, led the airborne prospection team. John Beall was an experienced mining engineer and a specialist in phosphates. Other US geologists came with first-hand experience of the many metal–uranium associations in the American Southwest. In addition, the CEA's top uranium geologists and engineers spent three weeks in the US, starting at AEC headquarters in Washington, DC, and ending at the sedimentary uranium deposits in Colorado and Utah. The trip added considerably to their knowledge of uranium deposits, which, as US geologists had discovered, were turning out to be more varied, widespread, and exploitable than previously thought.

In 1954 SOMAREM added two more ground-based prospecting teams and reported "most honest and efficient" collaboration between various geologists and prospectors, despite "the diversity of languages and origins."[7] Some of SOMAREM's work in the 1954–55 prospecting season followed on the heels

WORLD EVENTS

August 1953 France sends Mohammed V to exile in Madagascar; riots follow.

December 1953 President Dwight Eisenhower announces Atoms for Peace initiative.

1954 Moroccan nationalist campaign intensifies, with acts against colonial officials and institutions.

August 20 1955 Uprising in Oued Zem signals increasing anti-French violence in Morocco.

November 1955 Mohammed V returns from exile.

March 1956 Kingdom of Morocco officially gains independence.

URANIUM-SPECIFIC EVENTS

March 1953 France and the US sign secret agreement to prospect for uranium in Morocco.

Late 1953 SOMAREM geologists make first search in upper Moulouya valley.

Late 1954/ early 1955 SOMAREM continues extensive research and airborne reconaissance.

Fall 1955 SOMAREM suspends activities.

End of 1955 SOMAREM geologists leave Morocco.

1953 | 1954 | 1955 | 1956

of their previous searches, such as examination of the Permo-Triassic sandstone of Argana in the western reaches of the High Atlas Mountains and test works at Choukrane on the southern rim of the phosphate fields. At the same time, teams explored farther south and west. They discovered the most interesting indicator in a quartz vein in the Ordovician sandstones at Cheib er Ras, northwest of Taouz, and began borehole drilling there. Tellingly, however, while SOMAREM now claimed 25 separate research permits and the AEC speculated on the presence of a uranium province, no deposits of commercial importance turned up.

Meanwhile, the situation in Morocco deteriorated. Violence worsened through 1954. Leading colonial figures were assassinated, and strikes crippled vital industries. Just as the rising tensions in Morocco called into question SOMAREM's purpose as a symbol of French–American unity, sea changes in US atomic policy cast doubt on SOMAREM's purpose as a secret meeting point for the two atomic programs.

The end of SOMAREM

At the UN in December 1953, President Dwight Eisenhower proposed that the atomic powers create a stock of fissile material for sanctioned, peaceful uses—a program known as Atoms for Peace. Eisenhower's speech represented a major shift in US nuclear policy. Amendments to the McMahon Act—a 1946 law that placed the development of nuclear technologies under civilian control—permitted the AEC for the first time to transfer fissile materials to friendly states. In the years since the end of World War II, scientists had learned that uranium was more widespread than they had initially thought. Furthermore, chemical concentration techniques made exploitation of lower-grade deposits feasible—South Africa, for example, had started operation of the world's first ion-exchange treatment plant in 1952—and increasingly capable rival atomic programs like France's were emerging.

Under those circumstances, the US was creating a new strategy for nuclear raw materials. The postwar goal of securing the world's uranium, or at least denying it to all others, was shifting. The US now sought to establish favorable exchanges that committed friendly countries to US technologies and peaceful uses. The US also had new goals in northwest Africa: Secure the Strategic Air Command air bases if possible, deny strategic resources to the USSR, and shift from protecting France's stability and postcolonial ego to befriending newly independent non-European nations. Finding uranium in Morocco, in other words, became less and less of a priority.

In fact, it is questionable whether by the beginning of 1955 the French and American creators of SOMAREM really wanted to find uranium. The hurried character of SOMAREM's last prospecting campaign suggests the allies were hoping to verify that easily mined uranium was *not* present in Morocco. Instructions for "detailed prospection campaigns in limited areas" gave way to "wide regional reconnaissance conducted both on the ground and in the air." SOMAREM's geologists detected "numerous zones of anomalies and several uranium occurrences in new regions and types of rocks"—but nothing they judged exploitable.[8]

Meanwhile, violence in the protectorate peaked in the summer of 1955, when a brutal attack by nationalists on a colonial farming community at Oued Zem provoked an equally brutal military response. SOMAREM geologists were not immune to the spreading violence. One SOMAREM dispatch reported that "the incidents that occurred over the summer in different regions of Morocco led the USA Consul General to ask us to send back to Rabat two American geologists. . . . Three weeks later two French geologists were called back to the flag."[9]

US observers thought Morocco might descend into the sort of war that was engulfing its neighbor, Algeria—and that the result would ultimately be Moroccan independence. Given the new US goals in northwest Africa, SOMAREM was now more of a liability than an asset. Its management suspended activities. By the end of 1955, the French–US geological adventure was over. SOMAREM's French and US geologists quietly departed Morocco for good; the enterprise sold off its workshops and laboratories and rented out its jeeps and Piper Super Cub.

Uranium's symbolic and strategic value

The suspension of SOMAREM did not signal a loss of interest in African uranium. On the contrary, the US continued to collect uranium intelligence in the wider region of the western and

FIGURE 3. A US ATOMIC ENERGY COMMISSION PIPER SUPER CUB AIRPLANE. Planes such as this one would have been used to conduct aerial searches for Moroccan uranium. (Image courtesy of the Smithsonian National Air and Space Museum.)

southern Sahara. Meanwhile, the French had their own extensive explorations under way in northern and central Africa. They began with leads in the deserts of Algeria, then struck a significant supply in Gabon and an even bigger one the next decade in Niger—all facilitated by the airborne radiometric techniques first practiced by Foote at SOMAREM.

In November 1955 Mohammed V returned in triumph, and Morocco gained its independence. The question of how to continue the search for uranium in Morocco was now the kingdom's. Ultimately, Morocco sought aid within the international frameworks stimulated by the US Atoms for Peace initiative. Between 1960 and 1985, eight technical assistance missions of the International Atomic Energy Agency supported Moroccan uranium prospection—often traversing the same grounds SOMAREM had covered and relying on SOMAREM's field reports. But despite the many new techniques brought to bear, including helicopter-borne gamma-ray spectroscopy and geochemical fluorometry, the results were the same. Although many tantalizing occurrences of uranium appeared, the lethargic and sometimes erratic nature of the uranium market—in which future, optimistically projected values always outpace present, stagnant ones—meant there was no current economically viable framework in which Moroccan uranium could be exploited.

Nevertheless, Morocco absorbed a lesson. Not only might uranium's economic value quickly rise if nuclear power booms, uranium exploration serves to assert sovereignty, markedly raising the mineral's strategic value. In 1975 the kingdom made its own provocative move and sent thousands of subjects and soldiers streaming over its southern border into the Spanish territory of Western Sahara to claim it for Morocco. The region, an arena for guerrilla warfare and UN missions, is still under dispute. In the 21st century, following airborne prospection reconnaissance campaigns, Morocco has attempted to lure foreign interests to prospect for uranium there to complement its vision of the geopolitically contested territory.

As we approach the 80th anniversary of the Einstein letter, that initial atomic-age epistle motivated by worry over uranium sources, the status of uranium has changed considerably. Through the labors of thousands of geologists, geophysicists, geochemists, mineralogists, metallurgists, prospectors, and diplomats around the world, scientists and atomic programs came to understand that an element once thought very rare is in fact widespread. Uranium is available in many forms in many locations around the globe, ready for mining and refining whenever a nuclear renaissance might appear on the horizon.

Morocco's uranium deposits were ultimately deemed economically negligible—but uranium's importance never was and never will be simply economic. The undercover intelligence-gathering and bilateral agreements that characterized the SOMAREM episode might be past, but uranium's strategic and symbolic importance is still with us. Historian Gabrielle Hecht has noted the key role uranium played in the run-up to the 2003 invasion of Iraq—the danger of nuclear proliferation looming behind the invocation of "yellowcake from Niger."[10] And anyone doubting the strategic importance of uranium need look no further than North Korea and Iran—two countries with domestic uranium resources at the ready. As for Morocco, its uranium ores still lie dormant, but their strategic value persists to this day.

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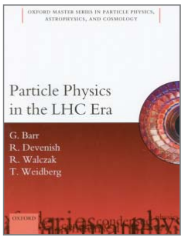
BOOKS



Particle Physics in the LHC Era

G. Barr, R. Devenish, R. Walczak, and T. Weidberg

Oxford U. Press, 2016. $125.00 (432 pp.). ISBN 978-0-19-874855-7

Particle physics is undergoing a midlife crisis. Born out of nuclear physics and cosmic-ray physics in the second half of the 20th century, it went through a turbulent adolescence of rapid discoveries in the 1960s and 1970s and entered an adult phase of spectacular recognition and success during which precision measurements confirmed earlier intuitions one by one. With the discovery of the Higgs boson at the Large Hadron Collider (LHC) in 2012, particle physics checked its last dream off the list and settled into a somewhat affluent lifestyle. In the short span of half a century, the discipline has made enormous progress and has achieved a precise understanding of the fundamental building blocks of ordinary matter.

And yet something is missing. Something big, actually. We know that most of the universe is made of mysterious substances—namely, dark matter and dark energy—which we do not yet understand. We also have no firm grasp on the origin of the parts of the universe that we do understand. The LHC, the same shiny machine that has delivered some incredibly satisfying results, has also so far disappointed hopes that it would unveil what lies ahead.

So, if particle physics were a person, they might decide to go into therapy. The therapist might suggest sitting down and writing out all their past deeds, how those incredible feats were achieved, and what it all means. The result would be something very close to *Particle Physics in the LHC Era* by Giles Barr, Robin Devenish, Roman Walczak, and Tony Weidberg.

This is indeed a valuable textbook, written by recognized experts in experimental particle physics and aimed at students at the advanced undergraduate or early graduate level. It has two ambitious goals. The first is to cover the whole field of particle physics. Its topics range from the hardware details of particle detectors to the intrinsic properties of the Higgs boson, from explaining why LHC magnet coils are made of peculiarly twisted filaments to discussing the cosmological constant and the accelerating expansion of the universe.

The second goal is, in the words of the authors, to "teach the maximum amount of physics with the minimum level of maths." The book starts with a self-contained chapter that introduces the basics and covers such mathematical tools as fundamental symmetries and some group theory. It moves on to a discussion of the hardware of particle physics, specifically accelerators and detectors, and then covers the different aspects of the standard model and its experimental tests. Along the way, the authors discuss the Klein–Gordon and Dirac equations, the principle of gauge symmetry, electroweak interactions, quantum chromodynamics, charge–parity violation, neutrino oscillations, and the Higgs boson. Both goals are largely achieved.

As with any ambitious endeavor, there are weaknesses and omissions. The most obvious, reflected even in the title, is the admitted bias toward LHC physics. As a result, some parts of the book might soon be outdated, and more importantly, experimental programs such as those involving neutrino or astroparticle physics receive a somewhat cursory treatment. On a more formal level, the treatment of Feynman diagrams, the fundamental tool for actual computations in quantum field theory, falls slightly short: Given the amount of theoretical material already covered in the initial chapters, simply providing the fundamentals of Dirac matrix algebra would have empowered the reader to compute basic amplitudes and processes, but those mathematical preliminaries are instead left to the Further Reading sections. Other topics that perhaps deserved mention are statistics and data analysis, which are crucial for budding particle physicists.

