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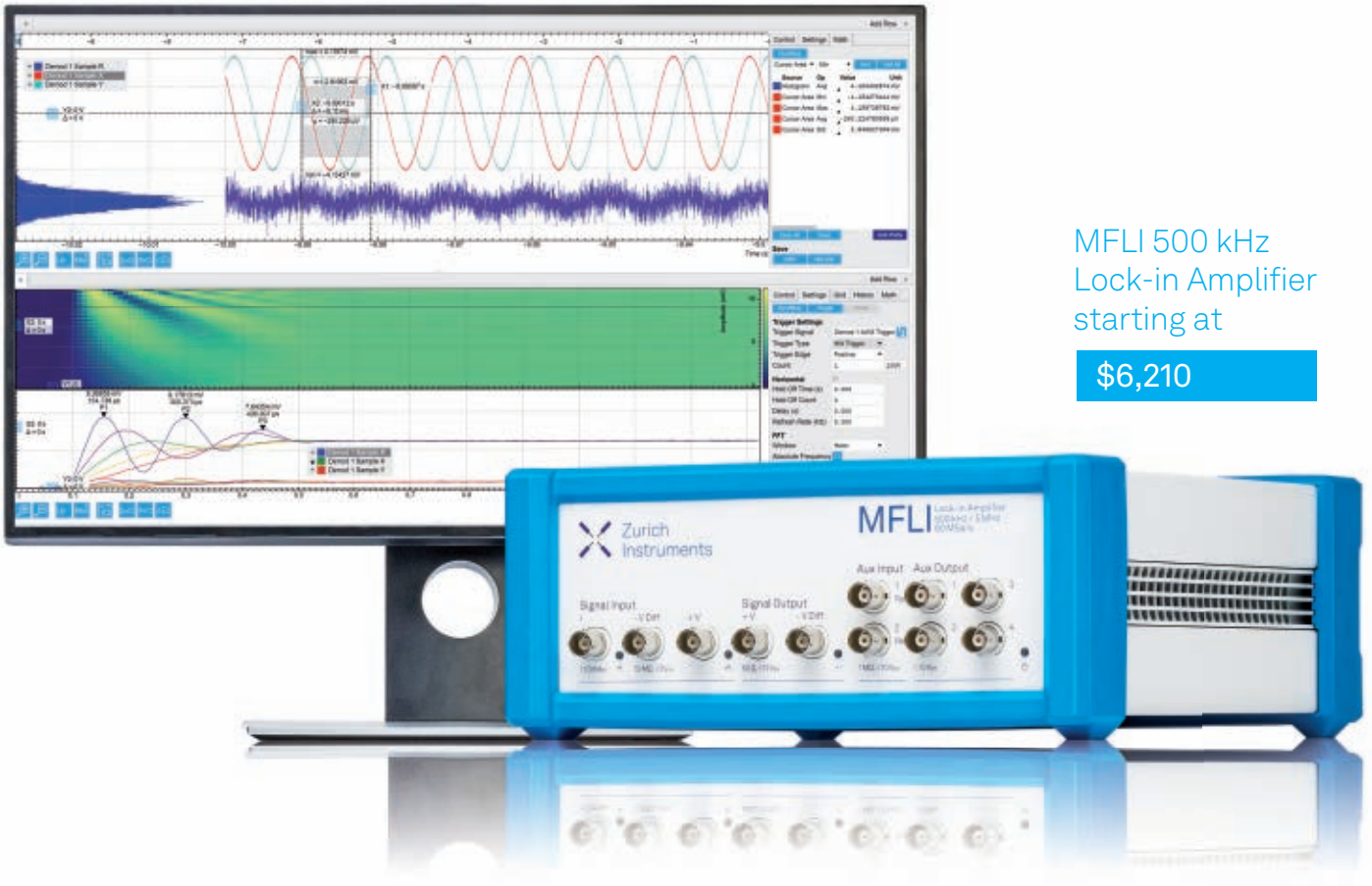

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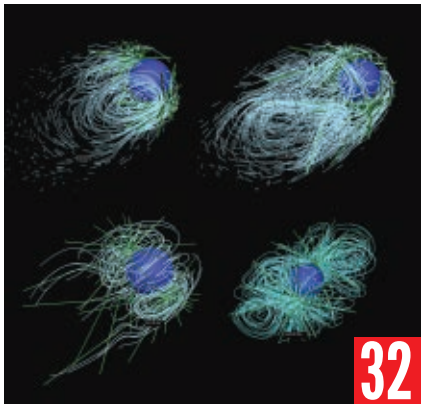

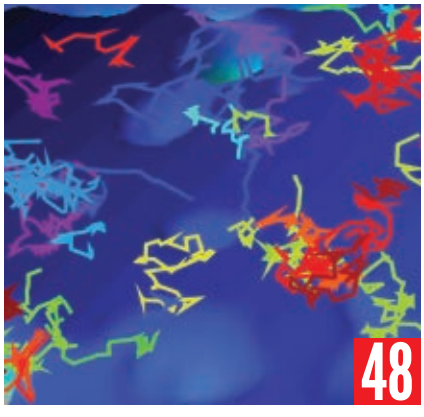

PHYSICS TODAY

September 2019 | volume 72 number 9

FEATURES

ON THE COVER: Computer scientist Manohar Vanga generated this image from a photograph by iteratively adjusting the colors of a pixel's neighbors via a random walk in color space. Random walks are the crucial ingredient in a new study that brings physical intuition to a perplexing mathematical problem. To learn more, turn to the news story that begins on **page 18**. (Image courtesy of Manohar Vanga, Max Planck Institute for Software Systems.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org

O. MASSON ET AL., PNAS 2019

▶ Radiation forensics

In fall 2017 air monitors across Europe detected a plume of radioactive ruthenium. To this day no one has accepted responsibility for the radionuclide's release. PHYSICS TODAY's Andrew Grant details a recent study implicating a nuclear facility in Russia that was producing a radioactive source for a neutrino experiment.

physicstoday.org/Sep2019a

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▶ X-ray source upgrade

The US Department of Energy has approved an $815 million upgrade to its Advanced Photon Source user facility outside Chicago. PHYSICS TODAY's Alex Lopatka describes the improvements that will allow for x-ray beamlines that are between 100 and 1000 times as bright as those currently in use.

physicstoday.org/Sep2019b

VLADIMIR SHILTSEV

▶ Vodka 101

Bottles of Russian Standard vodka claim that its 40/60 mixture of alcohol and water was devised by Dmitri Mendeleev, who created the periodic table 150 years ago. Physicist Vladimir Shiltsev debunks that myth and lays out the facts about vodka and Mendeleev's research on the topic.

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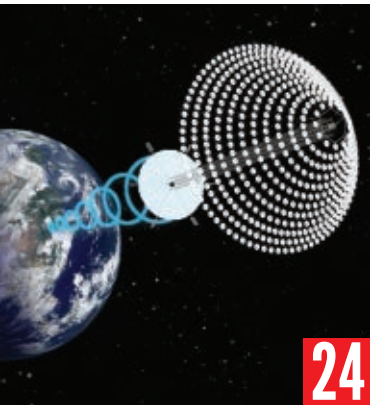
DEPARTMENTS



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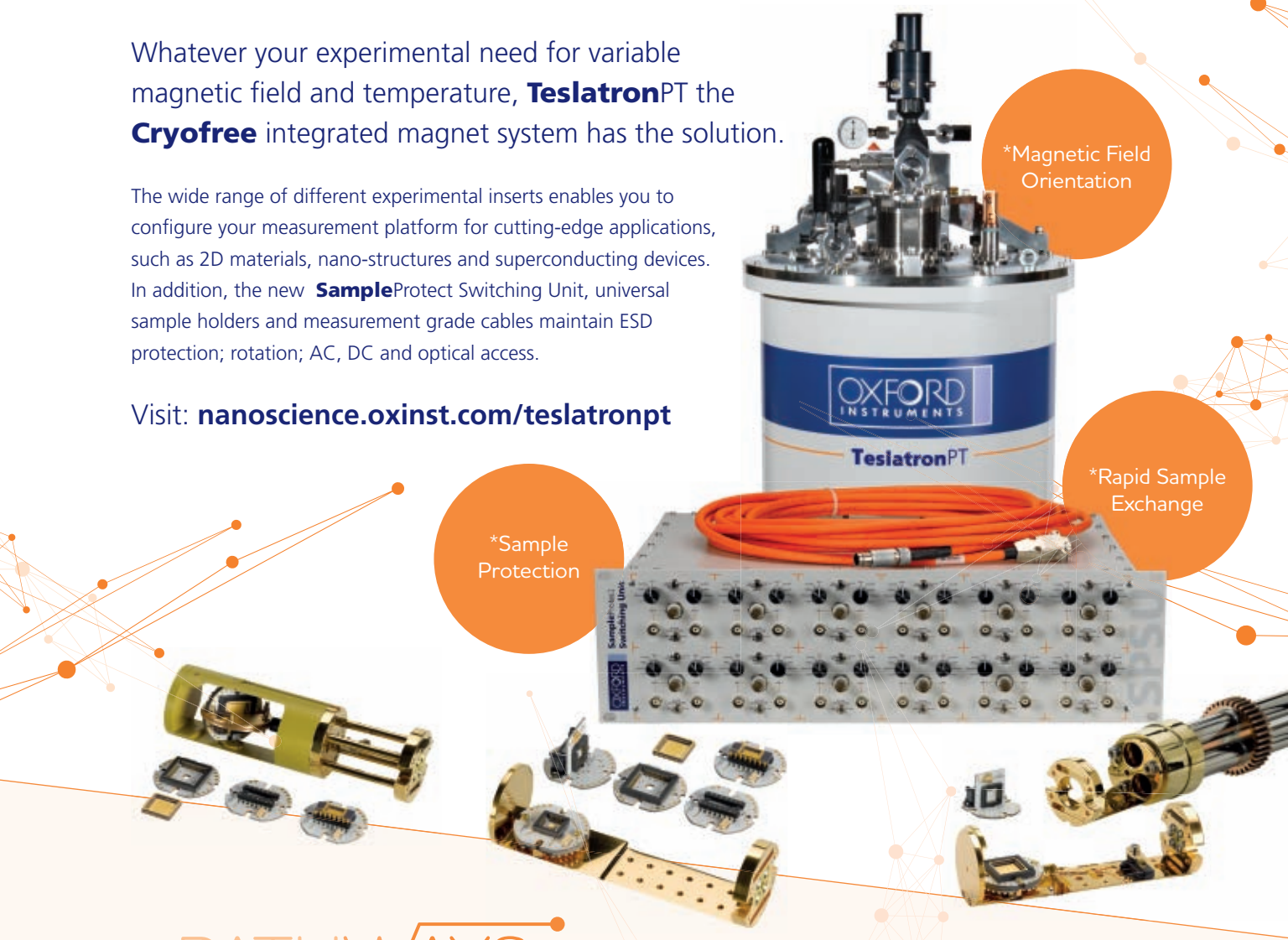

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Charles Day

At this year's March meeting of the American Physical Society in Boston, PHYSICS TODAY conducted a series of focus groups. The goal: to find out from readers what they like and don't like about the magazine and when and how they read it.

Most of the volunteers were graduate students and postdocs. Surprisingly perhaps, those early-career scientists overwhelmingly favor the print version of PHYSICS TODAY. They read the magazine at home, on commuter trains, in bars. "It's the only print magazine I read," one participant told us.

I'm glad that the print issue continues to be appreciated. Although print newspapers have declined and even died as classified ads moved online to Craigslist and its ilk, magazines continue to thrive. Ads are intrusive and annoying in YouTube videos, online newspapers, and network TV shows. But in a magazine, ads can be flipped over or gazed at. Another advantage that magazines have over webpages is their superior appearance. A magazine's fixed physical format gives art directors the freedom to fill pages with gracefully designed spreads. When designing online content, art directors have to contend with different devices and browsers. The one-size-fits-all result is less attractive.

Images from recent online articles. (Credits, clockwise from top left: Caltech/IPAC/R. Hurt; Toni Smith, USGS; Paul Connolly; Cynthia B. Cummings.)

All that being said, it frustrates me that more of PHYSICS TODAY's print readers don't visit the magazine's website. If they did, they'd discover compelling content that is not available in print. It's online because it's breaking news, because it doesn't fit in one of the print magazine's editorial departments, or because it features video, audio, or other media than prose and pictures. The 21 000 words of online content we posted this past July are equivalent to five feature articles in length!

What might you have missed? In May PHYSICS TODAY associate editor Christine Middleton analyzed some troubling aspects of how the media portrayed the contributions of a female physicist to the first direct image of the ring of photons around a supermassive black hole's event horizon. In June we published a captivating account of the resolution of a 123-year-old mystery: How identical forms of a crystalline solid can melt into distinct liquids. In July we published a Q&A with a particle physicist who is applying the machine learning and data visualization skills she acquired at CERN in a job at a startup in Dublin that remotely monitors the health of dairy cows.

If you're an experimenter, you have another reason to visit our website. In July PHYSICS TODAY launched its revamped, easier-to-use Buyers' Guide, a browsable, searchable catalog of lab equipment and software. Look for it under the Resources tab on the website's navigation bar.

One reason you might not be visiting our website, besides being happy with the print issue, is that it's not a habit. The selection of websites that I routinely visit is a modest one that comprises the BBC, the *Washington Post*, the *Guardian*, *Science*, and *Nature*. Even though I've subscribed to the *Economist* since graduate school, I rarely visit its website. But don't worry! You needn't try to remember to visit physicstoday.org. If you sign up for our The Week in Physics alert, you'll receive a weekly email that contains links to fresh online content. Please do. PT

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A renaming proposal: "The Auger–Meitner effect"

We are writing to propose that the Auger effect be renamed the Auger–Meitner effect to recognize Lise Meitner's contribution to it. Meitner is better known for her work on nuclear fission, for which she was nominated for the Nobel Prize more than 30 times (reference 1; see also the article "A Nobel tale of postwar injustice," by Elisabeth Crawford, Ruth Lewin Sime, and Mark Walker, PHYSICS TODAY, September 1997, page 26). However, she is less widely recognized for her discovery of what has since become known as the Auger effect and her subsequent publications on the topic[2] in 1922 and 1923.

When an electron from an atom's inner shell is ejected—for example, by UV radiation or nuclear beta decay—an electron from a higher energy level will drop into the vacancy and emit a photon or eject another electron. A cascade develops as other electrons change their state by falling into the energy levels abandoned by the earlier ones. According to Meitner's 1922 description, "a primary (nuclear) β-ray transforms itself in the nucleus into a γ-ray. The γ-ray either goes through unchanged as a γ-ray, or it ejects secondary β-rays from the electron shells. In this way the characteristic x-ray spectrum of the atom is excited, which itself can of course also eject electrons from lower energy levels."[2]

Again, in 1923 Meitner wrote that "the primary β-rays eject outer electrons from the daughter atom, which excites the Kα radiation, which in turn ejects *L*-, *M*- or *N*-electrons from the same atom."[2] She also pointed to the possibility that radiationless transitions could account for the ejection of orbital electrons during beta decay.

LISE MEITNER (left) talking with student Susan Jones Swisher and faculty member Rosalie Hoyt at Bryn Mawr College, April 1959. (Photo by Heka Davis, courtesy of AIP Emilio Segrè Visual Archives, PHYSICS TODAY Collection.)

The significance of Meitner's discovery was not immediately realized, undoubtedly because she did not emphasize it in her publications; she instead focused on the emission energies of the original beta decay, which due to the simultaneous emission of the then-unknown neutrino resulted in a puzzling energy distribution.

In 1923, a year after Meitner first described the effect, Pierre Auger's cloud-chamber work allowed him to independently observe the cascade that now bears his name.[3] There followed a lively correspondence involving Meitner; Auger; theorists Niels Bohr, Oskar Klein, and Svein Rosseland (who had raised the possibility of radiationless transitions in 1921); and others.[4] The Auger effect remains an area of active research, and Auger, a truly great scientist in many ways, went on to do wonderful things in astronomy. Among his many honors were adoption of the related terminology "Auger electrons" and "Auger peaks," and naming of the Pierre Auger Obser-

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vatory in Argentina, which observes high-energy cosmic rays with "Auger showers."

Crediting Meitner for being the first to observe the effect has been discussed for at least 30 years. Science writer Richard Sietmann states that "Meitner was the person who really should have taken credit for the so-called 'Auger' effect," although he also suggests that shared credit would be acceptable.[5] In another review, Olivier Duparc writes, "While L. Meitner should have shared the Nobel Prize with [Otto] Hahn, the Auger effect has rightly been attributed to Auger."[5] We think there is a strong enough claim to honor both contributors.

Such renaming has precedent. In astronomy, for example, according to a private communication last year between David DeVorkin of the Smithsonian's National Air and Space Museum and one of us (Matsakis), the Hertzsprung–Russell diagram was originally called the Russell diagram. And in October 2018, a resolution to rename the Hubble law as the Hubble–Lemaître law was approved by 78% of the International Astronomical Union's voting membership.

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Iran's actions threaten Iranian scientists

The PHYSICS TODAY news story "Iranian scientists persevere under renewed sanctions" by Toni Feder (January 2019, page 22) blames the US embargo for hardships that Iranian scientists encounter as they pursue international collaborations. Only two sentences in the four-page report mention Iran's recent actions against numerous scientists in the country who have Western connections, and no mention is made of the long prison terms or death sentences they have received "for collaborating with a hostile government."

Omid Kokabee, a physics doctoral student at the University of Texas at Austin, was sentenced to 10 years on a "collaboration" charge and spent 2011–16 in an Iranian prison; he was released only after he developed kidney cancer (see "Physicist imprisoned in Iran is granted medical furlough after surgery," PHYSICS TODAY online, 25 May 2016). Ahmadreza Djalali, a Swedish resident and a principal investigator on two European research projects in disaster medicine, was arrested in 2016 after he was invited to a scientific workshop in Tehran. In 2017 he was sentenced to death for his refusal to spy for Iran's military.[1]

Xiyue Wang, a doctoral student in history at Princeton University, was sentenced in 2017 to 10 years in prison when his studies of ancient documents in Tehran were interpreted as espionage.[2] Meimanat Hosseini-Chavoshi, an Australian citizen and fertility expert, was detained on her research trip to Iran last December on charges of trying to "infiltrate" Iranian institutions.[3]

In 2018 several Iranian environmental scientists were rounded up on suspicion that their studies of wildlife might have revealed information about Iranian military sites. One of them, Kavous Seyed-Emami, a Canadian citizen and professor at Imam Sadiq University in Tehran, died in prison after intense interrogations.[4] Four others have been accused of "sowing corruption on Earth," a charge that can carry a death sentence.

The above-mentioned cases represent the tip of the iceberg. Anyone who has dual citizenship or is a doctoral student residing or studying in another country is taking serious chances when returning to Iran for a professional or family visit. Although the US sanctions contribute to the hardships experienced by our Iranian colleagues, the actions of the Islamic Revolutionary Guard Corps are largely responsible for making the lives of the Iranian scientists miserable.

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More whiffs of the aromatic universe

Authors Alessandra Candian, Junfeng Zhen, and Xander Tielens ("The aromatic universe," PHYSICS TODAY, November 2018, page 38) give us a glimpse of the remarkable progress made by astrophysicists and astronomers in identifying carbon-based molecules found in the interstellar medium. That progress includes the identification of a subset of the diffuse interstellar band, one of the most enduring astrophysical riddles.

In addition to the emission of IR vibrational radiation and absorption across the visible spectrum into the UV, polycyclic aromatic hydrocarbon (PAH) molecules can also emit radiation from thermally populated excited electronic states. That radiation can have an important stabilizing effect on the molecules. The effect, predicted by Abraham Nitzan and Joshua Jortner in 1979, has been observed in several molecules, including fullerenes in which the radiation was seen to be enhanced two orders of magnitude or more relative to purely vibrational cooling.[1]

Also, the hydrogen-containing PAH molecule anthracene was identified as a radiator,[2] and thermally emitted photons have been measured[3] from pure carbon clusters as small as C_4^- and C_6^-. The large disparity in cooling rates for C_4^- and C_6H^- also illustrates the extreme variation caused by seemingly very small differences in molecular composition.[4] At excitation energies in which radiation competes with electron emission from those species, the photon-emission rate constants are $8 \times 10^4\ s^{-1}$ for C_4^-, for example,[5] and the energies removed (1.34 eV and 2.71 eV for the two allowed transitions) are an order of magnitude higher than vibrational quanta. Such extreme molecule-specific radiative cooling translates into strongly varying molecular survival probabilities after photoexcitation and may have significant implications for the populations of fullerenes, PAH molecules, and other molecules in interstellar space.

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The aromatic infrared bands (AIBs) discussed by Alessandra Candian, Junfeng Zhen, and Xander Tielens were discovered in interstellar and circumstellar environments in the 1970s. Since then, their origin has been a topic of interest. The hypothesis advanced by

Candian and her coauthors that the AIBs arise from individual, free-floating polycyclic aromatic hydrocarbon (PAH) molecules is widely accepted but has not been proven. (For a detailed critique of the PAH hypothesis, see reference 1.)

Candian and her coauthors state that no specific PAH has been definitively identified with any of the AIBs, which are sometimes referred to in the literature as the unidentified IR emission features. Also, the AIBs are conjectured to arise from the absorption of UV radiation by PAH molecules that then undergo IR fluorescence. Although evidence of PAH absorption in the UV is expected, none has been found so far.[2] It is difficult to understand how only a specific set of PAHs can arise from a wide range of astrophysical conditions.

The broad, smoothly varying shapes and widths of the AIBs are characteristic of solid-state emission bands. "Plateau" emission features underlying the main AIB peaks also suggest a solid-state or small-grains origin.[3]

Continuum emission in reflection nebulae and in the interstellar medium is consistent with nonequilibrium thermal emission from very small grains (nanoparticles) with tens to hundreds of carbon atoms.[4] PAHs do not explain the continuum emission because molecules have no absorption between absorption bands, nor to our knowledge do any laboratory or theoretical spectra convincingly replicate the continuum emission under the AIBs. A small-grain component may produce the continuum emission, which is consistent with the production of the plateau emission.

Amorphous carbonaceous nanoparticles might account for both the continuum emission and the AIBs. Many laboratory and amorphous carbonaceous materials—including hydrogenated amorphous carbon, soot, quenched carbonaceous composite, kerogen- and coal-like substances, and mixed aromatic and aliphatic organic nanoparticles—have been proposed as candidates for the AIB carriers.[5] In the interstellar medium, one would expect abundant elements such as nitrogen, oxygen, and sulfur rather than just the carbon and hydrogen of PAHs, since the dust grains are formed in many complex interstellar and circumstellar environments.[1]

All the above proposed AIB sources would contain aromatic PAHs and aliphatic hydrocarbons in varying amounts. Such materials typically can explain some but not all of the emission bands, and the laboratory materials often show spectral bands that are not observed in the AIBs. Unfortunately, it is not yet possible to theoretically derive emission spectra of amorphous carbonaceous particles nor to closely simulate conditions in the interstellar medium in laboratory studies.

Efforts to pin down the carrier of the AIBs continue in astronomical and laboratory studies. The wonder is how nature can produce such a relatively simple spectrum from intrinsically complex organic material that has defied definite identification for nearly four decades.

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▶ Candian, Zhen, and Tielens reply: Klavs Hansen and Piero Ferrari insightfully point out the importance of electronic fluorescence from thermally populated electronic states. Direct electronic fluorescence is a well-known process that occurs when excitation is temporarily trapped in, for example, the S_1 state during the internal conversion cascade whenever relaxation to the ground state is hampered by a large energy gap. Because internal conversion is a reversible process, an excited electronic state can be revisited and electronic fluorescence can also compete with vibrational fluorescence later on during the relaxation process. Delayed electronic fluorescence emission was measured in the 1960s for small polycyclic aromatic hydrocarbons (PAHs), including coronene[1] ($C_{24}H_{12}$). As Hansen and Ferrari point out, it was

also measured more recently in elegant thermo-ionic studies on small carbon-chain and fullerene anions.

Delayed fluorescence is controlled by the energy gap, which sets the fractional population of electronic states, and by competition between radiative and nonradiative processes, which depopulates electronic states. Despite the potential importance of delayed fluorescence, systematic studies of it are lacking, and it has received scant attention in astronomy. As Hansen and Ferrari emphasize, molecular stability in the interstellar medium may be closely tied to delayed fluorescence. Electronic fluorescence may also provide a means to characterize and identify specific molecules present in space. The narrow bands in the visible spectrum of the stellar outflow, the Red Rectangle, are generally ascribed to electronic fluorescence of large molecules, illustrating that further study of the processes involved might be beneficial.

Alan Tokunaga and Roger Knacke return to arguments first raised against the interstellar PAH hypothesis in the late 1980s. Studies driven by those arguments greatly elucidated the characteristics of the aromatic infrared band (AIB) carriers and helped to solidify the presence and importance of PAHs in space.[2] The AIBs are carried by 50 carbon-atom PAH species. Some very weak AIBs may be due to functional groups—for example, methyl or quinone groups—attached to an aromatic skeleton, but their fractional coverage is small compared with aromatic H. Although some of the debate may seem semantic, we emphasize that 50 C-atom species behave, emit, and evolve like molecules. A treatment based on solid-state physics is sometimes convenient but obfuscates the underlying molecular physics. Three issues raised by Tokunaga and Knacke—the AIB profile, the underlying continuum, and the dearth of electronic absorption features—are a result of thinking about the PAHs through a solid-state physics lens rather than from a molecular perspective.

Anharmonic behavior is a key aspect of vibrational spectroscopy. Recently, anharmonic density functional theory calculations of moderately sized PAHs have come within reach, and resulting spectra agree well with laboratory experiments.[3,4] Calculations following the energy cascade of highly excited PAHs are in good agreement with AIB positions and provide a natural explanation for the observed, red-shaded AIB profiles.[5] Anharmonic interactions may also lead to a vibrational quasi continuum.[6] Alternatively, the delayed electronic fluorescence process pointed out by Hansen and Ferrari may result in a near-IR continuum.

Finally, the rapid (10–100 fs) nonradiative decay channels provided by conical intersections of highly excited electronic states[7] broaden UV absorption bands, and astronomical instruments are not well suited to detect resulting weak and broad features. The nano-grain approach misses those molecular-physics aspects and cannot explain the observations.

After the discovery of the first diatomic molecules some 100 years ago, astrophysicist Arthur Eddington lamented that "atoms are physics, but molecules are chemistry." Ever since, astrophysicists have regretted that sometimes simple physical formulas have to give way to complex chemical solutions in a molecular universe. To us, though, interstellar molecules provide a tool to probe macroscopic aspects of the universe, whereas the harsh environment of space offers unique insight in microscopic processes controlling excitation and relaxation of isolated molecules.

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PROFESSOR IN PLASMA SCIENCE AND APPLICATIONS

(AP 18-05)

Institut national de la recherche scientifique (tenure-track position)

Context and summary

Institut national de la recherche scientifique (INRS) is the only institution in Québec (Canada) dedicated exclusively to graduate level university research and training. The influence of our faculty and students extends around the world. In partnership with the community and with industry, we are proud to contribute to the development of society through our discoveries and through the training of young scientists.

INRS would like to fill a new faculty position in the area of plasma science and applications. The successful candidate will collaborate with the multidisciplinary research program at the INRS Énergie Matériaux Télécommunications Research Centre by bringing recognized expertise in experimental plasma physics applied to materials synthesis, characterization, and treatment.

Main duties and responsibilities

- Develop an original and innovative program of applied and fundamental research in plasma physics oriented preferably (but not exclusively) towards the following applications:
  - Plasmas for the synthesis of thin film and nanomaterials relevant to various fields of application (catalysis, energy conversion, photonics, 3D printing, etc.);
  - Plasmas for the treatment of organic and inorganic materials relevant to various fields of application (etching or nanostructuration of materials, modification of polymers, treatment or destruction of cells, restorative surgeries, etc.);
- Secure external funding from a variety of funding agencies, both provincial and federal, also involving various partners from the public and private sectors whenever needed/pertinent;
- Participate in teaching and training at the graduate level (both M.Sc. and Ph.D. students), as well as supervising post-doctoral fellows and research personnel.

Requirements

- Doctorate in physics, chemistry, physical engineering, chemical engineering, materials science or related fields, with specialization in experimental plasmas or plasma-assisted processes;
- Have a thorough knowledge of plasma physics (atomic-scale mechanisms, properties of plasmas and sources, plasma diagnostics);
- Relevant postdoctoral research experience would be an asset;
- Strong scientific publishing record illustrating leadership and innovation;
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Centre Énergie Matériaux Télécommunications
1650, boulevard Lionel-Boulet, Varennes (Québec) J3X 1S2 CANADA
Varennes is located on the South Shore of Montreal.

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Institut national de la recherche scientifique (INRS)
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Tropical biodiversity faces intersecting threats

As global climate and land use both change, many rainforest species could struggle to find new habitats.

Over the past half century, the Amazon rainforest has lost some 20% of its area, mostly to cattle ranching. Other tropical forests around the world have suffered a similar decline. Rainforests are home to around half of Earth's terrestrial plant and animal species, including unknown numbers that have yet to be discovered. As deforestation continues, those species could be lost.

That's not news, of course: Rainforest conservation movements have been around for more than 30 years. But now, Rebecca Senior of the University of Sheffield has probed the problem from a new angle: As part of her PhD research under the joint supervision of David Edwards and Jane Hill, she found that not only does deforestation reduce the amount of available habitat, it also makes it harder for rainforest species to shift their ranges in response to climate change.[1]

As the world warms, species will find themselves increasingly ill-adapted to their current homes. Tropical species, such as the frog in figure 1, could be at particular risk because they're used to temperatures that change little from month to month and from year to year. For example, the climate is so steady in Macapá, a small city in northern Brazil at the mouth of the Amazon River, that the all-time record high temperature is only 20 °C warmer than the all-time record low. (For Washington, DC, in contrast, that difference is 67 °C; for Fairbanks, Alaska, it's 91 °C.)

Species may be able to escape the worst effects of the warming climate by moving to cooler habitats, either farther from the equator or uphill, but only if they can find a sufficiently unobstructed path to get there. Deforestation breaks up those paths. Senior and colleagues found that under the most severe warming scenario, less than two-fifths of Earth's rainforest area is connected to a region with an analogous future climate. Moreover, that number is getting worse: In 2000 almost half the rainforest was so connected.

FIGURE 1. THIS MICROHYLID FROG of the genus *Kalophrynus* makes its home in the rainforest floors of Borneo. The species may need to find a new habitat in a changing climate, but because the adults are only 3 cm long, they can't disperse far.

