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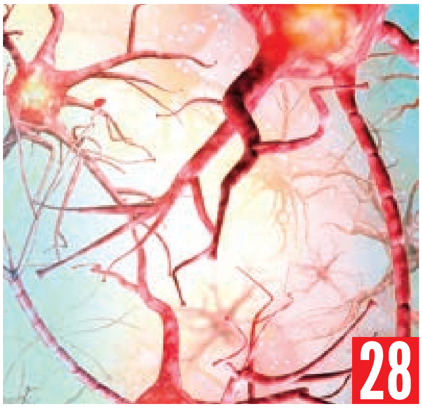

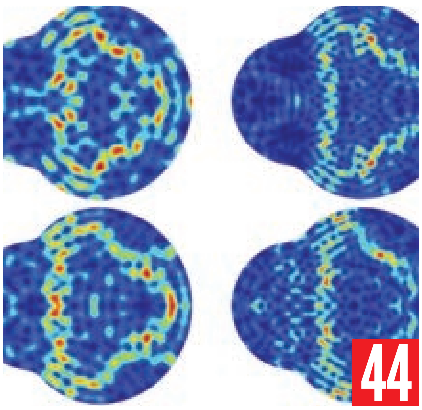

ON THE COVER: When a drop of diluted bourbon evaporates on a glass coverslip, the residual solids can leave behind an intricate weblike pattern. For a web to form, the drop's alcohol concentration typically must fall in the range of 20–25% alcohol by volume (ABV). The "whiskey web" shown here comes from a 12-month-old sample at 20% ABV, manufactured by Brown-Forman Corp. For a discussion of the fluid dynamics behind such patterns, turn to the Quick Study on **page 62**. (Image courtesy of Stuart J. Williams, University of Louisville.)

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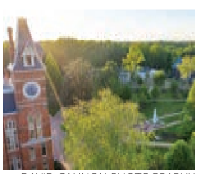

DAVID CANNON PHOTOGRAPHY

Undergrad physics

In 2008 Effrosyni Seitaridou joined Emory University's Oxford College in Georgia as the only tenure-track physics professor. In a recent essay, she describes how she bolstered the college's physics department by developing a clear mission statement and offering students research opportunities and meaningful advising.
physicstoday.org/Feb2021a

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Transient tracking

Astronomers in South Africa are developing a telescope network that will quickly and automatically observe transient objects, such as fast radio bursts, that are detected by other observatories. The project could gain importance once the Vera C. Rubin Observatory in Chile begins its high-resolution sky survey next year.
physicstoday.org/Feb2021b

UNESCO

US and UNESCO

Many scientists and policymakers hope that the Biden administration will rejoin not only the Paris climate agreement and the World Health Organization but also UNESCO, Physics Today's Toni Feder reports. The international group's initiatives address such issues as biodiversity, sustainability, and open access to science.
physicstoday.org/Feb2021c

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FROM THE EDITOR

The future of meetings

Charles Day

In 1911 the first of a series of biennial physics conferences funded by Belgian industrialist Ernest Solvay took place in Brussels. Chaired by Hendrik Lorentz, the invitation-only gathering was devoted to the theory of radiation and quanta. World War I and the influenza pandemic of 1918–19 interrupted the conferences. They resumed in April 1921.

The Solvay conferences' prompt resumption portends the revival of scientific meetings once the current COVID pandemic abates. Even now, as the first vaccines are beginning to be deployed and administered, it's possible to travel. If this year's April meeting of the American Physical Society (APS) were still being held in Sacramento, California, I could choose from several round-trip flights from Washington, DC, where I live, all for a reasonable $300 or so.

But just because scientists will be able to attend meetings again doesn't mean they'll still want to in the same way. It's worth exploring whether our experiences of the pandemic will transform when, where, and how meetings are held and conducted.

Hints of what's to come appeared in December's issue of *Washingtonian* magazine, which included the results of a mostly light-hearted survey of behavior and attitudes in times of COVID. Two readers' answers to the question about the worst day at work pertained to meetings: "6-hour Zoom workshop!" and "Panic attack on a Zoom call." Scientists will likely relish returning to the warmth, spontaneity, and serendipity of in-person meetings.

The same survey also asked readers what COVID adaptations they'd like to keep. "Extra time with my family" scored a response of 52% behind "takeout cocktails" (72%), "streeteries" (66%), and "curbside pickup for just about everything" (64%).

What COVID adaptations might scientists want to keep? Twice a year, new astronomy and physics faculty members are invited to attend a workshop hosted by APS, the American Association of Physics Teachers, and the American Astronomical Society. Usually, the workshop is held at the American Center for Physics in College Park, Maryland. Last year's fall event was held virtually. To quote Leah Poffenberger's story in December's *APS News*, "Based on the success of this year's online workshop, more New Faculty Workshops will likely go online in the future, even when the option to meet in person is available again."

During the pandemic the editorial boards of scientific journals and the governing boards of scientific societies have been meeting remotely. Meetings that consist largely of listening to presentations will likely remain online. Flying across country to sit in a room for 1–2 days will become less compelling, I suspect.

The Farnborough International Airshow in the UK, the North American International Auto Show in Detroit, and the Consumer Electronics Show in Las Vegas—to name three big international trade shows—will likely return to full, pre-pandemic intensity. It's too difficult to demonstrate new products except in the real, 3D world.

I'm less optimistic about the exhibits that accompany scientific meetings. Providing space for companies to display their wares to scientists is not the raison d'être of most scientific meetings. Attendees might wander the aisles of an exhibit floor to take a break from talks or to search for free refreshments. But in my experience, most booths have considerable amounts of visitor-less downtime.

Exhibitors who attend scientific meetings have pivoted to engaging potential customers through webinars and by upping their press release game. If those marketing efforts prove successful, I wonder if exhibitors will ever return to sending marketing staff, product samples, and portable booths to distant convention centers.

I also wonder about the continued viability of giant scientific meetings. The largest I've attended, the annual meeting of the American Chemical Society, was, it seemed to me, a collection of smaller meetings that happened to be in the same place at the same time. I like to think that inorganic chemists attended sessions on organic chemistry, but the scheduling of parallel sessions likely frustrated them.

Granted, giant meetings foster a sense of shared purpose through plenary talks and the presence of so many fellow professionals. But if the exhibit halls fizzle and if plenary talks are offered to members online, the days of the giant meeting could be numbered.

Indeed, when I look back at the meetings I've attended first as an astronomer and then as an editor, the small, focused ones stand out as the most worthwhile. Those, I predict, will survive and thrive. PT

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COURTESY OF KAITLIN M. BAUDIER, ARIZONA STATE UNIVERSITY

In his article "Does new physics lurk inside living matter?" (PHYSICS TODAY, August 2020, page 34), Paul Davies mentions many interesting phenomena in biology, including epigenetic influence in two-headed worms. I agree that such information might be important to both physics and biology.[1]

As I finished reading, I realized the article is advocating quantum biology. Davies cites a claim made by researchers in 2015 "that many biologically important molecules, such as sucrose and vitamin D3, have unique electron-conductance properties associated with the critical transition point between an insulator and a disordered metal conductor."

What I do not know is this: How could bulk material properties such as electron conductance be defined at the molecular level? In my opinion, geometry will be more important than material properties at that level.

Reference

1. J. J.-L. Ting, *J. Appl. Phys.* **125**, 144702 (2019).

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Paul Davies (PHYSICS TODAY, August 2020, page 34) states, "The synthesis of [Claude] Shannon's information theory and thermodynamics led to the identification of information as negative entropy." The second law of thermodynamics states that the overall result of any real physical process leads to an increase of entropy, or in an ideal process, the overall entropy remains constant, but there is no process that leads to an overall decrease of entropy. If information is negative entropy, then any real process destroys some information somewhere, or an ideal process preserves the overall information, but no process can increase the overall information in the universe.

DNA stores information, and living systems utilize it. How, then, did life begin from lifeless chemicals? Is the answer to that question the "new physics" that is required to reconcile physics and biology?

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The article by Paul Davies (PHYSICS TODAY, August 2020, page 34) addresses the importance of information theory in biological systems. As pointed out by Erwin Schrödinger, biological systems gain negative entropy from food and have tremendously less entropy than physical or thermodynamical systems.

Let me quantify that statement. Claude Shannon showed that the entropy in information theory is related to a thermodynamical system through $-k_B N \ln p$, where k_B is the Boltzmann constant, p is the probability of a given state, and N is the state's number of degrees of freedom.[1] The fact that a biological system has huge negative entropy can be explained simply by considering N.

If a DNA molecule acts as one unit of a degree of freedom, as it should, the entropy of a human body is about 12 orders of magnitude smaller than that of a system having free molecules in equilibrium at the same temperature, since the molecular weight of a DNA molecule is approximately a trillion times that of, say, a water molecule. That is, human cells are better ordered by a huge factor (10^{12}) than is a system in thermodynamic equilibrium.

That factor allows the human system to work with a thermal efficiency much higher than a supercomputer's. In a chess game between a person and a supercomputer, for example, the energy efficiencies differ by about six orders of magnitude. A human brain weighs about one-millionth of what a supercomputer does; thus the efficiency per unit weight of a human brain can be 1 trillion times greater, in agreement with the amount of negative entropy of the human cell system.

Since the molecular weight of human DNA is not much different from that in other living cells, a similar argument applies to most living systems. Most other animals do not play chess, but the amount of information processed in their visual and other sensory systems can be similar in magnitude to the human brain's processing capacity. Furthermore, I would say that life is a process of maintaining the system's huge negative entropy through cell division (reconstruction of a cell) and autophagy, while disease and death arise in the gradual and sudden increase of internal entropy or loss of negative entropy.

Reference

1. See, for example, L. Brillouin, *Science and Information Theory*, Academic Press (1962).

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▶ **Davies replies:** I greatly appreciate this helpful feedback on my article "Does new physics lurk inside living matter?" Julian Ting raises a question about quantum tunneling through organic molecules. Single-molecule conductance experiments are now established technology and are being developed for DNA sequencing. Ting is correct that the geometrical configuration of the molecule can be extremely important, especially in the case of folded versus unfolded peptides.

However, although individual organic molecules may be insulators or conductors, I am unaware of any simple relationship between single-molecule conductance values and bulk conductance values. The full details of the claimed "quantum criticality" of key biological models may be found in the paper by Gábor Vattay and coauthors,[1] which I cited in my article. I discuss other examples of quantum tunneling in organic molecules in my book *The Demon in the Machine: How Hidden Webs of Information Are Solving the Mystery of Life* (2019). The discussion there includes the important work of my Arizona State University colleague Stuart Lindsay on tunneling through nucleotides and peptides.

Edwin Kerr touches on what I regard as one of the deepest outstanding challenges in explaining life's origin: the emergence of encrypted-information processing—what biologists call translation (from the 4-letter DNA alphabet to the 20-letter amino-acid alphabet). All known terrestrial life uses a common code, an encryption–decryption system. There is no agreement about how the specific coding assignments, or indeed *any* coding assignments, first evolved. How did such "software" come out of chemistry—that is, "hardware"? As Kerr surmises, I do indeed think that this transition is where new physics may lie. I should clarify, however, that the accumulation of information in living matter is entirely consistent with the second law of thermodynamics: Living organisms are open systems, and they export entropy into their surroundings to pay for the information gained.

Finally, I am grateful to Akira Hasegawa for emphasizing the astonishing thermodynamic efficiency of the human brain, which deploys legions of Maxwell-demon-like molecules to operate gated ion channels that enable information to propagate between neurons with relatively little waste heat.

Reference

1. G. Vattay et al., *J. Phys.: Conf. Ser.* **626**, 012023 (2015).

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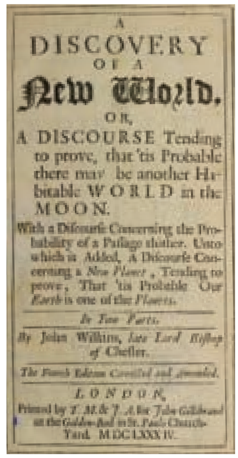
Journey to where outer space begins

Jonathan McDowell's Quick Study "Where does outer space begin?" (Physics Today, October 2020, page 70) gives an excellent outline of the rationale for adopting a definition based on the balance between gravity and aerodynamic force and justifying an 80 km altitude as a boundary between aeronautical and astronautical domains. It also notes the physiologically derived Armstrong limit of 19 km, where blood begins to boil.