Overall, though, *Particle Physics in the LHC Era* is a very successful enterprise. The book is a worthy successor to classic texts like Donald Perkins's *Introduction to High Energy Physics* (Addison-Wesley, 1972) and Francis Halzen and Alan Martin's *Quarks and Leptons: An Introductory Course in Modern Particle Physics* (Wiley, 1984). This volume has the potential to bring a new generation of particle physicists to the brink of current knowledge and help prepare them to go out and push the frontier.

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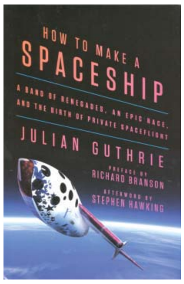
How to Make a Spaceship

A Band of Renegades, an Epic Race, and the Birth of Private Space Flight



Julian Guthrie

Penguin Press, 2016. $28.00 (448 pp.). ISBN 978-1-59420-672-6

Hanging in the National Air and Space Museum's Boeing Milestones of Flight Hall is *SpaceShipOne*, the winner of the Ansari XPrize in 2004. The $10 million prize was awarded for the first piloted, non-governmental spacecraft to fly twice in two weeks above 100 kilometers—the now widely accepted, if arbitrary, definition of where outer space begins. The XPrize's aim was to stimulate private space tourism. A dozen years after the prize was awarded, we are still waiting for suborbital tourist flights to begin.

Julian Guthrie's book about the XPrize, *How to Make a Spaceship: A Band of Renegades, an Epic Race, and the Birth of Private Space Flight*, is structured around intertwined biographical segments. The first half is largely about Peter Diamandis, the XPrize's creator. The son of a doctor in the New York City suburbs, Diamandis was eight years old when he watched Neil Armstrong and Buzz

Aldrin walk on the Moon. He satisfied family expectations by finishing Harvard Medical School, but he remained obsessed with space.

When the "New Space" movement sprang up in the 1970s and 1980s out of frustration with NASA's human spaceflight programs—stuck in low Earth orbit after the end of the Apollo missions—Diamandis became one of the movement's most creative members. He and two friends formed Students for the Exploration and Development of Space, which targets high school and university students, and established the International Space University, which offers both a summer program and a master's degree in space studies.

In the early 1990s, inspired by the Orteig Prize that Charles Lindbergh had won for the first nonstop flight from New York City to Paris, Diamandis decided to create the XPrize to stimulate spaceflight. However, he struggled for years to find sponsors for the prize money. Eventually he gave the Ansari family naming rights in return for a substantial donation. Diamandis then used that money to make a payment on an unusual insurance contract—effectively placing a bet that someone would win the prize before it expired at the end of 2004. If anyone successfully completed the challenge, the insurance payout would provide the $10 million reward.

The second half of the book features Burt Rutan, the famous aviation designer who created the prize-winning craft, and his team. Guthrie details the construction of Rutan's *SpaceShipOne*, its test flights, the personal dramas of its pilots, and the team's ultimate triumph. Alongside Rutan's story, Guthrie includes chapters about Erik Lindbergh, who overcame physical disabilities to raise additional prize funds by restaging his grandfather's 1927 flight, and other XPrize competitors, notably ones in Romania and Britain.

No one should mistake this work for history, or even objective journalism. Guthrie, an experienced freelance journalist, bases her account on interviews with participants she obviously admires. The subjects opened their diaries and personal documents to her—but those valuable sources deepen the book's dependence on the principals' points of view. The book also has an annoying quirk: Guthrie includes many asides in tiny print at the bottom of pages. But *How to Make a Spaceship* will be enjoyed by its intended audience and will provide a starting point for a more academic history.

One question Guthrie avoids is why a suborbital tourism market has been so slow to develop, despite the optimism in 2004. Clues can be found in *SpaceShipOne*'s test flights and in the 2014 crash of its successor, *SpaceShipTwo*, which resulted in the death of one of the copilots. Spaceflight was supposed to become routine, but Rutan's winged design, with its unique mechanism for tilting the tail boom up during reentry, requires expert piloting. Piles of money are needed to build a spacecraft safe for tourists, and several suborbital ventures have already failed for lack of capital.

SpaceShipTwo continues because of the deep pockets of Virgin Group founder Richard Branson, who bought the rights to Rutan's technology for his company Virgin Galactic and who wrote the foreword for *How to Make a Spaceship*. However, Virgin Galactic only recently resumed test flights and may soon be surpassed by its rival Blue Origin, owned by Amazon billionaire Jeff Bezos. Blue Origin's automated, vertically launched *New Shepard* rocket includes a booster that can be recovered and reused and a crew capsule for a parachute landing. It has already flown without passengers; Blue Origin plans to launch employees this year and tourists next year. Bezos and Elon Musk of SpaceX, who appear briefly in *How to Make a Spaceship*, have displaced Guthrie's main actors to become the new faces of New Space. Perhaps the next few years will produce the space-tourism breakthrough that Diamandis has long tried to facilitate.

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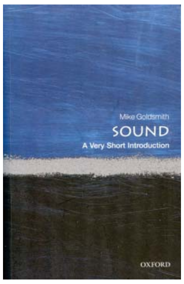
Sound

A Very Short Introduction

Mike Goldsmith

Oxford U. Press, 2016. $11.95 paper (144 pp.). ISBN 978-0-19-870844-5



Sound helps shape how we experience the world, and an understanding of sound is critical in domains as diverse as psychology, linguistics, architecture, animal behavior and evolution, oceanography, and, of course, music. Thus the physics and technology of acoustics are inherently of interest to a great many people, scientists and the lay public alike.

The special place of sound in science and culture, and a general fascination with the topic, inspired physicist and science writer Mike Goldsmith to write *Sound: A Very Short Introduction*. At 144 pages, the book, part of Oxford University Press's Very Short Introductions series, lives up to its title. Within its eight brief chapters, *Sound* covers the diverse fields noted above and more, and it includes some basic physics. The author has written other popular and children's books on science, and his experience comes through in the engaging, easy-to-read style of *Sound*. Equations are kept to a bare minimum, and most phenomena are explained with familiar examples. Goldsmith has worked at the National Physical Laboratory in Teddington, UK, and his specific background in the measurement of sound, notably its speed in various media, is conspicuous in several chapters.

The book opens at the absolute beginning, the Big Bang, and progresses through acoustic landmarks in biological and human history toward the present. Following a basic treatment of acoustics that focuses on measurements and on the wave nature of sound, there are chapters on music, hearing and speech, technologically produced sound, sounds we cannot hear (infrasound and ultrasound), sounds in liquids and solids, and noise.

For readers who are not physicists or engineers, however, some fundamental issues should have been clarified early in the book. For example, although Goldsmith extensively discusses the wave aspect of sound, he does not mention the particle velocity aspect—longitudinal movement of molecules in the fluid medium that carries a sound wave—despite noting in a later section on microphones how some instruments respond to that velocity.

For readers who are biologists, some of the evolutionary and physiological explanations are certain to raise eyebrows. The book's introduction rather glibly states that the main impetus to the evolution of animal hearing was communication. Most current analyses, however, indicate that hearing evolved for defense, as predators inevitably make some noise when moving. Additionally, hearing generally precedes sound communication in the evolutionary tree; many animal groups hear but do not use sound for communication.

A fair amount of discussion is devoted to echolocation in bats via ultrasound signals, an excellent example of acoustic autocommunication. Indeed, those signals, not studied until the late 1930s, inspired much of the development of radar during World War II. The author describes the lengthy constant frequency and the short frequency sweep emissions that bats use as echolocation signals, but he misses the main points regarding their pulsed nature and the particular abilities that the pulses afford: Bats do not hear effectively during their own broadcasts, and pulses allow them to listen to and analyze the returning echoes during the interpulse intervals. Constant frequency signals enable bats to estimate the velocity of flying prey; sweep signals give extremely precise information on how far away they are. Those issues could have been resolved with a close peer review, and such missed opportunities render the book less valuable for nonbiologists, who would benefit most from accurate descriptions.

Goldsmith carefully distinguishes longitudinal sound waves from various transverse mechanical waves, such as those that occur in earthquakes, but he does not relate the distinction to animal communication signals. Because the types of mechanical waves are often muddled in the biological literature, biologists would have benefited from the author's physical perspective, which could highlight why the distinction is critical for understanding how different types of signals disperse in the environment. The book includes a number of line illustrations, and many of them are quite helpful for depicting complex acoustic phenomena. But the book's compact size and small print is best suited to schematic diagrams, and the several drawings that attempt to depict biological and instrumentation details are not particularly effective.

Despite those shortcomings, *Sound: A Very Short Introduction* is an enjoyable read. I learned quite a lot about many topics in the process of my review. The book has something for everyone, and the author has done a remarkable job in assembling so much information and condensing it into a truly pocket-size edition. I do not know of another title that covers so much about sound in a nontechnical yet scientific manner.

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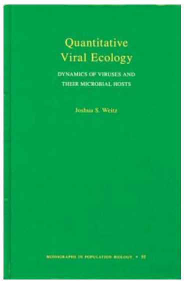
Quantitative Viral Ecology

Dynamics of Viruses and Their Microbial Hosts



Joshua S. Weitz

Princeton U. Press, 2016. $69.95 (360 pp.). ISBN 978-0-691-16154-9

Quantitative Viral Ecology: Dynamics of Viruses and Their Microbial Hosts takes on a topic of vast scientific and societal importance. Consider, for example, the ocean's surface, where microbes constitute most of the biomass. Viruses control the microbe population through infection and release organic carbon and other nutrients back into the environment. That has big effects on ecosystem function, since without the turnover of biomass, many sources of food would not be available to other organisms.

The same scenario plays out in many locations. Indeed, microbes, and consequently microbial viruses, inhabit essentially every natural niche on Earth, including waters, soils, sediments, higher organisms, and air. They also live in artificial environments such as homes, waste reactors, and city streets.

The book's topic is not something a traditional physicist would study. However, physical ways of thinking permeate every chapter. Author Joshua Weitz, whose research is in ecology but who holds a PhD in physics, takes a theoretical, model-building viewpoint as the key to interpreting classic and state-of-the art experiments. Modeling is a central and defining feature of physics, and oftentimes simple models—of springs, beads, liquid droplets, and so forth—are immensely useful for conceptualizing problems and identifying main drivers of observed behavior.

The book is aimed at a scientifically educated audience ranging from students to researchers. Each chapter ends with a concise, point-by-point summary that I found useful for quick reference. The chapters contain tutorials on important modeling tools such as mean-field theories, dimensional analysis, and qualitative analysis of dynamical systems. There are also simple explanations of sophisticated tools, including agent-based models and complex networks. I personally loved the book's spherical-cow attitude—though I should talk about "spherical viruses" in this case—and I use this approach in my daily working routine.