Moving home

Senior started with a plan for a completely different project on land use, biodiversity, and climate. Many of the world's rainforests are selectively logged, a practice that degrades the forest but doesn't destroy it. Senior traveled to Borneo to test the hypothesis that logging would disrupt the cooler microclimates—burrows, tree holes, and the like—where animals can take refuge in especially hot weather. If she'd found a difference, she would have gone on to study the behavior of frogs in the different types of forest to see how they adapt. But in fact, the microclimates in logged and intact forests were almost identical.[2] "That's good news for biodiversity," says Senior, "but it rendered my original plans irrelevant."

Her new plan was inspired by a paper by Georgia Tech's Jenny McGuire and colleagues on the connectivity under climate change of natural lands in the US.[3] What would the same analysis reveal about the world's tropical forests? Senior asked. The basic idea—that forest clearing would make it harder for species to move to cooler regions—had been suggested before but never rigorously tested, in part because of a lack of data on forest geography. But a set of high-resolution satellite maps, released in 2013 and covering the years 2000–12, made such an analysis possible.[4]

Similarly reliable maps aren't yet available for all the variables that contribute to a region's projected future climate—such as rainfall and temperature variability—but for average annual temperature, at least, they are. Senior and colleagues combined the forest maps with current climate maps and the future temperature projections of the so-called RCP 8.5 trajectory, which assumes that greenhouse gas emissions continue to rise unchecked throughout the 21st century. Under that scenario, by the year 2100 the average global temperature is likely to rise by almost 4 °C, an amount that would have drastic consequences

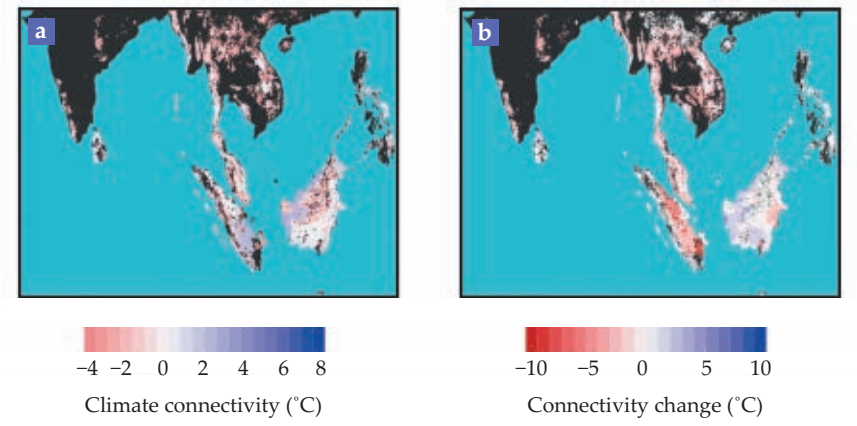

FIGURE 2. CLIMATE CONNECTIVITY, shown here **(a)** for the Asian tropics for the year 2012, is defined as a region's current average annual temperature minus the projected future temperature of the coolest destination to which it's connected. Positive connectivity, shown in blue, means that species stand a good chance of coping with climate change by moving; negative connectivity, shown in red, means they don't. **(b)** Changes in land use between 2000 and 2012 have changed the climate connectivity in many regions. Most, but not all, of those changes are for the worse. (Adapted from ref. 1.)

for Antarctic glaciers and thus for sea levels (see PHYSICS TODAY, February 2018, page 16). But what about for wildlife on land?

The researchers deliberately sought a broad result to apply generically to tropical forest species, from insects to frogs to trees. That meant making some broad generalizations about how species propagate and disperse. "We assume that over decades, most species' ranges will shift via populations gaining a selective advantage in the coldest parts of their range, rather than through the more sporadic movement of individuals within generations," Senior explains. Among other things, that assumption implies that species never shift from cooler to hotter territory, even if the move would help them reach an even cooler home. Some fast-moving or migratory animals might be able to explore more possible habitats than assumed. On the other hand, slow-growing plants might not be able to disperse their seeds far enough to keep up with temperature changes, no matter how much suitable habitat is available.

Forest patches were considered to be connected to each other if they were up to 2 km apart—effectively an assumption that species can cross up to 2 km of nonforest. "This, of course, is very dependent on the species and what exactly the 'nonforest' is," explains Senior. Furthermore, the researchers required that for a tropical species to get from one point to another, every region in between must have sufficient forested area—a threshold they set at 10 km^2—to sustain the species at a reasonable intermediate climate. But that number, too, is species dependent. Species that can survive and reproduce in areas as small as 1 km^2 may have significantly more paths available to them, whereas those that need much more room could have even more trouble reaching new homes.

Climate change is likely to create novel ecosystems, as species from different lowland regions all seek the same higher ground to escape the heat. The consequences of those encounters are beyond the scope of the study—but, as Senior notes, species have adjusted to new neighbors before. "There's plenty of paleontological evidence that species have moved up- and downhill, or toward and away from the poles, as Earth's climate has changed in the past," she says. "But this is the first time that they will have to do so through such a fragmented landscape."

Missed connection

Although crunching the data from all the world's tropical forests was a computational challenge, the methodology was fairly straightforward: For each point of origin, find the coolest reachable destination, subject to the above rules. Then subtract the projected late-21st-century average temperature at the destination from the late-20th-century average temperature at the origin. That difference, which the researchers call "climate connectivity," is shown in figure 2a for the forests of South and Southeast Asia. If the connectivity is positive or zero, then a species at the origin can reach a new habitat that will be no hotter in the future than the origin is now. If the connectivity is negative, then it can't.

Based on the global forest-cover maps from 2012, the researchers calculated that 62% of tropical forest area has negative connectivity. But the point isn't so much about that specific number—the result of numerous generalizations and assumptions—as it is about how the connectivity is affected by human land-use patterns. That dependence is quantified by the change in connectivity between 2000 and 2012, as shown in figure 2b.

The only variable driving the change in connectivity is the change in forest cover; the initial and projected climate maps, for example, are the same in each case. Even so, much of the worldwide forest area saw a nonzero connectivity change. Most of the changes were negative, the result of deforestation that cuts off paths to cooler regions. But some were positive because forest conversion isn't a one-way street. The world's tropical forests saw a total loss of some 860 000 km^2 between 2000 and 2012—but also a gain of 120 000 km^2, which restored some paths or created new ones that weren't there before.

If changing land use is part of the problem, it can also be part of the solution. "We're interested in identifying the priority regions for enhancing climate connectivity," says Senior, "where the smallest amount of reforestation would improve connectivity the most." To do that, the researchers want to refine their model to include species-specific dispersal patterns, the effects of precipitation, and other variables that can cause species to shift their habitats. "There are a lot of open questions, and this is really just the beginning of understanding how these factors interact."

Johanna Miller

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Random walkers illuminate a math problem

A family of tricky integrals can now be solved without explicit calculation.

In a 1905 issue of *Nature*, statistician Karl Pearson of University College London asked readers for their help with a problem he named the random walk[1]: A walker starts at an origin point and walks l yards in a straight line in a random direction. The walker then turns and proceeds another l yards in another random direction, and the process repeats n times. Having found the solution only for the case of two steps, Pearson wanted an expression for the probability that the walker is a radius r from the starting point after n steps.

In the intervening 114 years, the random walk—or, more colorfully, the drunkard's walk—has been applied to such diverse fields as ecology, economics, computer science, biology, chemistry, and physics, and it helped produce the art on the cover of this issue. Physicists use the random walk to model diffusion, Brownian motion, polymers, and even quantum field theory. Random walkers can move in one, two, or more dimensions, and their steps can have a fixed length or a probabilistic distribution of possible lengths. Figure 1 is an example of a simulated two-dimensional random walk with a fixed step length.

Random walks can now add solving integrals to their resume because of the work of Satya Majumdar and Emmanuel Trizac of Université Paris–Sud/CNRS.[2] The project started one Sunday in May 2018 when a Twitter post captured their attention. The tweet, from Fermat's Library (@fermatslibrary), presented a mathematical oddity: A family of successively larger integrals follows an apparent pattern that breaks down unexpectedly without an intuitive mathematical explanation. But when the integrals are framed as random walks, all becomes clear.

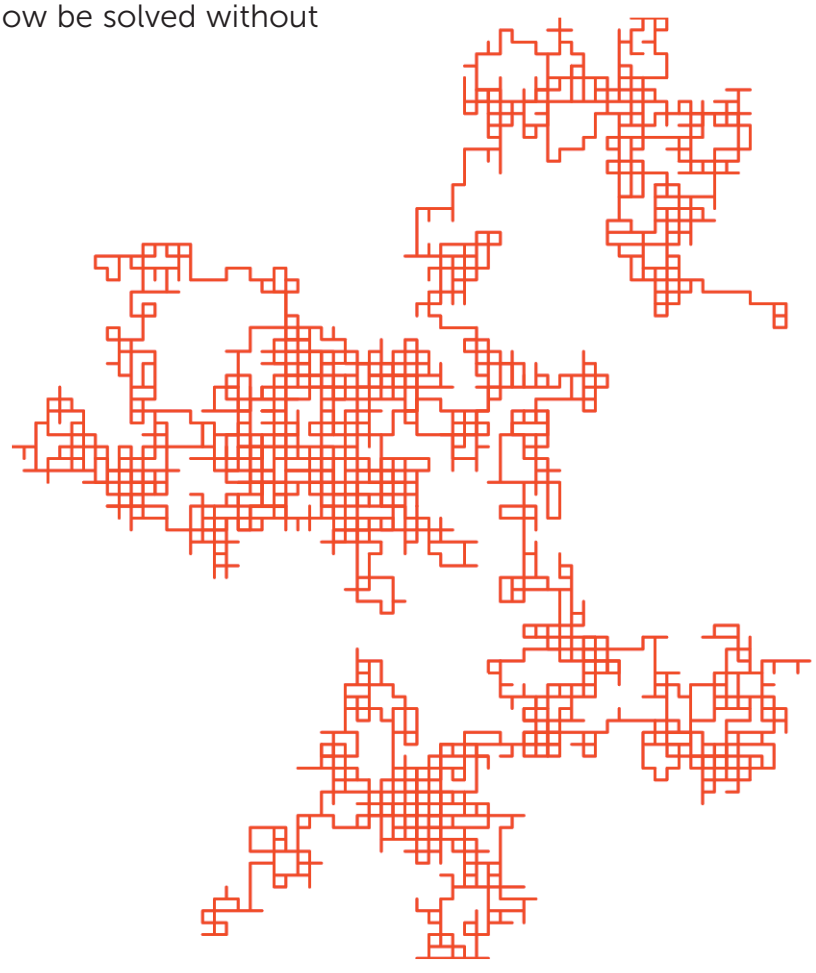

FIGURE 1. THE PATH OF A TWO-DIMENSIONAL RANDOM WALK is generated when a simulated walker probabilistically takes horizontal or vertical steps of a fixed length.

Integral to our understanding

The integrals I_n in question are shown in figure 2. They are one variant of Borwein integrals, which integrate over products of $\sin(a_n x)/a_n x$ factors; the a_n coefficients take a different value for each factor and for each variant. The integral I_1 with only the $n = 1$ factor is π. The integral I_2 with two factors, I_3 with three factors, and even up to I_7 with seven factors are also all π. But the integral I_8 with eight factors is short of π by less than 10^{-10}. That odd behavior was first reported in 2001 by David Borwein of the University of Western Ontario and his son Jonathan Borwein of Simon Fraser University.[3] Numerical calculations uncovered the deviation, which, because it was both small and unexpected, was first attributed to a software bug. But it wasn't a bug; it was a behavior found in all variants of the $\sin(a_n x)/a_n x$ integrals, now named after the two researchers, and in many related integrals with additional functions in the integrand.

The Borweins found an expression for the first integral that deviates from the pattern in all Borwein integrals. If the first coefficient a_1 is larger than the sum $a_2 + \ldots + a_j$ of all the rest of the coefficients, the integral gives the expected value. In I_3, for example, the coefficients are 1, ⅓, and ⅕; $1 > ⅓ + ⅕$, and the integral is π, as expected. Once the sum exceeds the first coefficient, the value of the integral changes. For the integrals in figure 2, that transition first happens for I_8, which is less than π. But mathematicians have lacked an intuitive understanding of why the change happens.

Inspired by the tweet, Majumdar and Trizac hoped a physics perspective might offer some insight to the problem, and they began searching for a relevant reformulation. The pattern breaking reminded the pair of a phase change, but the resemblance proved fruitless. It was then that the structure of the integral reminded them of a Fourier transform.

$$I_1 = \int_{-\infty}^{\infty} \frac{\sin(k)}{k}\, dk = \pi$$

$$I_2 = \int_{-\infty}^{\infty} \frac{\sin(k)}{k} \frac{\sin(k/3)}{k/3}\, dk = \pi$$

$$\vdots$$

$$I_7 = \int_{-\infty}^{\infty} \frac{\sin(k)}{k} \frac{\sin(k/3)}{k/3} \cdots \frac{\sin(k/13)}{k/13}\, dk = \pi$$

$$I_8 = \int_{-\infty}^{\infty} \frac{\sin(k)}{k} \frac{\sin(k/3)}{k/3} \cdots \frac{\sin(k/15)}{k/15}\, dk \approx (1 - 10^{-10})\pi$$

FIGURE 2. BORWEIN INTEGRALS integrate over products of factors of the form $\sin(a_n x)/a_n x$. One variant, with $a_n = 1/(2n - 1)$, is shown here. The first seven integrals, I_1 to I_7, all equal π. Beginning at I_8, all of the subsequent integrals are slightly, and increasingly, less than π.

With that insight, the connection to random walkers became obvious.

Walk the line

Majumdar and Trizac restricted their imagined random walkers to a 1D walk with the ability to share the same position. They started with an infinite number of random walkers spread out evenly along an infinitely long line. When all the walkers take random steps, the number of walkers that leave a position—call it position $x = 0$—is the same as the number of walkers that land on that same position. No matter how many steps the random walkers take, the total number at $x = 0$ stays the same.

But what if the random walkers occupy a finite space? If they start from $x = 0$ and take an initial step with a size equally distributed in the range $|\Delta x| \le 1$, the walkers will be evenly spread from −1 to 1 (see the left panel of figure 3), and the Fourier transform of that rectangular distribution is $\sin(k)/k$ in terms of the conjugate variable k. The first Borwein integral in figure 2 can be reimagined as the Fourier transform of $\sin(k)/k$ evaluated at $x = 0$, or the density of random walkers at the origin. For those walkers at $x = 0$, the initial distribution looks the same as the case with walkers spread to infinity.

The second integral calculates the fraction of walkers at $x = 0$ after they each take a second step with $|\Delta x| \le \frac{1}{3}$. Another step with $|\Delta x| \le \frac{1}{5}$ produces the situation in the third integral, and so on. With each step, the random walkers spread out more (see the middle and right panels of figure 3) and look less like the infinite case, but it takes eight steps for the number of walkers at the origin—and thus the Borwein integral—to change. That's because the density at $x = 0$ stays the same as the infinite case until the information that initially there were no walkers beyond ±1 reaches the origin. A random walker starting at $x = -1$ and acting as a messenger travels at most $\frac{1}{3} + \frac{1}{5} + \ldots + 1/(2j-1)$ after j steps. The walker gets to the origin only after the eighth ($\frac{1}{15}$) step. That argument, based on the rate at which information propagates, is equivalent to the Borweins' expression, but Majumdar and Trizac show why it's correct.

Their intuitive picture does more than reveal when the results of the integrals change; it also offers a way to avoid directly calculating those complicated integrals. One simply finds the normalized density of random walkers at $x = 0$. The density after the first step—and the next six steps—is ½, which needs to be multiplied by a factor of 2π to get the value of the first seven integrals. That calculation-free route to the solution will be important for other integrals that haven't been or can't easily be numerically solved.

All in the family

The method from Majumdar and Trizac applies to all variants of Borwein and many similar integrals. One such family of integrals takes the form of those in figure 2, with the addition of a $\cos(k)$ factor in the integrand. With a similar Fourier transform reimagining, the integrals still represent the density of random walkers, but now at $x = 1$. The random walkers at at that position know that there are no walkers beyond $x = 1$. But they are unaware that there are no walkers below −1. Thus they behave the same as if the walkers stretched infinitely far, until the information from $x = -1$ reaches them—that is, when the steps add up to 2. That happens at the 57th step, which is when the value of the integral decreases by 10^{-110}.

The same logic can be applied for families of integrals in which the walkers start evenly distributed in a finite range or all the walkers start at two points $\pm b$, as defined by a coefficient b in a cosine or Bessel function. The walkers can take steps with a range of sizes, as defined by the coefficients a_n in $\sin(a_n x)/a_n x$ factors, or any other distribution of steps as long as they are bounded. And if no longer confined to 1D, random walkers can be applied to integrals in any number of dimensions. "We have put forward a tool that hopefully will prove useful for computing even more complex quantities," says Trizac.

In addition to their purely mathematical interest, $\sin(ax)/ax$ functions and integrals of those functions appear frequently, perhaps unsurprisingly, in Fourier analysis—for example, the $\sin(ax)/ax$ function is used to smooth Fourier series. Fields such as acoustics and optics rely heavily on Fourier analysis for signal processing. But the connection with random walkers may open up new avenues for applications.

Heather M. Hill

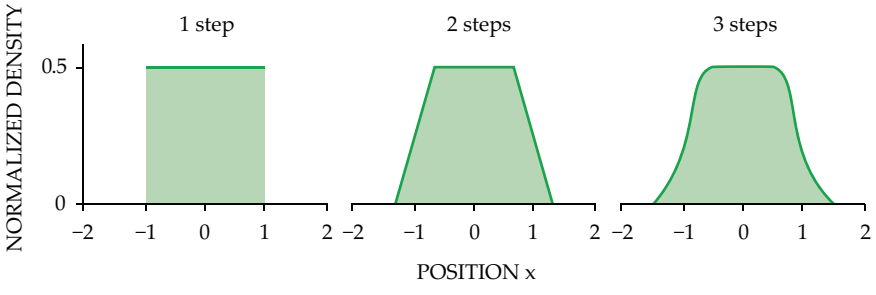

FIGURE 3. THE DISTRIBUTION OF RANDOM WALKERS evolves as they take steps dictated by the integrals in figure 2. After their first step, the walkers are evenly distributed between −1 and 1 (left panel). After a step of length from $-\frac{1}{3}$ to $\frac{1}{3}$, some walkers spread out beyond ±1 on the number line (middle panel). After another step of up to $\pm\frac{1}{5}$, the walkers spread out even more (right panel). In all three, the normalized distribution at $x = 0$ remains ½. (Adapted from ref. 2.)

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When a novel metal alloy relieves stress, it chills out

To make solid-state refrigeration technology more efficient, researchers exploit the large, reversible temperature swing of a material comprising nickel, manganese, and titanium.

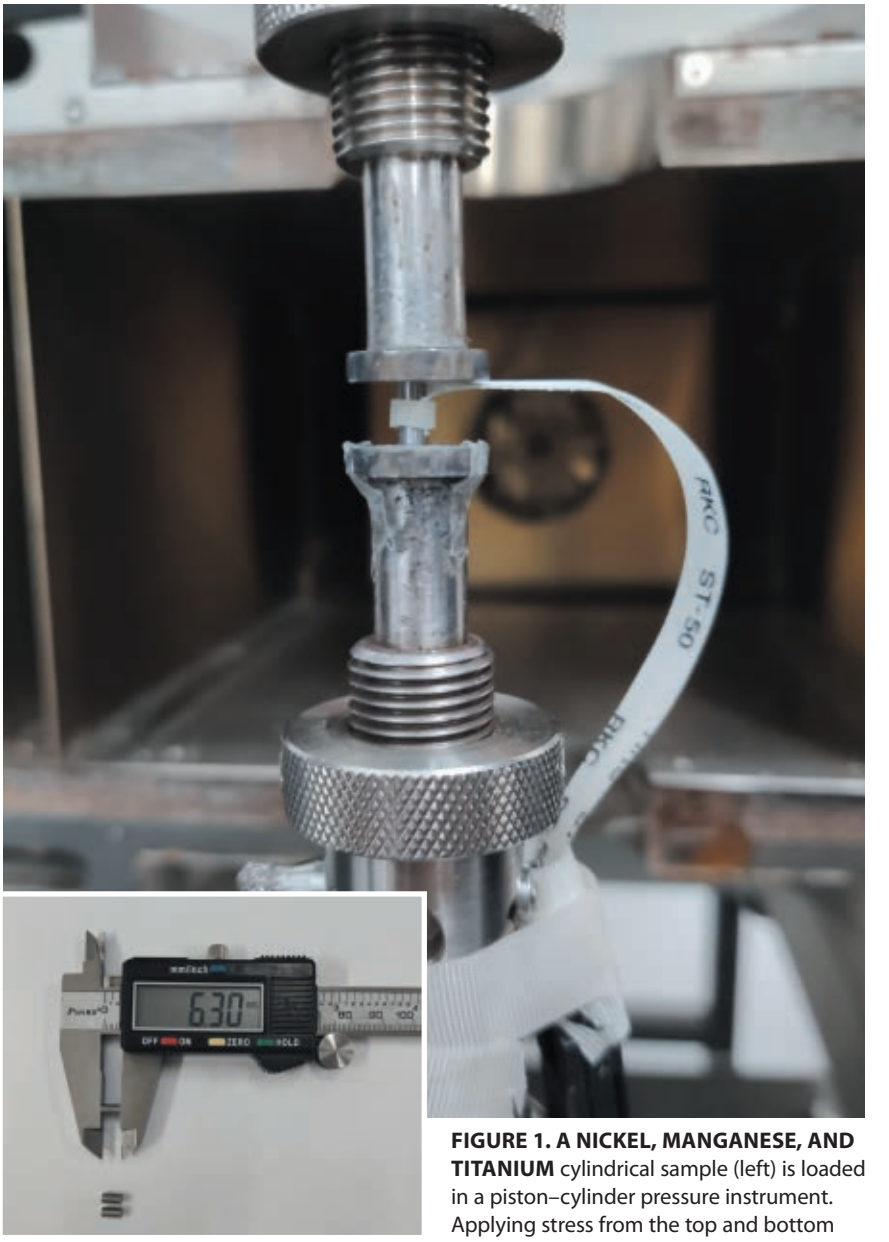

FIGURE 1. A NICKEL, MANGANESE, AND TITANIUM cylindrical sample (left) is loaded in a piston–cylinder pressure instrument. Applying stress from the top and bottom squeezes the sample, which decreases its volume and increases its temperature, the latter measured using a thermocouple (white ribbon). When the compressive stress is unloaded, the temperature reverses and the sample cools. That temperature drop makes it a promising material for solid-state refrigeration. (Photos by Shengwei Li.)

The home air conditioner and refrigerator owe their success to vapor-compression technology. First, a compressor squeezes refrigerant vapor before it's sent to a condenser. There the hot, pressurized gas cools and becomes a liquid. The liquid is then piped into an evaporator, where it depressurizes and sucks up the surrounding heat. As the environmental temperature decreases, the liquid gains heat and evaporates before reentering the compressor and repeating the process.

Although inexpensive, the vapor-compression refrigeration cycle is neither particularly efficient nor the most environmentally friendly process. Hydrofluorocarbons and other refrigerants inevitably leak out of the appliances and into the atmosphere, where they're potent contributors to the greenhouse effect. Solid-state alternatives that apply a magnetic or electric field or stress to specially designed alloys have been gaining traction for decades. But the technology hasn't quite achieved the temperature drop necessary to compete with commercially available cooling techniques (see the article by Ichiro Takeuchi and Karl Sandeman, PHYSICS TODAY, December 2015, page 48).

Nickel–titanium, nickel–manganese, and other shape-memory alloys have already been studied as potential solid-state refrigerants because they undergo structural phase transitions (see PHYSICS TODAY, May 2010, page 20, and August 2016, page 18). During the transformation of NiMn-based alloys from one phase to another, the material distorts from a high-symmetry crystal phase to a low-symmetry one. As a magnetic field or stress is applied to the alloy, its volume changes, and consequently so do the entropy and temperature. The phenomenon is known as a magnetocaloric or elastocaloric effect,[1] and both can be generated in the same material simultaneously. So far most solid-state refrigeration researchers have focused on maximizing a NiMn-based material's magnetocaloric response by enhancing the difference in magnetizations of the transforming phases. But such a design has tradeoffs: Optimizing the magnetocaloric effect reduces the elastocaloric effect.

Now Daoyong Cong of the University of Science and Technology Beijing and a team of engineers, materials scientists, and physicists have taken a different approach that focuses on the elastocaloric effect. Rather than optimize the magnetic properties of the material, the

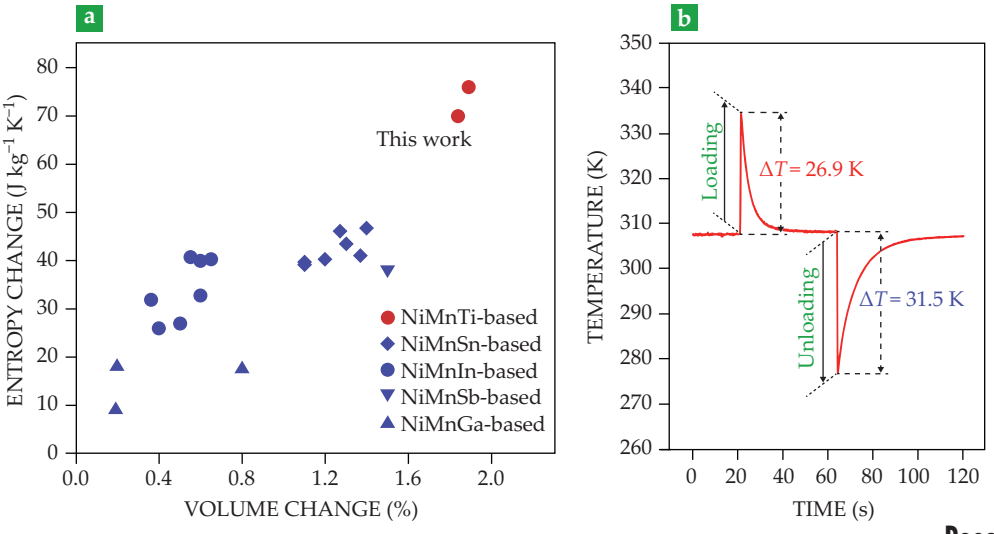

FIGURE 2. SHAPE-MEMORY ALLOYS experience a structural phase transition when squeezed, which alters the metal compound's crystal lattice. **(a)** The volume change and entropy change of a newly designed material (red circles) are larger than other materials with different metal stoichiometry. **(b)** Loading and unloading a stress of 700 MPa to a specially designed alloy comprising nickel, manganese, and titanium generated an adiabatic temperature swing of about 30 K. (Adapted from ref. 2.)

team adjusted the alloy composition with an eye toward maximizing the material's volume change when squeezed. The elastocaloric effect generates a temperature change that could be big enough for large-scale refrigeration applications.[2]

Designing a metallurgical marvel

The alloy Cong and his colleagues made, which comprises nickel, manganese, and titanium and is shown in figure 1, isn't entirely new. Materials made with those elements have already been explored.[3] "People always treat these alloys as magnetic shape-memory alloys," says Cong. "They want to have magnetic order and thus multicaloric—magnetocaloric and elastocaloric—properties in these alloys."

The first test alloy used a different composition of metals from previous studies: 50% nickel, 38% manganese, and 12% titanium. But differential scanning calorimetry measurements showed that the temperature at which the phase transition takes place is a bit too far above room temperature for an ideal refrigeration technology. After tweaking the Mn and Ti percentages in several more trials, the researchers settled on a composition, $Ni_{50}Mn_{31.5}Ti_{18.5}$, that experiences a transition closer to room temperature. They also added a trace of boron to make the alloy less brittle.

Testing many different compositions was time well spent. Tuning the alloy's Ti content changes its transition temperature, which makes the material useful for other heat pump applications. "I always thought that the best elastocaloric materials are not yet discovered, as nobody seriously investigated that possibility," says Jaka Tušek of the University of Ljubljana in Slovenia. "Until now practically all the elastocaloric materials were simply taken from already known shape-memory alloys," he says, "but this work shows that there is still significant room for improvement in developing new elastocaloric materials." In addition, engineers still need to develop a refrigerator design that can repeatedly compress the material and efficiently expel waste heat.

In situ synchrotron high-energy x-ray diffraction experiments with the new alloy showed that the material's volume decreases by 1.84–1.89% during its phase transition. The change is more than other similar shape-memory alloys as shown in figure 2a. In those alloys, the electronic contribution to the entropy change is small,[4] and the magnetic contribution is negligible in the absence of a magnetic field. Those material properties led the researchers to suspect that the entropy change of their material, and consequently the expected temperature change, would arise predominantly from crystal-lattice volume changes.

To test their hunch, the team applied 700 MPa of compressive stress to the sample and measured the temperature variation using a thermocouple as shown in figure 1. When compressed, the alloy experiences a temperature increase ΔT of about 30 K as shown in figure 2b, 20% higher than any other elastocaloric material measured thus far. "It's so large that it's almost unheard of in this field of caloric materials," says Ichiro Takeuchi of the University of Maryland. After the material expels heat to the environment and the stress is removed, the material then absorbs nearly the same amount of heat, which makes the temperature swing reversible.

Reaching a compromise

At least two big wrinkles still need to be ironed out. The material's phase transition demands 700 MPa of stress, which is currently applied by a laboratory-scale instrument. A solid-state refrigerator will "need to effectively utilize the work released during the unloading of the material," says Tušek, so that it can be affordable and efficient for commercial-scale applications. The material still needs to be tested to determine if it can withstand the millions of stress cycles a commercially available unit would need to perform. "Just as tweaking the composition led them to get this amazing ΔT, the fatigue is something that could be potentially engineered as well to get a material with a long life," says Takeuchi.

However, altering an alloy's composition has tradeoffs. Adjusting the structure to improve its strength or stability may decrease the magnitude of its elastocaloric effect. But, Takeuchi says, "They start off with such a high ΔT that it gives them room to do this adjustment." So even though the elastocaloric effect may decrease if the material needs strengthening, the large temperature change already achieved affirms that it is a promising candidate for commercial solid-state refrigeration.

Alex Lopatka

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A tiny swimmer generates rapid, far-reaching signals in water

Colonies of a single-celled organism synchronize their contractions to release toxins that may deter predators.

FIGURE 1. MANU PRAKASH (LEFT) AND ARNOLD MATHIJSSEN collect a sample of marsh water that contains *Spirostomum ambiguum*. (Image provided by Manu Prakash.)

In flocks of birds, schools of fish, and colonies of bacteria, individuals can interact in ways that benefit the group. Advantages conferred by working together may include better protection against predators, greater ease of foraging, and more efficient locomotion. Group behavior in many species arises from cascading signals transmitted by individuals. Understanding how signaling works across the natural world not only provides insights into biodiversity, but also helps engineers design groups of robots that autonomously coordinate movements in challenging environments.