As I recount in reference 1, in 1684 John Wilkins, an English clergyman and cofounder of the Royal Society, imagined that the Moon might be inhabited.[2] Although Wilkins recognized that the upper air was cold and thin and that there would be no inns en route to offer victuals and shelter, he affirmed that it might be "possible to make a Flying Chariot. In which a Man may sit, and give such a Motion unto it, as shall convey him through the Air. And this perhaps might be made large enough to carry divers Men at the same time" (page 184). He went on to make the remarkable prediction "That supposing a Man could Fly, or by any other means, raise himself Twenty miles upwards, or thereabouts, it were possible for him to come unto the Moon" (page 162).


A
DISCOVERY
OF A
New World.
OR,
A DISCOURSE Tending to prove, that 'tis Probable there may be another Habitable WORLD in the MOON.
By John Wilkins, late Lord Bishop of Chester.
LONDON,

TITLE PAGE from *A Discovery of a New World, or A Discourse Tending to Prove, that 'Tis Probable There May Be Another Habitable World in the Moon . . .* , 4th ed., by John Wilkins, 1684. (Public Domain Mark 1.0.)

Three centuries later those two benchmarks were met, only a few years apart. No human reached an altitude of 32 km (20 miles) until the Bell X-2 rocket plane hit 38.5 km in 1956, just 13 years before *Apollo 11* took men to the Moon. And although ballooning began long before heavier-than-air aviation, the 32 km threshold was not breached until the Stratolab High V balloon did so in 1961, shortly after Joseph Kittinger Jr's famous parachute jump of 31 km from the US Air Force's Excelsior III balloon in August 1960.

In space exploration, as in so many other long journeys, the first 20 miles are the hardest.

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1. R. D. Lorenz, *Exploring Planetary Climate: A History of Scientific Discovery on Earth, Mars, Venus and Titan*, Cambridge U. Press (2019).
2. J. Wilkins, *A Discovery of a New World, or A Discourse Tending to Prove, that 'Tis Probable There May Be Another Habitable World in the Moon . . .* , 4th ed. (1684), book 1.

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Correction

January 2021, page 23—Manitoba, Canada, was mistakenly listed as relying mainly on fossil fuels. Most of the province's energy is hydroelectric. PT

Borexino experiment detects neutrinos from the Sun's carbon-nitrogen-oxygen cycle

The cycle's catalytic reactions account for just 1% of the Sun's energy, but they are the dominant energy producers in heavier stars.

In 1920, Arthur Eddington proposed that the Sun shines from the fusion of four protons into helium nuclei. The proposal was inspired by Francis Aston's measurement earlier that year of the mass difference between the four protons and a helium nucleus and by Albert Einstein's revolutionary thesis on the equivalence of mass and energy. Despite those foundations, Eddington's idea faced what was then a reasonable objection: The Sun isn't hot enough to sustain nuclear fusion.

Quantum mechanics was in its infancy at the time. It took eight more years for George Gamow to realize that two protons could overcome their Coulombic repulsion and get close enough to fuse through quantum tunneling. In the late 1930s, Hans Bethe and Carl Friedrich von Weizsäcker, independently, finally deduced the detailed nuclear reactions in which hydrogen in stars is converted into helium: the proton–proton (pp) chain and the carbon-nitrogen-oxygen (CNO) cycle.[1]

FIGURE 1. THE BOREXINO NEUTRINO DETECTOR, after being wrapped in an aluminum-reinforced wool blanket in 2014 and after the installation of a temperature control system in 2019. Solar neutrinos are detected in its inner 8.5-meter-wide balloon filled with 280 tons of petroleum-based scintillator liquid. The scintillator emits flashes of light when the neutrinos scatter from its electrons.[2]

The relative importance of those two mechanisms depends mostly on stellar mass and the metallicity—the abundance of elements in the core that are heavier than helium. Hydrogen-burning stars like the Sun sustain themselves by converting four protons into a helium nucleus, with the release of two electron neutrinos and 26.73 MeV. In our Sun, a relatively low-mass star, 99% of helium synthesis occurs through the pp chain. The remaining 1% is made through the CNO cycle, in which the heavier elements carbon, nitrogen, and oxygen (known by astrophysicists as "metals") act as catalysts for hydrogen burning. It depends sensitively on a star's core temperature. Heavier stars have hotter cores, and the CNO cycle is the dominant mechanism in stars significantly heavier than the Sun. Like the pp chain, it releases two neutrinos for each ^{4}He nucleus.

Both sets of neutrinos emerge from the Sun's core and reach Earth in just eight minutes. In their flux—about 60 billion neutrinos per square centimeter per second—and energy distribution they carry a detailed account of the fusion reactions. But with a mean free path of roughly a light-year through rocky matter, neutrinos are exceedingly difficult to detect. Even so, for more than 50 years physicists have been catching glimpses via their weak interactions inside underground detectors made of tons of material. (See the article by John Bahcall, Frank Calaprice, Arthur McDonald, and Yoji Totsuka, PHYSICS TODAY, July 1996, page 30, and PHYSICS TODAY, December 2015, page 16.)

The most energetic solar neutrinos are born from the decay of boron-8. Although scarce, their high energy makes them relatively easy to identify by Cherenkov radiation or inverse beta decay. Others from the pp chain are lowest in energy but most abundant. By contrast, neutrinos from the CNO cycle occupy an elusive middle ground that, for observers, combines the worst of both worlds: They are both scarce and too low in energy to rise above background radioactivity.

But now, the Borexino detector at Italy's Gran Sasso National Laboratory has identified CNO neutrinos for the first time, and a collaboration of nearly 100 scientists have measured their interaction rate at just a handful of counts per day per 100 tons of scintillator.[2] “The measurement is heroic,” says Wick Haxton from the University of California, Berkeley. “No one anticipated that Borexino would be able to pull out the CNO signal from the background.” The achievement completes the spectroscopy of solar neutrino fluxes and isolates the mechanism that governs the evolution of stars more massive than our Sun.

Purification

Five years ago, the Borexino collaboration began its hunt for CNO neutrinos on the heels of its 2014 measurement of the spectral flux of pp neutrinos (see PHYSICS TODAY, November 2014, page 12). Like the pp neutrinos, the CNO neutrinos register when they scatter from electrons in the scintillator, whose light emission is picked up by photomultiplier tubes surrounding the scintillator tank. From the number of photons and their arrival times, researchers reconstruct the electron recoil energy and interaction point in the detector.

In operation since 2007, the neutrino detector was built with an onionlike structure to achieve the utmost radiopurity at its core. The inner sanctum, an 8.5-meter-diameter nylon balloon containing 280 tons of petroleum-based scintillator, resides inside another balloon filled with a buffer solution—both within a stainless-steel sphere studded with 2212 photomultiplier tubes. That sphere, in turn, is surrounded by a tank filled with 2400 tons of ultrapure water.

Shown in figure 1, the detector lies under 1.4 km of the Apennine Mountains, 120 km east of Rome. The overlying rock and surrounding water shield the detector from cosmic rays. The nylon barriers and buffer solution protect the innermost vessel from external sources of radioactivity and from gammas in the photomultiplier tubes. Besides those measures, the collaboration adapted distillation and filtration methods from petroleum engineering to purify the liquid scintillator.

Unfortunately, the very nature of the scintillation emission makes it impossible to distinguish a signal emitted by neutrino-scattered electrons from one emitted in nuclear beta decays or Compton scattered by γ rays. That means the radioactive background had to be kept at or below the level of the expected signal rate—a few tens of events per ton of scintillator per day. In contrast, materials such as air, water, and metals are usually contaminated with radioactive impurities at levels up to 100 000 decays per ton per second.

The CNO experiment ran from July 2016 to February 2020, with 1072 days of live time. The collaboration filtered the number of events in the detector’s 100-ton fiducial volume by applying selection criteria that removed contributions due to impurities, cosmogenic isotopes, and instrumental noise. Figure 2 shows the surviving count rate as a function of energy. The central task for the Borexino collaboration was to disentangle the signals of the CNO-neutrino recoil electron from those of cosmogenic ^{11}C and beta decays in bismuth-210. The collaboration was able to reduce the ^{11}C contributions by looking for their time correlation with cosmic rays, but ^{210}Bi, as part of the decay chain of the pervasive contaminant radon-222, was more insidious.

Temperature stabilization

The energy spectrum of the beta decay from ^{210}Bi is located in nearly the same energy window where the CNO neutrino–electron recoil signal is expected. Fortunately, another isotope, polonium-210, is a daughter of ^{210}Bi and in the same lead decay sequence. Being an alpha emitter, ^{210}Po is much easier to identify, so the collaboration used it as a proxy to study the behavior of ^{210}Bi. The ^{210}Po turns out to contaminate the scintillator by detaching from the wall of the inner nylon balloon. The upshot: The ^{210}Po (and hence ^{210}Bi) couldn’t be filtered away as part of the purification campaign.

Nevertheless, the researchers realized that they could effectively ignore the isotopes’ presence on the balloon and instead focus on protecting the purity of the fiducial volume inside it, from which signals are selected. That focus required them to eliminate any temperature fluctuations, which might induce convection currents in the scintillator and drive detached ^{210}Bi toward the center. To that end, they wrapped the detector in a wool blanket, shown in figure 1, to insulate it from room air.

The detector also sits on a floor in thermal contact with mountain rock that acts as a deep thermal sink. To stabilize the vertical convection, the researchers attached horizontal heating circuits to the detector. As a final measure, they installed a feedback-control loop in the experiment hall to stabilize the room’s temperature against variability from changes in the seasons. The effort paid off: From their observations of ^{210}Po, the researchers inferred the diffusion distance of ^{210}Bi (with a half-life of five days) as less than the separation between the balloon wall and the fiducial volume.

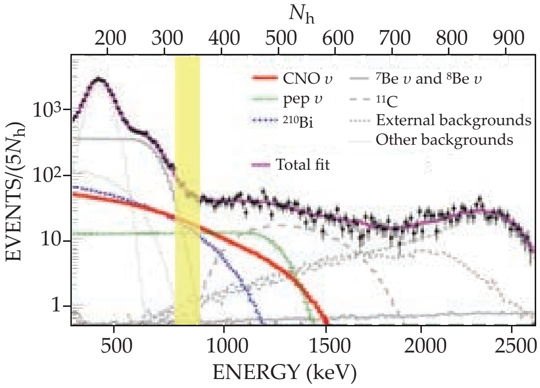

FIGURE 2. THE SPECTRAL FLUX (red) of carbon-nitrogen-oxygen neutrinos from the Sun is the distribution of recoil energies of scattered electrons. That signal is obtained by subtracting background contributions from other solar neutrinos such as proton-electron-proton (pep) neutrinos (dotted green), naturally occurring radionuclides such as bismuth-210 (dashed blue), and other sources of noise (gray). The black dots represent the total signal as a function of energy. N_h represents the number of photoelectrons detected by photomultipliers. The CNO signal is completely hidden in the background; the yellow band represents the region with the largest signal-to-background ratio for CNO neutrinos. (Adapted from ref. 2.)

Metallicity

After accounting for other neutrinos and subtracting the background radioactivity caught in the detector, the collaboration converted the handful of observed CNO neutrino interactions per day to derive a total flux of CNO neutrinos on Earth of $7.0^{+3}_{-2} \times 10^8$ cm^{-2} s^{-1}. That result quantifies the relative contribution of CNO fusion in the Sun at about 1%, as predicted by theorists. And because the CNO fusion cycle is catalyzed by reactions with C, N, and O, the neutrino flux depends directly on the abundance of those elements in the solar core.

Two long-established methods for determining the solar metallicity have given discordant results. Helioseismic data suggest that the Sun's interior is metal-rich, whereas photoabsorption measurements of solar surface abundances reveal an environment about 30% lower in metals. According to Frank Calaprice, one of the members of the Borexino collaboration, the newly published value for the flux is not precise enough to resolve the discrepancy, "but newer data taken in the few months since the paper was written lean toward a more metal-rich solar core."

According to Haxton, one explanation for the discrepancy may come from the effect of planetary formation on the early Sun. Jupiter and Saturn are both enriched in C and N by factors of 4 to 7 relative to the Sun's surface. Late in the evolution of the solar system, those planets are likely to have stripped as much as 90 Earth masses of metal from the remaining gas in the planetary disk. The late accretion of metal-depleted gas onto the Sun's chemically isolated convective zone could dilute the outer portion of the Sun.[3] Indeed, volatile elements such as C appear depleted in the accreting gas streams of very young, planet-forming systems.[4]

Mark Wilson

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4. M. K. McClure, *Astron. Astrophys.* **632**, A32 (2019).