The tone is relaxed and matter-of-fact, and Weitz avoids promoting specific visions, paradigms, or interpretations. Rather, he gives a precise account of the state of debates in the literature and explicitly addresses both the limitations and the potential of current approaches. Chapter 2, one of my favorites, contains dimensional analysis of the key parameters—"life history traits" in ecological terms—that affect viral dynamics. It contains some extraordinarily clear demonstrations of the powerful insight dimensional reasoning can provide. Chapter 6 is also intriguing; it gives a global perspective on ocean viruses' abundance and diversity and discusses virus–microbe infection networks. Viral diversity and sheer number are incredible and probably still incompletely understood.

Chapters 3–5 use ordinary differential equation models to describe population dynamics and the evolution of viruses and their microbial hosts. Chapter 7 addresses the wide-open and complex problem of the coexistence of many viral and microbial species in the ocean, where predators such as zooplankton are also present. The last chapter offers a more speculative overview of open problems and should be valuable for any reader.

My favorite quote from the book is, "A healthy scientific field requires a balance of theory and empiricism," and I can definitively say that the text practices what its author preaches. Although the emphasis is on theory, both classic and state-of-the-art experiments are discussed and compared with predictions—and at times theory and experiment obviously disagree. Readers with an experimental background can obtain ideas for new experiments and specific questions to test.

The book will be especially exciting for theorists with an applied math, engineering, or physics background. According to Weitz, quantitative viral ecology is an area in which new, "big" data are becoming available. But, as many probably know, a big pile of messy data does not necessarily mean more knowledge. New theoretical tools will be needed, together with new theoreticians to design them. *Quantitative Viral Ecology* offered me a great opportunity to discover a new area, and I cannot exclude the possibility that I will be among those exploring it.

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Interaction-Induced Electric Properties of van der Waals Complexes. V. N. Cherepanov, Y. N. Kalugina, M. A. Buldakov. Springer, 2017. $54.00 *paper* (109 pp.). ISBN 978-3-319-49030-4

Introduction to Computational Mass Transfer: With Applications to Chemical Engineering. 2nd ed. K.-T. Yu, X. Yuan. Springer, 2017. $179.00 (417 pp.). ISBN 978-981-10-2497-9

Protein-Based Engineered Nanostructures. A. L. Cortajarena, T. Z. Grove, eds. Springer, 2016. $209.00 (286 pp.). ISBN 978-3-319-39194-6

Stochasticity in Processes: Fundamentals and Applications to Chemistry and Biology. P. Schuster. Springer, 2016. $189.00 (718 pp.). ISBN 978-3-319-39500-5

Computers and computational physics

Computational Chemistry: Introduction to the Theory and Applications of Molecular and Quantum Mechanics. 3rd ed. E. G. Lewars. Springer, 2016. $119.00 (728 pp.). ISBN 978-3-319-30914-9

Computational Fluid Dynamics: Incompressible Turbulent Flows. T. Kajishima, K. Taira. Springer, 2017. $99.00 (358 pp.). ISBN 978-3-319-45302-6

Data Science and Complex Networks. G. Caldarelli, A. Chessa. Oxford U. Press, 2016. $64.95 (130 pp.). ISBN 978-0-19-963960-1

Multimedia Forensics and Security: Foundations, Innovations, and Applications. A. E. Hassanien et al., eds. Springer, 2017. $179.00 (414 pp.). ISBN 978-3-319-44268-6

Secure Data Deletion. J. Reardon. Springer, 2016. $109.00 (203 pp.). ISBN 978-3-319-28777-5

Condensed-matter physics

Control of Magnetotransport in Quantum Billiards: Theory, Computation and Applications. C. V. Morfonios, P. Schmelcher. Springer, 2017. $59.99 *paper* (252 pp.). ISBN 978-3-319-39831-0

Dynamics of Glassy, Crystalline and Liquid Ionic Conductors: Experiments, Theories, Simulations. J. Habasaki, C. León, K. L. Ngai. Springer, 2017. $179.00 (600 pp.). ISBN 978-3-319-42389-0

Rheology of Biological Soft Matter: Fundamentals and Applications. I. Kaneda, ed. Springer, 2017. $129.00 (390 pp.). ISBN 978-4-431-56078-4

Cosmology and relativity

Deconstructing Cosmology. R. H. Sanders. Cambridge U. Press, 2016. $39.99 (144 pp.). ISBN 978-1-107-15526-8

Theory and mathematical methods

Advances in Discretization Methods: Discontinuities, Virtual Elements, Fictitious Domain Methods. G. Ventura, E. Benvenuti, eds. Springer, 2016. $129.00 (269 pp.). ISBN 978-3-319-41245-0

Advances in Dynamical Systems and Control. V. A. Sadovnichiy, M. Z. Zgurovsky, eds. Springer, 2016. $179.00 (471 pp.). ISBN 978-3-319-40672-5

Analog and Digital Signal Analysis: From Basics to Applications. F. Cohen Tenoudji. Springer, 2016. $99.00 (608 pp.). ISBN 978-3-319-42380-7

Consensus Problem of Delayed Linear Multi-agent Systems: Analysis and Design. C.-L. Liu, F. Liu. Springer, 2017. $54.99 *paper* (124 pp.). ISBN 978-981-10-2491-7

The Continuum Limit of Causal Fermion Systems: From Planck Scale Structures to Macroscopic Physics. F. Finster. Springer, 2016. $129.00 (548 pp.). ISBN 978-3-319-42066-0

EPFL Lectures on Conformal Field Theory in D ≥ 3 Dimensions. S. Rychkov. Springer, 2017. $54.99 *paper* (72 pp.). ISBN 978-3-319-43625-8

Finite Element and Discontinuous Galerkin Methods for Transient Wave Equations. G. Cohen, S. Pernet. Springer, 2017. $129.00 (381 pp.). ISBN 978-94-017-7759-9

Global Well-Posedness and Asymptotic Behavior of the Solutions to Non-classical Thermo(visco)elastic Models. Y. Qin, Z. Ma. Springer, 2016. $89.99 (200 pp.). ISBN 978-981-10-1713-1

Introduction to Turbulent Dynamical Systems in Complex Systems. A. J. Majda. Springer, 2016. $59.99 *paper* (91 pp.). ISBN 978-3-319-32215-5

Lectures in Feedback Design for Multivariable Systems. A. Isidori. Springer, 2017. $99.00 (413 pp.). ISBN 978-3-319-42030-1

Mathematical and Computational Approaches in Advancing Modern Science and Engineering. J. Bélair et al., eds. Springer, 2016. $189.00 (806 pp.). ISBN 978-3-319-30377-2

Moving Interfaces and Quasilinear Parabolic Evolution Equations. J. Prüss, G. Simonett. Birkhäuser, 2016. $149.00 (609 pp.). ISBN 978-3-319-27697-7

Neoclassical Theory of Electromagnetic Interactions: A Single Theory for Macroscopic and Microscopic Scales. A. Babin, A. Figotin. Springer, 2016. $189.00 (696 pp.). ISBN 978-1-4471-7282-6

Non-classical Continuum Mechanics: A Dictionary. G. A. Maugin. Springer, 2017. $199.00 (259 pp.). ISBN 978-981-10-2433-7

Science Dynamics and Research Production: Indicators, Indexes, Statistical Laws and Mathematical Models. N. K. Vitanov. Springer, 2016. $109.00 (285 pp.). ISBN 978-3-319-41629-8

Theoretical Physics 4: Special Theory of Relativity. W. Nolting. Springer, 2017. $39.99 (143 pp.). ISBN 978-3-319-44370-6

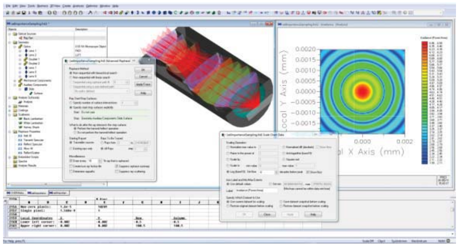
Topological Quantum Numbers in Nonrelativistic Physics. Reprint. D. J. Thouless. World Scientific, 2016. $67.00 *paper* (426 pp.). ISBN 978-981-02-3025-8 PT

NEW PRODUCTS

Focus on software and instrumentation

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. For all new products submissions, please send to Rnanna@aip.org.

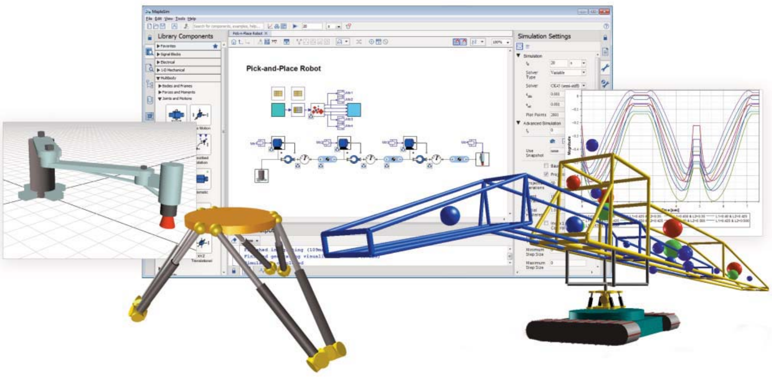
Andreas Mandelis



Optical systems software

The latest version of Photon Engineering's FRED software for virtual prototyping of optical systems, FRED 16.41, includes features designed to make the software more usable, diverse, and efficient. It uses ray tracing, a technique that has been improved in the new release, to simulate the propagation of light through optomechanical systems. For example, the Optimum version of FRED will now use up to 63 threads for multithreaded ray tracing and analyses; the software can now ray trace up to 2^{63} rays. The ray buffer preference settings have been modified so that the 64-bit version of FRED can store up to 10^9 rays in RAM at a single time. Improvements have also been made to model loading and updating, diffraction efficiency specification, and geometry editing, and a new volume hologram efficiency feature has been added. Applications for FRED include illumination and imaging and nonimaging optics, imaging and multiwavelength systems, and stray-light and laser studies. ***Photon Engineering LLC***, *310 S Williams Blvd, #222, Tucson, AZ 85711, http://photonengr.com*

Modeling and simulation software



A new version of MapleSim, Maplesoft's modeling and simulation software platform, provides tools to increase productivity and enhance cross-tool compatibility. MapleSim 2016.2 features live simulations that let users see results as the simulation is running, so they can track progress and immediately investigate unexpected outcomes. A 3D overlay for comparing simulation visualizations shows changes in the behavior of the model under different conditions. Revision-control tools allow multiple users to work on the same model. In addition to exporting models to the internationally recognized Functional Mock-up Interface standard, MapleSim now supports direct import of models created in other FMI-compatible software, such as LMS Imagine.Lab Amesim, for model exchange and co-simulation. Users can work with MapleSim modeling and analysis tools on models developed with other software. ***Maplesoft***, *615 Kumpf Dr, Waterloo, ON N2V 1K8, Canada, www.maplesoft.com*