Large aquatic organisms are well equipped for communication. Sensory tools including sight, sound, and smell offer possibilities for transmitting signals between distant neighbors. Microscopic swimmers lack complex sensory channels. For them, signaling may take the form of flows generated by swimming. An individual may sense the movement of fluid from a neighbor and adjust its behavior. (See the article by Eric Lauga and Raymond Goldstein, PHYSICS TODAY, September 2012, page 30.) But hydrodynamic signals generally decay with distance and only transmit information among individuals that are already close together. Some bacteria congregate into groups of 10^8 cells per cubic centimeter to coordinate their movements via hydrodynamic signals. Active cellular communication within a fluid may also entail a single cell swimming to deliver a signal to another cell, so messages only travel as fast as the cell can swim.

In a pond in California's Bay Area, single-celled *Spirostomum ambiguum* has found a way to generate eddies that travel orders of magnitude faster than the organism can swim. By observing the creature's quirky movements, Arnold Mathijssen and Manu Prakash from Stanford University, along with Joshua Culver and Saad Bhamla of Georgia Tech, discovered a new form of rapid, long-range signaling between single-celled organisms.[1]

The ultrafast hero

The Baylands Nature Preserve in Palo Alto, the background in figure 1, has proven to be a reliable source of fast-moving microswimmers, ideal for the team's ongoing investigation into single cells' power output capacities. One day, on peering at the brackish waters through a hand-made, pocket-sized microscope, Prakash noticed a tiny creature that contracted its body so rapidly that it seemed to disappear.

Prakash was not the first to notice *Spirostomum ambiguum*. The marsh-dwelling creature has attracted biologists' attention[2] since 1873. At 1 mm to 4 mm long, *S. ambiguum* is exceptionally large for a single-celled organism. It can shorten its body in an extremely rapid contraction and shrink to less than half its normal size in just 5 ms. After contracting, the organism relaxes to its full length over a leisurely 1 s, shown in figure 2. During contraction, the cell endures an acceleration 14 times the force of gravity (14*g*). An airplane that accelerates at more than 12*g* is illegal in some aerobatics races because of danger to the pilot.

The Stanford researchers collected water samples containing *S. ambiguum* to investigate its extraordinary behavior. They wanted to find out why the crea-

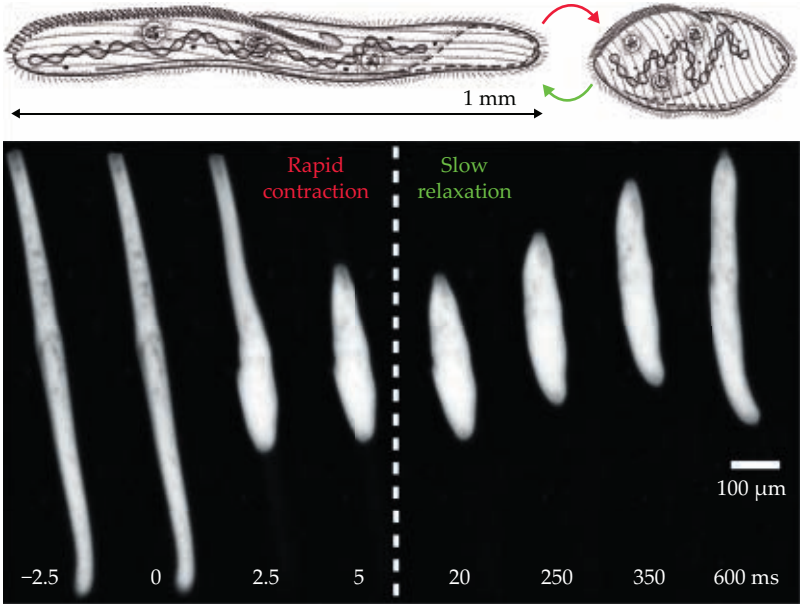

FIGURE 2. A *SPIROSTOMUM AMBIGUUM* CONTRACTS AND RELAXES. The single-celled organism rapidly contracts by 60% in 5 ms (red) and then relaxes in 1 s (green). (Image adapted from ref. 1.)

ture evolved the ability to contract so rapidly and how it did so without damaging its internal structures. When Bhamla (formerly a postdoc in Prakash's lab and now an assistant professor at Georgia Tech) started to grow cultures of the creature in the lab, he found a surprise. The cells assembled into clusters and appeared to contract together, sending a pulse of motion through the colony. "This was an exciting and serendipitous discovery," Bhamla recalls.

Stirring things up

To learn more about *S. ambiguum*'s behavior, Mathijssen (a postdoc in Prakash's lab) adapted a colleague's earlier experiment designed to investigate how an individual cell senses the movement of water around it. He and Bhamla stimulated a single *S. ambiguum* with gentle electrical pulses that caused it to contract, and they used micron-scale plastic beads to visualize the resulting flow fields around it. By observing the beads with a high-speed video camera, they found that a single cell's contraction generated a turbulent flow in the surrounding fluid.

The smaller a swimmer is, the more it has to accelerate to generate turbulence.[3] The characteristic flow around any swimmer is dictated by the relative importance of viscous and inertial forces on the fluid's motion, a ratio described by the dimensionless Reynolds number *Re*. A large swimmer in water, like a human, swims at a high Reynolds number ($Re \sim 10^5$). The viscous forces are negligible, and the swimmer's motion easily churns up eddies. A tiny swimmer, like *S. ambiguum*, swims at a low Reynolds number ($Re \sim 0.1$). Viscous forces dominate, and the swimmer's motion is unlikely to impart enough force to stir up the water.[4] But when *S. ambiguum* contracts, it accelerates enough to overcome the viscous effects of the water and generate a turbulent flow. In those milliseconds, the Reynolds number surges to 50.

To investigate what advantage generating a turbulent flow provides *S. ambiguum*, Mathijssen and Bhamla first sought to identify the mechanism that triggers the creature's contraction. Zoologists had posited that an individual *S. ambiguum* contracts when it senses a change in its surroundings, perhaps the presence of a freshwater flatworm or other predator. The Stanford researchers designed an experiment that mimicked the sucking motion of a predator's filter-feeding action. They suctioned liquid out of a small hole in a pair of slides containing a single *S. ambiguum* in water. As the suction drew the cell closer to the hole, its body became stretched. The cell contracted when it reached a critical strain threshold.

The strain required to trigger contraction matched the threshold for opening ion channels commonly found on a cell's outer membrane.[5] Once the channels are open, ions can enter the cell and engage filaments that make the cell contract—a common situation in other organisms, though biologists have not directly observed it in *S. ambiguum*.

An aquatic game of telephone

The observation that fluid flow triggers the cell's contraction suggested that *S. ambiguum* can both generate and read hydrodynamic signals. Prakash says, "That was the 'aha' moment!" The team's calculations showed that the turbulent flow produced by a contracting cell could generate a contraction-inducing strain in a neighbor up to a millimeter away.

To test the theory that *S. ambiguum* relies on hydrodynamic flows for communication, Mathijssen and grad student Culver investigated cells gathered in close proximity. If a cell felt an impulsive, turbulent flow, it would contract and generate its own turbulent flow, which would in turn cause other cells to contract. A hydrodynamic wave propagated through clustered cells at 0.25 m/s, hundreds of times faster than the cells' normal swimming speed of 0.2 mm/s. Figure 3 shows a wave of contractions propagating through a colony of cells.

Mathijssen proposed that a critical population density of cells allows the hydrodynamic signal to propagate throughout the colony. Below that density, the signal does not reach the entire network. Percolation theory—how information spreads throughout a network based on size, shape, and orientation of interacting nodes—suggests that at about 2 individuals per square millimeter, the signal propagates in a fractal path and quickly reaches the edge of the colony. Below that density, the signal dies out. Above it, the signal spreads radially from the first cell but travels at a slower velocity.

FIGURE 3. CONTRACTIONS PROPAGATE THROUGH A *SPIROSTOMUM AMBIGUUM* COLONY. The connecting lines and colors indicate the order in which the individual organisms contracted. (Image adapted from ref. 1.)

The authors proposed a possible functionality for the colony's collective contraction. When subjected to mechanical or electrical stimulation,[6] *S. ambiguum* releases toxins from pockets fixed to the cell membrane. The researchers found that the organism releases the toxin at the exact moment that it contracts. The vortex flow generated by contraction transports the toxin rapidly into the surrounding medium, faster than the toxin can diffuse on its own.

The results suggest that coordinated contractions may help the colony avoid danger. Flows generated by a large predator may prompt an individual to contract and signal its neighbors to do so as well. Synchronized toxin release may help the colony deter multicellular predators like the flatworm *Stenostomum sphagnetorum*, which learns to avoid the elusive prey.

Rachel Berkowitz

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Prospect of off-planet outposts spurs interest in space resources

Stakeholders in space exploration consider implications of a transition from science fiction to science fact.

An apparent confluence of political will and technological readiness has fans of humankind's expansion beyond Earth hopeful that their dreams may soon become reality. Alongside a rise in missions to the Moon by agencies and private companies in the US, Europe, China, Japan, India, and Russia, commercial sectors are buzzing with related activities. And various governmental and nongovernmental bodies are strategizing about environmental, ethical, legal, sociological, and other issues of space utilization and colonization.

With interest in space travel growing—spurred in part by billionaire entrepreneurs such as Jeff Bezos and Elon Musk—enthusiasts say the time is right to figure out how to use space resources, including water, solar power, and lunar regolith. Doing so would expand space exploration, increase commercial activities in space, and lead to technological advances for humanity, says Angel Abbud-Madrid, director of the first graduate degree program in space resources, which he and colleagues launched last year at the Colorado School of Mines. (For more about Abbud-Madrid's career path, see the interview at http://physicstoday.org/abbud-madrid.)

Have water, can explore

The only space resource exploited to date is the view of Earth from orbit for such applications as global positioning systems, weather prediction, communications, and science missions. A few years ago the prospect of mining asteroids for platinum and other metals to use on Earth was "the rage," says George Sowers of the Colorado School of Mines. But the business case didn't hold up. One exception might be rare-earth elements, but in the near to mid term, he says, "bringing stuff back to Earth is not economically viable." For now, the focus has shifted to using space resources *in situ*.

Water is a primary target resource in space. Electrolyzed into hydrogen and oxygen, it becomes fuel that could replenish satellites in orbit and propel rockets for exploring the solar system and returning to Earth. Astronauts and space tourists could drink water, use it for gardening and hygiene, and shield themselves from ionizing radiation with meter-thick sheaths of it around habitats or spacecraft.

In 2016 rocket manufacturer United Launch Alliance announced that the company would buy liquid oxygen and hydrogen propellants in low-Earth orbit for $3000/kg. Sowers made that offer in his previous job as ULA chief scientist. He says that a mining company could be profitable at that price, and many companies have begun working toward it. NASA and other space agencies are likely to be key initial customers.

The cost for a rocket to escape Earth's gravity is about $4000/kg, Sowers estimates. With humans aboard, the cost skyrockets, to "maybe as high as $1 million per kilogram," he says. That's because of the additional cargo—water, food, systems for pressure, waste disposal, and so on—needed to keep humans alive and return them to Earth. Once the requisite prospecting is completed and technologies are developed, space-sourced propellants would dramatically reduce the cost of every activity in space, including exploration beyond the Moon, Sowers says.

One of the great discoveries of planetary science is that water ice abounds in the solar system, says Sowers. It exists on asteroids and at the poles of Mercury, the Moon, and Mars. Ice in the permanently shadowed regions of the Moon is a focus of NASA's next manned lunar mission (see PHYSICS TODAY, July 2019, page 22). But details about its condition are sparse: How deep is the ice and how is it distributed? How dirty is it? How can it best be excavated?

Dale Boucher is CEO of Deltion Innovations, a Canadian company that specializes in robotics for space mining. Lunar surveys to date indicating the presence of hydroxyl bonds and possibly water have about 5-kilometer resolution, he says. The next stage is to drill for samples. "We need to send probes to prove that the lunar reconnaissance signatures are actually water," he says. The mechanical, thermal, and chemical properties of the ore bodies will determine the equipment needed for mining.

Water could be mined by heating *in situ* either the Moon's surface or subsurface or by first extracting and then heating ice to release and capture water vapor. Solar power—the preferred energy source for activities on the Moon, although nuclear fission is also being

A ROBOTIC ROVER IS TESTED IN A BIN OF SIMULATED SPACE DIRT at NASA's Kennedy Space Center in Florida. The robot is called RASSOR 2.0—the Regolith Advanced Surface Systems Operations Robot.

discussed—could be tapped for the mining process and for electrolyzing the water and liquefying the oxygen and hydrogen.

LaNetra Tate, Game Changing Development Program executive at NASA headquarters in Washington, DC, leads a team that is working to demonstrate the extraction of polar ice on the Moon and its conversion to usable water. Her team is also pursuing the extraction of oxygen from the lunar soil, or regolith. Many challenges relate to testing equipment in simulated lunar environments and figuring out how to create operations on the lunar surface, she says. "Many things we can figure out from here, but nothing is better than doing it there."

Researchers around the world are exploring how to use the lunar regolith. It resembles tiny bits of broken ceramics—it has jagged edges and is highly abrasive. One idea is to use silicates from lunar regolith as a raw material for constructing solar panels. Oxygen, which by mass makes up more than 40% of the regolith, could be extracted and used for breathing or for rocket fuel.

With 3D printers, regolith—alone or with added polymers—could be formed into almost anything in space. "It's very feasible," says Robert Mueller, cofounder of Swamp Works, a technology innovation lab at NASA's Kennedy Space Center. "You can melt it and make aerospace-grade composite basalt glass materials. You could build rockets or rocket parts."

As robots become more autonomous, space activities will become economically viable, says Philip Metzger, a planetary scientist who moved to the University of Central Florida after a 30-year career at NASA. And when robots can build robots, it will become viable to build things on the Moon, "because you won't have to launch everything from Earth."

The solar wind deposits helium in the lunar regolith; a small fraction (10–30 parts per billion) is helium-3 and could

conceivably be extracted and transported to Earth for fusion energy production. "One shuttle's worth of helium-3 could power the US for a year," says advocate Clive Neal, a geologist at the University of Notre Dame. He concedes, though, that the technology doesn't exist yet.

Space-based industry

John Mankins, who worked at NASA for 25 years, is president of the California-based R&D consulting startup Artemis Innovation Management Solutions. He champions a half-century-old idea: Collect sunlight in space, convert it into electricity with photovoltaic arrays, and use solid-state electronics to convert it into microwave energy; a coherent array of transmitters would send the beam to Earth. The allure is that it would be an inexhaustible source of green power and would therefore help mitigate climate change on Earth.

In space the light intensity would be much higher than on Earth's surface, since the atmosphere absorbs from 40% to 90%. Simpler antenna arrays on the ground would collect the power. From geosynchronous orbit about 36 000 kilometers away, with a transmitter diameter of 1.8 kilometers and a wavelength of 12 centimeters, the beam diameter at Earth would be about 6 kilometers, says Mankins.

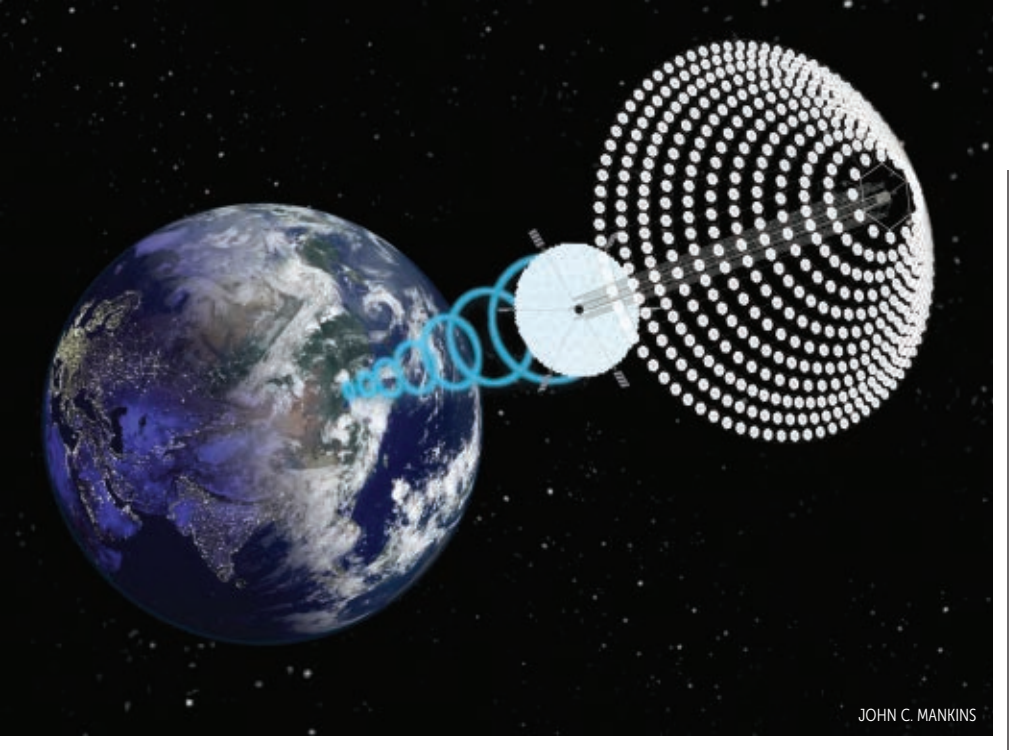
COLORADO SCHOOL OF MINES

MINING WATER ON THE MOON: In experiments to simulate mining on the Moon, concentrated solar energy is used to release water vapor from an icy lunar regolith simulant.

Disturbance to terrestrial activities would have to be avoided, says Sowers, and "you also have to worry about people's perceptions of safety." Launching large solar power satellites from Earth is impractical, he continues, "but if you can build them in orbit, with materials from the Moon, the disadvantages go away."

Solar power from space or helium-3 for fusion would both be "positive outgrowths of developing the Moon," says Sowers. "They are ways to preserve our Earth." Metzger puts it more strongly: "If we get energy, we can solve all the other global and environmental problems."

The 1967 United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space binds parties to use the Moon and other celestial bodies only for peaceful purposes and specifies that space exploration should be for the benefit of all countries; as of this June, 109 countries—including the US—are signatories. In 2015 the US passed the Commercial Space Launch Competitiveness Act, which explicitly allows exploitation of space resources. It is typically interpreted as "you can keep what you pick up, but you can't claim terri-



A SCHEME TO BEAM SOLAR POWER entails collecting sunlight and beaming it to Earth. An array of mirrored heliostats (conical structure) collects the sunlight, and a photovoltaic array (disk) converts it into electricity, which is then converted into a coherent microwave beam and sent to receivers almost anywhere in view on Earth. The image depicts the SPS-ALPHA, or Solar Power Satellite by means of Arbitrarily Large Phased Array.

tory." Luxembourg followed with a similar law in 2017.

In a bid to become the European hub for space resources, Luxembourg has created a business environment to lure space-related companies. It offers political support and has set aside €200 million ($224 million) to subsidize them. So far, more than 20 such companies are based there. "About 2.5% of the country's GNP is in the space industry," says Pete Worden, a retired NASA scientist who now serves on the Luxembourg government's space resources advisory board. "They felt that if they could stake a claim in space resources, they'd be in good economic shape for the future."

The United Arab Emirates is also looking to space to diversify its economy and for educational and training purposes. The country aims to create a settlement on Mars by 2117. It would be a joint effort with international stakeholders, says Mohammed Al Ahbabi, director general of the country's five-year-old space agency. Toward that goal, the UAE is building a simulated Mars environment in Dubai for experiments in space-resource utilization and other activities that would be necessary for living on the red planet. On 25 September the country will send its first astronaut to the International Space Station, and next year it will launch a spacecraft that will orbit Mars. "We want to become a meaningful contributor to humanity's exploration efforts in space," Al Ahbabi says.

Metzger cites a 2016 study by the semiconductor industry predicting that by mid century, if current trends continue, computing will grow to the point that it alone will consume the entirety of today's global power production. "We either destroy the environment, limit the amount of computing, or we move off the planet," he says. Data is the easiest thing to move, "so we can create server farms in space and send the data back to Earth." By moving a large portion of the industrial footprint to the Moon, "we clean up our planet."

Ground rules

Matthew Weinzierl, a Harvard Business School professor who studies the public and private space sectors, says that for new space-based activities to develop to any sizeable scale would require "a spectacular breakthrough along the lines of manufacturing or solar energy from space." Space tourism could lead to a "virtuous cycle of space services development," he says. But many uncertainties remain. "It's hard for me to see meaningful [lunar] settlement over the next several decades," he says, adding that a limited station, such as those on Antarctica, seems more likely. Ian Lange, an

economist at the Colorado School of Mines, doubts that the space resources and travel industries could maintain funding through an economic downturn. Still, he says, if launch costs continue to drop, "it will be a game changer as it will become cheap to start putting infrastructure in space."

When technical revolutions lead to economic revolutions, social upheaval often results, says Metzger. "It takes time to find justice. The same will happen when we get industry off the planet." It's not too soon to be "intentional" about expanding to space, he says, both to benefit humankind and to avoid war.

The Hague International Space Resources Governance Working Group, which comprises representatives from governments, academia, and companies, is putting together recommendations intended to set a baseline for future space-related activities. Among the topics the group is addressing are the sharing of benefits, regard for the interests of all countries and humankind, creation of safety zones in space, and monitoring and avoidance of harmful effects of space utilization.

Michelle Hanlon, a space lawyer in Mississippi and a member of the Hague working group, says the biggest issue internationally at the moment is what it means that space is the province of all humankind. Some countries believe that if you mine resources, the benefits should be shared with the entire international community, she says. Others, like the US and Luxembourg, say that you can keep what you extract. "We can't develop laws until we see how technology shakes out," she says. "The Moon will get crowded. What happens if two companies set their sights on the same crater?"

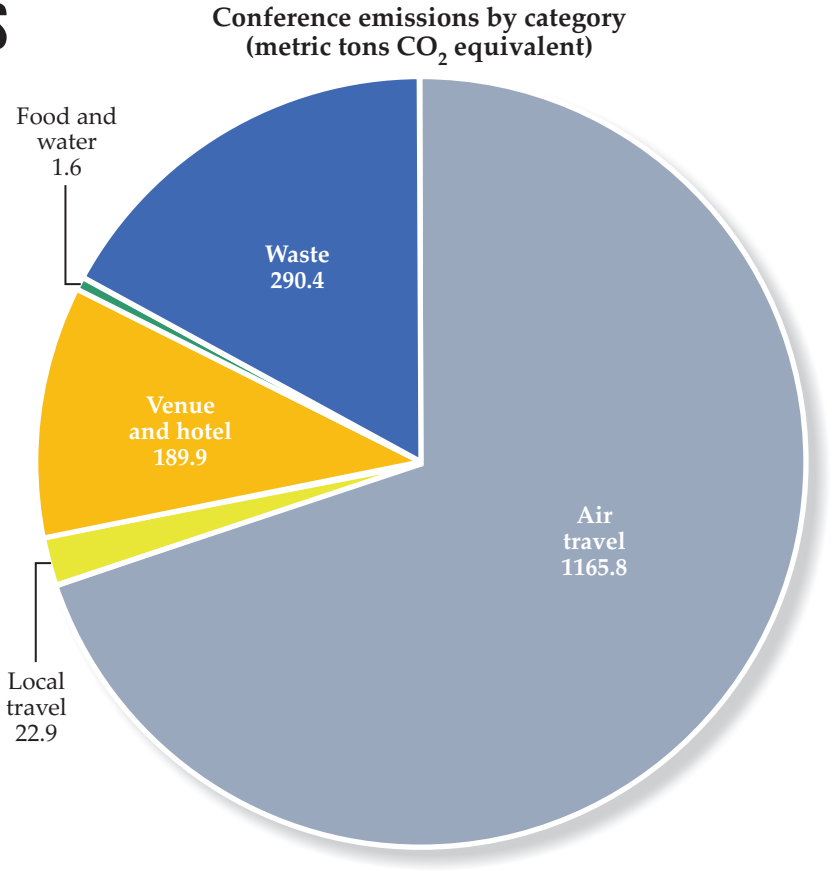
Technical, social, political, economic, and other issues related to space resources are addressed in the Colorado School of Mines' new space resources program, which offers certificates and master's and PhD degrees. This fall 30 incoming students are joining the 45 in last year's inaugural group. The bulk of the students are mid career and participate remotely from 12 countries on 4 continents. "My classmates have incredible roles at NASA, SpaceX, startups, and more. It's incredible interacting with them," says Adam Janikowski, an investment banker in Hong Kong who is enrolled as a master's student. "I want to marry my engineering and financial backgrounds with this space education to give financial advice" to space-focused companies.

According to Michael Waltemathe, a theologian at Germany's Ruhr University in Bochum who works on space exploration issues, "History has shown that as soon as technology makes things possible, people will do the new things." Some groups are against space exploration for religious reasons, he says. The main arguments against it are that for the same money we should clean up our planet and feed the poor, not explore. But, he says, exploration could also be used to mitigate inequality. People from countries that can't afford their own launches could partake in future economic advantages by, for example, remotely controlling space-based robots. "We can't stop exploration, so we should set up rules beforehand to benefit as much of humankind as possible."

Toni Feder

Environmental sustainability goals drive changes in conference practices

Alternative formats for sharing information and facilitating discussion help scientists lower their carbon footprints.



THE SUSTAINABILITY REPORT for the Society for Conservation Biology's 2017 annual meeting in Cartagena, Colombia, showed that air travel made up more than two-thirds of the conference's carbon emissions. (Adapted from the *28th International Congress for Conservation Biology, Event Sustainability Report 2017*, Cartagena, Colombia, 23–27 July 2017, prepared by MCI Sustainability Services.)

In 2011 Peter Kalmus calculated the carbon emissions associated with his personal and professional activities for his previous year as a postdoc at Caltech. The climate scientist at NASA's Jet Propulsion Laboratory found that his air travel to two international and half a dozen domestic conferences accounted for more than two-thirds of his annual emissions.

Frequent travel is a professional norm in academia. Attending and speaking at conferences is expected of active researchers at all levels—from graduate students and postdocs vying for jobs to senior researchers whose expertise makes them coveted speakers. But as Kalmus found, traveling to attend conferences can greatly expand a researcher's carbon footprint. And according to a 2016 study published by Shahzeen Attari and collaborators in the *Journal of Climatic Change*, the large carbon footprint generated by scientists' travel undermines their ability to convince the public of the urgency of climate change.

A growing community of scientists and other academics is choosing other forms of transportation when going to conferences—or forgoing attendance altogether. Academic departments and in some cases whole institutions are adopting travel policies that discourage flying. But particularly for early-career researchers, meetings remain crucial for networking and professional development. Some conference organizers are responding by reducing the climate impacts of their events through increasing remote accessibility and hosting more environmentally friendly events. Technology is also enabling the development of hybrid formats that preserve some interaction while producing less emissions and increasing participation.

Getting around—or not

In 2015–16 two-thirds of the University of British Columbia's (UBC's) carbon emissions came from business-related air travel, according to a 2018 report by Simon Donner, a professor in the university's geography department, and his graduate student Seth Wynes. Conference attendance made up 55% of the air travel emissions; the rest was from fieldwork, collaborations, and the like. Similarly, the University of California, Santa Barbara (UCSB) found that about 30% of the campus's total emissions in 2012 were due to business-related air travel, making it the university's largest source of emissions. At ETH Zürich, air travel in 2016–18 made up more than half of the university's emissions.

Kalmus stopped flying in 2012. He now travels to conferences by car or train; once he even traveled on a container ship. On the website he founded, No Fly Climate Sci, he asks academics and especially Earth scientists to share personal stories around their decisions to fly less. "If we want collective action," says Kalmus, "we need to shift the culture. One way each of us can do that is by setting a provocative example."

Parke Wilde, an agricultural economist at Tufts University, and Joseph Nevins, a professor of geography at Vassar College, introduced a petition in 2015 that calls on researchers, universities, and professional societies to take steps to reduce academia's carbon footprint. Their "flying less" petition now has more than 600 academic signatories from around the world.

As members of the global collaboration behind the Compact Muon Solenoid experiment at CERN, Fermilab scientists Mike Albrow and Boaz Klima typically videoconference with team members several times a week. Although remote

MARGARET LINDEMAN

GRADUATE STUDENTS SUSHEEL ADUSUMILLI (LEFT) AND SARAH SHACKLETON undertook the nearly four-day train trip to the fall 2018 American Geophysical Union meeting in Washington, DC, with 10 of their coworkers from Scripps Institution of Oceanography at the University of California, San Diego.

communication is instrumental to their work, they note that in-person meetings are invaluable to build relationships, establish trust, and encourage informal, in-depth discussions. Such meetings also provide a broader view of the large, complex experiment outside each researcher's narrow focus.

For a 2017 opinion piece in *Eos*, Judith Totman Parrish, professor emerita in the department of geological sciences at the University of Idaho, estimated the emissions generated by those who flew to the fall 2012 meeting of the American Geophysical Union (AGU). She randomly sampled the meeting's nearly 22 000 attendees to estimate the distribution of distances traveled. Then, using the fuel consumption of representative jets and the emissions from burning jet fuel, she determined the total emissions for those attendees. Her calculation yielded 0.71 metric tons CO_2 per person; other analyses have found comparable results.

For the 2018 AGU fall meeting in Washington, DC, which had about 28 000 attendees, 20 or so researchers from around the country chose to travel by train and used #traintoAGU on Twitter to document their trips. Twelve graduate students from the University of California, San Diego, made the 68-hour train journey despite having to pay out-of-pocket for the additional cost; the university's policy, which applies to all official travel, is to only reimburse up to the equivalent airfare.

Universities and academic departments in Europe have taken the lead in implementing travel policies to reduce their carbon footprints. Ghent University in Belgium, for example, bars air travel to destinations that can be reached within six hours by land and recommends ground travel within eight hours. That range includes major cities in France, the Netherlands, Germany, and even England.

The department of geography at Concordia University in Montreal, the Lund University Centre for Sustainability Studies in Sweden, and others have policies that acknowledge the urgency of reducing academia's climate impact and set out clear guidelines for doing so: Researchers should prioritize travel-free meetings and conferences, use ground transport whenever feasible, and justify any travel they do undertake. To make individuals more aware of their own CO_2 contributions, many policies ask researchers to track their emissions by keeping records of flights and using emissions calculators (see the box on page 31).

Another approach is to compensate for carbon emissions. The University of Maryland's Climate Action Plan 2.0, a 2017 update to their original plan from 2007, acknowledges that "restricting air travel would hinder important university work." So in 2018 the university began purchasing carbon offsets to make up for its air-travel emissions. The same year, UCLA began assessing carbon mitigation fees on all business-related flights. The fees, which are paid by the traveler's department, feed a fund that will be used for greenhouse-gas-reducing projects on campus.