Stretchy molecules rupture far from the crack

Newly observed molecular consequences of fracturing in an elastic sheet reveal some surprises.

FIGURE 1. IN THE BLINK OF AN EYE, a single pinprick can prompt an inflated balloon (shown here filled with water) to tear itself to shreds: The energy stored in the stretched latex is more than enough to power the rapidly propagating cracks. When less energy is available, damage in an elastic solid develops more slowly. The molecular details of material failure are key to how the process plays out. (Image by Jose Luis Stephens/Shutterstock.com.)

Anyone who's ever stuck a pin into a balloon knows well what happens next: The tiny puncture swiftly grows into one or more fractures that propagate across the balloon's surface. Captured by high-speed photography, as shown in figure 1, the phenomenon is spectacular.

Inflated balloons store so much energy in their stretched latex that they invariably burst when pierced. But elastic material failure isn't always so certain. Car tires, soft medical implants, and O-ring seals all routinely experience stresses and strains that may or may not be enough to cause them to rupture. The safe use of elastic materials depends on understanding just how much deformation they can withstand before they break. In other words, how much energy does it take to propagate a crack in a stretchy substance?

That complicated problem involves physics on multiple size scales, from the macroscopic bulk down to individual molecules. For decades, models that seek to span those scales have been stymied by a dearth of information. After all, it's not possible to just zoom in with a microscope to see what the molecules are doing.

Or is it? Costantino Creton of ESPCI Paris, his recently graduated PhD student Juliette Slootman, and their colleagues have now reported an unprecedented look at the molecular-scale damage in a fractured elastic material.[1] Their experiment relies on new molecules, recently developed by coauthor Robert Göstl, that become fluorescent when ripped apart. The researchers find that many more molecular bonds are broken than anticipated—not just on the newly torn edge but tens of microns away.

Rubber theory

The leading model of fracture in elastic materials stems from a 1967 theory by Graham Lake and Alan Thomas,[2] two scientists from the UK-based Natural Rubber Producers' Research Association. The organization was founded in 1938 to better understand a major cash crop of what were then the British colonies of Southeast Asia. Today it's wholly owned by the Malaysian Rubber Board and has been renamed the Tun Abdul Razak Research Centre after Malaysia's second prime minister.

Rubber, as Lake and Thomas knew, is made of a random tangle of polymer chains. What makes it a stretchy solid rather than a goopy liquid are the chemical cross-links that bind the chains together where they touch. To break a solid piece of rubber in two, all the covalent bonds that connect atoms on opposite sides of the fracture plane must be severed.

But simply adding up the dissociation energies of all those bonds gives a value far smaller than the experimentally measured energy required to propagate a crack in the material. Lake and Thomas's in-

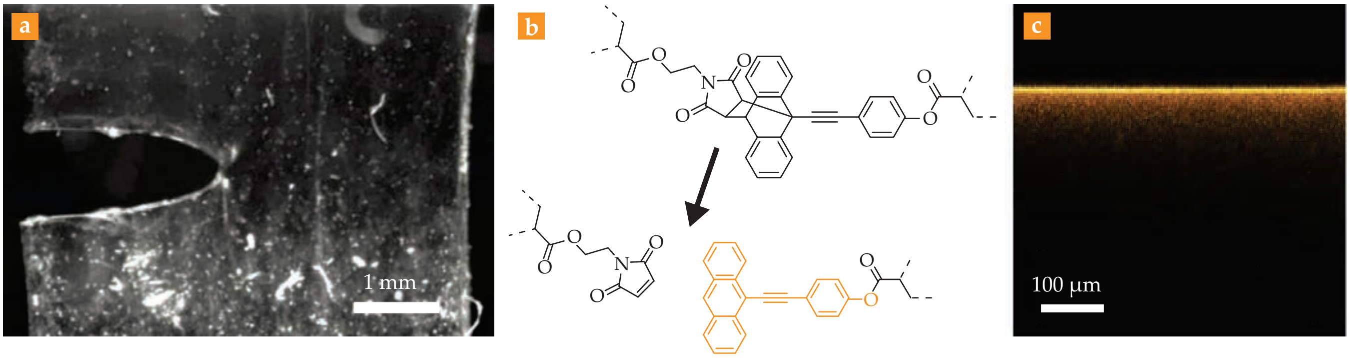

FIGURE 2. A MOLECULAR VIEW OF ELASTIC FRACTURE. A notched transparent elastic sheet **(a)** is put under increasing stress until it ruptures. **(b)** The sheet has been infused with molecules specially designed to break under tension. The orange portion of the broken molecule is fluorescent. **(c)** By placing the torn halves of the sheet under a fluorescence microscope, researchers can therefore visualize the spatial extent of molecular damage. Here, the fluorescence signal reveals that chemical bonds many tens of microns away from the nascent crack can still break. (Adapted from ref. 1.)

sight explained the discrepancy.

It's not possible, they reasoned, to tug apart only those bonds that lie in the plane of the crack. Rather, all the bonds in each polymer chain—at least between two successive cross-links—must be subject to the same tension. Only one bond per chain might break, but all the others must be stretched almost to their breaking point, which takes almost as much energy.

The theory works well in some situations, but it fails to explain many observed phenomena, such as the fracture energy's dependence on temperature and its correlation with crack propagation speed. Researchers thus assume that a certain amount of extra energy is consumed through viscoelastic dissipation—the jostling of polymer chains against one another—in the highly stressed region just ahead of the crack tip (visible in figure 2a). An empirical correction term accounts for the dissipation.

That *ad hoc* fix isn't physically satisfying in all cases. Among other things, it seems to imply that molecules jostle one another on length scales even smaller than the intermolecular separation. But for lack of any direct insight into what the molecules were really doing, it was the best that researchers could manage.

Molecular probes

Plenty of experiments have attempted to look at the molecular dynamics of soft materials, often by incorporating specialized molecules that convert the effects of mechanical stress into an optical signal of some kind. In 2014 Creton's group investigated the properties of a novel elastic material, made of two distinct but intertwined polymer networks, using a molecule that emitted photons immediately when its chemical bonds were severed.[3] The real-time nature of the signal is useful in some cases, but performing optical microscopy at the same time as a mechanical fracture test is cumbersome—and when Creton and colleagues tried using the same molecule to investigate the fracture of a simple, single-network material, they saw no signal at all.

As a postdoc at Eindhoven University of Technology in the Netherlands in the mid 2010s, Göstl wanted to develop a molecule whose mechanical response to stress could be optically investigated after the fact rather than in real time. He had several other desirable properties in mind, including a visible-wavelength signal and the absence of signal from the molecule's unstressed state. He also sought a high quantum yield, so useful results could be obtained without incorporating so many copies of the molecule that they change the material's bulk properties. "Previous molecules had one or more of these properties," he explains, "but they were never all available in the same molecule."

Figure 2b shows what he came up with.[4] The top molecule, under enough tension, reliably breaks apart into the fragments shown at the bottom. Because two bonds break simultaneously, the electrons rearrange into new chemical bonds to stabilize the broken molecules and keep them from reacting further. (The inverse of that process, which forms bonds instead of breaking them, is such a common tool in organic chemistry that it has its own name: the Diels–Alder reaction.) And the portion of the product molecule shown in orange is fluorescent: It absorbs violet light at 405 nm and reemits at longer wavelengths.

Distant damage

Now a group leader at the DWI–Leibniz Institute for Interactive Materials in Aachen, Germany, Göstl collaborates with groups such as Creton's to use the molecules he developed to solve problems in soft-matter research. Slootman, who trained and worked as a chemist before switching to polymer science for her PhD, had the necessary skills to synthesize elastic sheets of polymethyl acrylate and polyethyl acrylate that incorporated 0.02% of the stress-sensitive molecules. She then ruptured the sheets and looked at them under a fluorescence microscope.

The largest concentration of fluorescence lay on the crack surface itself—the bright yellow line in figure 2c. But surprisingly, the fluorescence image showed plenty of broken molecules 100 μm and more away from the crack.

In molecular terms, that's enormous. A covalent chemical bond is a bit longer than 0.1 nm, and even the distance between successive cross-links in an elastic network rarely exceeds tens of nanometers. If a single bond were enlarged to the height of a human, 100 μm would be the distance from Chicago to New York City.

As the experiment reveals, not only does molecular damage in a fractured elastic sheet span more of the material than the Lake–Thomas theory accounts for, but there's also a lot more of it. All the bonds in the fracture plane still have to break, and the distant broken bonds are extraneous to that requirement. A much larger portion of the fracture energy than anticipated therefore goes into severing chemical bonds—and much less energy is left for viscoelastic dissipation.

The result brings the researchers closer to a much-needed physically faithful model of fracture in elastic materials. It offers hope of eventual solutions to multiscale problems, such as how elastic energy stored in the material bulk finds its way to single molecular bonds and how to rationally design new materials that are more resistant to damage.

It also highlights the power of interdisciplinary research. "Creton alone wouldn't have had the tools to answer his questions," says Göstl, "and I alone don't have the polymer-science understanding to pose the questions. Only by closely exchanging ideas can we tackle the big, fundamental challenges."

Johanna Miller

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Photoelectrons shine a light on dark excitons

The population of the elusive quasiparticles is nearly twice that of their bright counterparts in a two-dimensional semiconductor.

When a valence electron jumps across a bandgap to the conduction band, it doesn't always escape the hole it left behind. In some materials, Coulomb forces are strong enough to hold negatively charged electrons and positively charged holes together in neutral electron–hole pairs known as excitons. The prevalence and dynamics of those quasiparticles affect the electronic and optoelectronic properties of the materials that host them.

Excitons come in two types, bright and dark. A bright exciton forms when a single photon is absorbed. In the case of dark excitons, the electron and hole are connected by an optically forbidden transition, meaning the electron didn't reach the conduction band through photon absorption alone—it also needed a boost from phonon scattering. Because they lack a signature formation or recombination pathway, dark excitons are difficult to study through the usual optical methods.

Now Julien Madéo and Michael Man, both at the Okinawa Institute of Science and Technology (OIST) in Japan, and their coworkers have turned instead to angle-resolved photoemission spectroscopy (ARPES) for observing dark excitons.[1] Their novel application of the technique detected both bright and dark excitons and monitored the populations over time. Using two different photon energies to create excitons produced the same surprising result: Dark excitons were twice as prevalent as their bright counterparts. The finding shows the importance of dark-exciton dynamics to understanding the optoelectronic properties of exciton-rich materials.

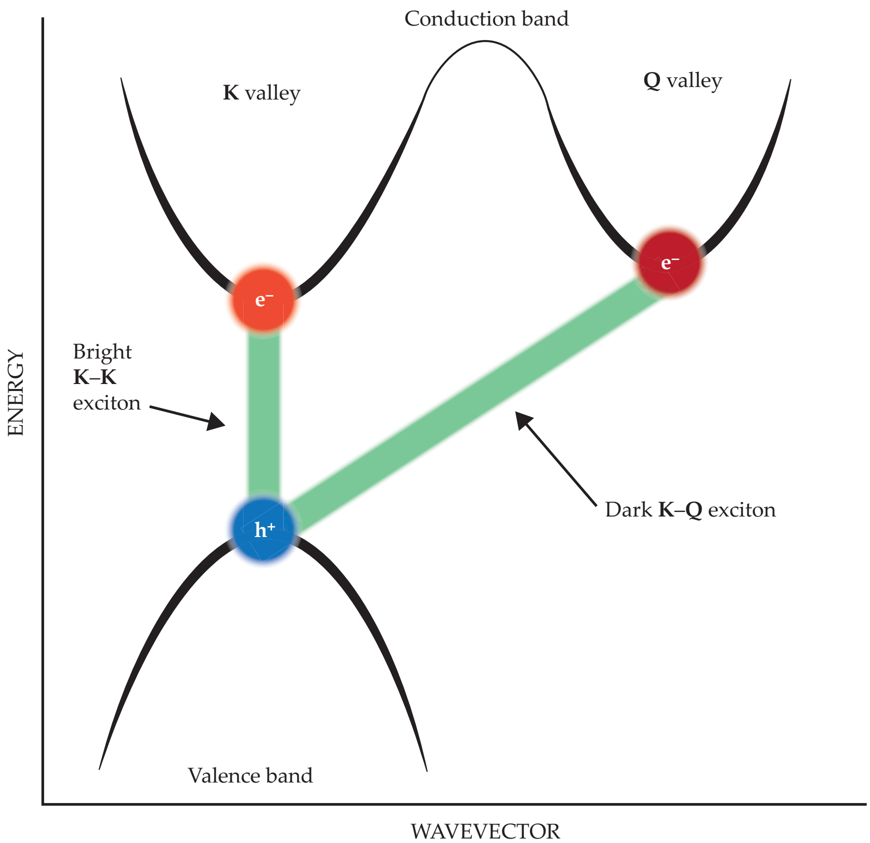

FIGURE 1. THE ELECTRON BAND STRUCTURE in monolayer tungsten diselenide has both a valence-band peak and a conduction-band valley at wavevector **K**. An electron can jump directly across the bandgap by absorbing a single photon to form a bright **K–K** exciton. However, the WSe_2 conduction band has a second energy minimum, at wavevector **Q**, whose depth is almost identical to that at the **K** valley. A **K–Q** exciton is called dark because it can form only if phonon scattering knocks an excited electron into the **Q** minimum. (Adapted from ref. 1.)