Fast multiwavelength meter

The 438 series multiwavelength meter from Bristol Instruments can measure the wavelength, power, and signal-to-noise ratio (SNR) of as many as 1000 discrete optical signals. According to the company, it is the fastest multiwavelength meter available. It features high accuracy and straightforward operation and has a rugged design. Its precise, reliable, and efficient wavelength-division multiplexing testing can meet the needs of demanding applications. The meter combines Michelson interferometer-based technology with FFT analysis. Wavelength is measured to an accuracy as high as ±0.3 pm and power to an accuracy of ±0.5 dB; optical SNR is automatically calculated to greater than 40 dB. A measurement rate of 10 Hz enables a reduction in wavelength testing times, and a broad operational wavelength range of 1000–1680 nm covers all optical communications bands. ***Bristol Instruments Inc***, *50 Victor Heights Pkwy, Victor, NY 14564, www.bristol-inst.com*

High-resistivity measurement software

Tektronix has developed software to help users perform high-resistivity measurements to verify the electrical properties of insulating and other materials they are developing or evaluating. The Kickstart-FL-HRMA application allows for materials characterization by means of setups and methods consistent with ASTM D257 and IEC 60093 standards. Designed to control the Keithley model 6517B electrometer and model 8009 resistivity chamber, the software automates bulk and surface resistivity measurements for fast, accurate, repeatable results without custom programming. Users can visualize the step response of the material and decide on an appropriate time interval for testing. KickstartFL-HRMA uses the Keithley alternating polarity measurement technique to eliminate inherent background currents. Optional probes allow for observation of resistivity changes that result from environmental factors such as temperature and humidity. ***Tektronix Inc***, *14150 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com*

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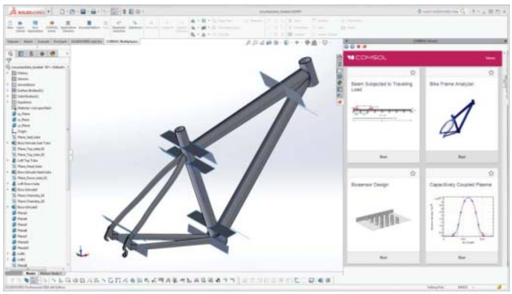
Magneto-transport measurement system

Attocube Systems and Specs Surface Nano Analysis have collaborated in the field of quantum transport measurement at low temperatures. To allow for the exploration of a very large phase space at cryogenic temperatures and high magnetic fields, they have designed a system that combines the attoDRY2100 dry magnet cryostat, the atto3DR 3D sample rotator, and the measurement electronics of Specs' Nanonis Tramea. Optimized for quantum transport measurements, Tramea is a compact and ultrafast multichannel data acquisition system with low noise and high precision. It offers complete software control and easy handling. The software integrates the attoDRY2100's automatic control of temperature—from 1.5 K to 300 K—and magnetic field of 9 T or more and the atto3DR's arbitrary orientation between sample surface and magnetic field direction, as defined by the atto3DR. According to the companies, the combination of advanced instrumentation and software can provide fast results with reliable, repeatable, state-of-the-art specifications. ***Attocube Systems Inc****, 139 Fulton St, Ste 704, New York, NY 10038, www.attocube.com*



Software for CAD synchronization

Comsol has updated the add-on to its Multiphysics software, LiveLink for SolidWorks, which allows users to link SolidWorks geometries with Multiphysics simulations. Specialists can now build simulation apps that integrate with computer-aided design (CAD) to let users analyze and modify a geometry from SolidWorks software. They can launch, browse, and run apps from within the SolidWorks interface. A bike-frame analyzer app added to the application libraries demonstrates the new capabilities. It leverages LiveLink to interactively update the geometry while computing the stress distribution in the frame. Users can test frame configurations for parameters such as structural dimensions, materials, loads, and constraints; the app computes the stress distribution and the deformation of the frame. ***Comsol Inc****, 100 District Ave, Burlington, MA 01803, www.comsol.com*

PXIe instruments for waveform tuning

Keysight Technologies has announced both an arbitrary waveform generator (AWG) with three highly synchronized channels for precise tuning of I/Q waveforms (I/Q denotes in-phase/quadrature) and envelope tracking and a PXI oscilloscope that the company claims is the first full-featured one on the market. Suitable for creating digitally modulated waveforms for wideband communication systems and high-resolution waveforms for radar and satellite tests, the M9336A PXIe AWG includes multiple independent or synchronized signal outputs. Built with Keysight's InfiniiVision technology, the M9243A PXIe modular oscilloscope provides up to 1 GHz bandwidth for quick analysis and troubleshooting of wideband signals. With an update rate of 1 000 000 waveforms/s and advanced probing technology, the oscilloscope enables troubleshooting of random and intermittent signals not easily seen with digitizer technology. ***Keysight Technologies Inc****, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

NEW PRODUCTS

Universal benchtop digital controllers

The CS8DPT Platinum series universal benchtop digital controller from Omega Engineering is suitable for laboratory and other applications that require portable temperature, process, and strain measurement and control. Simple to configure and use, it features a universal input that reads most temperature, process, and bridge-type inputs and has dual LED displays. The instrument handles 10 common types of thermocouples, multiple resistance temperature detectors, thermistors, various process (DC) voltage and current ranges, and strain inputs. It comes standard with a USB port. With optional serial and Ethernet connectivity, the controller can serve webpages over an Ethernet local area network or the internet. Users can monitor and control a process remotely through a Web browser without special software or a computer and receive messages from the controller on an internet-enabled pager or cell phone. ***Omega Engineering Inc****, 800 Connecticut Ave, Ste 5N01, Norwalk, CT 06854, www.omega.com*

Data analysis and graphing software

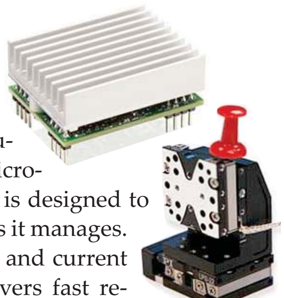
OriginLab has added more than 100 new features, improvements, and apps to the latest version of its data analysis and graphing software, Origin and OriginPro 2017. Ease-of-use enhancements include a revamped plot menu with large icons to help users quickly find the graph type they need, simpler column and cell notation for defining column formulas, and the Origin central startup dialog. It provides graph and analysis samples, easy access to existing templates and projects, resources to explore and install apps, and videos and tutorials. Among the 14 new apps for extending graphing and analysis features are principal component analysis for spectroscopy, enzyme kinetics, and an updated LaTeX. Other additions to Origin 2017 include two-way variance analysis for mean value plots, built-in formulas and metadata for parameter initialization, and support for the full Numerical Algorithms Group Mark 25 library. ***OriginLab Corporation****, One Roundhouse Plaza, Ste 303, Northampton, MA 01060, www.originlab.com*

Software for PXI RF test systems

National Instruments has announced the latest version of its measurement software for PXI RF test systems. NI-RFmx 2.2 can be used with the second-generation PXI vector signal transceiver (VST) to test 4.5 G and 5 G RF components such as transceivers and amplifiers by means of a wide range of carrier aggregation schemes. With the VST, users can simultaneously generate and measure up to 32 LTE carriers, each with 20 MHz of bandwidth, and run the software to specify various carrier-spacing schemes. The new release features algorithm improvements that reduce measurement time. For example, users performing modulation quality and spectral measurements for wireless technologies can reduce by 33% the time it takes to assess error vector magnitude. The NI-RFmx provides improved support for measurements such as intermodulation distortion, third-order intercept, and both Y-factor and cold-source noise figure. ***National Instruments****, 11500 N Mopac Expy, Austin, TX 78759-3504, www.ni.com*

Stepper motor controllers

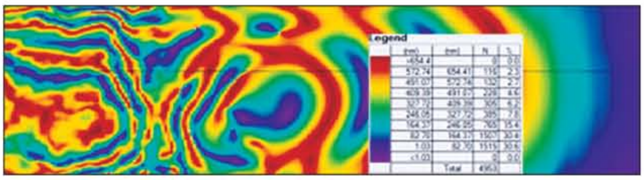
MDC Vacuum Products now offers 4.3-inch touch-screen controllers for precision motion applications. They are compatible with all standard stepper motor options for rotary, linear, and XYZ stages. The controller package includes everything needed to drive an MDC motorized feedthrough. For simple installation, all cables and connections are pre-terminated to work together. Controllers are available in single- or three-axis versions. They can be programmed to deliver output commands directly to the motor or can be connected to a computer via RS-485 with options for RS-232, USB, Ethernet, and DeviceNet connections. The computer interface is controlled via ASCII command set software. The controllers feature up to 256× software-selectable microstepping, 10 user-selectable set points with dedicated acceleration and speed profiles, and dynamic torque control when used with MDC-compatible motors. ***MDC Vacuum Products LLC****, 30962 Santana St, Hayward, CA 94544, www.mdcvacuum.com*



Miniature positioning systems driver

Physik Instrumente has introduced an economic OEM driver for miniaturized piezo inertia positioning stages. Applications include precision optomechanical alignment, biomedical instrumentation, photonics alignment automation, microscopy, and micromanipulation. The versatile model E-872 stick-slip motor driver is designed to complement the size of the ultracompact inertia motor positioners it manages. Control is simple with step and direction input via TTL signals, and current consumption is low. The high 20 kHz full step frequency delivers fast response. A version with 256 microsteps allows for smooth motion with nanometer resolution. ***Physik Instrumente LP****, 16 Albert St, Auburn, MA 01501, www.pi-usa.us* PT

PHYSICS TODAY SNAPSHOT ADS



OBITUARIES

To notify the community about a colleague's death, send us a note at http://contact.physicstoday.org. Recently posted notices will be listed here, in print. Select online obituaries will later appear in print.

Spartak Timofeevich Belyaev

Spartak Timofeevich Belyaev, who made outstanding achievements in many-body physics and nuclear theory, died in Moscow on 5 January 2017 after a short fight with pneumonia.

Spartak was born on 27 October 1923 in Moscow. His unusual first name combined with a traditional Russian patronym and family name is typical for the generation born after the 1917 revolution. Spartak graduated from high school in June 1941, at the start of World War II. In August he volunteered for the army and served as an operator of the field-intelligence radio complex. After the Russians captured the Reichstag in Berlin in 1945, he was one of many soldiers who left his signature on the walls.

In 1946 Spartak entered the physics department of Moscow University. When the new physical–technical department, known as Fiztech, was established one year later, he moved there with some classmates. In 1949 he started his research work at the famous laboratory #2, led by Igor Kurchatov; the lab became the core of the Atomic Energy Institute, now the Kurchatov Institute. The lab had an unusual concentration of extremely bright physicists with dramatically different personalities; they included Gersh Budker, Victor Galitsky, and Arkady Migdal.

After graduating in 1952, Spartak demonstrated his outstanding theoretical ability in his 1955 PhD: With Budker as his adviser, he presented the first consistent theory of relativistic kinetic equations with applications to plasma physics and relativistic electron beams. His next achievement was using Green's functions and diagram techniques to develop the theory of the nonideal Bose gas in 1958. His fundamental result, the existence of a condensate even in an interacting system, required what was later called spontaneously broken symmetry, an idea that Spartak broadly applied. In the same spirit, a few weeks later, Lev Gor'kov published his theory of superconductivity.