A 2019 study by Donner and Wynes in the *Journal of Cleaner Production* pushes back against the assumption that restricting travel impedes researchers. A snapshot of 165 UBC researchers showed no relationship between academic productivity and air travel emissions.

Thinking outside the box

Conferences don't have to look like they do now. "A whole lot of the excitement is in intermediate or hybrid formats," says Wilde. For example, Ken Hiltner, an English professor at UCSB, developed the Nearly Carbon-Neutral (NCN) conference. The emissions from two pilot conferences in 2016 were less than 1% of comparable traditional events.

For an NCN conference, speakers prerecord their talks. During the conference, which typically lasts two to three weeks, participants can visit the conference

ONLINE RESOURCES

- **No Fly Climate Sci** (https://noflyclimatesci.org) and the **Flying Less petition** (https://academicflyingblog.wordpress.com) bring researchers together to push for changing the academic flying culture.
- The **CoolClimate Calculator** (https://coolclimate.berkeley.edu/calculator) estimates your carbon footprint based on your lifestyle.
- **Mozilla Hubs** (https://hubs.mozilla.com) provide virtual spaces for remote gatherings.

website, watch the talks, and participate in a written Q&A for each session. The talks for Hiltner's two NCN conferences were prerecorded and closed-captioned for accessibility. He admits that NCN conferences can't replace face-to-face interaction; however, speakers at the 2016 pilot event gave overwhelmingly positive feedback about the experience. And as Kalmus notes, traditional meetings have their own drawbacks. "You have five days of these intense posters and short talks and meeting lots of people. It's really daunting, and my brain gets saturated," he says. "I'm sure we all have different experiences, but I think a lot of us would agree that there might be a better way, which may involve flying less."

Multilocation conferences are another option. The number of locations can vary from a few to dozens, and each hub has both in-person and live-streamed content. It's a compromise that preserves some of the interactions of a typical conference while also reducing travel.

Kim Cobb, a climate scientist at Georgia Tech, is hoping to create a hub in the southeastern US for the International Conference on Paleoceanography this year in Sydney, Australia. Researchers can then remotely attend the conference by watching the live stream together. She will also be the first person to remotely give a keynote address at that conference.

Many large in-person meetings already make some of their talks available online, and attendees often have the option to receive conference materials electronically. The American Astronomical Society is moving toward replacing paper posters with iPosters, which are displayed on large monitors and remotely viewable. Through its eLightning program, AGU had more than 800 interactive electronic poster presentations at its fall 2018 meeting. Many of the presenters also hosted virtual poster sessions with remote attendees. About 1800 people accessed approximately 70 sessions that were available live or on demand through AGU GO, AGU's remote participation platform.

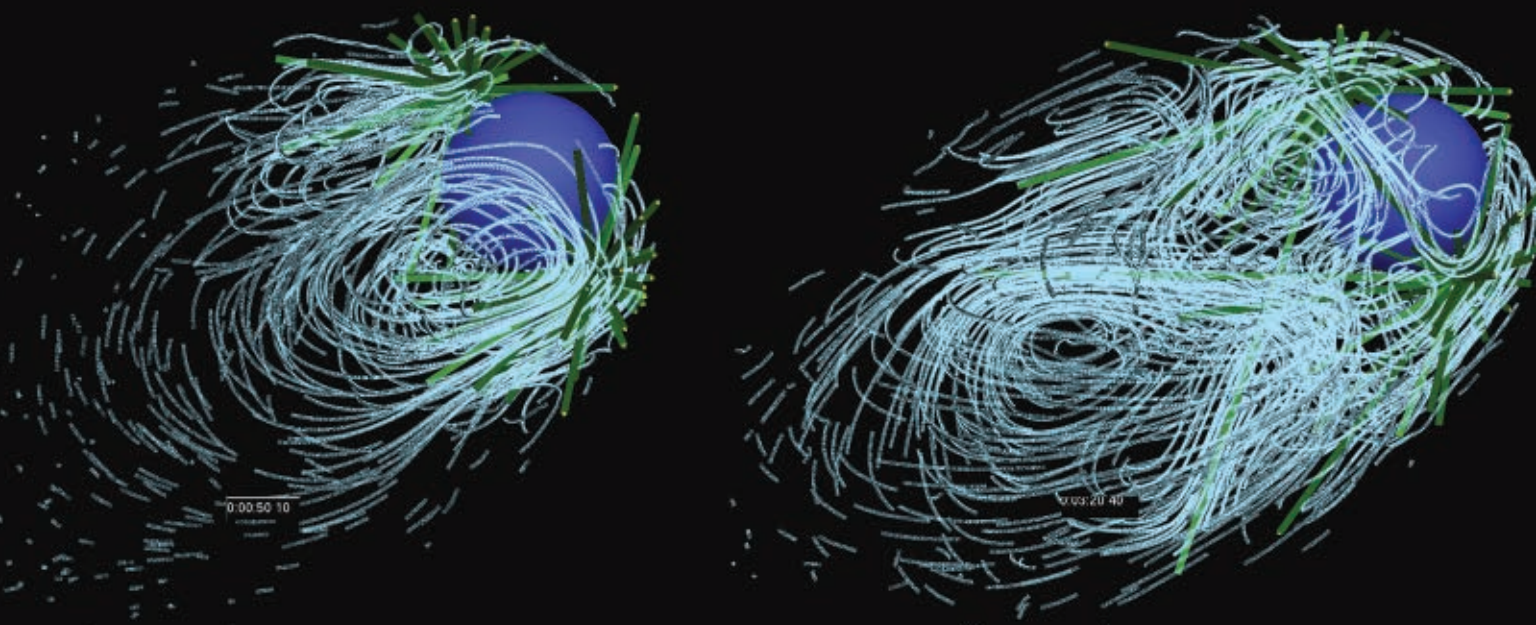
Blair MacIntyre, a computer scientist at Georgia Tech and research scientist on Mozilla's Mixed Reality team, envisions augmented and virtual reality transforming the remote conference experience as technology improves. Attendees could gather in virtual rooms for talks or poster presentations. Those rooms could be predesigned 3D environments with multimedia elements—such as documents, videos, and models—for visitors to explore. Eventually, in-person and virtual attendees may navigate and interact in the same conference space or even share a virtual beer.

A different vision

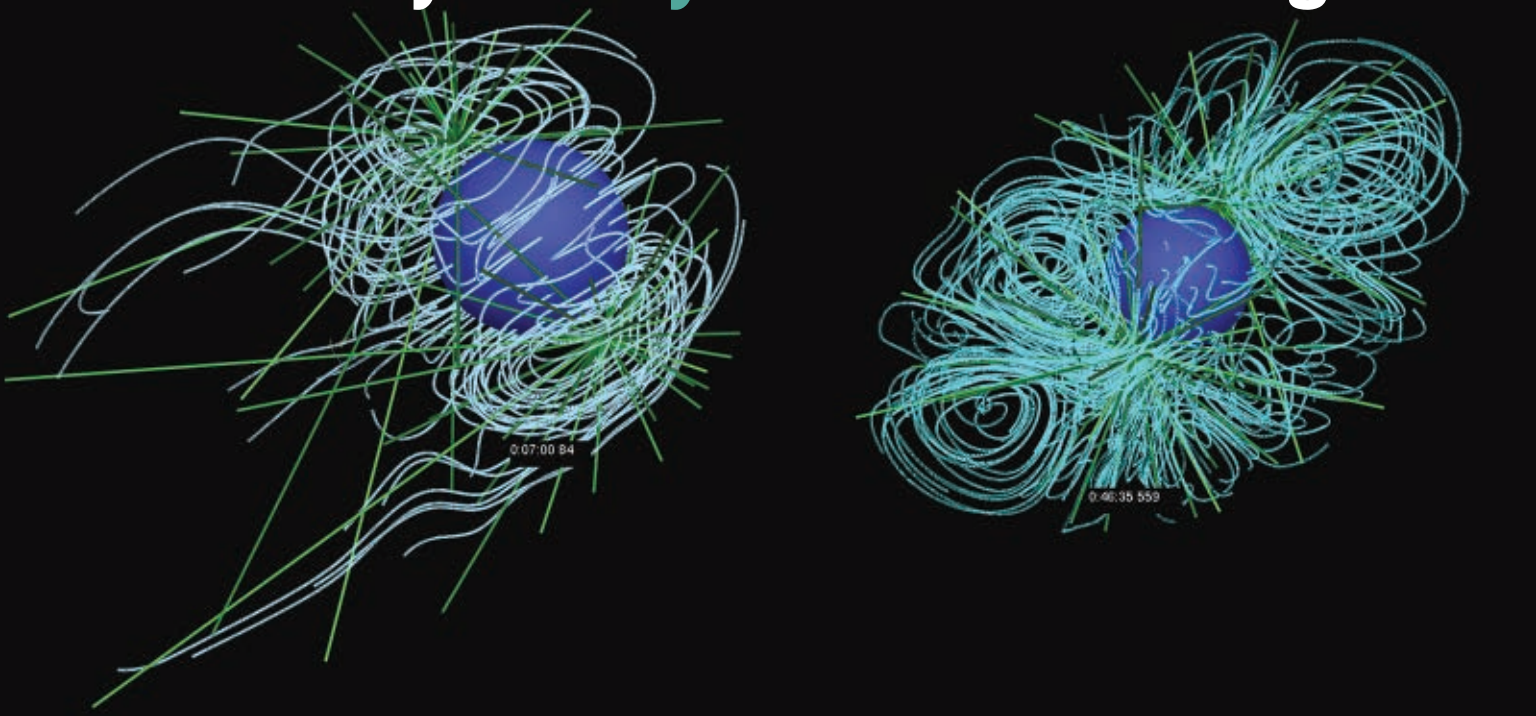
"Virtual conferencing right now does not completely replace in-person conferences in a way that satisfies most people," says Wynes. And as long as conference talks are a measure of success, early-career researchers may find themselves penalized if they forgo travel. Cobb, a tenured professor, says, "We really have to put early-career scientists front and center and challenge ourselves, those of us who hold privilege, to lead and really push for those structural changes that need to happen."

Says Wilde, "Currently, it's hard to be a successful researcher, or a successful academic, without being a jet-setter. But that leaves some people out." Through remote conference participation, researchers with less funding and those in the developing world can be brought into the scientific community. Those with caregiver responsibilities—in particular new mothers—can continue their professional development and thrive. Alternative conference models can also increase access for people with mobility limitations. "In a world where there were more options for remote conferencing," says Wilde, "there would also be more variety in successful career paths."

Christine Middleton PT



The stormy fluid dynamics of the living cell



Flow lines from a simulation of pronuclear migration. (Courtesy of Tamar Shinar.)

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Daniel Needleman
and Michael Shelley

The flows inside cells are intricate and often counterintuitive. Measurements, models, and simulations are helping to unravel the complexities.

Cell biology has its beginnings in the first observations of cells through primitive microscopes and in the formulation of cell theory, which postulates that cells are the fundamental building blocks of life. Light microscopes showed that the insides of cells contained complex structures, such as nuclei, spindles, and chromosomes. The advent of electron microscopy in the mid 20th century brought the first truly detailed views of cell innards. Images revealed complexity at all observable scales, including cell-spanning networks of polymers, intricate organelles made of membranes, and a variety of micron- to nanometer-sized sacs and granules such as vesicles, lipid droplets, and ribosomes. (For a glossary of cellular components, see the Quick Study by Ned Wingreen, PHYSICS TODAY, September 2006, page 80.) Those structures are immersed in or part of the aqueous cytoplasm—the cell's fluidic medium.

Scientists have known for centuries that some plant and amoeboid cells have cytoplasmic flow inside them, as illustrated in figure 1a. Modern light microscopy has shown that such directed motions in cells are quite common. Researchers have studied those flows using such sophisticated methods as particle imaging velocimetry and simulations (see figures 1b and 1c). Such flows underlie the most basic biological functions of cells and can be a cause, an effect, or both. In any case, understanding them requires the study of forces and stresses that are created from activity inside the cell itself.

The self-contained character of subcellular fluid mechanics makes its nature fundamentally different from other areas of fluid dynamics—weather, for example. Both systems are incredibly complex, but weather is driven externally, by daily and yearly cycles of rotation and orbit, whereas cells are driven internally. What's more, the basic fluid-dynamical equations and thermodynamics of the atmosphere are known. That information enables one to predict its short-term behavior. By contrast, although our basic understanding of the molecular constituents that make up cellular structures is firm, biophysicists don't yet have a sophisticated enough theoretical understanding to fully comprehend and predict a cell's dynamics. Nonetheless, as with weather, we believe that fluid mechanics and flows will be an important part of the story.

Crowded and complicated

The cytoplasm is not a simple liquid. As shown in figure 2a, even a cellular volume of a few cubic microns is filled with an aqueous slurry of components: working proteins, polymer meshes, and organelles of different sizes and compositions.[1] The slurry is active—that is, its component parts convert a local source of (usually chemical) energy to change their shape and generate forces. And the slurry can change markedly over the life of the cell. For example, organelles such as the endoplasmic reticulum—essentially tubes in the cytoplasm—fragment during cell division but otherwise form an interpenetrating structure.

Actin and microtubule polymers are another example of active cellular components. Both are stiff filaments that constantly assemble and disassemble, with lifetimes on the order of seconds or minutes. Individually, they are transitory, but collectively, they self-organize into much longer-lived subcellular structures. Microtubules organize themselves into the spindle that segregates chromosomes during cell division, and actin organizes itself into a specialized layer of proteins known as the cortex, which has different functions, such as controlling cell shape, in different cells. Figure 2b shows an electron-tomography reconstruction of a mitotic spindle of a nematode embryo, *Caenorhabditis elegans*. Just 10 μm long, the spindle is a dense network of 10 000 microtubules that holds the chromosomes at its center and reaches throughout the cytoplasm.

From one viewpoint, the cell is the ultimate multiscale system, with scores of interlocking components. From another, its subcellular structures, such as the nucleus, spindle, and endoplasmic reticulum, are active materials that can be conceptualized at a coarse-grained level. Indeed, the perspective for best viewing the cell and its contents depends on the problem at hand.

An interest of ours is how, after fertilization, DNA from mother and father come together and become positioned in the middle of the cell. Figure 2c shows snapshots of that process. At its start ($t = 0$ s) the DNA is located inside membrane-bound organelles called pronuclei, with arrays of stiff microtubules attached to the male pronucleus. Those structures come together to form the pronuclear complex ($t = 45$ s), which migrates through the cytoplasm to the cell's center, where it rotates to align with the cell's long axis ($t = 105$ s). There, the pronuclear membrane breaks down and the mitotic spindle

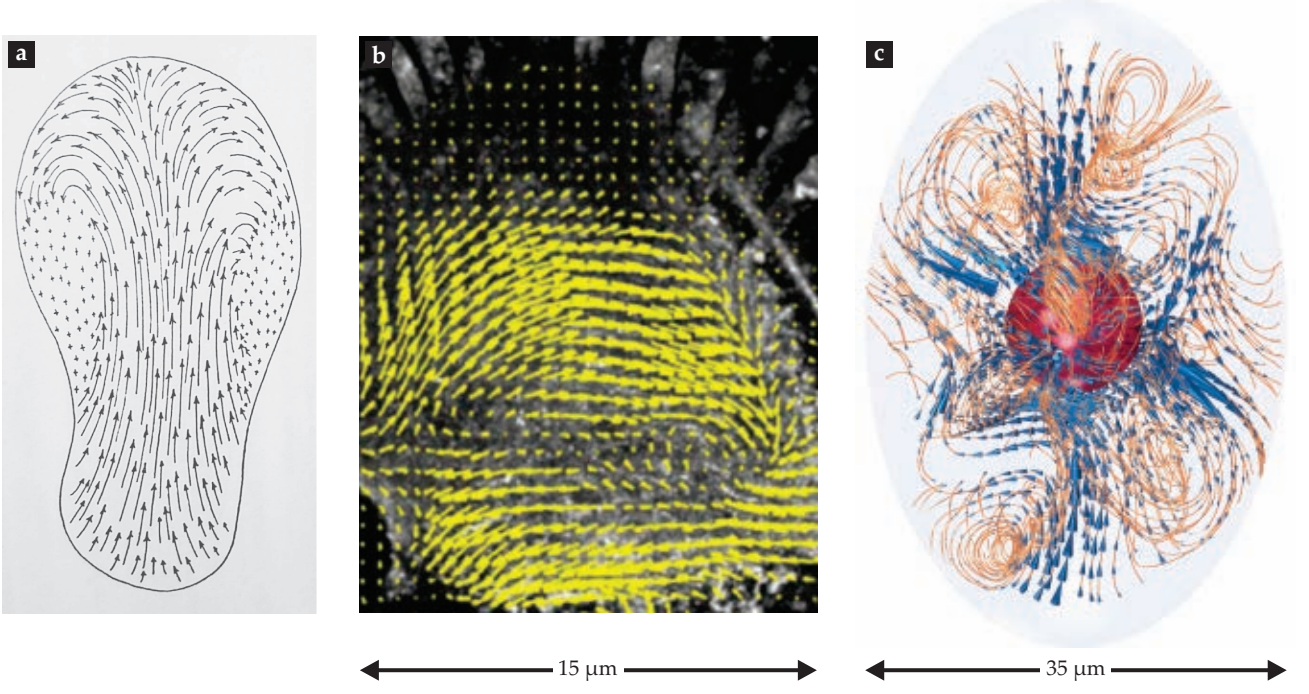

FIGURE 1. IMAGING SUBCELLULAR FLOWS. (a) An 1857 illustration of the flow of granules in the cytoplasm of a crawling amoeboid cell, *Pelomyxa palustris*, as observed by microbiologist Franz Schulze. (Adapted from ref. 12.) **(b)** The instantaneous flow velocities (yellow arrows) of the cytoplasm in a *Drosophila* oocyte. The motion is driven by microtubules and molecular motors. (Adapted from ref. 13.) **(c)** A three-dimensional fluid-dynamics simulation of flows produced during the positioning of the pronuclear complex in a nematode embryo (*Caenorhabditis elegans*). In this model, positioning is achieved using molecular motors that walk along microtubules.[5] (Courtesy of Ehssan Nazockdast.)

forms (t = 285 s, roughly corresponding to figure 2b). To understand pronuclear migration, it's useful to think of the cytoplasm as a viscoelastic continuum.

Accounting for forces

Living cells are small, and their internal motions are slow. That truism simplifies the fluid dynamics. Consider a body of linear dimension l moving with speed u in a cell whose cytoplasm has a viscosity μ and density ρ. The cytoplasm's Reynolds number, the ratio of inertial to viscous forces, is given by

$$Re = \frac{\text{inertial force} \sim \rho u^2 l^2}{\text{viscous force} \sim \mu u l} = \frac{\rho u l}{\mu} \quad (1)$$

Take the transport of an $l \approx 10$ μm pronucleus in *C. elegans* as a paradigmatic example. The cell's cytoplasm has a viscosity about 1000 times that of water, and the embryo's pronucleus moves through it with speed $u \approx 0.1$ μm/s. That yields a Reynolds number of approximately 10^{-9}, a situation in which inertial forces are so low they're irrelevant.

Such a low Reynolds number puts us in the regime famously discussed by Edward Purcell[2] in his paper "Life at low Reynolds number," in which the velocities of objects follow from balancing applied forces with viscous drag. Whereas Purcell's article explored small things living and moving in fluids, here we explore fluids moving in small things.

One can think of the cell's interior, crowded with various organelles and polymer networks, as an active, multiphase material that is both viscous and elastic.[3] For viscoelastic materials a common measure of the relative importance of viscous to elastic responses is the Weissenberg number,

$$Wi = \dot{\gamma}\tau_e \quad (2)$$

where $\dot{\gamma}$ is a typical strain rate of the flow and τ_e is the relaxation time of the elastic medium. The migration of the *C. elegans* pronuclei to the center of the cell is slow and happens over the time scale of minutes. So, we estimate $\dot{\gamma} \sim u/l \sim 10^{-2}\ s^{-1}$. The faint elastic response[4] of the embryonic cytoplasm produces a relaxation time $\tau_e \sim 1$ s. Thus, $Wi = 10^{-2} \ll 1$, and for the purposes of studying positioning, the cytoplasm can reasonably be treated as a purely viscous medium.

That approximation considerably simplifies the response of the cytoplasm to motion, but it's not universal. Some events, such as ruptures of the nuclear membrane, can be more rapid; in cancer cells they happen on time scales of seconds. Such fast motions yield much higher values of *Wi*. In general, a cell's internal mechanics are cell-type and cell-stage dependent, and its mechanical responses are a function of both the length and time scales of the measurement[1] and of where in the cell the responses are measured.[4]

Viscous forces alone lead to unusual features of cell mechanics. One is the nature of drag on moving objects: At low Reynolds number, drag scales with length as $\mu l u$. Consider a microtubule having the same linear dimension as the pronuclear payload, l = 10 μm, and moving at the same speed. That microtubule is just 25 nm in diameter, which makes its surface area 1/1000 that of the pronucleus, yet it's drag is nonetheless 1/4 of the pronucleus drag. That's because drag in that regime results from objects shearing the viscous fluid; even thin objects carry along and distort large regions of fluid (compare the left and right sides of figure 3a). Our daily experience, by contrast,

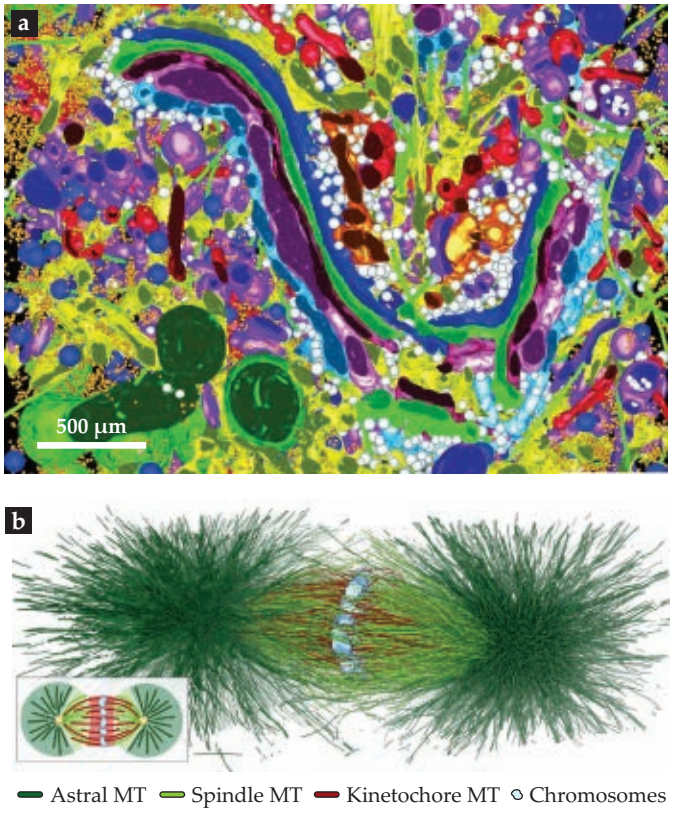

FIGURE 2. COMPLEX COMPONENTS, STRUCTURES, DYNAMICS. This electron-tomography reconstruction **(a)** reveals the tightly packed composition of a 3-μm-wide region of a human pancreas cell. False colors indicate distinct classes of its organelles and cytoskeletal filaments. (Adapted from ref. 14.) **(b)** An electron-tomography reconstruction of a nematode (*Caenorhabditis elegans*) mitotic spindle. The structure is approximately 20 μm long. Approximately 10 000 microtubules (MT) are shown, many connected to chromosomes in the center; the inset clarifies the spindle's structure. (Adapted from ref. 15.) **(c)** Fluorescence microscopy of microtubules in a single-cell *C. elegans* embryo reveals a sequence in which two clumps of parent DNA (dark circles) migrate, meet, rotate together as a fused pronuclear complex, and form the spindle. (Adapted from ref. 16.)

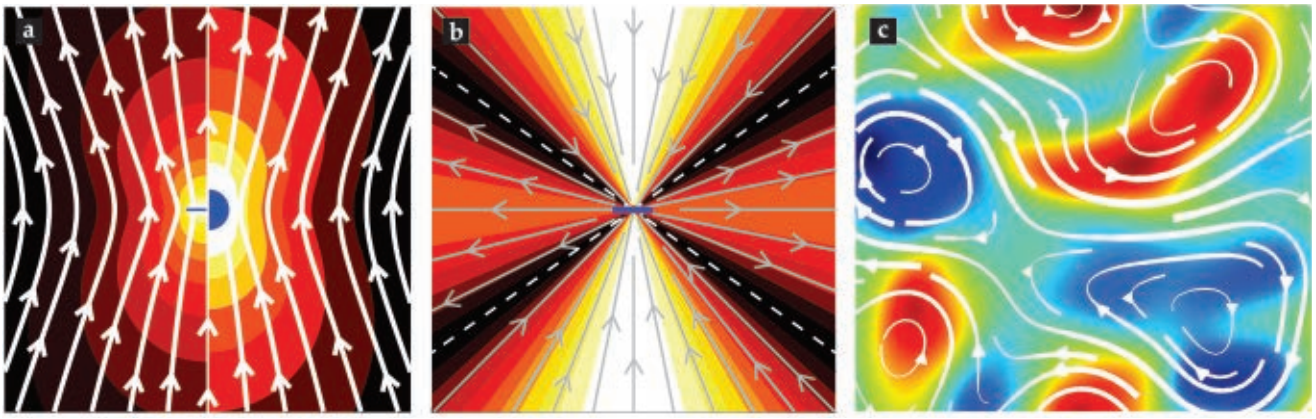

FIGURE 3. (a) FLOW LINES (white) are produced by a sphere (right) and a microtubule (left), both moving upwards at the same speed. The color field represents the magnitude of the fluid velocity, which subtly differs for the sphere and microtubule but is greatest (white) around both surfaces. **(b)** Fluid flow lines are created by a force dipole (center). **(c)** A detail from a simulation of the chaotic flows created by a suspension of mobile force dipoles; the color field represents flow vorticity. (Image courtesy of David Stein.)

takes place mostly in high-Reynolds-number environments, where just by moving we push fluid aside with the surface area we present to it.

That microtubules carry considerable fluid is underappreciated. Scientists unfamiliar with fluid mechanics tend to think of the cytoplasm as simply a source of local friction on objects moving through it. That assumption can lead to the wrong conclusion that drag is an additive force. It would imply, for instance, that the drag on a 10 000-microtubule array—roughly the number in the *C. elegans* pronuclear complex—would be 10 000 times the drag on a single microtubule. It turns out, though, that comoving microtubules in an array collectively entrain fluid, or equivalently, move in each others' wake. Thus, drag on the assembly is on the order of the drag on just a single microtubule.

When microtubules or other objects carry fluid around, confinement by cell boundaries can have a surprisingly strong effect. To appreciate the consequences, imagine the single-cell *C. elegans* embryo as a sphere of diameter $L \approx 50$ μm filled with purely viscous cytoplasm, and the pronucleus as a sphere of diameter $l \approx 10$ μm. A classical solved problem in a low-Reynolds-number flow is the drag on one sphere moving in a larger sphere. It depends fundamentally on only the geometric ratio—the so-called confinement number Cn, the ratio of the payload size to the confining dimension:

$$Cn = \frac{l}{L} \tag{3}$$

For $Cn = 0.2$ it takes almost twice the force to move the payload at a given speed as to move it in an unbounded medium. The required force increases quickly with Cn and is the cost of redirecting the induced cytoplasmic flow at the cell periphery. Further accounting for the presence of attached microtubule arrays, which effectively increases l and hence Cn, results in a 100-fold increase in drag.[5]

Internal forces drive internal flows

Motions, and hence flows, in cells are often driven by motor proteins that move in the cytoplasm. Many of those motor proteins can sequentially bind to, move along, and unbind from polymers, such as microtubules and actin. That generates forces between the motor and polymer, and the resulting directed motion is only possible because motor proteins transduce chemical energy supplied by adenosine triphosphate (ATP), which is held out of equilibrium with its breakdown products by the cell's metabolism. Energy available from the disequilibrium of ATP and its breakdown products acts as a battery that motor proteins can tap to perform mechanical work. When abutting or attached to other objects, the polymers themselves can also generate active forces through their assembly or disassembly.

For cellular forces, intuition can be highly misleading. For example, the magnitude of a conservative force such as gravity or electrostatics on an object can be measured by determining the experimentally applied opposing force that halts the object's motion. But that procedure fails utterly in the case of motor proteins. To understand why, keep in mind that the force between a polymer and an isolated motor is balanced by drag through the surrounding fluid.

Because of the motor's small size (about 1 nm) and speed (about 1 μm/min), that drag is about 1 femtonewton. Applying an opposing force to the motor slows it down, but a motor protein typically halts only when it is subject to forces in the piconewton range, thousands of times greater than the forces it exerts in the absence of additional applied forces. The upshot is that forces exerted by motor proteins *in situ* cannot be measured simply by subjecting the proteins to external forces.

Inside cells, motor proteins exert forces in different ways, and those forces have consequences for the flows they produce. For example, the mechanism of pronuclear migration is currently debated: Some researchers argue that the pronuclear complex is positioned by motors anchored at the cortex; others argue that it's positioned by motors in the cytoplasm. The first model postulates that motors fixed on the cell boundary reel in the microtubules they walk on. Microtubules would thus be transported to the cell surface and drag along the pronuclear complex and the neighboring fluid.

In the second model, by contrast, motors in the cytoplasm bind and walk along microtubules and thereby induce fluid to flow along the microtubules' surfaces. By momentum balance, pushing fluid backward propels the microtubule forward so that it "swims" through the cytoplasm. Measurements of fluid

flow should provide a clear way to determine which model is correct: Roughly speaking, motors at the cortex would drive fluid in the same direction as the pronuclei, whereas motors in the cytoplasm would drive fluid in the opposite direction. But the detailed predicted flow patterns are complicated by the incompressibility of the fluid and confinement from the cell boundary.[5]

The movement of motor proteins on polymers in the cytoplasm is ubiquitous in cell biology. The resultant forces between the motors and polymers must be equal and opposite. Thus, the forces those objects exert form force dipoles (see figure 3b). Collections of objects exerting dipolar forces on fluids can produce spectacular phenomena, such as self-organized, swirling flows called active turbulence, shown in figure 3c, and confinement-induced coherent flows. Both types have been observed in cell extracts and reconstituted mixtures of motor proteins and microtubules.[6]

That purified biological components can robustly create such intricate patterns of flow is remarkable. *In vitro* systems may chart a promising pathway to investigate principles relevant for subcellular biological fluid mechanics and self-organization. And they open the possibility of engineering artificial, active materials with lifelike properties. The dynamics of such collections of objects exerting dipolar forces on fluids can be characterized in terms of the activity number

$$A = \frac{\text{active forces} \sim \sigma c}{\text{viscous force} \sim \frac{u}{L}\mu} = \frac{\sigma c L}{u\mu} \tag{4}$$

Here c and σ are the concentration and magnitude of force dipoles, respectively; u is the characteristic fluid velocity produced by a dipole, and L is the system size. When A exceeds a critical value, the system changes to a state of active turbulence.[7]

When polymers are anchored to the cell boundary, as for the actin cortex, motors can move along the boundary. The force acting on the motor from the boundary is balanced by the drag force generated by the motor moving through, and shearing, the fluid that surrounds it. When such motors are at low density, they move relatively independently of each other. At high density, the parcels of fluid dragged by the motors overlap, which can lead to large-scale flows in the cytoplasm.