Reduced dimensionality

Although excitonic states exist in all bandgap materials, their natures vary. In bulk semiconductors, for example, the electrons and holes are often so weakly bound that room-temperature thermal fluctuations can break them apart. However, in transition-metal dichalcogenide (TMD) semiconductors, the attraction strengthens when the material's dimensions are reduced from three to two.[2] (For more about two-dimensional materials, see the article by Pulickel Ajayan, Philip Kim, and Kaustav Banerjee, PHYSICS TODAY, September 2016, page 38.) The electrostatic force that binds electrons and holes together is largely shielded in bulk TMDs, but not in monolayers. The tightly bound excitons are more robust, so they play a bigger role in electron dynamics and are easier to study.

Madéo, Man, and colleagues focused their attention on a particular TMD, tungsten diselenide. Bulk WSe_2 has only an indirect bandgap—the peak in its valence band and the lowest point of its conduction band have different momenta—so the gap can't be traversed using photon absorption alone. But monolayer WSe_2 has both a direct and an indirect bandgap, as illustrated in figure 1, so it can host both bright and dark excitons.

The bright excitons created through WSe_2's direct transition make the material photoluminescent and open potential applications in such devices as flexible transistors, photodetectors, and optical switches.[3] And because tightly bound excitons—both bright and dark—form readily in WSe_2, their dynamics control the compound's optoelectronic behavior.

The conduction band of monolayer WSe_2 has minima at two wavevectors, **K** and **Q** in the usual nomenclature, that correspond to high-symmetry points in the material's Brillouin zone, the unit cell in momentum space. Valence electrons can be excited into one of those two valleys, which have nearly identical energies but different momenta. The valence band peaks at the **K** wavevector, so a few-eV photon can push an electron across the bandgap into a **K** valley to form a **K–K** exciton. But the photon can't impart enough momentum to push that electron into the **Q** valley, which is why **K–Q** excitons are called "dark." Something else—typically a phonon—needs to provide an extra kick to make that transition happen.

Photoelectron probes

Optical techniques such as pump–probe and luminescence spectroscopy work fine for studying bright excitons but less well for dark ones. Dark excitons don't form by the absorption of photons at a particular energy, and their possible routes to recombination—scattering into a bright state, interacting with a lower-lying defect state, or another indirect path—produce ambiguous signals.

ARPES, on the other hand, directly characterizes the electrons in excitons rather than probing their transitions. It's a go-to technique for exploring electronic structures: Incident photons kick electrons out of a target material and the electrons' energies and momenta are measured. But experimental challenges have prevented its application to excitons. The experiment must have a source of extreme-UV (XUV) photons to break apart the tightly bound electron–hole pairs and eject photoelectrons, subpicosecond temporal resolution to follow the exciton population's evolution, and micron-scale spatial resolution to probe tiny samples of high-quality exciton-hosting materials.

"Several leading research groups in the world were thinking of ways to use ARPES-based methods to study excitons over the past decade," says Keshav Dani,

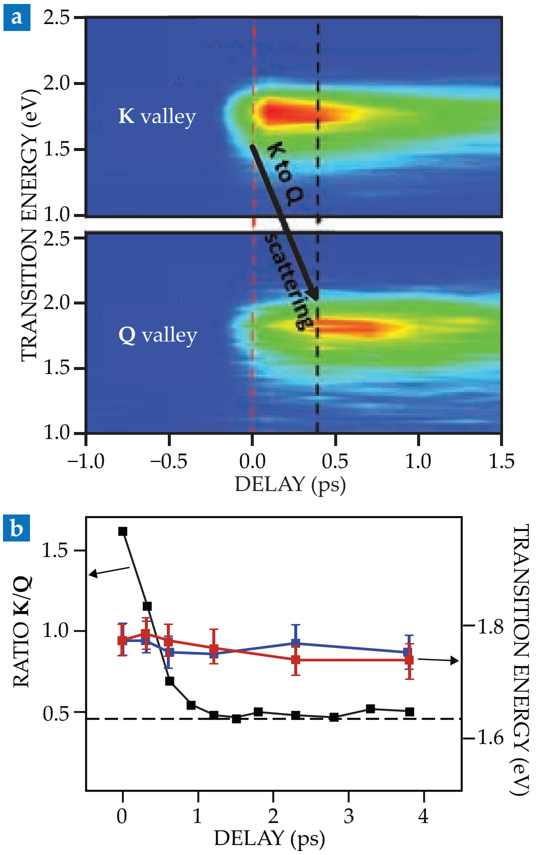

FIGURE 2. PHOTOELECTRONS FROM DARK AND BRIGHT EXCITONS have experimentally indistinguishable energies, but which conduction-band valley they reside in, **K** or **Q**, can be determined by their momenta. **(a)** When bandgap-resonant photons create excitons in monolayer tungsten diselenide, the electrons initially (red dashed line) populate the **K** valley. After about 0.4 ps (black dashed line), however, many of them have scattered to the **Q** valley. **(b)** The steady-state ratio of **K**- to **Q**-valley electrons (black) is about 0.5, indicating that the WSe_2 monolayer contained nearly twice as many dark excitons as bright ones. The energies of the dark (red) and bright (blue) excitons remain nearly constant throughout. (Adapted from ref. 1.)

head of the OIST group that led the study. In fact, developing capabilities for temporally and spatially resolved photoemission measurements in novel semiconductor systems was a goal of Dani's when he founded his group in 2011, the same year OIST opened. Dani credits the young university's emphasis on interdisciplinary and international collaboration with the group's success: "The unique institutional and administrative environment is fundamental to the sustained pursuit of creative, high-risk science." (For more about young research universities, see Physics Today, April 2020, page 22.)

When Dani began, no one apparatus combined the requisite technologies of XUV-photon sources (XUV-ARPES), subpicosecond temporal resolution (TR-ARPES), and micron-scale spatial resolution (μ-ARPES). And, according to Dani, "It's not possible to simply combine the standard technologies to do this." For their new instrument, one of the paper's lead authors, Man, prepared a μ-ARPES setup using a state-of-the-art electron microscope. Meanwhile, the other lead author, Madéo, developed a high-power, time-resolved XUV-radiation source that could be incorporated into the microscope. By combining those elements with a high-power femtosecond laser, they built an apparatus capable of TR-XUV-μ-ARPES.

Exciton detection

Madéo, Man, and colleagues created excitons in a WSe_2 monolayer by resonant excitation—sending in pulses of red photons whose energy, 1.73 eV, was just enough to create an exciton. Pulses of XUV photons then broke the excitons apart. When the excitation and measurement pulses were separated by just a few femtoseconds, the ejected electrons' momenta peaked at a value consistent with bright excitons. But once the delay between pulses extended to 400 fs, the peak shifted to a momentum value corresponding to a dark exciton (see figure 2a). The researchers attribute that shift to **K–K** excitons scattering into **K–Q** states. After about 1 ps, the ratio of dark to bright excitons reached a steady-state value of approximately 2:1 (see figure 2b).

In a second experiment, 2.5 eV photons pushed valence electrons across the bandgap. Some electrons used the additional energy to escape their holes, but after about 300 fs, excitons formed. Unlike what happened in the first experiment, the **K–Q** excitons formed directly and preferentially, and scattering pushed the population partly into the **K** valley. After about 1.5 ps, the excitons were again about twice as likely to be dark as bright.

Although the OIST researchers built their own apparatus, their success hinged on contributions from collaborators. The experiments required a high-quality WSe_2 monolayer sample, which was provided by Xiaoqin (Elaine) Li's group at the University of Texas at Austin. And after they made their first successful measurements in spring 2019, Dani and his group reached out to Tony Heinz (Stanford University) and his postdoc Ting Cao (now at the University of Washington) for help interpreting the results. Says Dani, "Discussions with Ting, Tony, and Elaine were invaluable in extracting the right physics out of our data."

Questions about dark excitons remain, and TR-XUV-μ-ARPES may be able to answer them. Future experiments could, for example, explain why above-gap excitation preferentially produces **K–Q** excitons, elucidate the role of impurities in exciton scattering, and investigate how dark excitons affect optoelectronic properties.

Lengthier experiments could measure how long dark excitons survive. The current study tracked the quasiparticles for only a few picoseconds, approximately the lifetime of a bright exciton. But a dark exciton's lifetime is expected to be much longer—perhaps on the order of nanoseconds or more—owing to its strong binding and indirect recombination pathways.[4] That would qualify dark excitons as candidates for use as qubits in future quantum computing devices.

Forbidden transitions involving an electron-spin flip can also produce dark excitons in TMD monolayers, and they're distinguishable from spin-allowed bright excitons by their energies. Although the current data lack sufficient resolution to separate out those contributions, higher-quality samples should make that possible. Says Dani, "I think the list of future experiments is endless."

Christine Middleton

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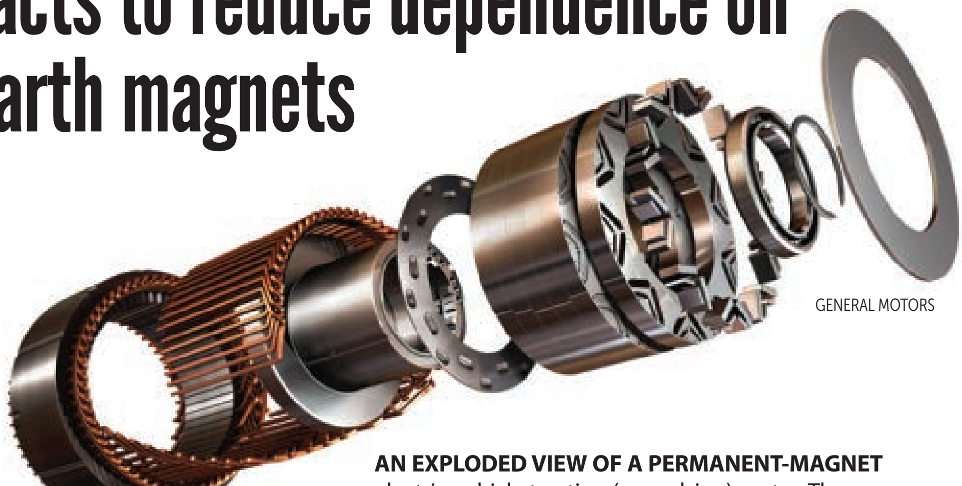
US government acts to reduce dependence on China for rare-earth magnets

Although the US has sufficient raw materials, the domestic supply chain to alloy and manufacture rare-earth permanent magnets is almost nonexistent.



GENERAL MOTORS

AN EXPLODED VIEW OF A PERMANENT-MAGNET electric-vehicle traction (propulsion) motor. The rare-earth-containing magnets are embedded in the rotor.

Driven by an expected surge in demand for electric vehicles (EVs), wind turbines, and other applications requiring permanent magnets, consumption of many rare-earth (RE) elements is expected to outstrip the global supply within a decade. Coupled with an almost total US dependence on China for separated REs and the magnets made from them, the impending shortage has prompted the US government to subsidize and stimulate domestic RE mining, metalmaking, and magnet manufacturing.

Rare-earth elements are those with atomic numbers between lanthanum (57) and lutetium (71). Scandium and yttrium are often considered REs because they share some properties. For a primer on rare earths' electronic properties, see the Quick Study by Jianshi Zhou and Greg Fiete, PHYSICS TODAY, January 2020, page 66.

Neodymium-iron-boron (NdFeB) magnets are the highest-performing, most compact, and most lightweight type of permanent magnet commercially available. Although neodymium is the principal RE used in magnets, NdFeB magnets often contain praseodymium because the two are difficult to separate.