VALERY PETROV, BUDKER INSTITUTE OF NUCLEAR PHYSICS

Spartak Timofeevich Belyaev

In 1957–58 Spartak spent a year at the Niels Bohr Institute in Copenhagen, at that time the mecca for nuclear physics. Nuclear structure and dynamics became a main subject of Spartak's interest. Aage Bohr, Ben Mottelson, and David Pines conjectured that the phenomenologically known nucleon pairing in complex nuclei is of the same type as the mechanism behind macroscopic superconductivity. Spartak worked out a full theory of nuclear pairing correlations and showed that they influence not only binding energies but all observable properties of complex nuclei, including vibrational and rotational excitations and transition probabilities. His many years of studying nuclear collective motion are summarized in his lectures published by the International Atomic Energy Agency and in the book *Collective Excitations of Nuclei* (Gordon and Breach, 1968). Niels Bohr, with his philosophy of science and scientific truth in contradistinction to clarity, greatly influenced Spartak's worldview, as can be seen in Spartak's publications devoted to Bohr's 100th anniversary.

In 1962 Spartak and Galitsky joined Budker at the Novosibirsk Scientific Center, established in 1958. Its Institute of Nuclear Physics, now the Budker Institute, was the cradle of new methods in high-energy and particle physics. Galitsky and Spartak assembled the theory department, and Spartak became its head after Galitsky returned to Moscow.

Overlapping scientific interests and the youthfulness of the department members created an extremely friendly atmosphere, which was supported by Spartak's personal style of paying attention to everyone and encouraging and openly criticizing ideas and individual achievements and by the general "disordered democracy" that was a way of life at the institute. Spartak also was extensively involved in discussions and evaluations of the institute's experimental program. He worked hard to manage the constantly growing weight of public duties. One of us (Zelevinsky) remembers how we frequently spent Sundays (the only nonworking day of the week at that time) from early morning to late evening in his home, doing parallel calculations at opposite sides of a large desk.

Encouraged by Budker, Spartak agreed to serve as rector of the young Novosibirsk State University. From 1965 to 1978, he put much effort into its development and growth, including searching for gifted young students all over Siberia and the Far East and connecting them to the research institutions of the Novosibirsk Scientific Center.

Spartak returned to Moscow in 1978 and became director of the Kurchatov Institute's large division for nuclear and general physics. He chaired the theoretical physics department at his alma mater of Fiztech and chaired the Nuclear Physics Council of the Russian Academy of Sciences. In the aftermath of the Chernobyl catastrophe in 1986, he led the investigating commission of the Russian Academy of Sciences and repeatedly visited the contaminated areas. His participation was critical for the development of the synchrotron light source at the Kurchatov Institute. His expanding scientific studies included the problems of interaction of ultracold neutrons with condensed matter, and he participated in various experimental activities, such as the Moscow–Heidelberg collaboration on double beta decay.

Former students from Spartak's time in Novosibirsk and Moscow are spread over the globe; they gratefully remember his lessons and influence on their lives.

Among the scientific awards he received were the 1998 L. D. Landau Gold Medal, the 2004 Eugene Feenberg Memorial Medal, and the 2012 Pomeranchuk Prize.

Neither years nor prizes changed Spartak's unique personality. Even into his nineties, the routine of his everyday life involved a daily half-hour walk from home to the office and back. While visiting Lake Michigan in 2004, he taught several younger people the correct dune-climbing technique. He never took medicine, which was not good during his fatal illness. He will stay in our memory as a great scientist and a superb human being.

Alexey Barabanov
Kurchatov Institute
Moscow
Vladimir Zelevinsky
Michigan State University
East Lansing

Mildred S. Dresselhaus

Mildred S. Dresselhaus, Institute Professor in the departments of electrical engineering and physics at MIT and a world-renowned condensed-matter physicist, passed away on 20 February 2017. Affectionately known as "Millie," she was an extraordinary human being who left an unforgettable, energetic imprint as a scientist, mentor, and friend. Her achievements have been widely recognized with the highest awards in science. She also had a significant impact on governmental science, education policies, and the advancement of women in science; she cared particularly for the success of the young generation.

Born in Brooklyn, New York, on 11 November 1930, Millie earned her bachelor's degree in physics from Hunter College in 1951 and her master's in physics in 1953 from Radcliffe College. She continued her PhD studies at the University of Chicago, in close contact with Enrico Fermi, and in 1959 defended her PhD thesis in physics, titled "Magnetic field dependence of the surface impedance of superconducting tin," under the formal supervision of Andrew Lawson.

Millie's lifetime of contributions has been described in many venues following her passing. As her longtime collaborators and friends, we share here some perhaps lesser-known aspects of her life. The "Queen of Carbon" advanced research in many aspects of nanostructured materials, and her expansive work on carbon-based nanostructures in particular spanned from the 1960s to the last week of her life.

In the 1960s Millie was the first to use magneto-optic measurements on graphite to properly identify electron and hole states in the Brillouin zone. In the 1980s she did important work with graphite intercalation compounds, a key component in today's lithium-ion batteries and two-dimensional materials. Her involvement with graphitic carbons grew, and the emergence of fullerenes, vapor-grown carbon fibers, carbon nanotubes (NTs), graphene nanoribbons, and low-dimensional thermoelectricity in the 1990s ignited her interest in nanoscale structures. In close collaboration with colleagues, particularly in Japan, Brazil, and the US, she investigated structures of graphene rolled up into carbon NTs.

In the late 1990s, Millie developed the use of resonance Raman spectroscopy to study single-wall carbon NTs. The technique was particularly useful for characterizing the properties and quality of nanocarbons, including fullerenes, carbon NTs, and novel 2D materials, and it led to the unveiling of the importance of electron–phonon interaction in those systems. Her insight into graphitic nanostructures created the foundation for a simple quantitative description of optical and vibrational spectra of nanocarbons, including the dependence of the NT energy bandgap on the chiral index and of the radial breathing mode frequency on the tube diameter.

DONNA COVENEY


Mildred S. Dresselhaus

In the following years, Millie got involved in the synthesis and characterization of doped NTs, graphene nanoribbons, and 2D materials. Being an expert in "any kind of carbon material" had not precluded her from contributing significantly to other areas of nanotechnology, including the recently discovered phosphorene and 2D materials such as tungsten disulfide, tungsten diselenide, and molybdenum disulfide. Equally important is her groundbreaking contribution to bismuth compounds used in thermoelectrics and topological insulators.

Millie was intimately involved with the series of NT conferences since they were first organized in 1999. In each of the 17 NT conferences to date, which took place on five continents and attracted hundreds of participants, not only was Millie a frequent invited speaker, but she took charge of the conference summary. She always sat in the front row and wrote notes for the length of the conference. With support of young scientists, her notes were turned into slides for her summary presentation at the conference's end. In her summary, she reviewed highlights and emerging challenges and suggested new directions for future research. For over a decade, Millie impressed audiences with her wisdom, energy, knowledge, sharpness, and modesty. With her continuous support, the annual NT conferences have evolved into the most prominent international NT event.

Knowing firsthand the obstacles faced by women in science and engineering—her own PhD adviser told her there was no place for women in physics—Millie worked throughout her career to improve the climate for them. She served from 1975 to 1977 on the National Research Council's Committee on the Education and Employment of Women in Science and Engineering, an early and influential effort on the subject, and up until her death, she regularly offered encouragement and guidance to women students and postdocs at schools where she had been invited to speak.

Through her life's work, Millie proved wrong her PhD adviser's prejudice against women in physics. She was a well-organized and hard-working scientist. Her workdays started at 5:30am and ended late at night. She kept a tight schedule that included research, daily family activities, and violin and viola playing, often as part of informal chamber music sessions with her family members, colleagues, and friends. She was extremely responsive in answering emails, reviewing papers and proposals, and preparing presentations. She never wasted her time.

Like a mother to her extended research family, Millie stimulated, challenged, and found the potential of her students and collaborators. Her hard work and service helped shape the careers and lives of many young people worldwide. As a teacher and mentor, she inspired many generations and will always be a role model. Even though emails, phone calls, faxes, and visitors kept her constantly busy, the door of her MIT office was always open. Her kindness and availability to help were off the scale.

When traveling, Millie always carried a heavy handbag filled with drafts of manuscripts to review. All told, she authored, coauthored, and edited around 1700 papers and books with her green and blue pens. At her destination, she would ask her hosts to fax or to scan and email the hand-corrected manuscripts to her coauthors or staff. Her hard work was supported by her husband, Gene, also a physicist at MIT; by colleagues and dedicated staff members at MIT; by her collaborators and family members; and by many friends in the chamber music sessions.

Millie has left a legacy of promoting science and influencing the new generation of scientists. Her passion for life and science lasted until the very last week of her life and will continue motivating many people, especially women, around the world. We will miss the Queen of Carbon. We will miss her smile, ideas, brilliance, lessons, generosity, modesty, and guidance. We are certain that she is watching us now, along with her old friends, from heaven or the metaspace.

Morinobu Endo
Shinshu University
Nagano, Japan
Ado Jorio
Marcos A. Pimenta
Federal University of Minas Gerais
Belo Horizonte, Brazil
Riichiro Saito
Tohoku University
Sendai, Japan
Antonio G. Souza Filho
Federal University of Ceará
Fortaleza, Brazil
Mauricio Terrones
Pennsylvania State University
University Park
David Tománek
Michigan State University
East Lansing

Anthony Philip French

Anthony Philip French, MIT professor emeritus in physics, died on 3 February 2017. French was singularly committed to the importance of physics teaching, and he achieved wide recognition for his influence on the teaching of physics at MIT, his five highly respected textbooks, his role in international efforts to improve physics education, his contributions to ongoing debates about goals and purposes of physics teaching, and his leadership in the American Association of Physics Teachers (AAPT).

Born on 19 November 1920 and raised in Brighton, England, French started undergraduate work at Cambridge University in 1939 just as World War II began. His interest in nuclear physics was awakened by Egon Bretscher, a Swiss physicist teaching at Cambridge. After graduating in 1942, French was recruited by Bretscher into the Tube Alloys Project, Britain's nuclear bomb program. In 1944 the program merged with the US's Manhattan Project, and French was sent to Los Alamos. There, working for Edward Teller's small group exploring the possibility of a fusion bomb, French measured cross sections for reactions of light nuclei, such as $d + d \rightarrow p + {}^3H$ and $p + {}^3H \rightarrow n + {}^3He$. His results showed that a fusion bomb was in principle feasible.

Los Alamos was an unforgettable experience for French. He was 23 and barely educated in physics when he was suddenly removed from grim wartime Britain and set down in the scenic mountains of New Mexico, where he could have oranges and eggs and work with some of the best and most famous physicists in the world.

After the war, French married Naomi

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Anthony Philip French

Livesay, a mathematician from Montana who worked in Richard Feynman's computing group at Los Alamos. They honeymooned by touring the American Northwest in an auto bought from Klaus Fuchs—who was later discovered to have given atomic-bomb secrets to the USSR. French and his wife then moved to England, where he joined the Cambridge University faculty and completed his PhD using declassified results from his Los Alamos work.

In 1955 French moved to the University of South Carolina, and shortly afterwards he became physics department chair. Over the next six years, as he hired faculty to bring physics research into the department, his own interests shifted from research to teaching, and he wrote his first textbook, *Principles of Modern Physics* (Wiley, 1958).