At what density of motors does the large-scale flow occur? Objects in a fluid create flow perturbations on the scale of their own size, so for the fluid to be entrained collectively, the spacing between motors must be comparable to their size. Motor proteins are a few nanometers in size but typically microns apart in cells. With that spacing, motors are unlikely to produce coherent flows—that is, to carry the fluid collectively. But in many contexts motor proteins transport not just themselves, but also micron-sized organelles. The additional fluid moved by the large payloads can be sufficient to produce bulk flows in cytoplasm. Known as cytoplasmic streaming, such bulk flows are observed in a wide variety of systems, including plant cells and egg cells.[8]

Diffusion helps and is hindered

The flows generated by cytoplasmic streaming or active turbulence can, in principle, advect and mix objects in the cytoplasm. In addition to being carried by the flows, mobile objects can also collide randomly with neighboring molecules and give rise to diffusive motion. The size of cells and the mobile objects in them greatly influences the efficacy of transport processes.[1] The Peclet number

$$Pe = \frac{ul}{D} \tag{5}$$

quantifies the relative importance of the rates of advection and diffusion for an object moving at a velocity u over a length l, where D is the diffusion coefficient. The dependence of Pe on the length scale over which transport occurs shows that advection becomes increasingly important as length scales get larger. The size dependence may explain why cytoplasmic streaming is most commonly seen in large plant and algal cells, but it doesn't solve the problem of how cellular reactants become well mixed. That process might require complex flows that stretch fluid to bring reactants into close proximity or to enhance the effective diffusion through dispersion (reference 8; see also the article by Michael Brenner and Howard Stone, PHYSICS TODAY, May 2000, page 30). The flows produced by active turbulence are well suited for such mixing and may be useful in microfluidic devices.

Models and methods

The numerical modeling of flows in cells is still in its infancy. The cells' internal complexity makes the task computationally demanding and reliant on fluid models to organize and account for the complexity. The most basic fluid model is the incompressible, homogeneous Stokes equations of a low-Reynolds-number flow, which is solved as a boundary-value problem using the forces and velocities of objects moving in the fluid. In other settings, the Stokes equations are replaced by simpler porous-medium approximations, or forcing terms are added to model the effects of immersed structures.

Usually, the modeling approach depends on the particular cell in question and on the goal of studying it. In the case of pronuclear positioning, microtubules are the objects through which forces are transmitted to the pronuclear complex. Simulating microtubules introduces a few challenges. For starters, microtubules are extremely thin and yet microns long. They are also numerous, typically with 10 000 in an array, which complicates the flow geometry. What's more, motor proteins can readily bend the microtubules, which further complicates the geometry. And finally, microtubules are transitory, typically living just 30 s, and they exhibit various lengths because of their constant assembly and disassembly. That heterogeneity leads to a wide range of time scales because relaxation times from bending are length dependent.

We have recently developed specialized methods to simulate the fluid dynamics of microtubule systems. The methods use Green functions of the three-dimensional homogeneous Stokes equations to derive integral equations on immersed and bounding surfaces. Because of the thinness of microtubules, the integrals over their surfaces can be further reduced to 1D line integrals. These reductions in dimensionality, together with other techniques, simplify the simulation of the flows generated by thousands of moving, bending microtubules over time scales (typically tens of minutes) that are relevant to pronuclear transport.[5]

Those methods are optimal for capturing the detailed hydrodynamics of microtubules, but they remain limited in scope

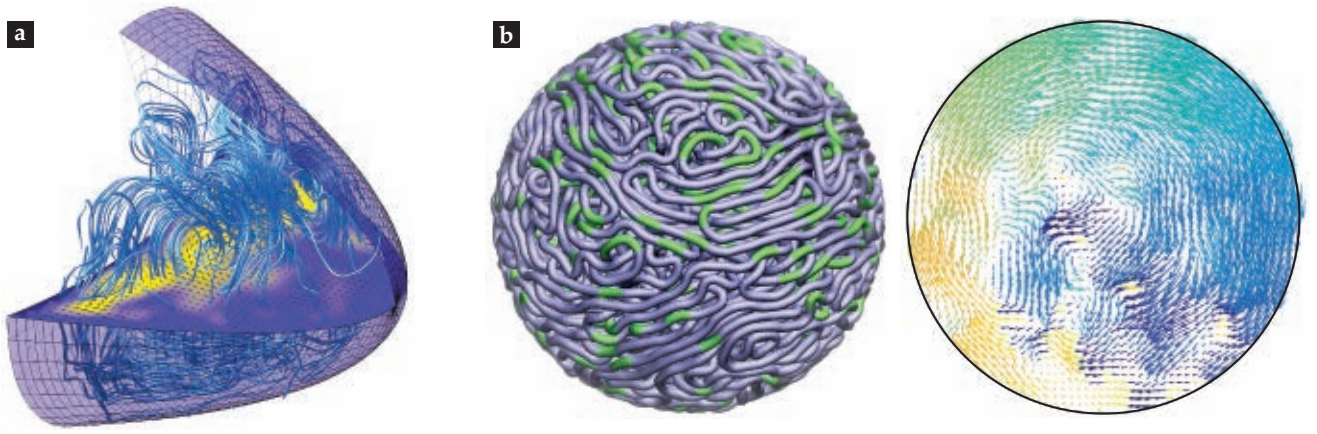

FIGURE 4. SIMULATING COMPLEX FLOWS. (a) A computational model of flows driven by motors moving on microtubules in a *Drosophila* oocyte. (Courtesy of Jörn Dunkel; image adapted from ref. 9.) **(b)** Simulations of chromatin (the functional form of DNA) in the nucleus being moved by internal molecular machines. At left, the chromatin self-organizes into an aligned structure. At right is the nucleoplasmic velocity field. (Adapted from ref. 11.)

and can handle at best a few thousand filaments. In other cases, researchers are interested in hundreds of thousands or even millions of cytoskeletal filaments. Capturing the hydrodynamics of such problems requires approaches that "coarse-grain" the fine details. In the example of *Drosophila* oocytes, molecular motors moving on wall-anchored microtubules set up complex flows believed to move signaling molecules about the cell and help establish its internal asymmetry, or polarity.[9] Biophysicists have studied the flows produced by the motors' activity by numerically solving a Stokes equation augmented by a coarse-grained forcing term that represents the directed motion of the motors moving along microtubules (see figure 4a).

For other problems it is useful to treat the internal mechanics of the cell as arising from a coarse-grained, possibly multiphase, complex material. In that general approach the cytoplasm is modeled as particle-packed, or visco(poro)elastic, and driven by internal forces from molecular motors or polymerization.[4] The biophysics of cell motility is one area in which considerable efforts have been made to simulate such coarse-grained models.[10] A related area is that of cell-shape changes, which arise naturally in cell motility and in cell–cell interactions.

Finally, not all cellular fluid dynamics takes place in the cytoplasmic volume. DNA can move in seemingly coordinated ways in the cell's nucleus. Recent modeling and simulations suggest that those motions may arise from force dipoles created by molecular machines acting within the fluidic nucleoplasm,[11] as shown in figure 4b.

A to-do list

For understanding subcellular fluid mechanics, this article has outlined five dimensionless numbers: the Reynolds, Weissenberg, confinement, activity, and Peclet. It is easy to think of others, such as the volume fractions of mobile particles and of polymer meshes and arrays. As the study of subcellular fluid mechanics matures, the dimensionless numbers postulated to describe it will grow, no doubt, to rival the variety commonly used to categorize the dynamics of Earth's oceans and atmosphere.

Much work remains. Biophysicists still lack validated theories of the collective properties of active fluidic materials and a framework that explains how large-scale behaviors, such as active turbulence, depend on the behaviors of constituent molecules. The contribution of fluid mechanics to distinct subcellular phenomena is also yet to be worked out. And its absence is a major hurdle to understanding the mechanics and behaviors of those phenomena.

Progress will surely require new conceptual and technical advances. The potential payoff for such work is huge. Not only will it provide insight into beautiful and mysterious processes that epitomize the unique properties of living matter, it will also have practical import. Just as an understanding of planetary fluid flows (see the article by Erdal Yiğit and Alexander S. Medvedev, PHYSICS TODAY, June 2019, page 40) has enabled predictions of the weather and led to transformative economic and social improvements, an understanding of cellular fluid flows will allow scientists to predict the behavior of biological processes. And those predictions, in turn, are likely to have a transformative effect on the treatment of diseases.

We appreciate Reza Farhadifar's help in preparing the figures.

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Getting rid of the Swedish BOMB

Thomas Jonter

Early in the Cold War, Sweden's leaders planned to acquire nuclear weapons. By the 1960s the country was an international leader of the disarmament movement.

Why do states develop nuclear weapons, and how can they be discouraged from doing so? That has been a central question in world affairs since the US dropped the first atomic bombs on Hiroshima and Nagasaki in Japan in 1945. Today that question has gained increased attention as the world seems to be heading into a new nuclear arms race after a period of successful arms reduction. Many international experts fear that more states will develop nuclear weapons in this new era. Can a further spread of nuclear-armed states be avoided or, at least, mitigated?

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The Riksdagshuset, seat of Sweden's parliament.

One way to answer that question is to look at nations that have abandoned their nuclear weapons ambitions. Sweden is one especially interesting example. A nuclear aspirant in the 1950s, it eventually changed its course and became one of the most recognized advocates for international disarmament.[1] By signing the Treaty on the Non-Proliferation of Nuclear Weapons on 19 August 1968 as a nonnuclear weapons state, Sweden publicly agreed not to acquire nuclear weapons, even though for more than 20 years it had been working on a program capable of producing its own arsenal.

This article explores why Sweden initiated nuclear weapons research but ultimately gave up those plans. One vital factor was how Prime Minister Tage Erlander (see figure 1) handled the issue. The Social Democrat was in power from 1946 to 1969 and was the most important player in the debates about Sweden's nuclear future. Erlander was initially in favor of equipping Sweden with nuclear weapons, but he eventually changed his mind after a decade of study and discussions with military, foreign policy, and nuclear experts.

FIGURE 1. SWEDISH PRIME MINISTER TAGE ERLANDER IN 1952. (Courtesy of Wikimedia Commons, PD-US-1996.)

The beginning of the Swedish nuclear program

The military was the first Swedish institution to look into the possibility of producing nuclear weapons. Only a couple of weeks after atomic bombs were dropped on Japan, military leadership asked the newly founded Swedish National Defense Research Agency (Försvarets forskningsanstalt, FOA) to write a report on how Sweden might use the new technology. In 1948 the first FOA report on the nuclear issue concluded that the prospects for starting a nuclear weapons program were bright: Even though huge financial investments would be needed to build a nuclear infrastructure, Swedish scientific know-how was fairly advanced and Sweden possessed large uranium deposits, although of low-grade quality. There was also strong consensus in Sweden that the nation should develop a civilian nuclear energy program. In 1947 a government-controlled company, AB Atomenergi (AE), was created to develop such a program.

In 1949 the FOA and AE signed an agreement for continued R&D work. The FOA was responsible for the overall nuclear weapons research, and AE would build reactors and a reprocessing plant to enable the production of weapons-grade plutonium and of fuel elements. In other words, the civilian nuclear power program would be designed so that it could easily enable the building of nuclear weapons if the Riksdag, Sweden's Parliament, decided to pursue them.

During the 1950s and 1960s, Sweden invested a large amount of resources into the dual-use program. AE built two heavy-water reactors to produce plutonium of weapons-grade quality and set up a uranium plant and a fuel element facility, and the FOA designed a program for weapons carrier systems. As early as 1955, the FOA concluded that with access to plutonium, it was technically feasible for Sweden to produce its own nuclear weapon. FOA scientists designed a nuclear weapons program with a goal to produce 100 tactical nuclear weapons.

One aim for Swedish politicians and researchers was to attain self-sufficiency for the nuclear program. Importing uranium was considered too difficult, given the strict US export control of nuclear materials and equipment, especially when the intention was to use them to manufacture nuclear weapons. For that reason, Sweden chose a technology that would allow the reactors, moderated with heavy water, to be loaded with natural, unenriched uranium. AE intended to import the heavy water from Norway. However, there were no guarantees that Norway would be able to meet Sweden's needs. The Swedes therefore hoped to build a full-scale heavy-water facility at Ljungaverk, in the northern part of the country.

But that production plant was never built; by the mid 1960s heavy-water technology had been replaced by light-water technology. Ågesta, a heavy-water reactor south of Stockholm (see figure 2), used heavy water from both Norway and the US, but only for civilian purposes. A second heavy-water reactor, Marviken, was built outside the city of Norrköping but never put into production.

The debate over acquiring nuclear weapons

Until the mid 1950s, plans for Swedish nuclear weapons were only discussed within a small circle of politicians, military officers, and scientists. A serious public debate started in 1954 after the publication of a report by the Swedish commander-in-chief, Nils Swedlund. In the study, known as ÖB-54, Swedlund advocated for the acquisition of nuclear weapons. According to him, nuclear weapons could first and foremost be used in the event of a foreign invasion, but they could also serve deterrent purposes.

As a direct consequence of the public debate, Sweden's political parties were forced to choose a side. In 1955 the Conservative Party was in favor of nuclear weapons acquisition, the Liberal Party was moderately amenable to the idea but remained uncommitted, and the Centre Party had not yet taken a position. Leading members of the prime minister's Social Democratic Party were divided, with some coming out in favor and some against. The Social Democratic Party also included a pacifist wing that was against any expansion of the armed forces. The Federation of Social Democratic Women (Sveriges socialdemokratiska kvinnoförbund, SSKF), headed by Inga Thorsson, was part of that wing, and it later became the strongest voice against nuclear acquisition.

FIGURE 2. THE ÅGESTA NUCLEAR POWER PLANT outside Stockholm. (Photo by Holger Ellgaard, CC BY-SA 3.0.)

Erlander was in many ways uniquely equipped to handle the challenge. Although his degree was in economics and political science, he had studied physics at university and was interested in nuclear research even before the atomic bombs were used. During World War II, he discussed the latest nuclear research results with his old college friend Torsten Gustafson, a professor of physics at Lund University. After the war, Gustafson served as Erlander's personal adviser in nuclear matters. In his memoirs, Erlander relates how he read scientific papers and talked to Gustafson and leading scientists, such as Nobel laureates Niels Bohr and Patrick Blackett, about both civilian and military uses of nuclear research.[2]

At the time, Erlander wanted to avoid an open public debate on the issue. In his view, the best option would be if his party could reach a consensus before negotiating with the Liberals and Conservatives. However, when the Conservative Party started to push more radically for nuclear weapons acquisition, it put Erlander in a difficult position. Since his own party was split on the issue, he was not sure how to respond.

Even though the FOA had been discussing the possibility of Swedish nuclear weapons for quite some time, it was not until November 1955 that the government held its first meeting on the issue and not until February 1956 that the Social Democratic Party Board formally sat down to discuss it. Before the board meeting, Erlander had several conversations with leading party colleagues representing different viewpoints to get a clearer picture of the situation. Based on those talks, Erlander prepared a proposal that he hoped would forestall deadlocks and conflicts.

In his recommendation, Erlander argued that Sweden could postpone making a decision on nuclear weapons. He presented two reasons: First, there was no need to decide at this time, since the government did not yet have sufficient knowledge about the technical prerequisites for nuclear weapons production. Second, international nuclear disarmament negotiations between the US and the Soviet Union were ongoing, and Sweden should not make them more complicated by deciding to produce nuclear weapons, which would likely lead to further global proliferation. If he could persuade both factions to wait for a firm decision, Erlander would gain some freedom of action. Meanwhile, opponents of Swedish nuclear weapons would continue to mobilize and to work toward international disarmament, and proponents would have the chance to make technical preparations for nuclear weapons production.

At the meeting, heated discussions followed, and the divide between opponents and proponents led to further splits in the

FIGURE 3. THE PALACE OF NATIONS IN GENEVA, European headquarters of the United Nations and, beginning in the 1960s, an important center for disarmament talks. (Photo by Becks, CC BY 2.0.)

Social Democratic Party. Most notably, SSKF chair Thorsson declared that her organization would publicly oppose the nuclear option. In the end, Erlander persuaded the party board to postpone a final decision until 1958. But the path to that vote was far from smooth. Thorsson and another female member of the party board, cabinet minister Ulla Lindström, left the meeting in protest. Erlander knew that the question of whether to equip the Swedish defense with nuclear weapons would be difficult to answer.

Decision time

By 1958 scientists were confident Sweden could, if it wanted, build nuclear bombs. Meanwhile, the political issue had only become thornier for Erlander and his government. Growing criticism within his own party and in the media, along with a grassroots campaign against nuclear weapons, forced Erlander to work out a compromise with other political parties in the Riksdag.

The Erlander government presented two proposals. The first, known as the device program, would be implemented if the Riksdag chose to acquire nuclear weapons. The second, the protection program, would be used if the Riksdag voted against their acquisition. It would focus on defense preparations against possible nuclear attack rather than on designing a nuclear device. Extensive research on civil defense and on other nations' nuclear weapons capabilities would be necessary to enable Sweden to protect itself against a nuclear-armed enemy. Erlander's government recommended adopting the protection program, arguing that it was not yet time to make a final decision about developing offensive nuclear weapons.

In July 1958 the Riksdag approved a bill granting the FOA more funds to conduct protection research. The Liberal Party and the Centre Party agreed with Erlander's government that a decision on nuclear weapons would be premature. The Conservative Party declared that it was in favor of acquiring tactical nuclear weapons even though it would not seek a final decision on the matter at that time.

Meanwhile, growing opposition to nuclear weapons within the Social Democratic Party placed pressure on Erlander, as reflections from his diary reveal. He was unsure how to handle the conflict, which seemed to have the potential to split his party. As early as 1957, Erlander himself began to have doubts about the nuclear option. As he put it in his memoirs, he "needed considerable years of reading, discussing and thinking before I came to a position that I considered satisfactory."[3] One reason for Erlander's careful handling of the issue was his scientific competence and knowledge. His natural-science background and interest in physics enabled him to understand the possibilities and obstacles of nuclear power and nuclear weapons better than most statesmen at the time.

Erlander did not come out publicly against the acquisition of nuclear weapons, even to other Social Democratic leaders. Instead, he prioritized gaining broad political consensus on nuclear weapons among the Social Democratic, Centre, and Liberal Parties. To maintain his neutrality, Erlander opened up the issue for a public discussion between politicians, media, peace organizations, and opposition groups.

Erlander's decision to step back from the debate allowed his party's strongest critics to start campaigning against nuclear weapons. Thorsson organized political grassroots meetings, while Östen Undén, the minister of foreign affairs, pushed for disarmament initiatives in the United Nations (UN; see figure 3). Nuclear opposition was also found outside the political parties. Labor unions, churches, temperance movements, and peace groups started to publicly oppose the nuclear option.

In 1958, 21 renowned authors, academics, and church leaders signed a petition that would become the foundation of the Action Network Against Swedish Nuclear Weapons (Aktionsgruppen mot svensk atombomb, AMSA). It recruited members from a relatively broad political spectrum, although in order to avoid being discredited by opponents and in the media, they banned communists from participating as speakers or having a prominent position in the organization. AMSA sent renowned academics and cultural figures to present the case against nuclear weapons in talks and debates. The media was also instrumental in getting the issue before the public. Between 1954 and 1959, nearly 3000 articles were published in Swedish newspapers and magazines.[4]

Starting in January 1957, Sweden held a seat on the UN Security Council, and was heavily involved in the committee charged with nuclear disarmament issues. In the same month, Sweden advanced a proposal for a nuclear test moratorium. Undén worked energetically to promote international disarmament during the next few years and greatly influenced public opinion in Sweden.

Meanwhile, the Social Democratic Party was undergoing changes. In December 1958 Erlander announced that his party would establish a committee to study and evaluate the nuclear option. Acting as its chair, he appointed members from both sides of the issue to seek a consensus position. In its far-reaching study, which was completed at the end of 1959, the committee discussed various technical obstacles to the possible production of nuclear weapons along with the international political situation. They concluded that the Riksdag could delay the decision until at least the mid 1960s, when international developments would provide an answer to whether Sweden could be safe without nuclear arms. In the meantime, defense research should continue.

Despite its difficulties drawing a precise boundary between offensive and defensive research, the committee did identify a limit: No research should be carried out that had a direct goal of enabling the manufacture of nuclear weapons. In practice, however, the FOA studied weapons design and calculated the possible cost of producing nuclear weapons. The concept of protection research served, for practical purposes, as a cover for continuing technical preparations that would enable Sweden to move quickly to nuclear weapons design should policy change. The Riksdag continued to support that freedom-of-action policy for several years.[5]

In the meantime, the campaign against acquisition was gaining steam. Public opinion started to lean more and more in the direction of no to Swedish nuclear weapons. Polls spoke for themselves: In 1957, 40% of the public supported the nuclear option, with 36% against it and 24% unsure. By 1965 only 17% were in favor, with 69% against and 14% unsure.

FIGURE 4. ALVA MYRDAL IN 1966. (Courtesy of the Dutch National Archives, CC BY-SA 3.0 NL.)

Disintegrating military support for nuclear weapons

As public opinion turned against nuclear weapons and Sweden became more engaged in international disarmament talks, the military command was preparing a new defense plan. The strong military consensus in favor of equipping the Swedish defense forces with nuclear weapons was beginning to disintegrate.

There were several reasons for the new disunity. One was that the doctrine of massive retaliation, in which nations would use nuclear weapons to cause massive destruction of enemy territory in the initial stages of a war, was beginning to fall out of favor with the Kennedy administration. The apparently reduced role of nuclear weapons in the US military's strategic thinking catalyzed a general reevaluation among Swedish military planners. In their emerging strategy, nuclear weapons would most likely be employed on a smaller scale based on ad hoc assessments of what the situation required.[6] Despite the apparent retreat, however, military leaders still believed it was important to keep their options open and continued to discuss the possible production of tactical nuclear weaponry.

Another reason for the lack of consensus was a growing conflict among the military branches. Both the armed forces and the navy feared they would lose out in future struggles for budget appropriations, since the air force was expected to be awarded the bulk of nuclear-related resources. But even in the air force, there were growing doubts about the advantages of nuclear weapons possession. It had other costly projects to defend, among them the development of a new fighter aircraft. If the nuclear weapons plans were implemented, one consequence might be the discontinuance or reduction of those aircraft. By 1965, the military had retreated even further from its earlier advocacy for nuclear weapons. In a 1965 report the commander-in-chief stated that the nuclear decision was a political matter, and merely requested funds to continue nuclear-related research.

Reactions from the US

The military retreat from pushing for nuclear weapons acquisition is best understood in the context of the US position on nuclear weapons. Nuclear collaboration between the two countries started at the end of 1940s, but it was not on equal terms. Sweden needed not only nuclear assistance from the US, but also help to strengthen its military capabilities. It gradually became clear that collaboration with the US came at the price of less independence and reduced possibilities of integrating the

plans for nuclear weapons manufacture within the civilian heavy-water program.[7] The US feared that if a peaceful and democratic country such as Sweden were to acquire nuclear weapons, the risk of further proliferation throughout the world would substantially increase.

The defense policy cooperation between Sweden and the US deepened during the second half of the 1950s. Eventually Sweden was given permission to procure and manufacture US missile systems. Dependence on US missile technology further curtailed its room to maneuver and gave US leaders leverage in persuading Sweden to abstain from the nuclear option. By 1960 the US government had adopted a firm policy of opposition to any Swedish acquisition of nuclear weapons.

Because of its civilian nuclear energy program, Sweden was also becoming more dependent on technological cooperation with the US. To constrain weapons proliferation, the US lowered the price of enriched uranium, which substantially reduced fuel costs for operating light-water reactors. That policy, enacted at the end of the 1950s, was put in place for two reasons: Weapons-grade material is harder to obtain from the spent fuel of a light-water reactor than of a heavy-water reactor, and any country that purchased enriched uranium from the US had to agree not to use it for nuclear weapons production.[8] Even with those limitations, Sweden decided that it was too expensive to run a heavy-water program for civilian purposes if a cheaper light-water option was available. The US policy change opened the door for Sweden to switch to light-water plants.

From the US perspective, it would be in their national interest to help Sweden if it were to be attacked by the Soviet Union. A 1960 US National Security Council document declared that "in the event of Soviet Bloc aggression against Sweden alone," the US would "be prepared to come to the assistance of Sweden as part of a NATO or UN response to the aggression."[9]

There is no evidence that the US ever communicated that intention to the Swedish government. However, the Swedish military command seems to have perceived a change in US attitudes and interpreted it to mean that Sweden was now covered by the US nuclear umbrella. That belief made it easier for the military to give up its nuclear ambitions and for proponents of a nuclear-armed Sweden, such as the Conservative Party, to abandon those plans.

The reversal is complete

At the beginning of the 1960s, international initiatives under Undén's leadership strengthened the disarmament movement. In 1961 Erlander told Undén that he now thought that acquiring nuclear weapons would increase Sweden's vulnerability and reduce both national and international security. Instead of passively adapting Swedish defense policy to international military–technical developments, Erlander and Undén decided that Sweden would seek to build a peaceful international order and support global disarmament.

Undén appointed Alva Myrdal (see figure 4) to develop and head a disarmament program. Myrdal was a prominent Social Democrat, sociologist, and diplomat. In her book *The Game of Disarmament*, she writes that she immediately began to sketch out a plan to develop strategies to enable Sweden to persuade nuclear powers to disarm. Under her leadership, Sweden in 1962 became a successful member of the new Eighteen Nations Disarmament Committee in Geneva. The committee was created by the UN to establish a dialogue between the US and the Soviet Union and set up disarmament negotiations. Sweden contributed greatly to the committee's work and successfully advanced disarmament policy.[10] In 1982 Myrdal received the Nobel Peace Prize for her work.

By the time Sweden signed the Nuclear Non-Proliferation Treaty and formally abandoned its nuclear weapons program in 1968, the FOA and AE had, in principle, assembled all the resources needed to produce nuclear weapons. However, some important ingredients were missing from a functioning production chain—namely, a uranium reprocessing facility and a supply of heavy water. Another unsolved problem was the weapons-carrier system. Although plans existed for two existing

FIGURE 5. A SAAB 32 LANSEN AIRCRAFT. Sweden considered using this Swedish-manufactured fighter plane as a potential nuclear weapons carrier. (Photo by Mattias Björklund, CC BY-SA 3.0.)

Swedish-made fighter aircraft, the Saab 32 Lansen (see figure 5) and the Saab 35 Draken, to deliver bombs, additional technical developments would have been necessary to carry them out.

Erlander's decisions were not the only reasons Sweden gave up its advanced nuclear weapons plans. A combination of reasons ultimately led to the abandonment of the nuclear option: rising public opposition toward the plans, tension between the goals of developing civilian nuclear power and maintaining freedom of action with respect to nuclear weapons, and the US policy of discouraging the Swedes from building the bomb. However, it is hard to imagine that Sweden would have reversed its plans to become a nuclear state without Erlander's skillful management.

What can be learned from Sweden's decision not to produce nuclear weapons? One lesson is that developing nuclear weapons capabilities is a time-consuming and technically complex process, even if a country already has a domestic nuclear infrastructure. The more open and democratic a country is, the more that process will allow for the mobilization of political opposition against nuclear weapons acquisition.

Because of the technical complications of the production process, a country with nuclear weapons ambitions may need to cooperate with other nations. That cooperation creates a dependence on more technologically advanced states or supranational organizations that may then influence the country to reconsider its nuclear weapons plans. Unfortunately, the recent US decision to withdraw from a nuclear deal with Iran suggests that President Trump and his advisers have not learned that second lesson. As Sweden's experience shows, diplomacy and successive nonproliferation agreements are the way forward if the aim is to have fewer, not more, nuclear weapons states in the world.

This article was adapted from my 2016 book The Key to Nuclear Restraint: The Swedish Plans to Acquire Nuclear Weapons During the Cold War.

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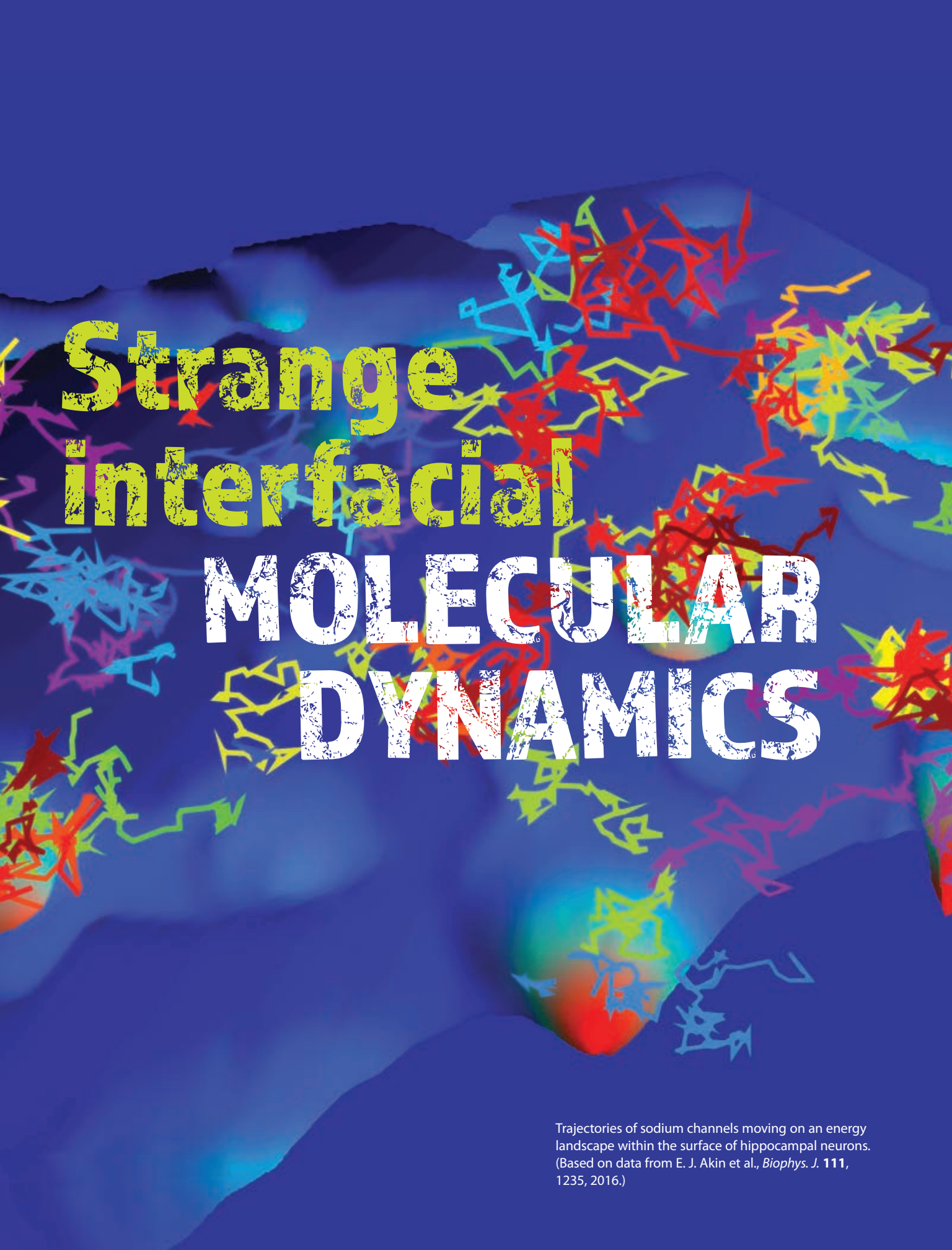

Trajectories of sodium channels moving on an energy landscape within the surface of hippocampal neurons. (Based on data from E. J. Akin et al., *Biophys. J.* **111**, 1235, 2016.)