The NdFeB magnets are manufactured either by sintering—melting and compressing powders—or by combining and pressing powders with a bonding material such as epoxy or a thermoplastic. Sintered magnets are capable of much stronger fields, whereas bonded ones can be injection molded, compression bonded, extruded, or 3D printed into more complex shapes. Sintered NdFeB magnets are the most commonly used by far: An estimated 160 000 tons were sold globally in 2020, according to industry consultant John Ormerod; bonded-magnet consumption last year was 12 000 tons. Peter Afiuny is executive vice president of the US's sole manufacturer of sintered NdFeB, Texas-based Urban Mining. He says the US accounts for around 20% of the $20 billion global demand for those magnets.

Skyrocketing prices last year for the REs used for magnets reflected increasing tensions between China and the West. The price of Nd jumped 75% from January to December last year, and NdPr was up 50%. Terbium, used along with dysprosium in small amounts to prevent demagnetization of NdFeB magnets at elevated temperatures, more than doubled in price during the same period.

Demand for NdFeB magnets will double this decade, analysts say, faster than the rate of growth for REs in consumer electronics, catalysts, phosphors, and other uses. Ryan Castilloux, managing director of the research and consulting firm Adamas Intelligence, forecasts that demand for REs as a group will climb 10% annually over the next 10 years. Alex King, founding director of the Critical Materials Institute at Ames Laboratory, notes that annual demand growth for REs has returned to its long-term trend of 13% following a downturn caused by a price spike in 2011 (see the plot on page 21). There is every reason to expect that trend to continue, he says.

An "unfathomable" amount of new Nd, Pr, Tb, and Dy oxides—5000 to 6000 tons each year—will be needed by the second half of the decade to keep pace with NdFeB magnet demand, says Castilloux. That would require a new mine the size of Mountain Pass in southern California each year. Mountain Pass is the sole US mine and currently supplies 15% of the world's REs. An annual shortage of 48 000 tons of NdFeB powders and alloys will develop by 2030, Castilloux predicts, roughly the amount needed to make propulsion motors for 25 million–30 million EVs.

Department of Defense acts

At 8%, Mountain Pass's ore-bearing rock has one of the world's highest RE ore concentrations. But all of its output is shipped to China for processing and separation into individual REs. With help from a $9.6 million grant last year from the Department of Defense, mine owner MP Materials plans to open a plant in 2022 to separate lighter-atomic-weight REs, primarily Nd and Pr, on site. It would be the first separation facility in the Western Hemisphere.

The Pentagon awarded a second grant to MP Materials to design a separation plant for heavy-atomic-weight REs, principally Dy and Tb. Mountain Pass ore has little heavy RE content; however, it could produce small quantities for defense purposes. The amount of the DOD grant wasn't disclosed.

Both awards, and two others provided by DOD to other RE companies, were issued through the Defense Production Act of 1950 and were prompted by executive orders and directives issued by President Donald Trump beginning in 2017. In July federal agencies were instructed to take unspecified actions to lessen US dependence on foreign sources of REs and 34 other "critical minerals." Without such assistance, Trump said, the US industry "cannot reasonably be expected to provide" RE oxides, metals, and alloys or NdFeB magnets. The orders stated that "purchases, purchase commitments, or other action taken under the Defense Production Act are the most cost-effective, expedient, and practical alternative method for meeting the need for this critical capability."

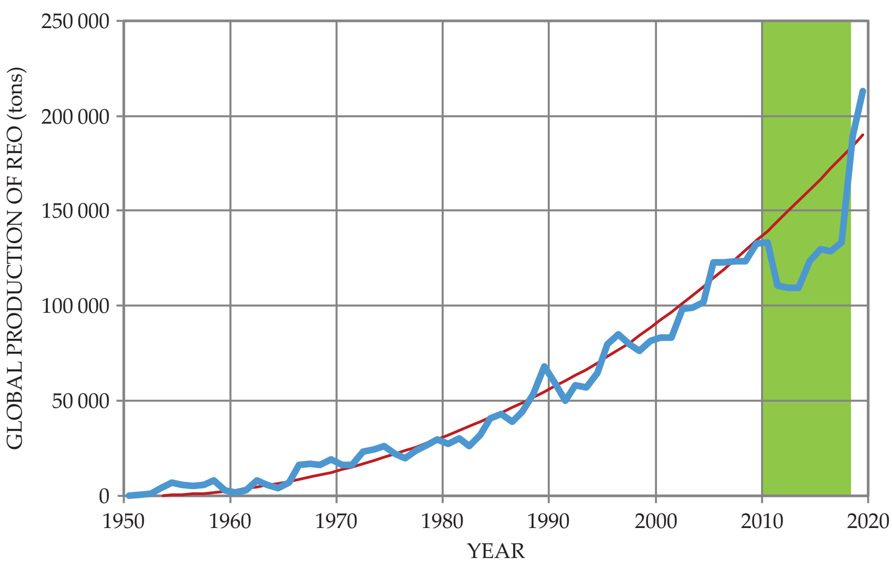
Lynas, the only other major producer of REs outside China, last year received a DOD grant of an undisclosed amount to design a heavy RE separation plant that it plans to build in Texas. The company currently processes Australian-origin ores in Malaysia.

The Pentagon last year also gave $29 million to Urban Mining, which recycles REs from discarded NdFeB magnets to make new magnets. Afiuny says the grant will help the company expand production capacity at its plant, which he says is the only NdFeB sintered magnet manufacturing facility in the Western Hemisphere. There are three bonded-magnet manufacturers in the US, says Ormerod. Other companies in the US customize magnets for specific applications, but their material comes mostly from China.

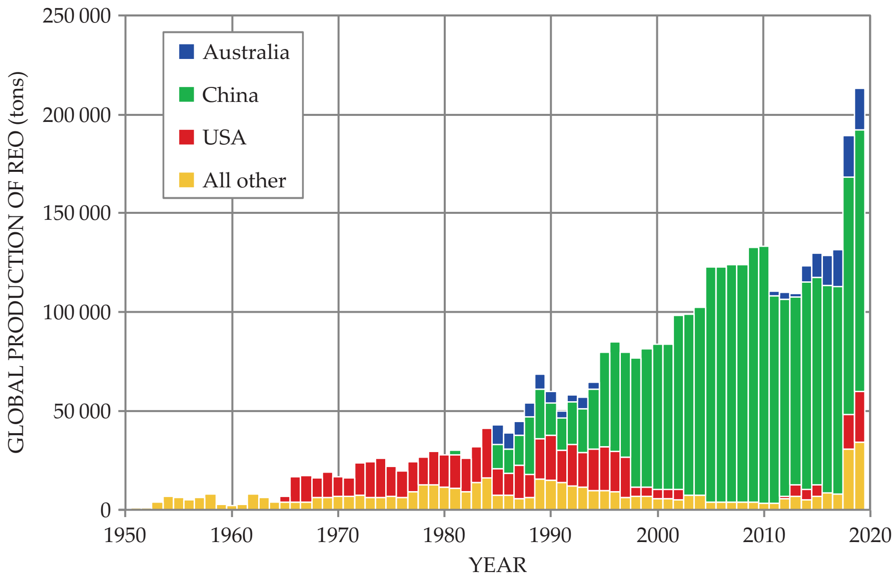
The Department of Energy announced in November that it will consider applications from industry to receive loan guarantees to help finance projects that would increase domestic output of REs and other critical minerals ranging in scarcity from aluminum to platinum group metals. The agency has around $40 billion in unused loan guarantees designated for clean-energy development and electric-vehicle manufacturing.

Before November's announcement, DOE had maintained that mining and separation operations were not eligible for loan guarantees because they are too far upstream in the manufacturing chain. In 2012 the department rejected a $280 million loan-guarantee application from Molycorp, the previous owner of Mountain Pass. That company filed for bankruptcy in 2015.

Tucked into the fiscal year 2021 National Defense Authorization Act is a requirement that within five years most



GLOBAL PRODUCTION OF RARE-EARTH OXIDES (REO), 1950–2019. The trend line (red) is fitted to the data (blue) through 2010 and extrapolated beyond that point. The drop of production below the trend line within the green band indicates the drop in demand following a price spike in 2011. (Adapted from A. King, *Critical Materials*, Elsevier, 2020, based on data from USGS Mineral Commodity Summaries.)



PRINCIPAL NATIONAL CONTRIBUTIONS to global rare-earth oxide (REO) production, 1950–2019. (Adapted from A. King, *Critical Materials*, Elsevier, 2020, based on data from USGS Mineral Commodity Summaries.)

military systems exclusively use REs mined and refined entirely outside China. It further directs the Pentagon to select the best options for improving the domestic availability of REs, such as providing funding or restricting foreign supplies. In 2018 Congress ordered the Pentagon to purchase only non-Chinese-made NdFeB magnets and magnet alloys but didn't rule out raw materials from that nation. China's share of the world's RE mining has declined in recent years, but it still makes about 90% of NdFeB metal and magnets; Japan produces nearly all of the rest. Much, though not all, of Japan's RE feedstock comes from Lynas. (See PHYSICS TODAY, October 2018, page 22.)

Surging demand

The global market for EVs could grow a stunning 36% annually over the next decade if nations adhere to commitments made under the 2015 Paris Agreement, according to the International Energy Agency. The European Union, the UK, and California have announced bans on sales of new internal combustion vehicles, to take effect in 2035. President Biden has proposed adding 500 000 EV charging stations by 2030 and providing new incentives for buying EVs.

Most EV propulsion motors use permanent magnets; Tesla, which employed induction-motor technology invented by Nikola Tesla in its first-generation Roadster, switched to permanent magnets for its mass-market vehicles. "Electric motors using [NdFeB] magnets are the motor that will drive electrification," Afiuny says. "There are no serious rivals."

MP Materials forecasts 31% annual growth in demand for magnets used in EV propulsion motors through 2030, according to the company's website. EVs alone could consume all the world's mined Nd and Pr by 2035, compared with 5% of total demand today, the company says.

Rapid growth also is expected for magnets used in wind turbines, with estimates ranging up to 25% annually. The European Union plans a fivefold increase in offshore turbines by 2030, to a total of 60 GW. An increasing proportion of turbines are so-called direct drive and use permanent magnets to couple the slow-moving blades to the generator. They require less maintenance and have fewer moving parts to wear out compared with conventional turbines, which use a gearbox to couple the blades to the generator.

Direct-drive turbines require 1 ton of NdFeB per megawatt, says Afiuny. In 2019 the average land-based turbine in the US produced 2.5 MW, according to Lawrence Berkeley National Laboratory. Offshore, direct-drive turbines dominate and are larger; 10–12 MW systems are expected to become more prevalent in the coming years. GE just unveiled a direct-drive turbine that will produce 13 MW.

Small NdFeB magnets are found in dozens of automotive components, including power windows, speakers, switches, and actuators. Apart from cars, the magnets are used in consumer electronics, including hard disk drives, speakers, and cell phone vibrators, and for actuators used in aircraft and other applications.

China remains essentially the world's only source of Dy and Tb, which are extracted from clays in the south of the country. Magnet manufacturers have achieved some success in reducing the amounts of the two elements without sacrificing performance. Meanwhile, engineers are figuring out ways to design motors to better dissipate heat, says King, which would lessen the need for Dy and Tb. Urban Mining developed an NdFeB magnet that uses 40% less Dy than conventional NdFeB and offers superior thermal performance, it says. Siemens, the world's largest producer of wind turbines, has recently begun making permanent magnets that are free of heavy RE elements.

There is a huge, virtually untapped potential for recycling magnet metal. Less than 1% of the NdFeB contained in components that have reached the end of their useful lives is reused in the US, says Urban Mining's Afiuny. Adamas forecasts that 90 000 tons of NdFeB magnets will be entering the waste stream globally each year by 2030. Still, demand growth will outpace the amount of material recovered.

As supply tightens, NdFeB magnets will likely become more limited to high-value applications such as EV propulsion, says King. That's what happened during the 2011 price spike, when automakers substituted other types of magnets in many applications such as windshield wipers and power-window motors, where high performance and compactness aren't so important.

Some studies have shown that cerium and lanthanum, both abundant, can supplant a portion of NdPr in some magnet applications. Meanwhile, in November 2020 Niron Magnetics of Minnesota announced a partnership with General Motors and Marquette University to develop an iron nitride permanent magnet for EV drivetrains. Niron claims the technology offers inherently higher magnetization and lower cost than NdFeB. DOE's Advanced Research Projects Agency–Energy supported that work with a $5 million grant.

Financing needed

MP Materials declined to comment for this article. Castilloux and King both say that Mountain Pass could meet North American demand for Nd and Pr through 2030. But since a typical RE mine contains only 15–25% Nd and Pr, globally 60 000 tons to 100 000 tons of RE mine production overall will be needed by the end of the decade just to meet magnet demand.