His book was admired by Jerrold Zacharias, the MIT professor leading the Physical Science Study Committee (PSSC) effort to reform physics teaching in US high schools. Zacharias wanted to introduce the modern outlook of the PSSC into college and university physics teaching, and he recruited French to MIT to help do it.

French developed a novel curriculum for an experimental introductory physics course at MIT. When he proposed to expand his course to include a few more students from the regular course, the department head said, "That's of no use to me. Take the whole thing," and French became the chief lecturer and manager of a course taken by more than 500 MIT students. Subsequently, he became associate head.

The acronym for French's course became notorious. French said, "I called it, blandly, 'Physics: A New Introductory Course.' . . . Within the first week, I couldn't imagine how I could have been so stupid, as it was known forever afterwards as the PANIC course!"

French was a skillful, lucid lecturer. Those qualities are also evident in his stylish writing. The four books he wrote while teaching PANIC are still in print. He used demonstrations well and devised several of his own. He was proud of his prize-winning pressure-of-light experiment and of his low-cost Fabry–Perot interferometer made from a microscope slide and a cover slip.

French's influence in physics education reached beyond MIT. From 1975 to 1981, he was chairman of the International Commission on Physics Education (ICPE) of the International Union of Pure and Applied Physics. He edited *Einstein: A Centenary Volume* (Harvard University Press, 1979) and coedited *Niels Bohr: A Centenary Volume* (Harvard University Press, 1985). Those efforts on behalf of the ICPE were recognized with the 1980 University Medal of Charles University, Prague, and the 1988 Lawrence Bragg Medal and Prize of the Institute of Physics. AAPT also presented him with awards for his exceptional work: a Distinguished Service Citation in 1976 for US physics education; the Oersted Medal, its most prestigious award, in 1989 for the teaching of physics; and the Melba Newell Phillips Medal in 1993 for services to AAPT.

French retired from MIT in 1991 but remained active. In 1993 he directed the creation of the examinations for the XXIV International Physics Olympiad. He continued to speak and write about how to improve physics instruction, and until this year he regularly attended the physics department's weekly luncheons.

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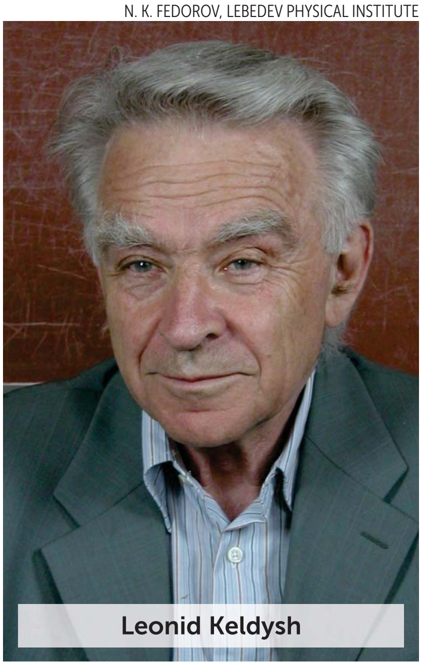
Leonid Keldysh

Leonid Keldysh, a world-prominent Russian theoretical physicist, passed away from pneumonia on 11 November 2016 in Moscow. He was one of the most imaginative and influential physicists of the past half century. In addition to developing the concepts that bear his name—including the Keldysh nonequilibrium diagram technique, the Keldysh theory of strong-field ionization, and the Franz–Keldysh effect—he also predicted the electron–hole liquid phase, the Bose–Einstein condensation of excitons, phonon-assisted electron tunneling, and superlattices in semiconductors. Each prediction opened a new field of research.

Keldysh was born on 7 April 1931 in Moscow. He belonged to a family of prominent mathematicians, including his mother, Lyudmila Keldysh, and stepfather, Petr Novikov, both professors at Moscow State University; uncle Mstislav Keldysh, a key figure in the Russian space program and president of the Russian Academy of Sciences in 1961–75; and brother Sergey Novikov, a Fields Medal recipient.

Following graduation from Moscow State University in 1954, Keldysh joined the theoretical physics department of the P. N. Lebedev Physical Institute, where he worked until the end of his life. His scientific supervisor was Vitaly Ginzburg, and his department head was Igor Tamm, both future Nobel Prize recipients.

N. K. FEDOROV, LEBEDEV PHYSICAL INSTITUTE



Leonid Keldysh

Early in his career, in 1957–58, Keldysh predicted an electric-field-induced shift of a semiconductor's absorption edge, now known as the Franz–Keldysh effect. It turned out to be of paramount importance in the development of a powerful spectroscopic technique for determining the band structure of semiconductors and phonon-assisted electron tunneling in semiconductors. Phonon-assisted tunneling was quickly recognized to be the main tunneling mechanism in silicon and germanium Esaki diodes.

In 1962 Keldysh proposed that spatially modulating a crystal lattice creates artificial band structures in semiconductors. In 1970, heterostructure superlattices were studied by Leo Esaki and Raphael Tsu and became the basis of many optoelectronic devices.

In a 1964 paper that has received 5000 citations, Keldysh developed a powerful formalism, today called the Keldysh nonequilibrium diagram technique, for describing nonequilibrium processes. Introducing a matrix Dyson equation for the time-ordered Green's functions, along with what is now known as the Keldysh–Schwinger contour, Keldysh generalized the Feynman diagram technique to nonequilibrium processes. Many laser-excited condensed-matter systems are described by the Keldysh formalism. Now a standard tool in theoretical physics, the approach is frequently applied to femtosecond spectroscopy, condensed-matter physics, quantum field theory, and quantum cosmology.

Keldysh's theory of strong-field ionization, which was published in 1964 and has received 5500 citations, laid the foundation for the field of intense laser radiation interaction with atoms, ions, molecules, and solids. The theory introduced optical tunneling and above-threshold ionization, experimentally observed about 15 years later. The Keldysh parameter determines the boundary between multiphoton and tunneling regimes. Optical tunneling underlies high-harmonic generation and attosecond science. In 2014 the *Journal of Physics B* celebrated Keldysh's contribution with a special issue called "Fifty Years of Optical Tunneling."

Keldysh submitted in 1965 his candidate of science thesis on the theory of nonequilibrium phenomena. But because of his outstanding level of scientific contributions, he was awarded the higher doctor of science degree (similar to Germany's *habilitation*).

In 1965 Keldysh and his PhD student Yuri Kopaev introduced the excitonic insulator concept now widely used for understanding the nature of various metal–semiconductor transitions. In 1968 Keldysh and his PhD student Alexander Kozlov predicted the Bose–Einstein condensation of excitons, a hot topic of current experimental research. In the same year, Keldysh predicted that nonequilibrium excitons in highly excited semiconductors would form electron–hole droplets. Keldysh's idea immediately stimulated intense experimental research that led to the discovery of that new state of matter. In other seminal papers, Keldysh studied the concepts of deep levels in semiconductors, impact ionization, and "phonon wind," subsequently validated experimentally.

A professor at Moscow State University since 1965, Keldysh established a world-renowned scientific school on nonequilibrium phenomena in condensed-matter physics and nonlinear optics. Of his more than 20 PhD students, 10 were awarded doctor of science degrees and became prominent physicists. From 2004 to 2011, Keldysh held a half-time, tenured professorship in the department of physics and astronomy at Texas A&M University. He served as an editorial board member for many physics journals and from 2009 to 2016 was editor-in-chief of *Physics-Uspekhi*.

During the challenging period for Russian science following the collapse of the Soviet Union, Keldysh served as director of the Lebedev Physical Institute and head of its theoretical physics department in 1989–94 and as head of the general physics division of the Russian Academy of Sciences in 1991–96. His leadership played a crucial role in preserving the institute and the high standards of Russian science. He was admirably strong and honest. It was impossible to persuade him to accept any decision with which he disagreed.

Among his many awards, Keldysh shared the 1975 Hewlett-Packard Prize of the European Physical Society, the 2011 Eugene Feenberg Memorial Medal, and the 2015 Lomonosov Grand Gold Medal of the Russian Academy of Sciences.

Keldysh neither read other people's memoirs nor wrote any himself. He believed that what mattered were not the personal life events but the contributions a person left. Leonid Keldysh left us a lot. His name will remain in physics forever through the theories he developed. We will always remember his passion for physics, benevolence and decency, kind smile, and gentle sense of humor.

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JOB OPPORTUNITIES

Independent Research Group Leader
(Novel Miniaturized Optical Imaging in Biomedical Applications)
Max Planck Institute for the Science of Light

The Max Planck Institute for the Science of Light in Erlangen plans to establish an independent research group to develop novel miniaturized optical imaging systems for biomedical applications, ranging from neuroscience to endoscopy. The group will be funded by the Max Planck Society and will be part of a new Center for Physics and Medicine that will be jointly run by MPL, the Friedrich Alexander University (FAU) and the University Hospital in Erlangen. The new research group will have unique opportunities for collaboration with the Institute of Physiology and Pathophysiology and other medical research groups at FAU. The group will be located at the new building of MPL and will have access to its state-of-the-art cleanroom and fiber fabrication facility, mechanical workshop, electronics workshop as well as high-quality laser labs. Applicants should have a doctoral degree in physics or a related field with outstanding postdoctoral experience in an area of immediate relevance to the planned research activities. The successful candidate will be offered a Max Planck Research Group with a nontenured W2 position (equivalent to assistant or associate professor level) for a period of five years. The term may be extended twice by two years conditioned on a positive review, available financial resources, and personnel regulations. The funding package includes resources for personnel, consumables, and investments. The cumulative amount of funding is competitive with top class start-up packages at the international level. The Max Planck Society aims to support talented researchers early in their career path and welcomes applications from highly qualified scientists. *The Max-Planck society strives for gender diversity. We welcome applications from all backgrounds.* The Max-Planck society is committed to increasing the number of individuals with disabilities in its workforce and therefore encourages applications from such qualified individuals. Applications should be sent electronically to our **HR Department** (personal@mpl.mpg.de). Your application should include a CV, a list of publications, names of two expert references, a one-page summary of scientific achievements, and a two-page research plan. The search committee will start reviewing applications on **June 12, 2017** but will continue to accept applications after this date, until the position is filled. For more information please consult www.mpl.mpg.de. Inquiries should be addressed to **Prof. V. Sandoghdar** (vahid.sandoghdar@mpl.mpg.de).

Georgia Southern University's Department of Physics invites applications for **Limited-Term Instructor or Assistant Professor in Physics**. The full text advertisement, including information about the department, faculty, and the complete position announcement with all qualifications and application instructions, is available at http://cosm.georgiasouthern.edu/physics/employment-opportunities. Screening of applications begins **June 1, 2017**, and continues until the position is filled. *Georgia is an open records state. Georgia Southern is an AA/EO institution. Individuals who need reasonable accommodations under the ADA to participate in the search process should contact the Associate Provost.*

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NOAO PROGRAM MANAGER

The Association of Universities for Research in Astronomy, Inc. (AURA) manages several astronomical observatory centers (including the National Optical Astronomy Observatory, the National Solar Observatory and the Gemini Observatory) and construction projects (Large Synoptic Survey Telescope and Daniel. K. Inouye Solar Telescope) in the United States and Chile under cooperative agreements with the National Science Foundation.