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Diego Krapf and Ralf Metzler

The motion underlying contact interactions that are vital for biology has farther-reaching implications than previously thought.

Biological functions such as gene regulation and metabolism in living cells rely on highly specific molecular interactions. The structure and dynamics of interfaces—from the nanoscale surfaces of intramolecular domains and the molecular surfaces of proteins, to the mesoscale surfaces of organelles, and even to the microscale surfaces of live cells—mediate those interactions. Our understanding of how interfaces evolve and how they couple to their complex environments is still developing, and several Nobel Prize–winning technologies have aided the endeavor to understand them (see box 1).

Here we discuss three examples of interfacial molecular dynamics: the distance fluctuations between the interfaces of internal protein domains, the coupling of proteins and lipid membranes to their surroundings, and the dynamics within lipid membranes—the thin layer separating a biological cell or an organelle from its surroundings. Even though the protein and membrane systems are highly dissimilar, their dynamics share many common fingerprints. Experiments and simulations demonstrate that both systems display rich and counterintuitive dynamics with strong deviations from researchers' expectations. Experimental evidence has shown that interfacial dynamics in biological systems involve memory effects, which in turn affect molecular biological function in ways that are still not well understood.

Until a few years ago, biological interfaces were studied primarily in terms of their chemical compositions and structures. It is becoming increasingly clear, however, that interfacial dynamics also are critical to the function of living organisms. They mediate processes such as the folding and internal dynamics of proteins, the formation of molecular complexes that can require multiple collision events to trigger specific binding, and the highly selective passage of molecules across membranes. Molecules in the water layer around large proteins and membranes not only associate locally with charge groups on individual amino acids in proteins and lipid membrane molecules; they also affect longer-range stabilization by forming so-called molecular water bridges. Water molecules mediate interactions between protein domains and membrane lipids through those bridges and establish a transient network that contributes to the stability of protein and membrane architectures. Molecular water bridges thereby affect the fluctuations in the structures of proteins and membranes and, in turn, influence the efficiency of biomolecular reactions.

Single particle paths

Membranes and molecules at interfaces are continuously bombarded by other small molecules and larger complexes in the surrounding aqueous environment. Thus, one may expect the dynamics of interfacial molecules to be dominated by diffusion as described in the theoretical works of Albert Einstein[1] and Marian Smoluchowski.[2] Within their framework, molecules are always jittering around randomly, completely independent of their pasts. Even for simple uncorrelated Brownian motion in which the mean squared displacement (MSD) is given by $\langle \Delta \mathbf{r}^2(t) \rangle \sim t$, a striking observation can be made: The path of a single diffusing molecule completely covers a two-dimensional surface, so it makes more sense to talk about the area rather than the distance covered by such a random walk. Indeed, in attempts to measure path length with increasingly better resolution, the length increases as a power-law until it reaches the

scale of the molecular free path. That increase is similar to the fractal effect that unfolds in trying to measure a coastline: Its length grows longer as the scale of measurement gets smaller[3] (see box 2). Fractality in the path or time coordinate of a random process is a common feature in molecular interfacial dynamics.

For hundreds of years, physicists have been studying the motion of individual particles to understand the physics of large systems. Their basic premise is that observed macroscopic properties arise at the most fundamental level from the dynamics and interactions of the individual components. To make sense of matter's behavior, one should probe the physics of its constituent parts—atoms and molecules. Single-particle tracking has a long tradition that originated with Jean Perrin's careful protocols, and what appeared to be science fiction not long ago is now routinely practiced: Careful experiments based on fluorescent tagging allow researchers to follow the motion of individual molecules in living biological cells.[4] Today, researchers can measure the locations of individual molecules with nanometer precision while following their motion with millisecond temporal resolution. The gap between the accessible time scales of simulations and experiments is continuously narrowing, and a significant overlap between simulated and experimentally measured dynamics is already possible.

BOX 1. MOLECULAR DYNAMICS AND THE NOBEL PRIZE

Four Nobel Prizes have been awarded for work directly relevant to our current understanding of the atomistic nature of matter and molecular dynamics. Jean Perrin received the 1926 Nobel Prize in Physics for his work on the diffusion of microscopic particles and colloidal sedimentation and for introducing systematic single-particle tracking. The 2013 Nobel Prize in Chemistry was awarded to Martin Karplus, Michael Levitt, and Arieh Warshel for their contributions to computational multiscale models, which paved the way for the molecular dynamics simulations presented here. In 2014 the Nobel Prize in Chemistry was awarded to Eric Betzig, Stefan Hell, and William Moerner for their work on superresolution microscopy, a technique that has allowed researchers to track individual molecules in live biological cells. And for the 2018 Nobel Prize in Physics, half went to Arthur Ashkin, and the other half to Gérard Mourou and Donna Strickland, for their advances in laser physics and optical tweezers, which paved the way for groundbreaking research in probing biological systems by exerting piconewton forces on single molecules.

Protein reconfiguration

Proteins—polymers composed of amino acid monomers with specific monomer–monomer interactions—are responsible for most of the essential processes in a living cell, including signaling, active transport, cellular metabolism, and modification of other proteins. A protein's transition from one conformation to another takes place in the heterogeneous energy landscape of the protein's highly dimensional phase space.

To function, most proteins in solution first fold into a predetermined structure. Once folded, they typically undergo major conformational changes. Transitions between different configurations are dominated by many small, local conformational changes that add up to a larger protein reconfiguration. The protein crosses a hierarchy of energy barriers but also encounters geometric hindrance, which is often neglected in models. A stark indication of the complexity of protein dynamics was shown in experiments by Hans Frauenfelder at the University of Illinois at Urbana-Champaign in the 1970s. They revealed that the distribution of binding times for ligands showed a power-law scaling over several decades in time. However, at the time it was not possible to tell whether the dynamics were a heterogeneous ensemble effect or due to an individual molecule.

In 2003 Sunney Xie's group at Harvard University used fluorescent imaging methods in single-molecule experiments; their work showed that internal conformation fluctuations take place on a strikingly large range of time scales, from hundreds of microseconds to seconds. The picture that emerged is one of conformational states with a broad power-law distribution of trapping times, or fractal time. Because of that distribution of trapping times, the distance $\mathbf{R}(t)$ between two protein sites exhibits anomalous diffusion.[5]

The single-molecule experiments were recently put into

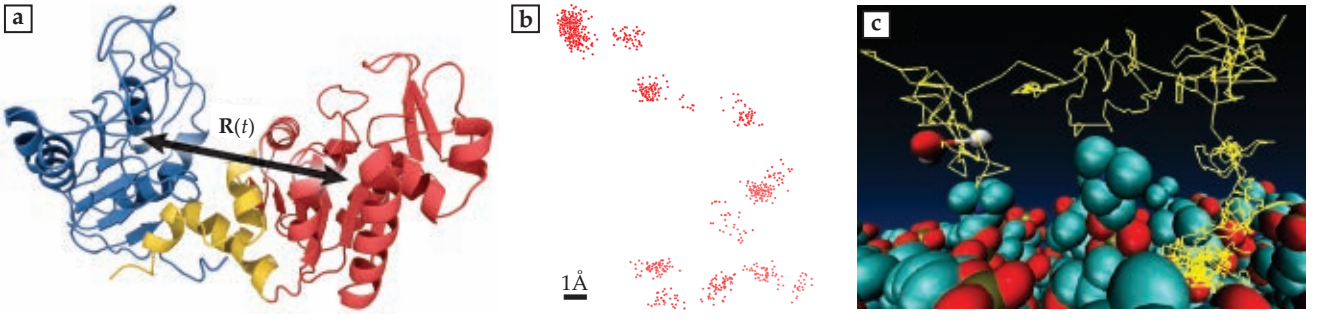

FIGURE 1. THE STRUCTURE OF A PROTEIN and its surrounding water molecules exhibit intriguing dynamics. **(a)** The yeast globular protein phosphoglycerate kinase has three domains, shown here in red, yellow, and blue. Its internal fluctuations can be characterized by the relative position $\mathbf{R}(t)$ of two amino acids within those domains. (Adapted from ref. 6.) **(b)** The positions of a water molecule at the surface of a protein jump between cages in which the molecule spends scale-free immobilization times. (Adapted from ref. 7.) **(c)** Simulations capture the jump-like motion of surface water molecules in the corrugated energy landscape created by lipid membranes. (Adapted from ref. 11.)

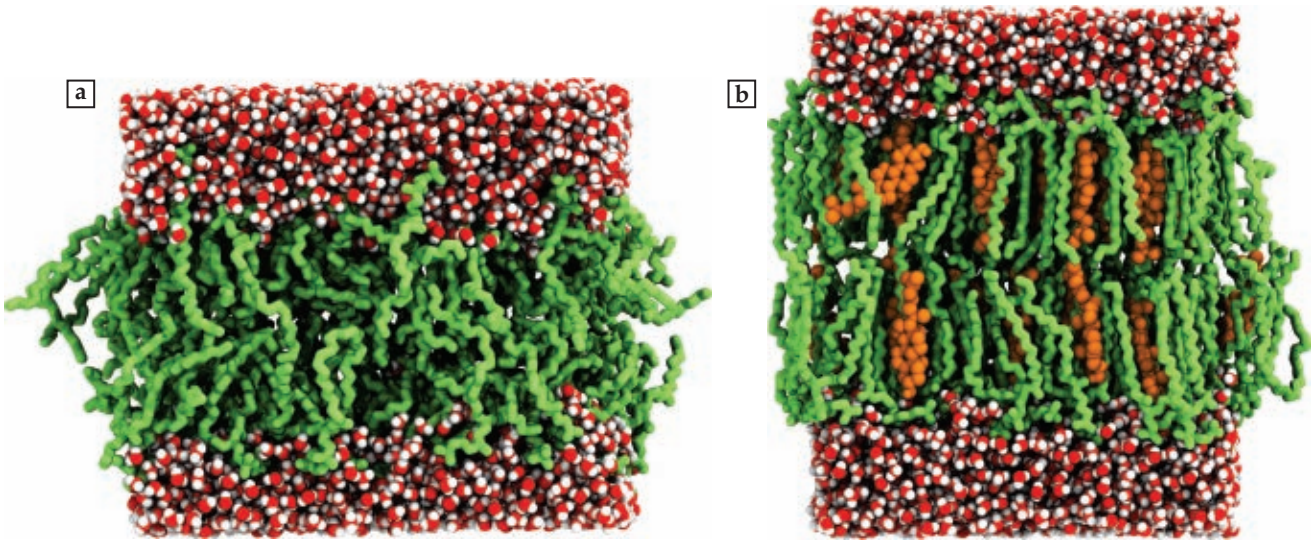

FIGURE 2. SNAPSHOTS OF LIPID BILAYER MEMBRANES with adjacent water layers from molecular dynamics simulations show the effects of membrane disorder. **(a)** A single-component lipid bilayer (green) exists in a disordered liquid phase. Water molecules (red and white) surround the bilayer. **(b)** When cholesterols (orange) are added, the bilayer transitions to a liquid ordered phase. Note that the bilayer width increases with decreasing lipid-tail entropy. (Courtesy of Matti Javanainen.)

a broader perspective in a supercomputing study. Jeremy Smith's group at Oak Ridge National Laboratory confirmed that $\mathbf{R}(t)$ for the amino acids in a protein, illustrated in figure 1a, shows a power-law distribution of trapping times in specific configurations. Moreover, the dynamics are seen to be nonstationary, or to age, down to picosecond time scales: The characteristic time of the interdomain distance autocorrelation function explicitly depends on the measurement time over seven decades in time.[6] Observables in ageing processes depend on how much time has lapsed since the system was initiated. Combining Smith's results with Xie's experiment accounts for ageing dynamics in a single protein over a mind-boggling 13 decades in time.

A paradigm shift is now under way in understanding protein dynamics, and the effects of the interfacial fluctuations can no longer be neglected. Those effects are likely at the core of protein conformational changes and function. To gain mechanistic insight into the emergence of complex organization in proteins, it is essential to probe their dynamics at the protein–water interface, which can dramatically alter intramolecular interactions.

Liang Hong's group at Shanghai Jiao Tong University provided one piece of evidence for strange dynamics at the protein–water interface through neutron scattering experiments of proteins hydrated by approximately a single water layer. The experiments were performed in tandem with molecular dynamics (MD) simulations.[7] The researchers demonstrated that the water molecules on the surfaces of two proteins—cytochrome P450 and green fluorescent protein—exhibit subdiffusion: They both had MSDs of the form $\langle \Delta \mathbf{r}^2(t) \rangle \sim t^{\alpha}$ with an anomalous diffusion exponent $\alpha \approx 0.80$ over times ranging from 10 picoseconds to 1 nanosecond.

The MD simulations showed a gradual change from subdiffusion to nearly normal diffusion ($\alpha \approx 1$) at 0.1 microseconds. The researchers interpreted the motion of the water molecules as a random walk with isolated, uncorrelated jump events between small cages, as shown in figure 1b. The jumps are interspersed with scale-free waiting times, and therefore, the process is ageing. Mediated by molecular water bridges, single arrested water molecules influence the larger region around themselves and thus affect the surface dynamics of the entire protein. The full consequences of those effects on protein function remain unknown.

What would cause the fractal immobilization times observed for internal and external protein interface dynamics? In the 1970s Harvey Scher at Xerox and Elliott Montroll at the University of Rochester showed that such scale-free dynamics may readily emerge from energetic traps with random depths (see box 3). The escape times are interspersed with waiting times, $\tau \sim \exp[-E_a/k_BT]$, where E_a is the energy depth of the well

BOX 2. MANDELBROT'S FRACTALS

Benoit Mandelbrot connected the notion of fractals to the geometric complexity of natural patterns.[3] He noted that "clouds are not spheres, mountains are not cones, [and] coastlines are not circles." Physicists are trained to study processes in terms of their specific time or length scales. In many natural patterns, however, the number of distinct scales involved is so large—more detail appears upon further magnification—that for all practical purposes, it is infinite. Such a system is called scale-free. Brownian trajectories share the scale-free property of fractal patterns. Notably, the surfaces of proteins can have a fractal topology, which must be carefully considered when examining motion within such a structure. Diffusion in a fractal is different from diffusion in a Euclidean space because the ramified, tortuous underlying structure pushes the random walk to retrace its path. Thus, the increments of diffusion within a fractal have negative autocorrelations. A step in one direction is likely followed by a step in the opposite direction, which is also seen in the diffusion of tracer particles in viscoelastic environments. An interesting feature of most fractals and of random walks is their self-similarity. If the path is cut into smaller pieces, each piece appears to be statistically the same as the whole.

and $k_B T$ is the thermal energy. When the energy depths are exponentially distributed and the temperature is below a critical value, the trapping times have a power law tail with infinite mean (see the article by Harvey Scher, Michael Shlesinger, and John Bendler, PHYSICS TODAY, January 1991, page 26). Given the highly complex nature of a protein surface, it is not surprising that its binding pockets have a heterogeneous distribution of trapping energies. The striking effects of such power-law distributed waiting times have been observed in several biological interfaces. They may be caused by specific attractive interactions, but topological hindrance may also come into play when a protein segment at one area in space impedes the passage of another segment.

Probing single molecules in their natural habitat is crucial to understanding their dynamics and function. When solvated in water, proteins perform extravagantly choreographed ballet dances that often include major displacements of subunits around hinge-like bonds. In addition to that motion, the liquid inside a cell is crowded with large, squishy biomolecules that are incessantly colliding like bumper cars. Over time scales of collisions between the large crowding molecules in the cellular environment, proteins trapped in certain conformations or surface water molecules immobilized for long times might be unlocked by nearby colliding molecules, which would lead to a renewal of the motion: The molecules could resume their vivid choreography and restart the ageing process. That picture is still speculative, but we expect the internal protein dynamics and the motion of the surface water to still be anomalous at least below typical renewal times.

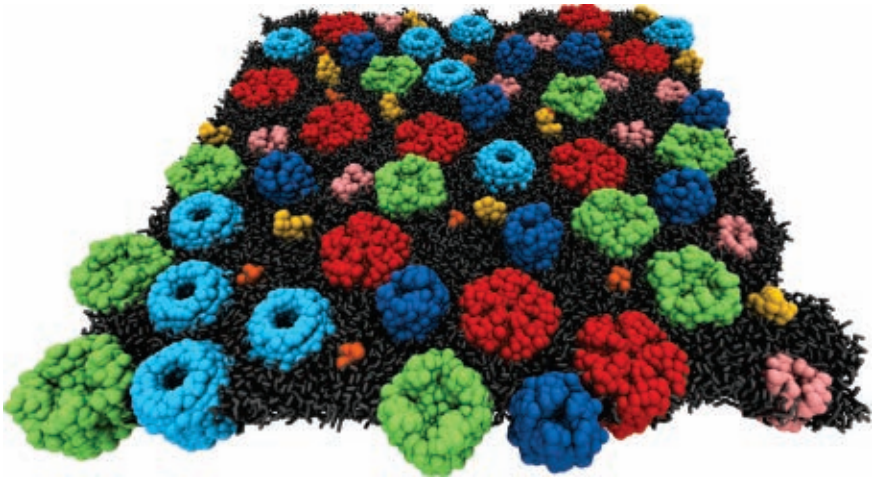

FIGURE 3. THE MEMBRANES OF LIVE CELLS are heavily crowded by embedded proteins. In order for coarse-grained molecular dynamics simulations to be realistic, a lipid bilayer is decorated with multiple membrane-embedded proteins.[10] (Courtesy of Matti Javanainen.)

In and around membranes

The same interfacial dynamics that affect single proteins are also important for lipid bilayer membranes that form the surfaces of cells and organelles. First consider the simplest model system for a biological membrane: a self-assembled bilayer of lipid molecules of identical chemistry (figure 2a). Biological lipids typically have a hydrophilic head group and a hydrophobic tail, so in aqueous environments they form bilayers with their tails pointing inward and their heads at the interface with the water. For waiting times shorter than 10 nanoseconds, each lipid's center of mass shows anomalous diffusion with an exponent $\alpha \approx 0.66$. Gerald Schneider at Louisiana State University and coworkers recently reported an even more marked subdiffusive regime below the nanosecond range in neutron-spin-echo experiments.[8] They found an exponent of $\alpha \approx 0.26$ corresponding to short-range motion comparable to the size of a lipid head group. Beyond 10 nanoseconds, most studies indicate a crossover to normal diffusion ($\alpha = 1$) in both experiments and all-atom simulations.

When cholesterol molecules—a type of lipid essential for the structural identity of animal cell membranes but better known for causing cardiovascular diseases—are added to the bilayer, they settle snugly between the tail groups of the bilayer lipids. As shown by Ilpo Vattulainen's group at the University of Helsinki, cholesterols decrease the accessible degrees of freedom of the membrane lipids. That restriction causes a more ordered bilayer structure and, because the lipid tails become more elongated, an increased membrane width (figure 2b). The short-time anomalous diffusion does not substantially change, but for some lipid chemistries, researchers have observed extended anomalous diffusion[9] beyond 10 ns with an exponent $\alpha \approx 0.8$.

The correlation between higher membrane disorder and longer-lasting anomalous diffusion is corroborated when proteins are added to the bilayer. Lipid bilayers in biological membranes comprise various lipids with different chemistries, and they are studded with membrane proteins much larger than the surrounding lipids (figure 3). Many of those proteins are tasked with gating specific molecules such as water, ions, proteins, or fragments of genetic code across the membranes; others act as chemical sensors. Experiments have recently shown that protein crowding in single-chemistry, lipid-bilayer model membranes causes persistent anomalous diffusion to at least tens to hundreds of nanoseconds. Interestingly, in crowded membranes the diffusion may no longer have Gaussian step sizes as in noncrowded membranes, and individual lipid and protein motions show intermittent mobilities that alternate between states with largely different diffusion coefficients.[10]

The lipids and proteins in bilayers interact both with each other and with their surroundings. To see the effects of those interactions, Eiji Yamamoto and colleagues at Keio University in Tokyo studied the motion of water molecules and proteins at the water–membrane interface. Their all-atom MD simulations showed that water molecules within 3.5 Å of the lipids are subdiffusive with $\alpha \approx 0.6$ on time scales from 1 to 1000 ps. The simulations revealed signatures of both scale-free immobilization time distributions and antipersistent motion or a negative velocity autocorrelation function. Whereas the antipersistent component has stationary displacements, the scale-free time distributions lead to ageing dynamics of the surface water and

BOX 3. FRACTAL-TIME PEARSON WALKS

When Karl Pearson conceived the random walk, he envisioned a man walking a given distance in one direction, turning in a random direction, and repeating the process. In the continuum limit, the process describes Brownian diffusion. Now consider the more general case when the random walker can rest for random times between sojourns. That could describe the motion of a water molecule that spends time in pockets on the surface of a protein.

The theory of such a stochastic process was introduced in 1965 by Elliott Montroll and George Weiss, then at the Institute for Defense Analyses and the National Institutes of Health, respectively. Their work gave rise to the famed continuous-time random walk (CTRW), a term coined by Harvey Scher in 1973. Scher and his colleague at Xerox, Melvin Lax, brilliantly succeeded in modeling their unconventional observations of electrical conduction in amorphous semiconductors in terms of a CTRW with scale-free rest times. Because the distribution of times was similar to Mandelbrot's geometric fractals, Mike Shlesinger from the Naval Research Office called it a time fractal.

Such dynamics occur when the distribution of rest times τ in a random walk is characterized by a power law tail $\psi(\tau) \sim \tau^{-\beta}$ with $1 < \beta < 2$, which leads to a diverging mean. The lack of a characteristic time scale causes subdiffusion, in which $\langle \Delta \mathbf{r}^2(t) \rangle \simeq t^{\alpha}$ with $\alpha = \beta - 1$, whereas the geometry of the trajectory is the same as in Brownian motion. The lack of an intrinsic time scale also gives rise to nonergodicity: Time averages no longer converge to their ensemble average, a phenomenon that has been observed in experiments (see the article by Eli Barkai, Yuval Garini, and Ralf Metzler, PHYSICS TODAY, August 2012, page 29). The sole time scale is given by the observation time T, and thus physical observables depend on T, which means that the system ages, similar to a glass.

the water mobility decreases with time. The time-dependent slowdown may increase the probability that water molecules dock at energetically favorable locations and stabilize the membrane by forming bridges between lipids. Roland Netz's group at the Free University of Berlin mimicked the jump-like and heterogeneous surface water motion on membranes by replacing the complex environment with a corrugated free-energy landscape, shown in figure 1c, that models the landscape created by the surface head groups of membrane lipids.[11]

Going one step further, Yamamoto and others have studied the surface motion of a protein that specifically binds to lipid head groups in multiscale MD simulations.[12] The results again reveal anomalous heterogeneities in the protein's diffusion with intermittent localization patterns characterized by an exponent $\alpha \approx 0.5$ from the subpicosecond range to around 10 nanoseconds. At that point the proteins cross over to normal diffusion with $\alpha \approx 1.0$. Both membrane-associated water and proteins exhibit similar anomalous dynamics, albeit with different effective diffusivities.

How do those observations translate into observations of membrane dynamics in complex living cells? Different experimental studies reveal two crucial factors. Due to the increased complexity of the study cases described above, subdiffusion of membrane proteins may reach longer macroscopic time scales of hundreds of seconds, and their motion can be strongly influenced by interactions with the intracellular scaffolds of semiflexible polymers that support the membrane. Scale-free trapping times cause membrane proteins to exhibit ageing dynamics on similarly long time scales.[13]

Using a combination of single-particle tracking and superresolution imaging in live cells, researchers found that the actin cytoskeleton that lies underneath the membrane forms a scale-free landscape, shown in figure 4, that causes the ageing protein dynamics to evolve on a fractal substrate.[14] By using interferometric scattering to track tagged membrane proteins, Philipp Kukura's group at Oxford University reported similar results describing membrane protein subdiffusion in living neurons that have membrane compartments in the cytoskeleton.[15] Simulations of a two-component lipid bilayer membrane by Petra Schwille's group at the Technical University of Dresden showed even more pronounced subdiffusion due to coupling to cytoskeletal scaffolds.[16] Maria García-Parajo's group at the Institute of Photonic Sciences in Barcelona, Spain, observed ageing motion in experiments but ascribed it to intermittent membrane protein diffusivity in regional patches,[17] which underlies behavior in simulations of protein-crowded model membranes.[10]

Origins and relevance of anomalous dynamics

The internal dynamics of proteins and membranes and the dynamics of surface-associated molecules are very rich and dominated by anomalous diffusion on many time scales. The physical nature of the subdiffusive dance has two faces. One is a random-walk-like, intermittent motion with scale-free immobilization events, possibly with superimposed local small-amplitude jitters. Such processes with diverging mean waiting time are inherently non-Gaussian. The other face is a viscoelastic-type anomalous diffusion governed by anticorrelated but stationary dynamics. Such antipersistent motions with power-law step correlations are normally Gaussian,[7] but in a heterogenous medium they may also become non-Gaussian.[10]

Ageing effects, identified on many time scales, cause a perpetual decrease of the effective diffusivity over time. In cases when ageing persists over many time scales, one must consider

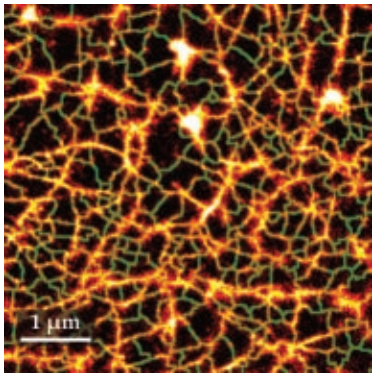

FIGURE 4. THE CYTOSKELETON STRUCTURE vicinal to the membrane of a human embryonic kidney cell can be probed by superresolution microscopy. The cortical cytoskeleton forms a scale-free fractal network (orange). The green lines show the compartmentalization of the membrane that is induced by the fractal actin structure. (Adapted from ref. 14.)

how much time has elapsed since the system was initialized. For a protein, that initialization might be when it was synthesized by a ribosome. Knowing when the dynamics began evolving is necessary to extract relevant physical parameters such as the value of the anomalous diffusion coefficient. We may ask whether ageing in the internal motion of individual proteins will persist over longer times in the crowded environment of living cells. Due to bombardment by other biopolymers, proteins may experience considerable impacts, a kind of massage causing the unlocking of stuck configurations and thus a rejuvenation of the dynamics that resets the molecule's internal clock and causes ageing to start again.

Scientists are still collecting evidence from experiments and simulations in an effort to understand the physical and biochemical consequences of interfacial dynamics. At ultrashort and short time scales, the observed anomalous diffusion in complex systems may point to fundamental interactions such as caging effects either in the dense array of lipids[8] or of the surface water.[7] Considering that water bridges can connect surface amino acids in a protein or connect lipid molecules in a membrane, they may not only add to the stability of protein or membrane architectures but also slow their motion. Moreover, when two biopolymers come close in the crowded cytoplasm of the cell, such water bridges may generate longer mutual contact times and thus facilitate chemical reactions and oligomerization.

The viscoelastic component in several of the observed systems appears to be a generic behavior in soft-matter systems. Because of the antipersistence of their trajectories, individual particles may remain mobile but are likely to be pushed back to their previous position over long times. Returning to the same location may increase the likelihood of repeated reaction attempts and further be beneficial in forming complexes, especially in real, highly mixed membranes. Being slow may not always be a virtue, but within cells it may underlie function.

The observed strange interfacial molecular dynamics reflect both energetic and dynamic disorder. The journey into exploring those effects and their implications for biological function has likely just begun.