There are few new mining prospects in the US. Texas Mineral Resources is proposing to develop, in partnership with the privately owned company US Rare Earths, a property in West Texas, primarily for heavy REs. Production could begin in 2023. Another potential source is the Bear Lodge area, on US Forest Service land in Wyoming.

Canada has several RE mining prospects. They include Quebec's Kwyjibo, owned by the provincial government, and the Ashram Deposit, owned by Commerce Resources. The Foxtrot mine in Labrador is owned by Search Minerals. In addition, Ucore Rare Metals of Nova Scotia plans to develop the Bokan-Dotson Ridge Project, a heavy RE deposit near Ketchikan, Alaska. That deposit is rich in heavy REs, and the plan has political support from the state's congressional delegation. The outlook for its development brightened as a result of the domestic RE-sourcing requirement in the National Defense Authorization Act. Ucore received a $1.8 million grant from the Army Research Laboratory last year to help fund development of its proprietary RE separation technology.

Although those prospects are promising, all of them currently lack the hundreds of millions of dollars needed to bring them to production, says Castilloux. "Investors see prices going through the roof, but not many are to the point where they want to become a financer. They're looking at which ones can we jump into and jump out of in six months and make a few million. There needs to be a longer-term interest in seeing these projects through." If financing were located, gearing up to full production would take five years or more.

Even when Mountain Pass begins separating oxides, the US will remain

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

LIGHT RARE-EARTH ELEMENTS are generally considered to be those ranging from lanthanum to promethium. The remainder are known as heavy rare earths.

dependent on China for metal making and magnet production.

"There are several chicken and egg situations for this industry," says Castilloux. "Having oxides-processing capacity in the US will bolster the business case for establishing metal-making capacity and magnet capacity." MP, for one, says it plans to manufacture NdFeB magnets by 2025.

Separating concentrated ores to individual RE oxides is the most capital-intensive part of the process, says King. China has heavily invested in plants that may not be the most efficient, he notes. "If we start today with all the research that has gone into separations and reduction, we should be able to build more efficient plants and compete with China on a free-market basis."

Ucore, which declined an interview request, plans to build a separation plant at its Alaska prospect and hopes that sales of oxides will help pay to develop the mine. "With the ability to refine raw materials into high-purity RE oxides, the significant capital costs to build an RE mine can then be justified," company chairman and interim CEO Pat Ryan said in an October 2020 statement. In the meantime, Ucore says its Alaska plant will separate REs from unspecified non-Chinese sources. But helping others process their material could undermine Ucore's own mining project, says Castilloux, who views the Alaskan deposit as one of the more economically challenging.

An alternative source

Growing demand and prolonged high prices may stimulate the extraction of REs from monazite, an RE-rich component of mineral sands. Last August, the Saskatchewan provincial government provided Can$31 million ($24 million) to build an RE processing facility. It will have a capacity to produce 500 tons a year of individual RE oxides from monazite when it begins operation in late 2022.

Energy Fuels, the largest US uranium miner, announced in December an agreement to acquire monazite sands from the Chemours Co's Georgia mine. Energy Fuels says it can recover enough mixed REs to meet 10% of US demand when it begins processing in the first quarter of this year. But while it considers whether to build its own separation facility, the company will ship its RE-rich concentrated ore to Europe or Asia for that purpose.

Medallion Resources in Vancouver, British Columbia, is completing a technical and economic feasibility study of a monazite-processing plant that would produce 3500 tons of REs annually, including 500 tons of NdPr.

Other nations with abundant monazite deposits include Australia, India, Indonesia, Madagascar, and the Philippines. Iluka Resources, an Australian mineral-sands mining company, has committed AU$35 million ($26.8 million) to upgrade its monazite-processing operation to produce RE enriched ores.

"Developing a US-based integrated RE magnet supply chain is a significant challenge requiring cooperative efforts from the mine to the magnet original equipment manufacturer," Ormerod sums up. "A close private–public sector coordinated effort is essential if the capital, economic, and technical hurdles are to be overcome."

David Kramer

Guiding inventions from lab to market

A career in technology transfer requires skills in multitasking, communicating, and negotiating; one reward is seeing scientific advances benefit society.

"What can I do with a physics degree?" In 2014, nearing the end of his PhD at the University of Texas at Dallas, Chris Wohlgamuth typed that question into a search engine. The prospect of applying for grant money had soured him on the idea of pursuing a tenure-track academic position, and nothing had panned out in industry. Through his online search, Wohlgamuth stumbled onto technology transfer. "I read that the field needs technically sound people that have some understanding of patent law and business acumen," he recalls. He landed an entry-level position as a technology licensing analyst at the Ohio State University, where he got on-the-job training for the business and law know-how he lacked. He is now a senior licensing specialist for the physical sciences at the University of Texas at Austin. The job involves guiding inventions—and inventors—from early stages through commercialization.

Dipika Singh got her first taste of commercialization in 2012–13 when she and her supervisor at the University of Nebraska Medical Center developed a proprietary medium for freezing neurons. Freshly extracted neurons are especially "finicky," she says, and without a method to cryopreserve them, researchers discarded valuable neuronal cells after harvesting what they needed from animals. Their medium is now commercially available, and she gets an annual royalty check from its sales.

At the time of her invention, Singh was 25 and deciding whether to pursue a PhD or explore the business side of biotech. "I am an instant-gratification type of person, so science was not kind to me at times," she says. She earned an MBA at the University of Colorado Boulder. While there, she did an internship at the university's tech transfer office. Seven years later she is a senior licensing officer at the university.

As a freshly minted physics PhD in 1991, Margaret Wilkinson went to work for Shell as a researcher. She tested fuel formulations and then moved into a policy position where she focused on recycling plastics. After a decade at the company, she joined the tech transfer office at the University of Cambridge. There were 6 people in the office; two decades later, there are 80. "Our mission is to help researchers use commercial avenues to develop ideas for the benefit of society, the economy, themselves, and the university," she says.

Cultural shift

The rapid growth of tech transfer in the US can be traced to the Patent and Trademark Law Amendments Act of 1980—known as the Bayh–Dole Act—which gave universities, nonprofits, and small businesses first dibs on inventions resulting from federally funded research. Previously, the government owned the intellectual property rights, says Rick Smith, director of Lehigh University's office of technology transfer. "Little was happening with those inventions." The hurdles were high and the incentives were low. "Allowing universities to own the intellectual property rights was a huge catalyst for tech transfer," he says.

Some institutions already had tech transfer offices—Stanford University opened its in 1970—but as a result of Bayh–Dole, nearly every research university and national lab in the country now has one. And many other countries have aligned their patent ownership rules with the US model.

According to the technology transfer association AUTM, from 2013 to 2018 the number of tech transfer jobs rose from 2353 to 2600 at the 187 US institutions that reported data. AUTM's latest salary survey, from 2017, reports that the median salary for entry-level licensing agents at US universities was $65 000 (standard deviation $12 000). A PhD would typically start at the associate

ENVAL

SHREDDING IS AN EARLY STEP in the process of separating plastic from aluminum in metallicized packaging. Enval, a company founded in 2005 after more than a decade of research at the University of Cambridge, uses microwave-induced pyrolysis to separate the materials for recycling.

LIMB LAB, ROCHESTER, MN, HTTPS://LIMBLAB.COM/

PROSTHETIC FINGERS made by Point Designs in Colorado. Founded in 2016, the company grew out of prosthetic design research that cofounder Jacob Segil conducted as a graduate student in mechanical engineering. The company produces prosthetics for machinists, woodworkers, and others who have lost fingers. The company is now fundraising to create a prosthetic thumb. Segil is managing director of a new initiative at the University of Colorado Boulder to help researchers win funding to create startups.

level, for which the median starting salary was $75 000 (standard deviation $26 000). For that level, the average bonus was $7000 for men and $5700 for women. Those salaries are higher than for new faculty and lower than median starting salaries for physics PhDs in the private sector, according to data from the Statistical Research Center of the American Institute of Physics (which publishes this magazine). Compensation can exceed $200 000 for directors of tech transfer offices.

Scott Elrod became an associate director for licensing in Stanford's tech transfer office in 2017 after more than three decades at Xerox's Palo Alto Research Center. The job is "intellectually very engaging because of the technical content," he says. "Elements like drafting agreements can be learned quickly, but instincts about business and value—being able to sense what has the potential to be realized commercially—can take years to develop.

"If you like multitasking and working on a diversity of projects, then tech transfer may be for you," Elrod says. Learning new things and seeing success "is the biggest buzz," says Cambridge's Wilkinson. Over the past 20 years, she says, academia's appetite to spin out companies has grown. Her office used to help create one or two a year; now it's more than 10.

"When I started out 35 years ago, I had to convince faculty it was in their interest to commercialize their work," says Jon Soderstrom, managing director of technology commercialization and faculty innovation at Yale University. "Nowadays, faculty are tuned in to the idea that for their technology to go anywhere, industry has to be engaged. It's become part of the culture."

No market, no patent

Tech transfer officers do a lot of outreach: They meet with new faculty and visit departments to describe the services they offer, give talks about tech transfer, post signs around campus, host workshops, and offer internships to students. The ball gets rolling on a new invention when a researcher fills out a disclosure form online or calls the tech transfer office. Informal conversations are also a common starting point. Benjamin Frisch is a physicist who works in knowledge transfer at CERN. "A lot happens around coffee," he says. "Many of the opportunities I have become aware of came up in conversations in CERN's main restaurant."

Once a researcher has disclosed an invention, the tech transfer officer has to decide whether to file a patent. "We sit down with the faculty member—or postdoc or student—and ask them to explain their work," says Soderstrom. Why is the work unique? Why is it useful? Who cares? Can it lead to something that is better, faster, and cheaper than what's already available? How much will it cost to develop the technology? Patents are worthwhile only if there is a market for the invention, notes Lehigh's Smith. He presents a wacky example from a class he teaches: "Take the bird diaper, now-expired patent number 5,934,226."

A physicist at Lehigh recently emailed Smith about a graduate student who was defending her PhD dissertation. The work was in nonlinear optical materials. "I filed a patent application that day," he says. The researchers could still submit their work for publication, "and sometimes you have to file quickly to protect a valuable creation."

The officer weighs the value of the invention and its commercialization potential against the costs of applying for and maintaining a patent. Those costs may start at a few hundred dollars to file a placeholder and can climb to tens of thousands of dollars. Yale reviews 250–300 new inventions a year, says Soderstrom, and tech transfer officers may have up to 1000 cases in their portfolio. "You have to triage, to figure out which ones to spend time on."

A fraction of the inventions that arrive in tech transfer offices make it to market, and bringing in big money is rare. Estimates for patenting range from a quarter up to three-quarters of disclosures; only some of those are developed into products, and even fewer are commercialized. "We can't commercialize anything unless the researcher is enthusiastic," Wilkinson says. "They have to be keen to put in time and effort." Licenses can fail, for example, if a company changes course or doesn't get funded; there may not be a market, or the invention may be immature and require significant further development. In her experience, a tenth to a hundredth of those that are commercialized bring in a "reasonable amount" of money, and she has seen two or three that have brought in "significant" revenue.

One of Cambridge's biggest earners came out of theoretical physics in the early 1990s: software to predict material properties from first principles. It's used by molecular modeling companies to develop drugs and novel materials. Another example out of Cambridge is Enval, a recycling company that uses microwave pyrolysis to separate materials in flexible plastic–aluminum laminate packaging such as food containers and toothpaste tubes (see image on page 25). The company was spun out of a chemical engineering research group in 2005 by graduate student Carlos Ludlow-Palafox and his PhD adviser Howard Chase.

Most research at universities and national labs is early stage—far from ready for commercialization. Tech transfer officers evaluate inventions and possible uses; often companies want additional data. For example, Smith says he is working with a large chemical company to license a new fertilizer developed by an academic researcher at Lehigh. The researcher and the company are collaborating to test nitrogen levels and prove the fertilizer's efficacy and its scalability for manufacturing.

Many universities have funds for such directed research or for the researchers to build a prototype. Companies tend to be risk averse, Smith says, and it's a challenge for new inventions to survive the "valley of death" between university research and commercialization.

Gains in translation

Olivia Nicoletti earned her PhD in materials science in 2012 and worked in tech transfer at Cambridge in 2015–20. "I worked with technologies from medical devices to quantum computers," she says. "You have to have a passion for technology. You have to be creative. You have to be a people person." A plus of tech transfer, she notes, is that the skills are transferable to other jobs. People move into innovation and intellectual property management, investment, negotiation, spinoff companies, and other areas; Nicoletti recently moved into venture capital.