The National Optical Astronomy Observatory (NOAO) seeks a full-time Program Manager (PM) to work closely with the NOAO Director and Deputy Director on all aspects of managing the NOAO program. The PM shall report to the NOAO Director and be a member of the Directorate Program Management team.

NOAO is the U.S. national center for ground-based optical and infrared (OIR) astronomy. In that role, NOAO operates and maintains OIR observational research facilities and related data systems in Arizona and Chile. It also coordinates and integrates observational, technical, and data-oriented capabilities provided by other U.S. federal and non-federal assets. NOAO is a Federally Funded Research and Development Center (FFRDC) sponsored by the National Science Foundation (NSF) and managed by the Association of Universities for Research in Astronomy (AURA), Inc., under a cooperative agreement with the NSF. NOAO consists of approximately 250 people located in Arizona and Chile and has an annual budget of approximately $35M.

AURA and NSF are collaboratively developing a plan to consolidate the existing Gemini and NOAO organizations with the future Large Synoptic Survey Telescope (LSST) operations organization into a new organization called the National Center for Optical-Infrared Astronomy (NCOA). If approved by NSF, NCOA will start operation on 1 October 2018. The successful candidate will transition along with the AURA management team into NCOA and become the NCOA PM in charge of the Program Management Office responsible for integrated program management of the entire NCOA organization.

This position is based at the NOAO headquarters in Tucson, AZ, located on the campus of the University of Arizona. The NCOA headquarters and Project Management Office will be based in the same facility. Travel will be required within the continental U.S. (usually to the Washington/Baltimore area) several times per year. At least once per year, travel to La Serena, Chile will also be required. If NCOA is approve, travel to Hawaii may also be required at least once per year.

The ideal candidate would have: Undergraduate and/or graduate degrees in a science, engineering, project management, operations management, or program management area, or equivalent relevant experience; At least five (5) and preferable ten (10) years of experience with program management with organizations with more than 250 employees, or equivalent relevant experience.

For more information or to apply, visit http://aura-astronomy.org/jobs/ and refer to **Job No. 17-0083**

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Assistant/Associate/Full Professors in
Department of Mechanics and Aerospace Engineering
Southern University of Science and Technology (SUSTech)

The Department of Mechanics and Aerospace Engineering at the Southern University of Science and Technology (SUSTech) invites applications for a number of tenured or tenure track faculty positions in all ranks. Candidates with research interests in all areas of Mechanics and Aerospace Engineering are encouraged to apply. We are seeking applications with expertise and experience in specific areas, including, but not limited to, solid mechanics, vibration, control, and the general area of aerospace engineering, Candidates should have strong commitment to teaching and demonstrated excellence in research. An earned doctoral degree is required at the time of appointment. Candidates for senior positions must have an established record in conducting globally recognized research and securing external funding. Established in 2012, the Southern University of Science and Technology (SUSTech) is a public institution funded by the municipal of Shenzhen, a special economic zone city in China. SUSTC is a pioneer in higher education reform in China. The mission of the University is to become a globally recognized institution which emphasizes academic excellence and promotes innovation, creativity and entrepreneurship. The University currently has over 200 faculty members, and is planning three faculties: Faculty of Science, Faculty of Engineering, and Faculty of Life and Health Science. The target faculty number will be 200 for Science, 300 for Engineering, and 150 for Life and Health Science Faculty. The newly founded Department of Mechanics and Aerospace Engineering is one of the nine departments in the College of Engineering. The department expects to add more than twenty new faculty members in core research areas in Mechanics and Aerospace Engineering. Shenzhen is a major city located in Southern China, situated immediately north of Hong Kong SAR. As one of China"s major gateways to the world, Shenzhen is the country"s fast-growing city, the high-tech and manufacturing hub, and home to some of China"s most recognized enterprises such as Huawei, Tencent and DJI. As a State-level innovative city, Shenzhen has chosen independent innovation as its development strategy. A picturesque coastal city, Shenzhen is also a popular tourist destination and was named one of the world"s 31 must-see tourist destinations in 2010 by The New York Times. SUSTech offers internationally competitive compensation packages with fringe benefits including medical insurance, retirement and housing subsidy. Salary and rank will commensurate with qualifications and experience. To apply, please provide a cover letter identifying the primary area of research, curriculum vitae, and research and teaching statements, and arrange for at least three recommendation letters, all forward to hiring@sustc.edu.cn.

LMU | LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN | FACULTY OF PHYSICS

As one of Europe's leading research universities, Ludwig-Maximilians-Universität (LMU) in Munich is committed to the highest international standards of excellence in research and teaching. Building on its more than 500-year-long tradition, it offers a broad spectrum that covers all areas of knowledge within its 18 Faculties, ranging from the humanities, law, economics and social sciences, to medicine and the natural sciences.

The **Faculty of Physics** invites applications for a

Professorship (W2)
(6 years/tenure track)
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The desired research field involves the design, measurement and control of solid-state-based quantum nanosystems using optical and transport techniques. Experience in nanoscale fabrication is desirable. Access to clean room facilities is available. Cooperation with the Center for NanoScience and the Munich Quantum Center is possible and desired.

LMU Munich seeks to appoint a highly qualified junior academic to this professorship and, therefore, especially encourages early-career scholars to apply. Prerequisites for this position are a university degree and a doctoral degree or a comparable specific qualification. With an excellent record in research and teaching to date, prospective candidates will have demonstrated the potential for an outstanding academic career.

The initial appointment will be for six years. After a minimum of three years, it can be converted into a permanent position pending a positive evaluation of the candidate's performance in research and teaching as well as his or her personal aptitude and if all legal conditions are met.

Under the terms of the "LMU Academic Career Program", in exceptional cases and subject to outstanding performance in research and teaching, the position may be converted from a W2 into a W3 Full Professorship at a later date.

LMU Munich makes a point of providing newly appointed professors with various types of support, such as welcoming services and assistance for dual career couples.

LMU Munich is an equal opportunity employer. The University continues to be very successful in increasing the number of female faculty members and strongly encourages applications from female candidates. LMU Munich intends to enhance the diversity of its faculty members. Furthermore, disabled candidates with essentially equal qualifications will be given preference.

Please submit your application, comprising a curriculum vitae, documentation of academic degrees and certificates, list of publications and research statement, in both printed and electronic form, to the **Dean of the Faculty of Physics, Ludwig-Maximilians-Universität München, Schellingstr. 4, 80799, Munich, Germany, dekanat@physik.uni-muenchen.de**, no later than **June, 30, 2017**.

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QUICK STUDY

Jean-Philippe Boucher and **Romain Labbé** are PhD students in fluid mechanics at the laboratory of hydrodynamics (LadHyX) at the École Polytechnique in Paris. **Christophe Clanet** is a CNRS research director at LadHyX.

Row bots

Jean-Philippe Boucher, Romain Labbé, and Christophe Clanet

By dipping their oars into the water asynchronously, a rowing crew can reduce the friction on their racing shell. Experiments with robots determine whether that trick increases the boat's speed.

Rowing is a challenging sport, and not just for athletes. It mixes physiology, mechanics, and fluid dynamics, so from a physicist's perspective, the sport is much more complex than the elegant movement of a rowing shell might suggest.

Many scientists have tried to work out the details of rowing propulsion, often with a view to improving the performance of rowing crews. For example, in a 1971 *Science* paper (volume 173, page 349), Thomas McMahon showed that the speed of a racing boat scales as the number of rowers to the power 1/9. In our research, we have taken a closer look at the boat speed within one rowing cycle. In a single stroke, a propulsive phase is followed by a gliding phase. As the figure shows, for racing boats, the variation in speed during the stroke is typically around 20% of the mean speed of 5 m/s or so. Such a variation is a consequence of the synchronized rowing of the crew, a technique that seems to be essential for success in top-level rowing competitions. Consider, however, that for a boat moving through water, larger fluctuations about the boat's average speed imply increased friction on the hull. As a consequence, the mean power dissipated due to fluid friction for speed variations typical of a racing boat is about 5% higher than it would be if the boat could somehow be propelled steadily at the same mean speed.

Desynchronizing the rowers can reduce speed variations. Nature employs an out-of-sync propulsion strategy in, for example, shrimp-like krill that swim with the so-called metachronal movement of five pairs of legs that are activated in a desynchronized way. Indeed, a 2010 study by Silas Alben and colleagues published in the *Journal of the Royal Society Interface* (volume 7, page 1545) showed that the krill's metachronal kinematics leads to the highest average body velocity for a given amount of work. Some fishing spiders also display unsynchronized swimming at the surface of water. Given that in rowing competitions, 2 km races are often won by less than a boat length, it's worth considering the possible advantage of unsynchronized rowing.

Row, rOw, roW your boat

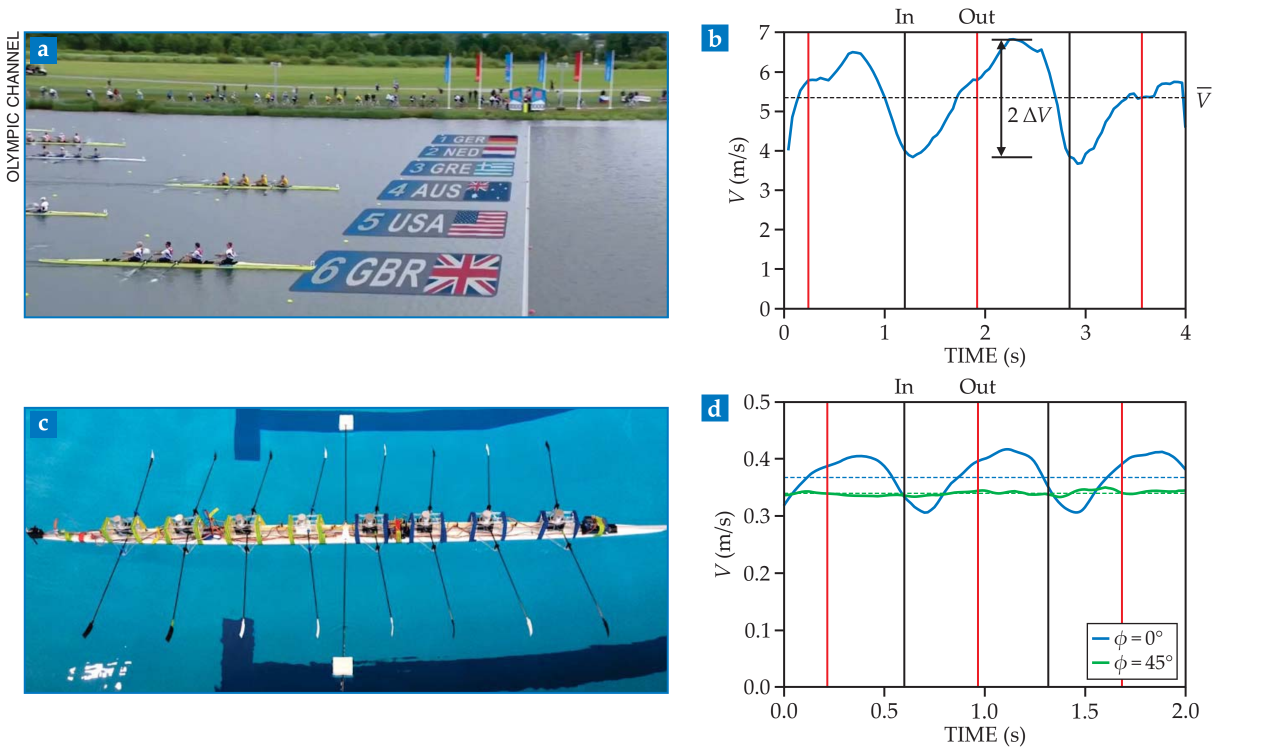
Phase-shifted rowing had been tried as early as 1929, by the London Rowing Club; you can see a video of the effort at www.youtube.com/watch?v=zQ6fxsmo3V8. But the London club's exercise and others conducted in the UK during the early 1930s led to indecisive results. As one reporter for the *Sydney Morning Herald* mused on 11 October 1933, the experiments raised the question of "whether the trifling gain is worth the loss of all the rhythm, apart from neutralising the genius of strokeship." At the 1981 and 1982 World Rowing Championships, the Soviet women's coxed four crew placed the coxswain (the person who steers the boat) between the two pairs so that they could row perfectly out of phase. However, on race days the crew chose to row in synchrony. Despite the full-scale trials and other studies, out-of-phase techniques never have convincingly been shown to be more or less efficient than conventional synchronized rowing.