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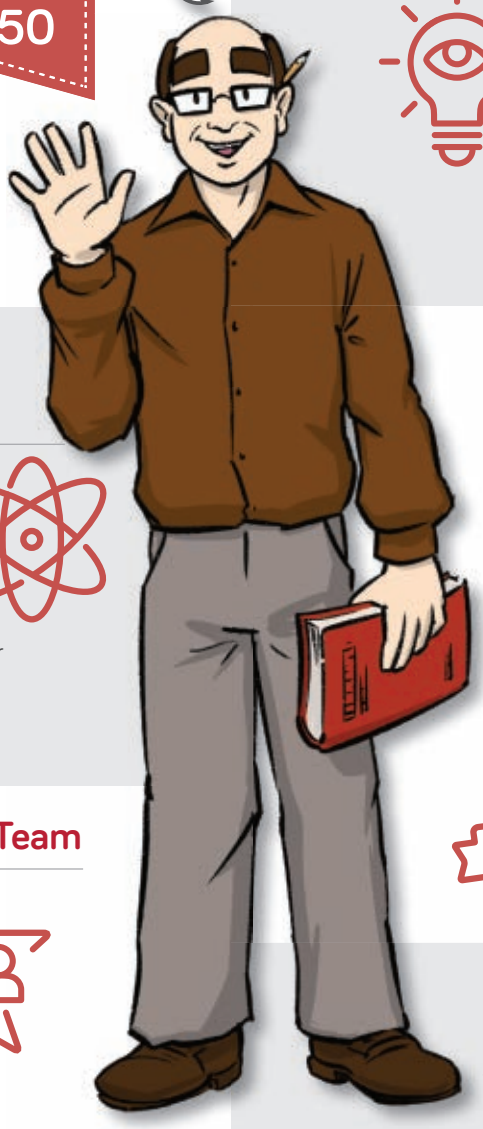

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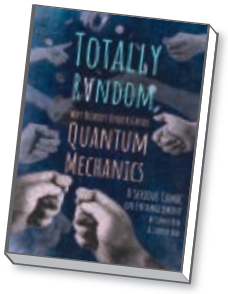
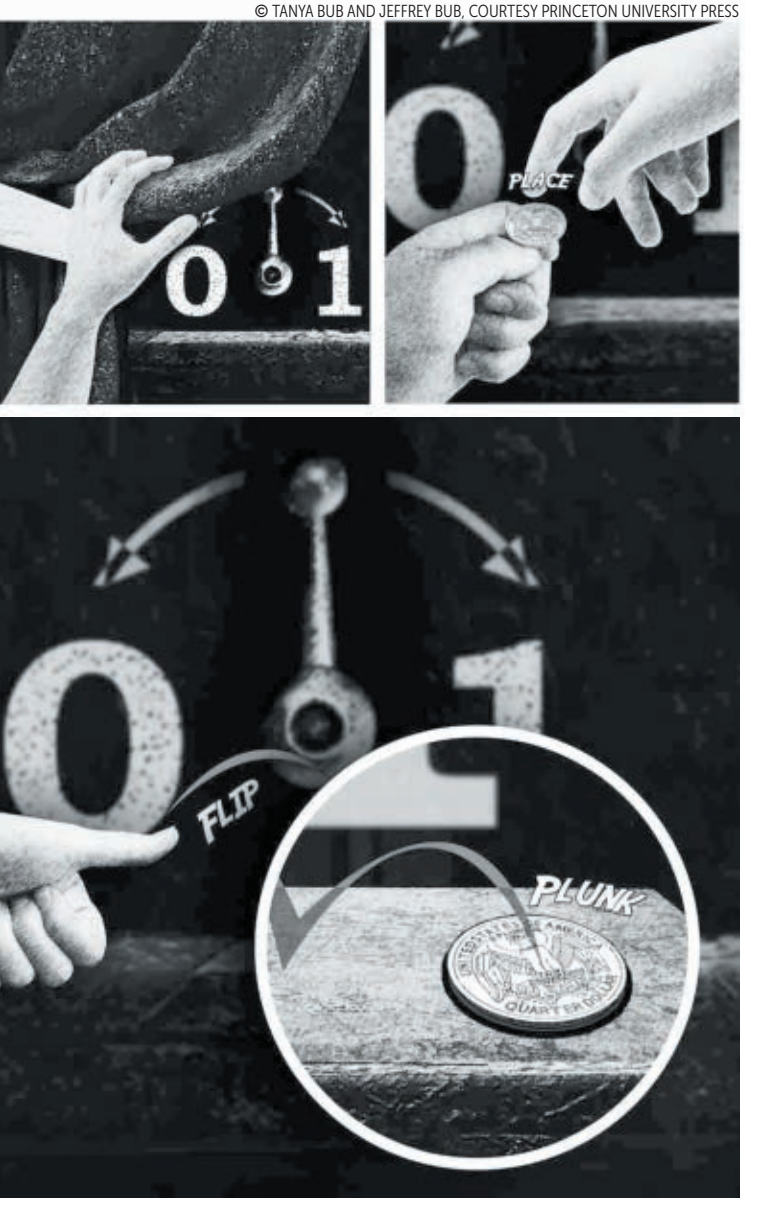
The mysteries of quantum mechanics in graphic-novel form



Totally Random
Why Nobody Understands Quantum Mechanics; A Serious Comic on Entanglement

Tanya Bub and Jeffrey Bub
Princeton U. Press, 2018. $22.95 (paper)



Richard Feynman famously claimed in his 1964 Messenger lectures that nobody understands quantum mechanics. His statement was doubly ironic: Feynman was unquestionably a master of quantum mechanics, and he used the theory's predictions to describe how nature behaves while saying that no one knows how it can behave like that. We have yet to resolve that second irony. We understand how to use quantum mechanics successfully, but we still lack an agreed-on description of the quantum world. *Totally Random: Why Nobody Understands Quantum Mechanics; A Serious Comic on Entanglement* is a highly original attempt to give even nonphysicists a personal experiential appreciation of that peculiar situation.

Jointly authored by graphic artist Tanya Bub and her father, philosopher of physics Jeffrey Bub, *Totally Random* is the result of the Bubs' intense intellectual discussions about quantum mechanics. Both Tanya and Jeff have alter egos who provide commentary throughout the book. But many other characters also contribute to the conversation. One is the reader, whose thoughts are channeled by a skeptical narrator. The founding fathers of quantum mechanics also appear; sources for their quotes are given in notes at the end of the book.

The first part of *Totally Random* acquaints the reader with the most puzzling features of quantum mechanics. Feynman thought the two-slit experiment contains the only real mystery of the theory, but Erwin Schrödinger would have disagreed; he believed that entanglement was the most mysterious phenomenon in the new quantum world. The Bubs side with Schrödinger, and as an expository device, they "hand" the reader a pair of quoins, or superquantum coins. When tossed, each quoin is equally likely to land on heads or tails, just like a normal coin. But when two people each lay one quoin on their thumbs with the heads facing up and toss them simultaneously, the quoins always land with one on heads and the other on tails. If the quoin tossers lay the quoins on their thumbs with faces oriented any other way, the quoins always land with the same face up. The quoins thus illustrate the scenario outlined by Sandu Popescu and Daniel Rohrlich in their 1994 paper introducing what is now called a PR box. That scheme explores the possibility of a theory even more nonlocal than quantum mechanics that still did not permit instantaneous distant signaling.

The Bubs show that those outcomes are puzzling because there is no way to rig each quoin in a pair to land the way it does without information about how the other quoin lands—information that would have to be transmitted arbitrarily fast if the quoins were tossed arbitrarily far apart. The quoin scenario is a nice metaphor

that brings home the significance of Bell inequalities and the subsequent experiments that verify the quantum-predicted correlations that violate them. It is only a metaphor, since the experimental correlations are not the superquantum correlations predicted by a PR box. As far as we physicists know, there are no quoins, no doubt to the disappointment of many young readers. But it is characteristic of comics to stretch what is possible to engage the reader's attention and imagination, and quoins are a significant improvement on the misleading metaphor of spooky action at a distance.

The "late great" physicists of the Copenhagen school—and their critics—appear in part two of *Totally Random*. Each group tries to convince the reader of how quantum mechanics describes—or fails to describe—our world. Their quoted views bring home the lack of consensus on quantum foundations that has by now persisted for nearly a century.

The quoin metaphor proves its worth in the final part of the book; it gives a real feeling for what quantum cryptography, computation, and teleportation are and how they are possible. I could quibble with some of the details here, but overall I have never seen such a simple and faithful account of the underlying principles.

Jeffrey Bub is a professor in both the philosophy department and the Joint Center for Quantum Information and Computer Science at the University of Maryland. He has published three scholarly books and numerous papers on the conceptual foundations of quantum mechanics. Unlike those works, *Totally Random* contains no mathematics. Its contents will be accessible to the interested reader who knows no quantum mechanics, and the authors thank six teenagers for their help in keeping it that way.

I would have loved this book as a teenager myself, and although it is unlikely to top the young adult reading charts, I expect it will inspire some to join the next generation of physicists and philosophers. As a reader of PHYSICS TODAY, you may want to buy copies for your family or friends. But don't part with the book without first reading it yourself, for it will surely give you a deeper appreciation of both the peculiarity and the power of quantum mechanics.

Richard Healey
University of Arizona
Tucson

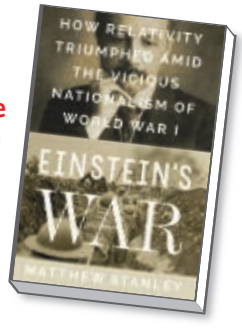

SCIENTIFIC MONTHLY (1920), PD-US

Eddington and Einstein, scientists and wartime visionaries

On 29 May 1919, two British expeditions observed a solar eclipse to test a key prediction of Einstein's general theory of relativity: that the Sun's gravity would bend light from distant stars. The announcement of favorable results catapulted Albert Einstein to a level of worldwide fame that has fascinated and perplexed scientists and historians ever since. Matthew Stanley's *Einstein's War: How Relativity Triumphed Amid the Vicious Nationalism of World War I* is a welcome contribution to this year's centenary of the famous eclipse.

Einstein's War focuses on two protagonists: Einstein himself and British astronomer Arthur Eddington. Stanley, a historian of science at New York University, weaves the two biographies deftly, tracing their individual career paths and scientific achievements. He handles the science ably, but his treatment of the social and political context stands out. The devastating carnage of World War I and the extreme nationalism that engulfed the hostile nations provide the dramatic backdrop to the author's narrative.

Einstein's War
How Relativity Triumphed Amid the Vicious Nationalism of World War I
Matthew Stanley
Dutton/Penguin Random House, 2019. $28.00



Stanley paints a vivid picture of both Eddington's wartime life as a Quaker pacifist in Cambridge, UK, and Einstein's isolation as a pacifist and internationalist in Berlin. One hundred years later, it is hard to imagine the brutality of the Great War and the vicious hatreds that it engendered among the citizens, including scientists, of the hostile nations. Stanley brings those realities to light and shows how Einstein and Eddington were two lonely beacons of sanity and humanity in a sea of vitriol and hatred.

The war had ended when British

astronomers returned from their eclipse expeditions and announced results that supported general relativity. The now-famous headline "Revolution in science" in London's *Times* triggered a media frenzy that catapulted Einstein to world fame.

According to Stanley, Eddington orchestrated a campaign to convince scientists, the media, and the public that the eclipse observation was a "crucial test" to decide between two competing theories of gravitation: Isaac Newton's and Einstein's. Stanley concludes, "If Eddington had not cared about pacifism, we would not have had the relativity revolution in 1919. . . . The world had just the right conditions for Einstein's sudden catapulting to fame. The horrors of the war, and pacifists' reactions to them, forged the intricate, fragile network that made relativity what it was."

There is no doubt Eddington was pleased that Einstein was a pacifist and internationalist or that he saw the potential for rekindling international collaboration with the eclipse expeditions. However, Stanley's thesis that Eddington masterminded the 1919 eclipse observation to maximize publicity for Einstein and his theory is a distortion of historical events.

Stanley claims that Eddington had to persuade Astronomer Royal Frank Dyson "that relativity was scientifically important even if it might be wrong" and that "technical interest and personal friendship seem to have been enough for Dyson to join in on Eddington's project" to test light bending at the 1919 eclipse. In fact, it was Dyson, then the chair of the Joint Permanent Eclipse Committee, and his colleague Herbert Hall Turner who made the decision to test light bending and invited Eddington to sit in on the committee's meetings.

Stanley also asserts that Eddington and Dyson made "extensive efforts … to get regular press coverage of the expeditions even before they found any results." But newspapers regularly covered eclipse expeditions, and this one was no exception. Reporters typically sought interviews with the scientists involved and often commissioned them to write articles about their work. The appearance of a few articles authored by Dyson or his colleagues did not constitute a publicity campaign.

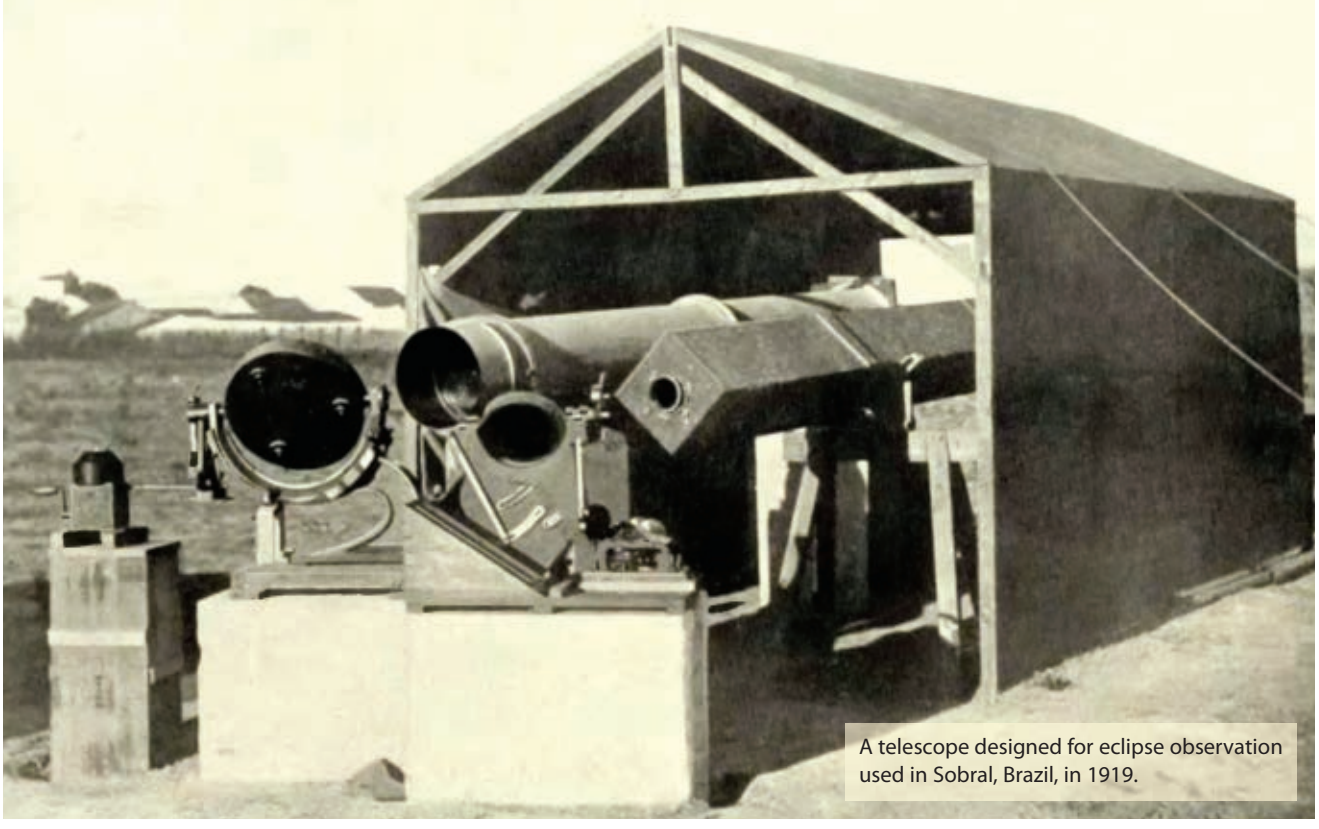
Einstein's War also glosses over the intense competition between British and American astronomers to be the first to publish definitive results. When the *New York Times* covered the British eclipse results under the headline "Lights all askew in the heavens," Stanley claims that it "was virtually the first mention of Einstein in the *New York Times*—he was a person of little consequence until this moment."

In fact, a year earlier, the *New York Times* had commissioned William Wallace Campbell, director of the Lick Observatory in California, to write an article about his eclipse expedition to Goldendale, Washington. Published on 10 June 1918, it included a subheading of "Test of the Einstein theory," under which Campbell wrote, "It is hoped that the measured positions of the recorded stars will serve as a test of correctness or falsity of the so-called Einstein theory of relativity, a subject which has occupied a foremost position in the speculation of physicists and others during the last decade." The press's interest had been primed well before Eddington and Dyson made any plans for the 1919 eclipse.

Interestingly, US astronomers seem to have believed that the British orchestrated events to bring publicity to Einstein. For instance, in a 1920 letter, Lick astronomer William Hammond Wright complained to Mount Wilson Observatory director George Ellery Hale, "I suppose we have all been worrying lately over the 'Einstein effect' chiefly as a result of the publicity which has been accorded to its so-called confirmation by the English Eclipse observations." Yale astronomer Ernest Brown visited the University of Cambridge in 1920 and confronted Eddington. Brown later wrote to a colleague, "Eddington told me that the booming of the relativity business was entirely the work of the London Times. Neither the Royal [Society] nor the [Royal Astronomical Society] was responsible for the big advertisement it got. . . . Our criticisms of the apparent advertising methods of the R.S. fall to the ground."

Historical inaccuracies aside, there is much to admire in Stanley's book. In today's world of rising nationalism and xenophobia, his gripping story of two visionaries rising above national hatreds is as refreshing as it is important.

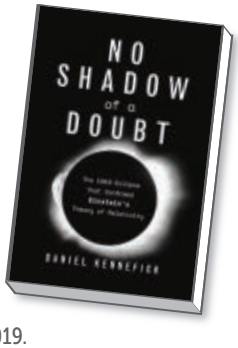
Jeffrey Crelinsten
The Impact Group
Toronto, Ontario, Canada



A telescope designed for eclipse observation used in Sobral, Brazil, in 1919.

C. DAVIDSON. PD-US

The significance of the 1919 total solar eclipse



No Shadow of a Doubt
The 1919 Eclipse That Confirmed Einstein's Theory of Relativity
Daniel Kennefick
Princeton U. Press, 2019.
$29.95

If you are interested in the first successful test of Einstein's prediction about light bending, you should find Daniel Kennefick's *No Shadow of a Doubt: The 1919 Eclipse That Confirmed Einstein's Theory of Relativity* very informative, despite its flaws. Kennefick delves into details of the 1919 solar eclipse expeditions, the people involved, the data analyses that followed, and much more.

One of Kennefick's main goals and achievements is to rescue from current obscurity many who played an important role in that century-old work. Who, for example, remembers Frank Watson Dyson, then the Astronomer Royal of Great Britain and director of the world-renowned Royal Greenwich Observatory? He was the first to realize the opportunities presented by the 1919 eclipse and was instrumental in obtaining funding for the expeditions. He also successfully persuaded the authorities to delay until after the eclipse the military conscription of the eclipse's best-known figure, astronomer and Quaker pacifist Arthur Stanley Eddington. Although he did not go there himself, Dyson was in charge of the eclipse expedition to Sobral, Brazil; Eddington led the one to Principe Island off the west coast of Africa.

Even less likely to be remembered is Charles Rundle Davidson, who worked for Dyson. Davidson went to Sobral, and despite his lack of university education became the final arbiter on all issues involving the use of eclipse observation equipment there. He was later intimately involved with the data analysis. Similarly, important contributors in Ireland—Howard Grubb, for example—have largely been forgotten. Grubb had much earlier made key optical equipment that was used to replace vital items stranded in the Russian Pulkova Observatory by the military hostilities of World War I.

As Kennefick makes clear, the results from the eclipse expeditions received worldwide publicity largely because of Eddington's involvement. That publicity made Albert Einstein a world-renowned figure. Kennefick also notes that Eddington hoped to help repair the damage World War I had inflicted on international cooperation among scientists. What better way to encourage reconciliation than for British scientists to verify a theory proposed by a German to replace that of the most famous British scientist of all, Isaac Newton?

A substantial part of *No Shadow of a Doubt* is devoted to a detailed discussion of the eclipse data analysis, including the seemingly arbitrary deletion of some of the data. One surprise is that the Principe plates were not retained and so could not be reanalyzed as the Sobral data were in the late 1970s. That reanalysis yielded nearly the same results as in 1919.

In my view, Kennefick overstates the significance of the 1919 findings, starting with the book's title. For example, Dyson was looking forward to later eclipses and opined that he wouldn't be surprised if future results did not support Einstein's prediction. That is hardly a statement an intimately involved scientist would make if he thought the 1919 conclusion had "no shadow of a doubt."

Kennefick also says that the 1919 eclipse "may well have been the most important scientific experiment of the entire twentieth century." Despite the "may," that sentence seems to me to be a stretch. Even if we agree to consider only tests of

the general theory of relativity, a strong case could be made that the 1922 eclipse measurements were at least as important. A Lick Observatory team made those measurements, which yielded a light deflection at the solar limb of 1.72 arcsec ± 0.11 arcsec probable error, in close agreement with Einstein's prediction of 1.75 arcsec. By contrast, the result from the 1919 eclipse was 1.98 arcsec ± 0.12 arcsec probable error for Sobral and 1.61 arcsec ± 0.3 arcsec probable error for Principe.

In soaring and elegant prose, Kennefick claims that Eddington and Dyson "deposed Newton's theory of gravity from its perch as the greatest achievement of the human intellect." In my view, not only is that placement of Newton's theory arguable, but the theory could well be considered to have been deposed before 1919. For the previous 60 years a glaring inconsistency of 43 arcsec per century had existed between observations of the advance of the perihelion of Mercury's orbit and the smaller prediction of Newton's theory. By contrast, Einstein showed some years before 1919 that his theory explained that inconsistency to within the uncertainty of its measurement. That result thus deserves much if not most of the deposing credit.

In addition to some problematic discussions of philosophical issues such as the distinction between science and nonscience, the book also contained a large number of errors. I mention only a few explicitly: Kennefick's description of the transverse Doppler shift and his definition of a parsec were off, his definition of a pulsar was wanting, and his labeling of the European Space Agency's Hipparcos mission as NASA's was embarrassing.

As a point of personal privilege, I note that Kennefick also errs when he describes how C. W. Francis Everitt used Gravity Probe B to test another prediction of general relativity, frame-dragging. Kennefick says that Everitt had "arranged for the analysis of the Gravity Probe B data to be done in the blind, with a key ancillary part of the experiment conducted by a separate group [mine] who were to keep their results secret until after Everitt's team presented their own measurements." However, the idea for blinded data analysis, described somewhat inaccurately by Kennefick, was mine. For various reasons, Everitt—for whom I have the utmost respect—did not follow that plan, contrary to a fair reading of Kennefick's whole statement.

Finally, I wondered throughout my reading of the book who Kennefick intended as his main audience. I didn't find a satisfactory answer. If the generally educated and curious layperson was the intended audience, then why did he write sentences such as "the theory of black holes led to fascinating concepts like black hole thermodynamics, Hawking radiation, and the Penrose process," without any explanation of those concepts? If the intended audience was professional physicists, then why did he discuss the basics of Euclidean geometry and elementary aspects of error analysis?

Kennefick's book is clearly based on extensive research and includes far more interesting material than I could possibly mention here. Perhaps the forewarned reader can successfully filter its disconcerting problems and take advantage of the apparently good information.

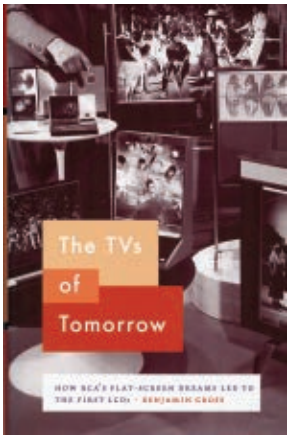
Irwin Shapiro
Center for Astrophysics,
Harvard & Smithsonian
Cambridge, Massachusetts

NEW BOOKS & MEDIA

The TVs of Tomorrow

How RCA's Flat-Screen Dreams Led to the First LCDs

Benjamin Gross
U. Chicago Press, 2018. $40.00



In 1968 scientists and engineers at RCA announced that they had created an electronic display that relied on liquid-crystal technology. Today LCDs are used in everything from bedside clocks to computer monitors and home televisions, but RCA shared in little of the financial glory from its invention. In *The TVs of Tomorrow*, historian of science Benjamin Gross uses laboratory notebooks and in-depth interviews with scientists at RCA to reconstruct the scientific path to the LCD. Gross also has a sharp eye for business history and explores the company's difficulties commercializing its new technology. The book will appeal to anyone interested in the intersection of scientific innovation and industrial research. —MB

Talk Nerdy

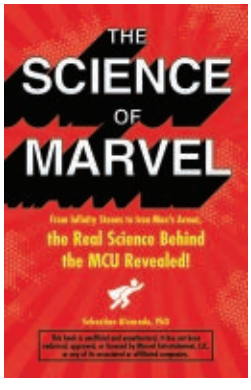
Cara Santa Maria, 2017–present

Decorated science journalist Cara Santa Maria just hit the 100-episode milestone of her weekly podcast *Talk Nerdy*. The show bills itself as "conversations with interesting people about interesting topics," and each episode features an in-depth interview with a scientist or science communicator. Recent guests have included geologist Lucy Jones, systems biologist Stacey Finley, and filmmaker and conservationist Byron Pace. Santa Maria, herself a PhD candidate, brings her own knowledge to the table but is skilled at letting her guests shine. Episodes are roughly an hour long and are available for download on iTunes and other podcast platforms. —MB

The Science of Marvel

From Infinity Stones to Iron Man's Armor, the Real Science Behind the MCU Revealed!

Sebastian Alvarado
Adams Media, 2019. $16.99 (paper)



Scientists haven't figured out how to give us mere mortals Captain America's strength or Spider-Man's spidey sense, but there's still plenty of physics, neuroscience, and biology to think about in the Marvel Cinematic Universe. In this short and engaging book, Sebastian Alvarado, a neuroscientist at Queens College, City University of New York, uses characters and plot points from the Marvel movies to spark discussions on scientific phenomena. Alien assassin Nebula inspires a section on cybernetic prosthetics, for example, and the showdown between *Black Panther*'s T'Challa and Killmonger gives Alvarado an opportunity to talk about nature versus nurture. Alvarado's love for the films is obvious on every page, but the book is not for those hoping for a lot of superheroes and very little science—at different points, Alvarado discusses de Broglie waves, the Schrödinger equation, flame emission spectroscopy, and protein tensile strength. —MB PT

NEW PRODUCTS

Focus on test, measurement, and analytical equipment

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 ptpub@aip.org.

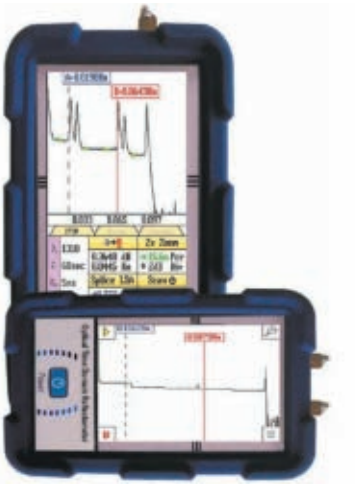
Andreas Mandelis

Thermal interface material

Indium Corporation has added to its line of thermal interface materials (TIMs) with the introduction of HSMF-OS, a non-silicone-based metal and polymer material developed for burn-in and test applications. HSMF-OS is designed for high insertion capability. Its high tensile strength and soft compliant polymer backing allow it to survive multiple insertions. It has been tested to withstand more than 5000 insertion cycles without loss of performance. One of the challenges associated with a burn-in TIM is the attachment method. HSMF-OS has inherent adhesive properties on one side that allow for hand placement. That removes the need for additional steps and fixtures without compromising thermal performance. The opposite side is aluminum; it will not mark or stain the device under test. According to the company, HSMF-OS offers consistently good performance without phase change. ***Indium Corporation**, 34 Robinson Rd, Clinton, NY 13323, www.indium.com*

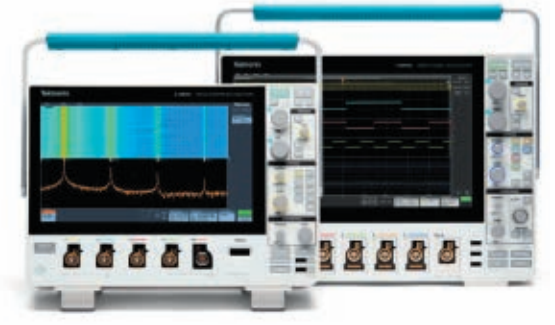
Flow cytometer for cell analysis

Agilent developed its NovoCyte Advanteon flow cytometer to deliver multicolor flow-cytometry assays with high sensitivity and detection speed to users in basic research, drug discovery, and clinical diagnostics fields. The NovoCyte Advanteon can be configured with one, two, or three lasers and up to 21 fluorescence channels. A large 7.2 log dynamic range and fully automated compensation features enable users to pick up both dim and bright signals in the same run. According to Agilent, the NovoCyte Advanteon's resolution metrics are among the best on the market. The system can easily discern particles in the range of 100 nm. The system's intuitive analytical software package allows it to be fully automated and makes it easy to use. ***Agilent Technologies Inc**, 5301 Stevens Creek Blvd, Santa Clara, CA 95051, www.agilent.com*



Optical time-domain reflectometer

According to Terahertz Technologies, its FTE7100 MicrOTDR with color touch screen is the smallest full-featured optical time-domain reflectometer (OTDR) available. When equipped with the optional videoscope, it is a multipurpose video inspection system with IEC61300-3-35 auto pass/fail capabilities. Other optional features include a broadband power meter and visual fault locator. The MicrOTDR is available in single-mode (SM) or multimode (MM) dual/triple wavelength configurations, or in SM/MM or coarse wavelength-division multiplexing (CWDM) quad-wavelength versions. The OTDR is operated with a standard 5 V USB charging system. It can also be connected to a laptop via the USB cable for real-time OTDR operation on Windows or via Bluetooth to a compatible Android phone or tablet. ***Terahertz Technologies Inc**, 169 Clear Rd, Oriskany, NY 13424, www.teratec.us*



High-resolution-display oscilloscopes

Tektronix has launched its 3 Series mixed domain oscilloscope (MDO) and 4 Series mixed signal oscilloscope (MSO). Designed for ease of use, the instruments feature intuitive touch-screen user interfaces and what the company claims is the largest and highest-resolution display in their class. The compact 3 Series MDO can cover a wide range of debugging and validation tasks. It offers a built-in spectrum analyzer up to 3 GHz, with a separate RF input and specifications comparable to a standalone analyzer. Sixteen digital input channels are available for mixed-signal analysis. The 4 Series MSO offers bandwidths up to 1.5 GHz and uses 12-bit analog-to-digital converters. It offers six input channels; when a logic probe is connected, FlexChannel technology lets any input channel be converted from an analog signal to eight digital channels. ***Tektronix Inc**, 14150 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com*

Optical thickness gauge

Bristol Instruments has added the model 157LS optical thickness gauge to its line of interferometer-based precision instruments. It uses light to measure material thickness up to 40 mm, with an accuracy of ±0.1 μm and a repeatability of ±0.02 μm, and without damage or deformation. Total thickness and up to 31 individual layers can be measured simultaneously. The new model extends the company's precise thickness-measurement capability to applications such as multielement lens assemblies and thicker optical components. ***Bristol Instruments Inc**, 770 Canning Pkwy, Victor, NY 14564, www.bristol-inst.com*

Soft x-ray solid-anode source

McPherson now offers 30 W electron-impact soft x-ray sources in single- and multi-anode versions, which it claims are a unique source of photons above ~70 eV. The compact model 642 can be used for soft x-ray measurement and wavelength calibration. Its dual output of equivalent beams also makes it useful for comparative applications such as spectroscopy and metrology. The x-ray photons follow the anode valence band structure, with line emissions from ≪1 nm to 25 nm. The model 642 is available as a single-anode source; the anodes can easily be exchanged at atmosphere. The larger model 642-1 has a multiple-anode carousel that lets users exchange anode materials without breaking vacuum. Operation is continuous wave; pulsed is optional. The option also exists to water cool the anodes and operate with power as high as 300 W. ***McPherson Inc**, 7A Stuart Rd, Chelmsford, MA 01824, https://mcphersoninc.com*

EDS system detectors

Ametek Edax has added a 160 mm^2 detector to its Elite T energy dispersive spectroscopy (EDS) system for transmission electron microscopes. The Elite T EDS system uses fast silicon drift detectors, now with 70 mm^2 and 160 mm^2 options and state-of-the-art integrated electronics. The system's geometric design provides an optimized solid angle that increases the count rates. The Elite T EDS system includes windowless detectors and does not require the typical protective window in front of the module. That design improves the light element sensitivity of the detector, enhancing the mapping speed and light element detection in low concentrations. It also allows flexibility for placement of the sensor to ensure the maximum exposure to the signal. The system is equipped with a precision motorized slide and optional shutter. ***Edax Inc**, 91 McKee Dr, Mahwah, NJ 07430, www.edax.com*

Electronic design software

Keysight has announced PathWave Design 2020, which includes the latest releases of its electronic design-automation software to accelerate workflows for RF, microwave, 5G, and automotive design. According to the company, the software suite's new tools and enhancements can shorten the design cycle and speed product development. Its libraries and customized simulators reduce setup time, and improved automation lessens manual work. The software integrates circuit design, electromagnetic simulation, layout capabilities, and system-level modeling. It reduces the time needed to import and export designs and to fix errors associated with changing tools. Improvements in data analytics allow for rapid analysis, such as on circuit simulations. ***Keysight Technologies Inc**, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Wide-bandwidth vector signal transceiver

National Instruments has expanded its vector signal transceiver (VST) product family to cover applications in X-band, K_u-band, and K_a-band radar and satellite communications components and systems. The PXIe-5831 VST delivers 1 GHz of instantaneous bandwidth for generation and analysis. A high-performance field-programmable gate array lets users perform fast, optimized measurements, inline signal processing, and high-speed data transfer. The PXIe-5831 combines the PXIe-5820 baseband VST with the PXIe-3622 vector-signal upconverter and downconverter for direct RF generation and analysis from 5 GHz to 21 GHz. Modular millimeter wave heads expand coverage to include frequencies from 23 GHz to 44 GHz with integrated and calibrated switching for up to 32 channels. That enables multichannel beamformer and phased-array measurements without the need for additional infrastructure. ***National Instruments Corporation**, 11500 N Mopac Expwy, Austin, TX 78759-3504, www.ni.com* PT

PHYSICS TODAY PRODUCT PICKS

OBITUARIES

Michael Pollak

Michael Pollak, a professor emeritus of physics at the University of California, Riverside, died on 22 March 2019 at home in San Luis Obispo. Mike excelled in both theory and experiment and was a thinker ahead of his time.