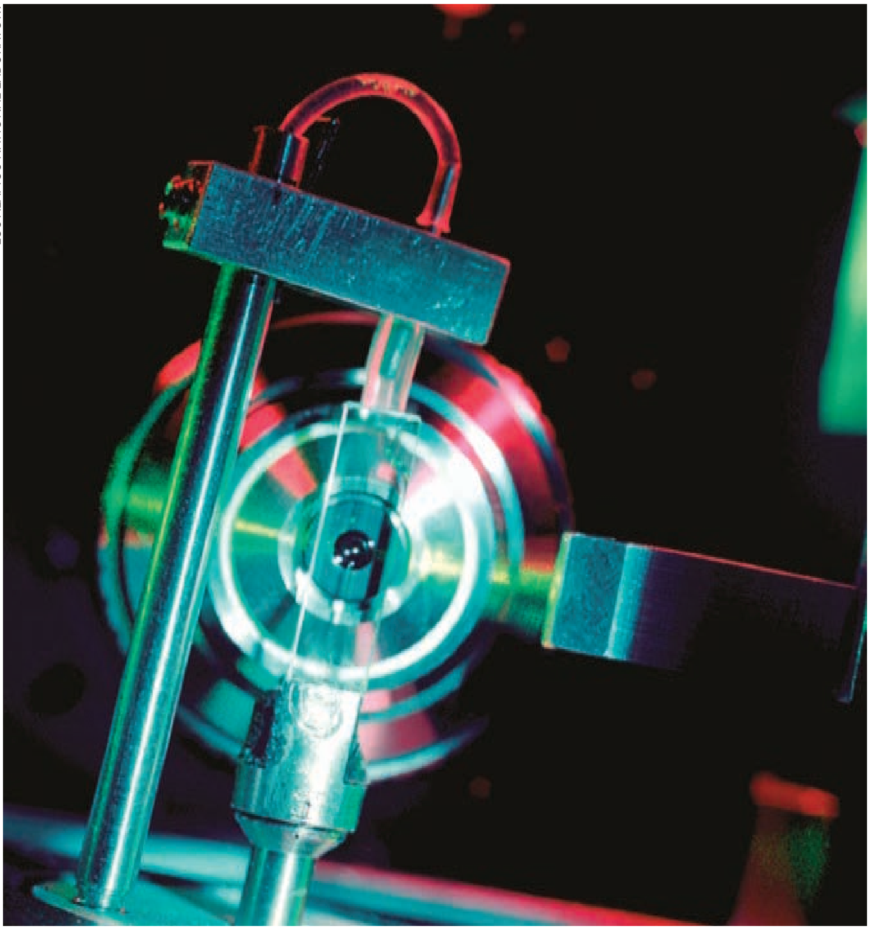
A difficult aspect of working in tech transfer, Nicoletti says, is telling people things they don't want to hear. "I had to tell people they would not be a good CEO for their company," she says, "and that the best thing to do would be to bring in a professional CEO. These are not easy conversations to have." Kathleen McDonald, who leads the tech transfer division at Los Alamos National Laboratory, agrees. "Tact and nuance are essential," she says. "People get defensive if you call their baby ugly."

Another challenge can be the long time it often takes to see an invention make its way to market. The Lehigh fertilizer, for example, has been in the works for more than three years and will likely be under development for several more years before it reaches product readiness, says Smith. There is a lot of variability, he adds. "Software can be quick, and pharmaceutical products can take a decade or more to reach the market."

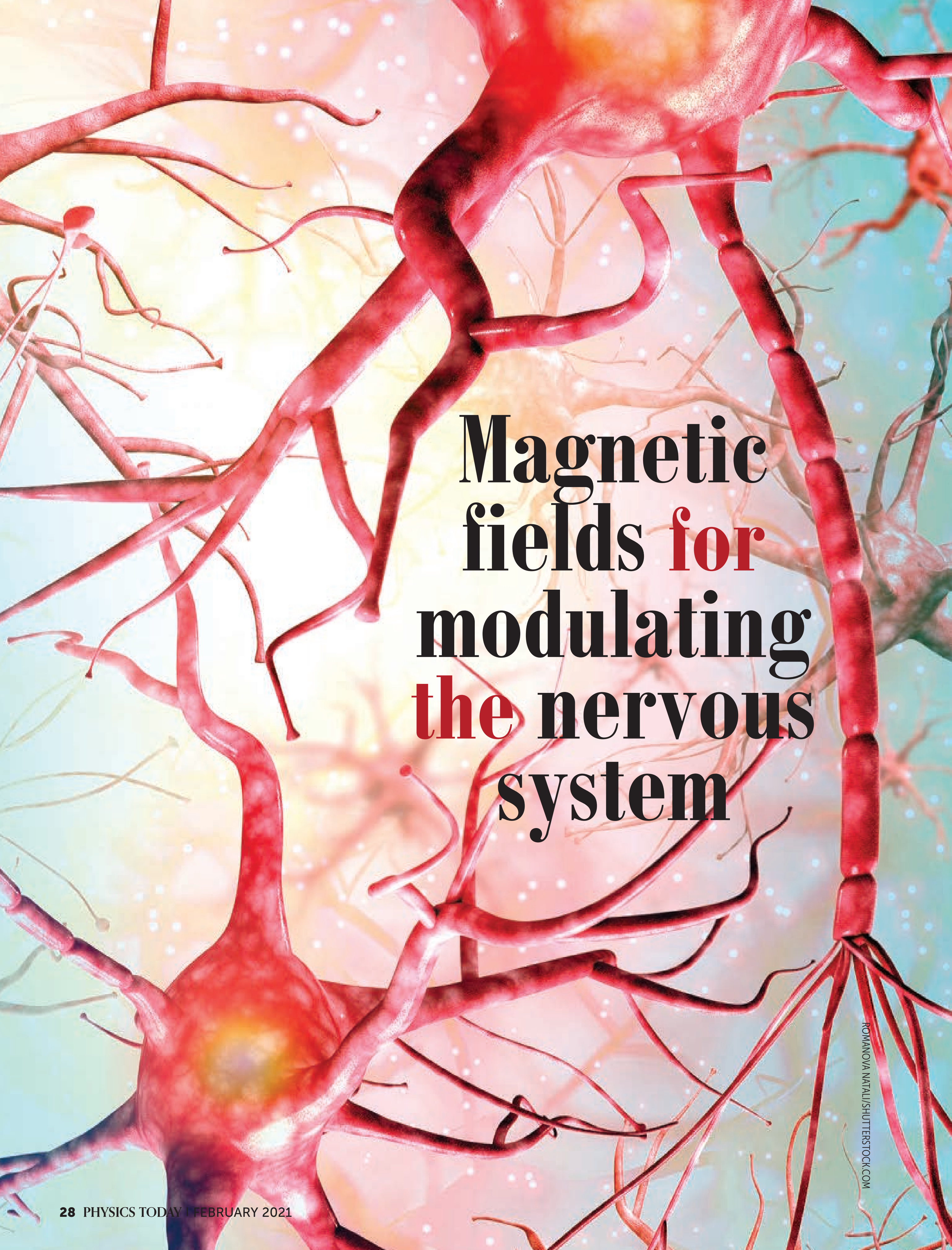
Part of the job is translating. For example, says CERN's Frisch, "quick" results for scientists may be different than for a company. And a tech transfer officer has to be able to translate from the technical language a researcher may use to explain to a nonscientist why they should care—without revealing confidential information. "It's a lot about communication," says Frisch. The job requires asking probing, intelligent questions, says Soderstrom. "Know-it-alls die in this business."

Toni Feder PT

LOS ALAMOS NATIONAL LABORATORY



ACOUSTIC CYTOMETRY grew out of work at Los Alamos National Laboratory and was originally licensed in 2006. Sound waves manipulate the flow of cells, which are then interrogated with lasers. Because of its flexibility, from holding single cells in view to enabling high-throughput cell scanning and sorting, the approach has become the dominant technology in flow cytometry—also developed at Los Alamos, in the 1960s. This image shows the inside of an acoustic cytometer. The current technology is sold by ThermoFisher as the Attune NxT acoustic cytometer.



Magnetic fields for modulating the nervous system

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Michael Christiansen is a postdoctoral scientist at the Institute of Translational Medicine at ETH Zürich in Switzerland. **Polina Anikeeva** is an associate professor of materials science and engineering and of brain and cognitive sciences at MIT in Cambridge, Massachusetts.

Michael G. Christiansen and Polina Anikeeva

Although targeted actuation of neurons via magnetic fields may benefit neuroscience research and medicine, some approaches have sparked controversy.

Neuroscience research has grown rapidly in recent years, driven at least in part by the emergence of tools and techniques that enable scientists to pose experimental questions that not long ago would have been unanswerable. Methods for triggering activity in the nervous systems of living animal models have proven particularly useful for mapping networks, probing structure–function relationships, and connecting physiology to behavior. In addition, therapeutically controlling the activity of neurons in patients can offer relief from some diseases. For example, an approach that clinicians use to stimulate neurons deep in the brain to treat Parkinson's disease has also shown promise for addressing persistent psychiatric disorders such as depression.

Technologies for stimulating neurons are poised to become increasingly significant, yet the presently employed methods have serious drawbacks. As is so often the case for biomedical technology, today's innovations will appear primitive in the not-too-distant future. Currently, clinical deep-brain stimulation is conducted primarily by inserting millimeter-sized electrodes that are powered by devices implanted in the body. Although effective at offering relief for patients, such drastic measures are justifiable in only extreme cases. Technology for more commonplace neuron stimulation, whether for experiments in model organisms or clinical therapy in humans, should be noninvasive or minimally invasive, wireless, able to access regions deep in the brain, spatially targeted, and selective to particular cell types.

That vision has attracted numerous engineers and scientists to independently focus on developing devices and methods for coupling noninvasive stimuli—including ultrasound, near-IR light, and time-varying electric fields—to the activity of neurons. Magnetic stimuli are especially appealing because of tissue's weak magnetic properties and low conductivity, both of which ensure that magnetic fields can reach deep physiological targets undiminished.

Additionally, magnetic stimuli form a vast possibility space, as indicated in figure 1. Quasi-magnetostatic fields at the human scale can rotate, pulse, or oscillate with characteristic frequencies ranging from millihertz to megahertz. Spatially, the fields can be uniform, possess gradients, or exhibit points of vanishing magnitude. Any of those features or some combination of them facilitates strikingly different approaches for actuation. The practical considerations for generating magnetic fields with those properties and the limits of feasible scalability can also vary profoundly.

Researchers have pursued the facile control of neurons via magnetic fields with such eagerness that soon afterward some of their claims have faced criticism, much of it framed in terms of the physical plausibility of the proposed mechanisms. Rather than avoid topics that have produced controversy, here we will consider their most discerning critiques.

The dream of magnetogenetics

Neurons propagate electrochemical signals by using voltage-gated biochemical machinery in their membranes. At the level of a single cell, a stimulus that depolarizes a small part of the membrane can cause an action potential that spreads throughout the cell. Some channel proteins function by locally increasing or decreasing the membrane's polarization in response to a particular physical stimulus. Introducing genes that code for those channel proteins thus offers a way to program neurons to be inhibited or excited on demand.

In neuroscience, a broadly successful technique termed optogenetics has taken precisely that approach with visible light.[1] Typically, the necessary genes are introduced to neurons in a selected site or cell type of interest in an experimental organism, and optical fibers or light-emitting devices deliver light for stimulation. Could a similar magnetogenetic approach—one that employs biogenic magnetic materials and externally applied magnetic fields—be possible? If it were, the technique would eliminate the need for setups with tethers and visibly detectable stimuli, but it would leverage many of the same prolific methodologies that have made optogenetics so successful.