To perform a systematic study of the influence of rower synchronization on boat speed, we built a boat at 1/10 scale with eight robotic rowers. A real racing boat with eight rowers, known as a coxed eight, has a length of about 20 m and weighs about 100 kg. Our 2-m-long model, shown in panel c of the figure, has a fiberglass hull with the same shape as on a real coxed eight. The mass ratio of robot rower to model boat is the same as for human rowers and racing boats, and we designed the mechanics of the robotic rowing to be as human as possible. With the help of a device called an Arduino board, we were able to control the stroke speed and synchronization of our robot rowers.

Which strategy is best?

We measured the speed of our rowing boat at the swimming pool of the École Polytechnique and explored how it changed as we varied the phase difference ϕ between consecutive rowers. Panel d of the figure shows the results for two of our trials, which you can view in the supplemental videos available online. In the synchronous configuration, $\phi = 0°$, the velocity profile of our boat is similar to the one obtained from videos of real rowing races (as in figure panel b). The speed increases during the power stroke, from a black vertical line to a red one in the figure plots, due to the propulsion given by the oar blades. During the recovery stroke, from red line to black line, the speed decreases, partly due to the hydrodynamic friction on the hull. The similarity of the velocity profiles proves that our model boat does a good job of imitating real rowing boats.

At a pace of one stroke per second, our boat moves at a mean speed close to 0.36 m/s, almost 0.2 boat length per rowing cycle. By means of comparison, real race boats travel roughly 0.45 boat length per rowing cycle in competitions. As with real boats, our model displayed large variations around its average speed—approximately 12% of the mean.



ROWING IN AND OUT OF SYNC. Great Britain holds a slim lead over Australia **(a)** halfway toward its victory in the men's four rowing final at the London 2012 Olympics. **(b)** The velocity V of the British boat was determined from a video of the race. The black vertical lines in the plot indicate the times at which the blades enter the water, and the red vertical lines indicate the times at which the blades are lifted out. The mean speed of the boat $\bar{V}$, about 5.3 m/s, fluctuates by about 20%, as indicated by ΔV. **(c)** Robots row a 2-m-long boat at the École Polytechnique swimming pool. **(d)** The robots were able to row synchronously ($\phi = 0°$) or asynchronously; in the out-of-sync trial plotted, each robot is 45° out of phase with its neighbor. As we expected, relative fluctuations were reduced for asynchronous rowing, but we were surprised to learn that the mean speed (indicated by dashed lines) was also reduced.

For phase-shifted rowers, we show $\phi = 45°$ in the figure panel and supplemental video. The bots row one after the other to propel the boat, and when the last rower on the boat finishes its power stroke, the first one starts anew. In this case the instantaneous velocity profile displays much less speed variation than in the synchronized case: about 2% of the approximately 0.34 m/s mean speed. The diminished fluctuations were expected, but we were surprised and initially puzzled that the mean speed of our boat was also reduced—by about 5%. We repeated our experiments for many phase differences spanning the range 0°–360°. Although the quantitative values varied, we found that compared with synchronized rowing, desynchronized rowing always decreases both the relative fluctuations and the mean speed.

Another propulsive mechanism

Our main result thus contradicts our initial intuition that reducing velocity fluctuations would increase the mean velocity. So, luckily for rowing athletes who have trained to row synchronously, we can confirm the commonly accepted wisdom that rowing together maximizes speed.

In our initial thinking, we failed to take into account that the rowers are not stationary. Indeed, if you return to the velocity profiles in figure panels b and d, you'll see that the speed in the synchronized configuration keeps increasing at the beginning of the recovery stroke—that is, after the oars have been lifted from the water, as indicated by the red lines. If the velocity keeps increasing when the oars are out of the water, there must be an additional propulsive force that does not depend on oars. In fact, the force results from the motion of the rowers on the boat. When the rowers return together to the stern of the boat during the recovery stroke, they pull the hull beneath them and accelerate the boat. Since the crew of a coxed eight weighs several times what the boat does, the rowers generate a significant force. When they are desynchronized, that inertial boost is reduced.

For krill, whose tiny churning legs are always underwater, there is no such inertial boost effect. They do better with desynchronized propulsion.

Additional resources

▶ B. Sanderson, W. Martindale, "Towards optimizing rowing technique," *Med. Sci. Sports Exerc.* **18**, 454 (1986).

▶ A. Baudouin, D. Hawkins, "A biomechanical review of factors affecting rowing performance," *Br. J. Sports Med.* **36**, 396 (2002).

▶ A. J. de Brouwer, H. J. de Poel, M. J. Hofmijster, "Don't rock the boat: How antiphase crew coordination affects rowing," *PLOS One* **8**, e54996 (2013).

▶ V. Kleshnev, *The Biomechanics of Rowing*, Crowood Press (2016).

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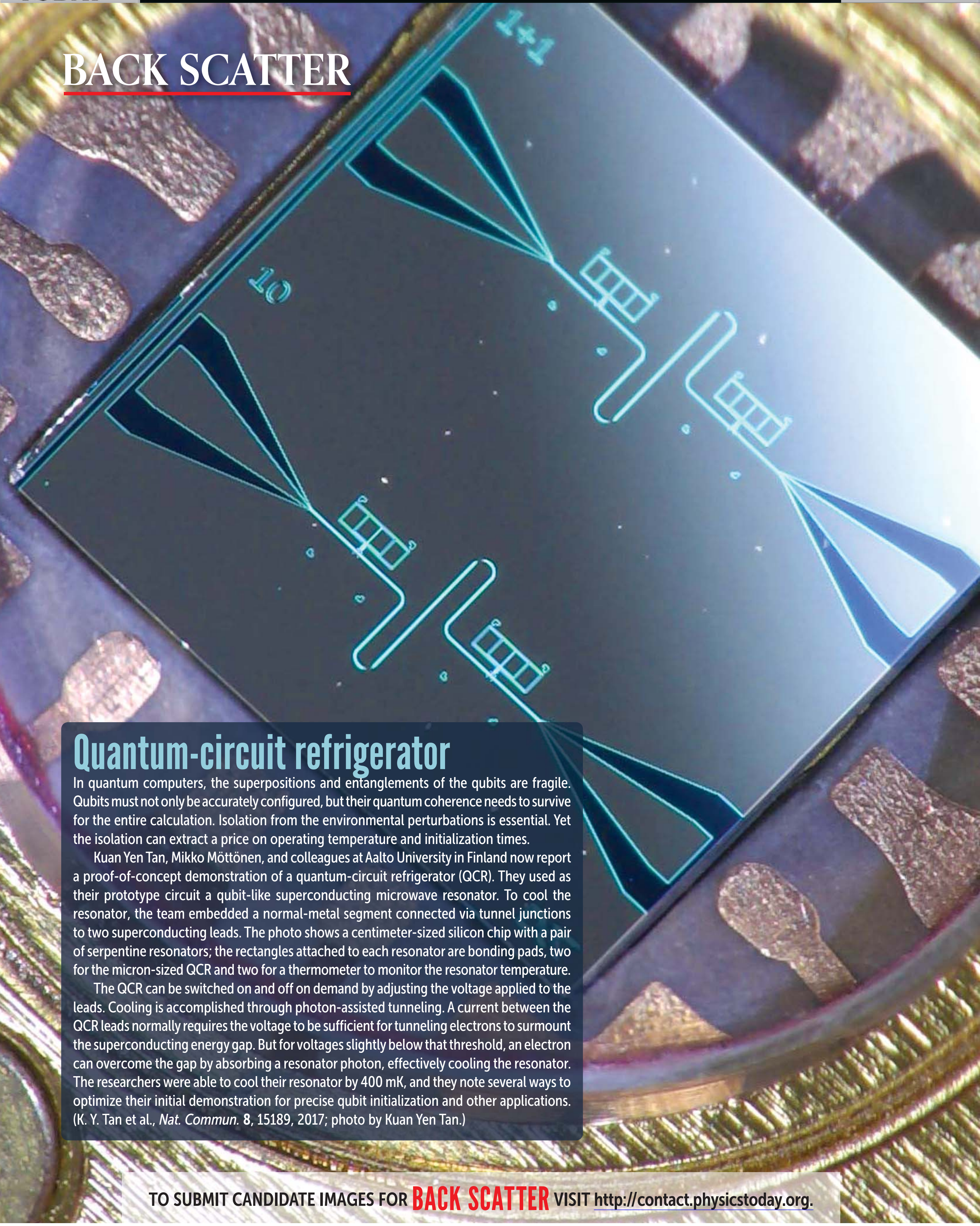

Quantum-circuit refrigerator

In quantum computers, the superpositions and entanglements of the qubits are fragile. Qubits must not only be accurately configured, but their quantum coherence needs to survive for the entire calculation. Isolation from the environmental perturbations is essential. Yet the isolation can extract a price on operating temperature and initialization times.

Kuan Yen Tan, Mikko Möttönen, and colleagues at Aalto University in Finland now report a proof-of-concept demonstration of a quantum-circuit refrigerator (QCR). They used as their prototype circuit a qubit-like superconducting microwave resonator. To cool the resonator, the team embedded a normal-metal segment connected via tunnel junctions to two superconducting leads. The photo shows a centimeter-sized silicon chip with a pair of serpentine resonators; the rectangles attached to each resonator are bonding pads, two for the micron-sized QCR and two for a thermometer to monitor the resonator temperature.

The QCR can be switched on and off on demand by adjusting the voltage applied to the leads. Cooling is accomplished through photon-assisted tunneling. A current between the QCR leads normally requires the voltage to be sufficient for tunneling electrons to surmount the superconducting energy gap. But for voltages slightly below that threshold, an electron can overcome the gap by absorbing a resonator photon, effectively cooling the resonator. The researchers were able to cool their resonator by 400 mK, and they note several ways to optimize their initial demonstration for precise qubit initialization and other applications. (K. Y. Tan et al., *Nat. Commun.* **8**, 15189, 2017; photo by Kuan Yen Tan.)

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