Mike was born on 1 September 1926 in Ostrava, Czechoslovakia. In 1940 he and his family immigrated to Palestine (now Israel), though Mike did return to Czechoslovakia for a time after the end of World War II. He received a BSc in electrical engineering from the Israel Institute of Technology (now the Technion) in 1953. Two years later he immigrated to the US and entered the University of Pittsburgh, where he earned an MS in 1957 and a PhD under Robert Keyes in 1958. For his thesis, he used piezoresistance measurements to study the conduction band of germanium.

After his graduate studies, Mike joined Bell Labs in Murray Hill, New Jersey, as a postdoc. In 1960 he accepted a permanent position as a staff scientist at Westinghouse Research Laboratories in Pittsburgh before becoming a professor at UC Riverside in 1966. Although he officially retired from the university in 1993, he continued to teach through 1998 and remained active in research. In his most recent publication, in January, he emphasized that the vast majority of materials on Earth are noncrystalline, from which it follows that methods to predict the materials' transport properties are linked to understanding disordered insulators in a fundamental way.

One of us (Castro Neto) was inspired by Mike's experimental and theoretical studies on electronic properties of DNA. Published in the mid 1960s, they are possibly the earliest works in which DNA was thought of as a disordered one-dimensional conductor. As Mike confided to Castro Neto, "It was too early, too soon" to receive appropriate attention from the scientific community. Not until the 1990s did 1D materials again became a hot topic in the context of Luttinger liquids and carbon nanotubes.

In the realm of conduction in disordered semiconductors, Mike was one of only a few contemporary physicists to be cited in the Nobel addresses of both Nevill Mott and Philip Anderson. He is best known for his proof that the Coulomb interaction between electrons in disordered Anderson insulators must cause the density of electronic states to vanish at the Fermi energy. That phenomenon became known as the Coulomb gap, and the system as the electron glass.

One consequence of Mike's result was that the electrical conductivity of the electron glass must vanish in the low-temperature limit more rapidly than Mott's variable-range-hopping prediction. In deriving the DC conductivity, Mike used percolation theory rather than Mott's local optimization scheme. Doing so revealed that Mott's optimized electronic transitions were also described by the smallest possible values of the largest resistance required to generate a connected conducting path across the system. One of us (Hunt) was influenced by Mike's work in the 1980s and 1990s on very slow relaxation processes and glass transitions in glassy electronic systems, work that connected with AC conductivity and dielectric relaxation in other frequency ranges Mike had investigated decades earlier.

At an afternoon tea gathering at Bell Labs in 1959, Mike and one of us (Geballe) learned from Anderson that he had been analyzing the impurity wavefunctions in silicon being mapped out by George Feher with his newly developed electron-nuclear double-resonance scheme. Anderson said there should be an observable contribution to the dielectric constant at doping levels just below those needed to form an impurity band.

Mike and Geballe measured the frequency-dependent conductivity with a series of properly doped samples, and with Mike's experimental skill we found convincing evidence. In 1960 we went to the International Conference on the Physics of Semiconductors, where Mike presented our work. It was held in Prague during a rare instance in which science, culture, and freedom intersected

Michael Pollak

behind the Iron Curtain. The conference attendees were invited to a spectacular performance of Antonín Dvořák's *Rusalka*. We went from our hotel to the opera house in an old-style streetcar. Mike was in his element, striking up random conversations—sprinkled with his usual banter and laughter—with nearby strangers.

His "drawn-out humor," as Mike translated it, was exactly the same in Czech. Mike's mother, an English teacher in Prague, enjoyed the freedom of showing us around town. I recall visiting a Jewish synagogue and the Old Jewish Cemetery, which I was told had been preserved by the Nazis for a museum to a past era. The joy of the mother–son reunion was tempered by his mother's unease that Mike might be detained at the airport, as his earlier departure from Czechoslovakia after World War II was not through official channels. Typical of Mike's perspective and positive attitude, he was unconcerned; he knew of worse places to be than postwar Czechoslovakia. Mike's contributions, both professional and personal, will remain lasting gifts.

Antonio H. Castro Neto
National University of Singapore
Theodore H. Geballe
Stanford University
Stanford, California
Allen G. Hunt
Wright State University
Dayton, Ohio

David James Thouless

Preeminent condensed-matter physicist David James Thouless, an emeritus professor of physics at the University of Washington (UW) and a 2016 Nobel laureate, passed away on 6 April 2019 in Cambridge, UK. His most notable contributions are the so-called Thouless energy for electron transport in disordered media; Kosterlitz–Thouless (KT) phase transitions in two-dimensional equilibrium; the TKNN topological invariant, which explains the perfect quantization in the integer quantum Hall effect; and the Thouless adiabatic charge pump. He himself identified topological phenomena as the common thread throughout his work.

David was born on 21 September 1934 in Bearsden, Scotland. After earning his physics undergraduate degree in 1956 from Cambridge University, he went to Cornell University; he received his PhD there in 1958. He did his thesis work, applying perturbation methods to nuclear-matter theory, under adviser Hans Bethe. He conducted research at the University of California, Berkeley, and at the University of Birmingham under mentor Rudolf Peierls before returning to Cambridge in 1961 as a lecturer and fellow of Churchill College.

That same year, only three years after getting his PhD, David published his monograph *The Quantum Mechanics of Many-Body Systems*. The impact was swift. In his UW office in Seattle after he and his wife, Margaret, moved back to Cambridge in 2016, I and several colleagues found translations in Russian from 1963 and in German and Japanese from 1964.

David accepted a professorship in mathematical physics at the University of Birmingham in 1965. It was there in 1973 that he and Michael Kosterlitz wrote the KT papers, with a core message that order–disorder phase transitions can be topological in nature and do not necessarily involve a change in a local order parameter.

Phase transitions display spontaneous broken ergodicity. At boiling, a gas and liquid coexist but do not fluctuate into each other and can be distinguished locally by a jump in the order parameter density. The classification of phase transitions by local order parameters dates back to Johannes van der Waals in 1873 and was canonized by Lev Landau in 1937. Superfluid helium-4 films escape that classification. The onset of disorder is expressed by a nonlocal string-type order parameter, which represents vortex–vortex interactions.

Topological phase transitions are not necessarily a fundamental departure from the Landau theory. Nonlocal topological order often turns local under duality-type phase transitions. The point is that KT fundamentally revolutionized our approach to all phase transitions. I routinely represent them all in terms of topological domain-wall-type deconfinement.

David liked to say that theory typically lags behind experimental discoveries. But that's not the case with KT transitions, also known as BKT transitions to credit Vadim Berezinskii's contribution. David Bishop and John Reppy confirmed the theory's predictions in superfluids only five years later, in 1978. During a 1999 symposium in Seattle on the occasion of his 65th birthday, David was presented with a framed copy of their original data. He hung it in his office next to his Wolf Prize certificate; the cherished gift now resides in the Nobel Prize Museum.

David and Margaret moved to Seattle in 1980, where both held UW faculty positions—Margaret, a virologist, taught in the School of Public Health. It was at UW that David, Mahito Kohmoto, Peter Nightingale, and I discovered in 1982 the TKNN topological invariant that explains the integer quantum Hall effect. The Hall conductance, we found, is an observable that can be expressed as a closed contour integral. That property explained why the Hall conductance can only yield a multiple of e^2/h and why it is topologically protected from adiabatic disturbances, disorder in particular. That work turned out to be an application of Chern invariants and later served as an example of a Berry phase.

This decade we are witnessing a technological revolution in experimental control at the atomic level that is leading to novel quantum materials with phases that are generalizations of the TKNN invariant, including topological insulators. The renewed interest in our work, and how it affects current research, coincides with David being awarded the Nobel Prize in Physics in 2016. It was almost too late because of his health, but at the Nobel ceremony in Stockholm, my family and I were able to witness him cognitively enjoying receiving the prize.

In the preface to his 1998 monograph *Topological Quantum Numbers in Nonrelativistic Physics*, David reflected on a discussion he'd had with Hans Dehmelt, the other Nobel laureate in the UW physics department. Dehmelt wondered "how the quantum Hall effect could possibly be used to determine the fine-structure constant when so little was known about the details of the devices used." Dehmelt received his physics Nobel in 1989 for the development of the ion trap. Next to his office, he displayed a Barnett Newman–like painting of perfect blue with one single dot, which resembled a trap filled with a single ion. In my presentations, I often contrast that reductionist painting with Vincent van Gogh's *Starry Night*, filled with vortices and chaos, to illustrate how complex systems include observables that are topologically protected and perfect. David played a central role in that fundamental shift in the paradigm.

Marcel den Nijs
University of Washington
Seattle PT

David James Thouless

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www.physicstoday.org/obituaries

Fritz Rohrlich
12 May 1921 – 14 November 2018

James Robert Anderson
23 September 1934 – 25 March 2018

Geoffrey V. Marr
30 January 1930 – 16 May 2017

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Arianna Bottinelli is a postdoctoral researcher in crowd dynamics at Inria Rennes in France. **Jesse Silverberg** is CEO and research director of Multiscale Systems Inc in Worcester, Massachusetts.

When dense crowds act like soft solids

Arianna Bottinelli and Jesse L. Silverberg

Although mass gatherings of people are normally safe, sometimes their physical interactions prevail over social norms and peaceful events can become disasters.

On a late June afternoon in 2017, one of us (Bottinelli) was passing by San Carlo Square in Turin, Italy. It was a warm, beautiful day with a festive vibe as people gathered to watch a soccer championship final on a large screen. Around 10:00pm, a loud bang—perhaps a fire cracker exploding or a security barrier falling over—startled several people and triggered a stampede. The festive summer night turned tragic, with some 1500 people injured and two fatally trampled. Sadly, such low-probability, high-impact tragedies happen during the friendliest mass gatherings and with little warning.

The crowd-dynamics research community strives to understand a broad range of human collective behavior—from stampedes like the one in San Carlo Square to pedestrian motion on sidewalks. That interdisciplinary effort has led to several advances, such as continuum hydrodynamic models that treat crowds as fluids and computer-vision techniques that detect anomalous behavior of thieves in public places. Those approaches work well when the crowd density is fairly low and people are generally able to move toward an intended destination.

But when the density reaches the level found at rock concerts, parades, and pilgrimages, people start to bump and press against each other. The physical properties of the crowd are no longer fluid-like but instead are closer to soft solids and granular materials. At such densities, pedestrians can be modeled as self-propelled particles subject to forces that represent social and physical interactions. Even though those social force models are simplifications of real crowds and require careful calibration to be predictive, they can qualitatively reproduce emergent crowd dynamics (see the Quick Study by Andrea Welsh, Edwin Greco, and Flavio Fenton, PHYSICS TODAY, February 2017, page 78). More generally, analogies between human crowds and physical systems have repeatedly demonstrated their utility for understanding crowd collective motion.

Conceptual analogies

A classic model for crystals is the ball-and-spring network, in which balls are positioned on a regular lattice and springs connecting nearest neighbors represent interactions given by physical potentials. That model leads to an exact expression for the dispersion relation, which relates the frequency and wavelength of vibrations propagating across the crystalline lattice. The vibrations are the lattice's elementary excitations and are essential for understanding bulk material properties, such as heat capacity and thermal conductivity. Vibrational modes thus provide a bridge between the large-scale collective properties of the crystal and the small-scale physical interactions of neighboring balls. When studying dense groups of people, modes are similarly useful because they relate large-scale collective crowd motion to the underlying network of physical contacts between people.

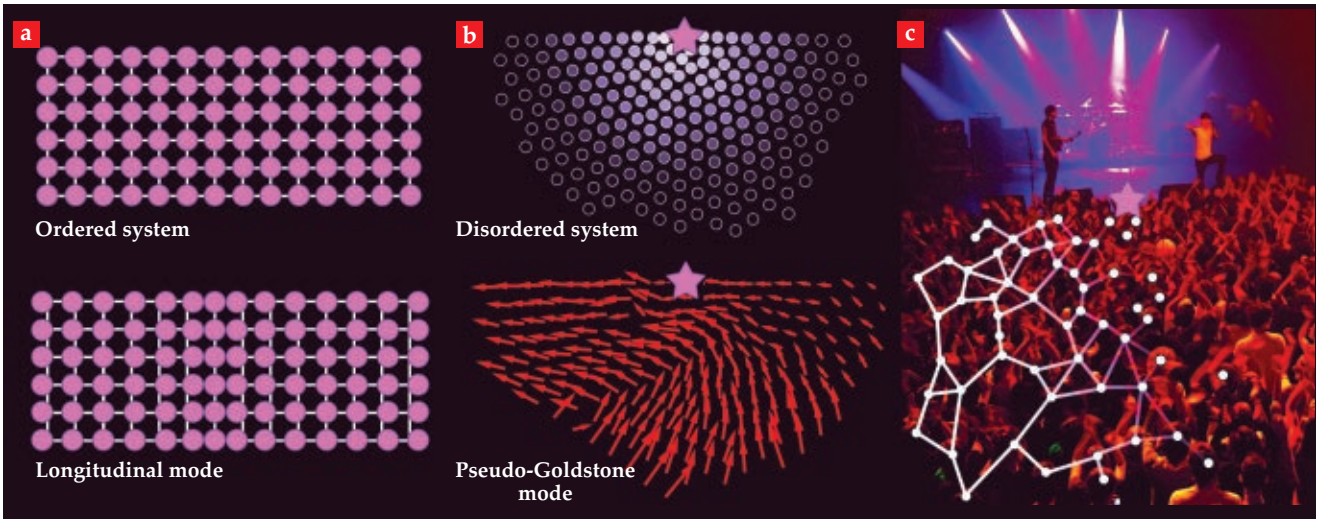
Examples abound of noncrystalline solids in industrial and technological applications: sand, coffee beans, and highly packed wheat grains, among others. Unlike crystals, granular materials exhibit a disordered, self-organized structure generated by complex interactions between grains (see the article by Anita Mehta, Gary Barker, and Jean-Marc Luck, PHYSICS TODAY, May 2009, page 40). To understand the properties of those and similarly dense and disordered systems, physicists have adopted an approach closely related to that used for studying crystalline solids.

When modeling grains and their interactions as a ball-and-spring network, physicists replace the regular lattice configuration of crystals with a quenched disorder—that is, a disorder frozen in time. Although that model was originally developed for granular materials, the disordered structure of the packings in two dimensions resembles that found in high-density crowds. And regardless of why a system might be disordered, one can ask how such disorder affects vibrational properties.

When scientists compute the modes for disordered packings, they find that the familiar system-spanning vibrations are almost entirely replaced by spatially localized vibrational patterns, typically correlated over a few neighboring grains. Three points are relevant. First, the specific spatial pattern of the localized vibrations is deeply connected with the underlying disorder. Second, disordered systems have an excess of low-energy, easily excited modes compared with those found in crystals. Those modes are quasi-localized, meaning they extend over a characteristic length scale—larger than a few grains but smaller than the system. Thus, when excited, they drive motion over the corresponding length scale. Third, grains are not constrained by a lattice structure, so they can rearrange their positions.

Vibrational analysis is a powerful tool for studying crowd dynamics because unlike more traditional approaches using force models, no crowd-system model needs to be built or calibrated. At its heart, the technique produces a correlation matrix that converts apparently random displacements of grains about their equilibrium position into specific predictions of coordinated motion.

Four years ago we had the idea to apply mode analysis to a simple, social-force model of crowds attracted to a point of interest, such as the stage of a rock concert, as shown in the



COLLECTIVE MOTION IN DENSE CROWDS. An ordered lattice **(a)** exhibits long-range collective motion in the form of vibrational modes, such as the longitudinal mode. **(b)** Individuals in a dense crowd gathering at a point of interest (star) pack into a disordered blob—the greater the pressure among people (dots), the brighter they are—with their own emergent, long-range, collective motion. The pseudo-Goldstone mode, represented by a vector field (arrows), is an example of such collective motion. **(c)** Empirical data collection at rock concerts can be used to extract the crowd's vibrational modes that arise from the underlying contact network (nodes and links). (Photo courtesy of Ulrike Biets.)

figure. In addition to verifying the spatially localized modes common to other granular systems, we found that the lowest-energy mode extends across the entire system and gives rise to a bulk-scale collective motion. The excitation is so special that it has its own name—the pseudo-Goldstone mode—and is known to originate from the model's broken translational symmetry. In this case, symmetry is broken by a point of interest that attracts the crowd.

Whether that collective motion is activated in a given crowd depends on how the crowd is perturbed and on how much energy comes from the perturbations. Testing that dependence and measuring the minimum perturbation energy needed to activate a pseudo-Goldstone mode requires fieldwork to gather video data on real crowds in high-density conditions.

Emergent collective motion can be activated in various settings—concerts, Black Friday sales, protests, religious pilgrimages, and sporting events, among others—simply because high-density crowds are disordered systems. Furthermore, the fact that pseudo-Goldstone modes have low energetic costs could explain why the density waves and their associated deadly pressures can emerge without notice and propagate across a crowd.

Ethics and experiments

Physical models of crowds explore a simplified model of reality, but how do they stack up to real groups of people? Can the models explain human psychology? How much energy is required to activate a pseudo-Goldstone mode? It's difficult to answer those questions without evidence, so we naturally turn to empirical data. Right away we run into a problem: It's not ethical to trigger a crowd disaster for the sake of science. And yet little observational data on crowd disasters is available for the vibrational-mode analysis described here.

What makes for good observational data? Ideally, one would have coordinates $[x_i(t), y_i(t)]$ for all $i = 1, \ldots, N$ people in the crowd over a period of time lasting minutes to hours. In the absence of volunteers who would wear tracking devices, we could extract the information from quantitative image analysis applied to security-camera footage. That approach requires an elevated, stationary, and continuous view of as much of the crowd as possible. Even so, predictions for collective motion cannot be validated unless it actually occurs. Given the significant potential for injury during such motions, we find ourselves in the dismaying position where we both do and don't want to observe their emergence.

The path ahead

What's next for collective motion studies of high-density crowds? Because research ethics rule out broad categories of experiments, we plan to take an observational approach to press several questions. Can a pseudo-Goldstone mode be measured in a real crowd? If so, does it predict the crowd's actual collective motion? Can the analyses be used to prevent crowd disasters?

Fortunately, we happen to enjoy going to concerts, and if you've ever been to a hard-rock show, you're already well aware of the high crowd densities near the band stage and of the way crowds tend to move as a collective whole. The path ahead? We're going to concerts. And we're taking our cameras.

Additional resources

▶ S. Henkes, C. Brito, O. Dauchot, "Extracting vibrational modes from fluctuations: A pedagogical discussion," *Soft Matter* **8**, 6092 (2012).

▶ A. Bottinelli, D. T. J. Sumpter, J. L. Silverberg, "Emergent structural mechanisms for high-density collective motion inspired by human crowds," *Phys. Rev. Lett.* **117**, 228301 (2016).

▶ J. L. Silverberg et al., "Collective motion of humans in mosh and circle pits at heavy metal concerts," *Phys. Rev. Lett.* **110**, 228701 (2013).

▶ D. C. Duives, W. Daamen, S. P. Hoogendoorn, "State-of-the-art crowd motion simulation models," *Transp. Res. Part C: Emerg. Technol.* **37**, 193 (2013).

▶ D. Helbing, A. Johansson, H. Z. Al-Abideen, "Dynamics of crowd disasters: An empirical study," *Phys. Rev. E* **75**, 046109 (2007).

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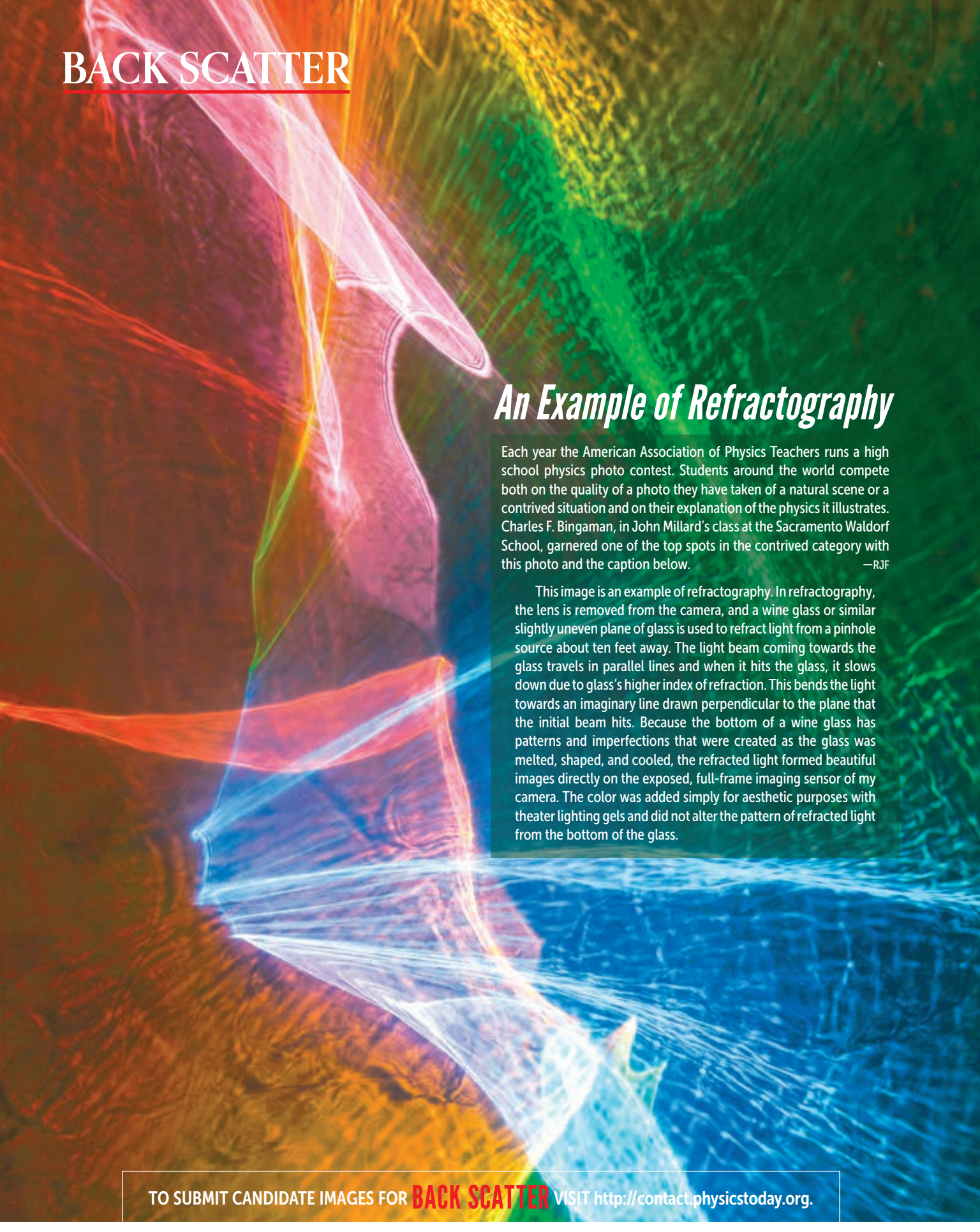
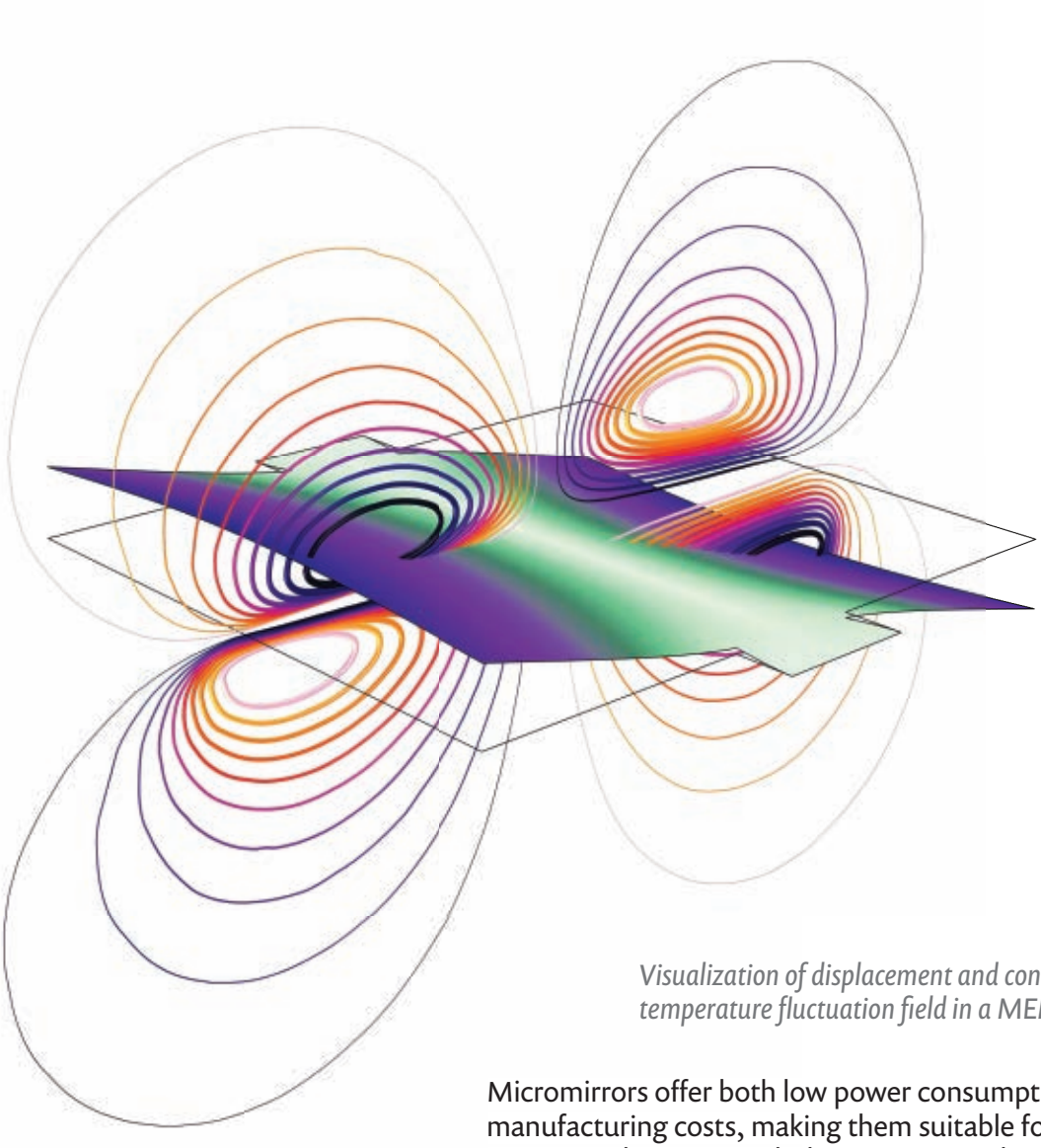


An Example of Refractography

Each year the American Association of Physics Teachers runs a high school physics photo contest. Students around the world compete both on the quality of a photo they have taken of a natural scene or a contrived situation and on their explanation of the physics it illustrates. Charles F. Bingaman, in John Millard's class at the Sacramento Waldorf School, garnered one of the top spots in the contrived category with this photo and the caption below. —RJF

This image is an example of refractography. In refractography, the lens is removed from the camera, and a wine glass or similar slightly uneven plane of glass is used to refract light from a pinhole source about ten feet away. The light beam coming towards the glass travels in parallel lines and when it hits the glass, it slows down due to glass's higher index of refraction. This bends the light towards an imaginary line drawn perpendicular to the plane that the initial beam hits. Because the bottom of a wine glass has patterns and imperfections that were created as the glass was melted, shaped, and cooled, the refracted light formed beautiful images directly on the exposed, full-frame imaging sensor of my camera. The color was added simply for aesthetic purposes with theater lighting gels and did not alter the pattern of refracted light from the bottom of the glass.

Predict micromirror performance with multiphysics simulation.



Visualization of displacement and contours of the temperature fluctuation field in a MEMS micromirror.

Micromirrors offer both low power consumption and low manufacturing costs, making them suitable for a variety of MEMS applications, including imaging technology. To design MEMS micromirrors that perform as expected, you need to account for thermal and viscous damping. Multiphysics simulation helps you do so efficiently and accurately.

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