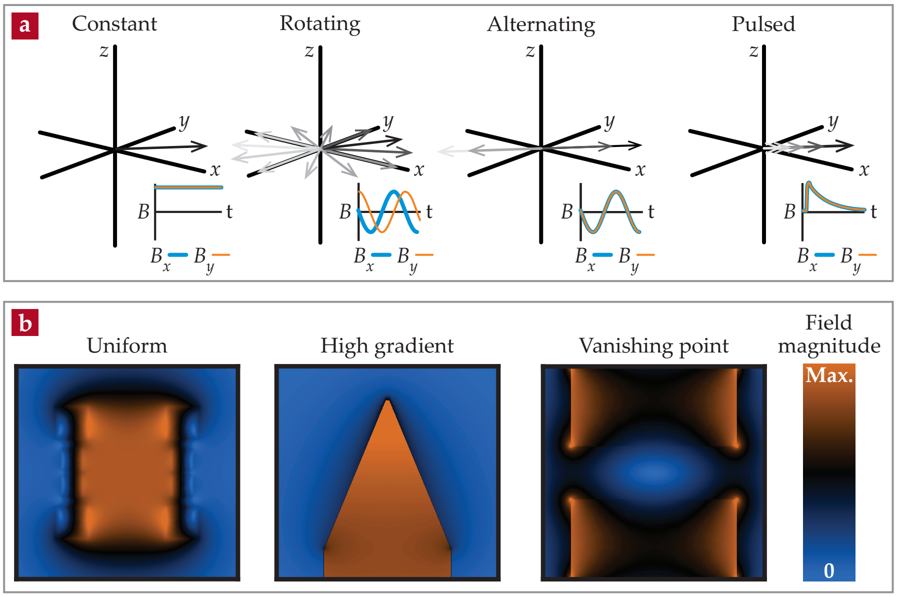

FIGURE 1. MAGNETIC FIELDS offer a large and diverse parameter space for engineering magnetic stimuli. **(a)** In addition to familiar temporally constant fields, quasi-magnetostatic fields can rotate, alternate, and pulse. **(b)** Distributions of field strength, such as uniformity, high gradients, and vanishing points, also offer various functionalities. The relative magnetic field magnitude is plotted for radial cross sections of several geometries with cylindrical symmetry: (from left) a Lee–Whiting coil, a conical permanent magnet, and two disk magnets with opposing magnetization. (Figure by Michael G. Christiansen; field plots created using FEMM software.)

Although a magnetic variant of optogenetics appeals to many researchers in the field, a direct analogy fails to acknowledge some underlying physical restrictions. The key difference, illustrated in figure 2, is the energy scales expected for the different stimuli (see the article by Rob Phillips and Steve Quake, Physics Today, May 2006, page 38). A photon of visible light carries enough energy to change the configuration or electronic state of a protein, as illuminated by examples ranging from fluorescent proteins to the opsins in our retinas that enable us to see. In contrast, realistic magnetic fields interacting with biomolecules or small biomineralized particles generate predicted energies of interaction that are far below the scale of background thermal fluctuations. That outcome is perhaps unsurprising when one recalls that the underlying motivation for using magnetic fields as stimuli is their ability to access deep physiological targets without appreciably interacting with tissue.

Reports of magnetogenetic techniques for neurons first appeared in prominent journals[2] in 2016. A common theme of the initial approaches was to modify the genetic blueprints for known channel proteins so that they also incorporated ferritin, an iron-storage protein. The authors then suggested, on the basis of known mechanical and temperature sensitivities of the unmodified channel proteins, that either heat flow in response to time-varying fields or magnetically mediated mechanical stimuli could trigger the channel to open and locally depolarize the neuronal membrane. Regardless of the suggested mechanisms, the studies presented numerous careful experimental controls that seemed to consistently suggest the existence of a real and reproducible effect.

However, those early studies of magnetogenetics soon drew criticism because they focused almost exclusively on demonstration and only loosely explained the possible basis for the observed effects.[3] The core argument was that simplified physical models of ferritin ought to place realistic bounds on the expected energy of interaction with attainable magnetic fields. Without any need for heroic mathematics, the scale of those energies can be compellingly shown to be orders of magnitude too weak to actuate membrane proteins in the manner envisioned. Several independent research groups subsequently reported an inability to demonstrate similar magnetogenetic effects in their own laboratories, although a failure to replicate is not necessarily conclusive. The authors of the original works have since pointed out ways in which the replication attempts may have differed from their original experiments.

A conceptual rebuttal to the biophysical argument against ferritin-mediated magnetogenetics has been that the magnetic moment of ferritin may be about 75 times larger than expected, which would allow for an assortment of hypothetical actuation mechanisms.[4] Such a large magnetic moment would be surprising given the extensive body of literature characterizing ferritin, although a fresh investigation may be warranted. Even if anomalously enhanced magnetic properties could be definitively ruled out by experiment, asserting the impossibility of magnetogenetics may be overly reductionist.

A feeble magnetic moment for ferritin at most precludes the possibility of direct actuation. Some of the relevant magnetic stimuli produce off-target effects, including induced voltages and mild nonselective heating. In principle, a modified channel protein that lowers the threshold of response to those influences by any means, magnetic or otherwise, might lead to selective actuation effects. An indirect mechanism of that sort might help explain experimental observations, although a strategy that depends on many external factors is likely to face difficulties in replication or routine use.

Recent experimental work has indicated a possible chemical pathway for actuation that involves iron released from ferritin.[5]

However, the way that magnetic fields alternating at kilohertz or megahertz frequencies might trigger ion release remains unanswered. Other experiments that used modified channel proteins suggest that extinguishing temperature sensitivity eliminates magnetic response and that having a magnetocaloric cooling effect may trigger a related channel sensitivity to cold rather than heat.[6]

An encouraging feature of recent efforts is a renewed focus on probing and explaining mechanisms. Nevertheless, one of the significant difficulties in making comparisons and drawing conclusions in the magnetogenetics literature is the sheer variety of magnetic stimuli, which allows every group to adopt its own seemingly unique stimulation paradigm. The situation is especially evident in the remarkable contrast between the magnetic conditions employed in the most recent experiments, ranging from 12 μT fields varying at 180 MHz to 250 mT fields varying at 800 mHz.

Yet another route to magnetogenetics that researchers have suggested draws inspiration from nature. Numerous organisms exhibit what's known as magnetoreception—the ability to sense Earth's comparatively weak 50 μT magnetic field, usually as a cue for migratory navigation (see the article by Sönke Johnsen and Ken Lohmann, PHYSICS TODAY, March 2008, page 29). Specialized magnetic receptor cells, similar to sensory systems that detect light or sound, have been hypothesized to exist. If such cells were unambiguously identified and thoroughly studied, perhaps their mechanism of sensation could be replicated through genetic modification. But that remains a remote possibility considering that decades of vigorous research and debate have yet to produce satisfactory explanations for natural magnetoreception.[7]

Mediation by magnetic materials

Another widespread category of techniques for magnetic stimulation of neurons employs synthetic nanomaterials. Usually introduced by direct injection, the materials offer an energetically plausible means of coupling an externally applied magnetic field to well-understood forms of stimulation. Whereas clusters of noninteracting atoms are expected to exhibit modest magnetic moments at best, collective ferro- or ferrimagnetic ordering mediated by exchange or superexchange interactions can lead to magnetic moments that are many orders of magnitude larger.

For magnetized particles smaller than a critical size range that depends on composition and geometry, opposing magnetic domains do not form, and the structures are approximately uniformly magnetized. The presence of magnetic order does not necessarily imply that the orientation of the magnetization remains constant. Rather, the magnetization orientation can rapidly precess and jump stochastically among certain preferred directions. Under conditions at which the rate of the stochastic jumps is much faster than the time scale of measurement, magnetic particles are said to be superparamagnetic.

Examples of magnetic nanoparticles do occur in nature, most famously in bacteria that employ chains of magnetite or greigite particles for coordinating their movement along magnetic field lines (see the article by David Dunlop, PHYSICS TODAY, June 2012, page 31). However, for neurostimulation methods based on magnetic nanoparticles, researchers typically prefer synthetic materials that can be produced in large quantities with tailorable surface chemistries. Because of their biocompatibility, ferrites are common, especially maghemite, magnetite, and similar compounds doped with neighboring transition metal elements, such as manganese, cobalt, and nickel. Many approaches have been reported, so researchers find it helpful to classify them by the ways they transduce magnetic fields to detectable stimuli. Those categories, which are summarized in figure 3, include the production of forces or torques, magnetoelectric coupling, actuation via dissipated heat, and triggered release of chemical agonists.

Sensory neurons in the peripheral nervous system contain channel proteins that respond to membrane tension or other mechanical cues to produce the sensation of touch. Combining magnetic and mechanical actuation is therefore a natural and intuitive idea. An extensive body of literature exists that addresses biological effects produced *in vitro* with magnetically applied forces, including examples of neural stimulation. But those methods typically require high field gradients, on the order of 10–10^3 T/m, which prohibits scaling them to most *in vivo* contexts.

In contrast, mechanotransduction via torques generated by rotating or alternating uniform fields is a comparably scalable strategy. Particles suitable for applying torques must possess sufficiently large moments and anisotropy that links their physical orientation to their magnetization. For single-domain nanoparticles, large moments and high anisotropy tend to

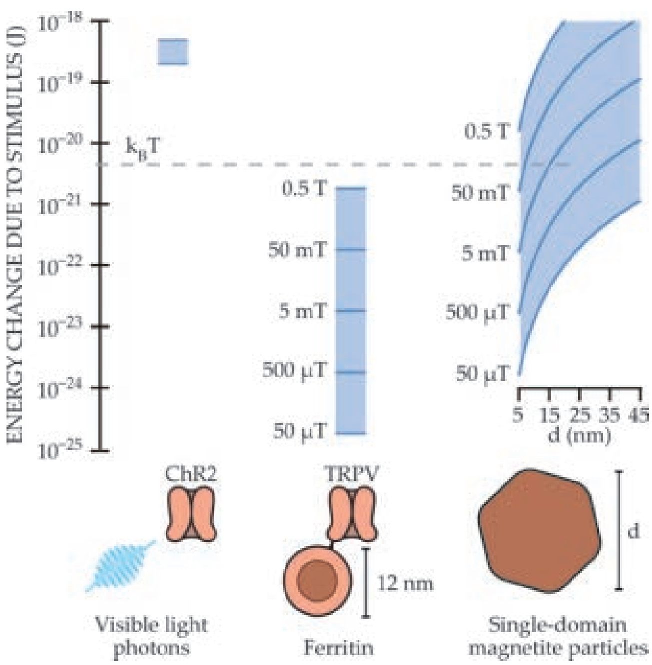

FIGURE 2. VARIOUS STIMULI can be used by researchers to affect the activity of neurons. Comparing the energy scales of the stimuli helps illustrate the fundamental challenge of using the genetically expressed protein ferritin and magnetic fields to stimulate neurons. Proteins such as ChR2 that respond to visible light (left) interact with photons that have an energy much higher than background thermal fluctuations k_BT, whereas the magnetic core of ferritin, attached to the channel protein TRPV (center), interacts only very weakly with magnetic fields. In contrast, single-domain synthetic magnetic particles made of magnetite (right), for example, have higher energies of interaction that also increase with particle size. (Figure by Michael G. Christiansen.)

increase the likelihood of aggregation and settling, but one potential work-around employs pseudo-single-domain nanostructures such as nanoscale disks. They exhibit intermediate vortex states between uniform magnetization and multiple domains, which, in the absence of an applied field, reduces the net magnetic moment and particle interactions.

Whereas mechanotransduction requires genes for introducing mechanically sensitive channel proteins into neurons that don't intrinsically express them, all neurons that propagate action potentials possess voltage-gated ion channels and respond to electric fields. Accordingly, researchers have suggested using nanoparticles with magnetoelectric properties to enable magnetic stimulation without requiring genetic manipulation. Magnetoelectric materials change their electric polarization in response to an applied magnetic field, and the strongest effects are seen in composite structures. They function by using strain fields to go between magnetic and electric properties: A magnetostrictive material, in which magnetization influences strain, is joined to a piezoelectric material, in which strain affects electrical polarization.

One reported use of magnetoelectric core–shell structures for stimulating brain activity in mice employed barium titanate as the piezoelectric shell and $CoFe_2O_4$ as the magnetostrictive core.[8] Given that appreciable magnetostrictive properties typically require materials with high anisotropy, as is the case for $CoFe_2O_4$, the low-frequency (0–20 Hz) magnetic stimulation in that work seems more likely to produce physical rotation rather than truly magnetoelectric effects. Additional study of nanoscale magnetoelectric composite materials with other magnetic stimulation paradigms may be warranted. Alternatively, researchers have recently investigated the use of magnetoelectric composites on a larger scale and saw promising results.[9]

In addition to containing voltage-sensitive channel proteins, many neurons have heat-sensitive ones. Magnetically, heat can originate from a hysteresis effect as the nanoparticles respond to alternating magnetic fields with frequencies ranging from kilohertz to low megahertz and amplitudes typically not exceeding 100 mT. The maximum permissible amplitude varies with frequency and is constrained by the need to limit off-target heating of tissue via weak eddy currents. Heat dissipation by magnetic nanomaterials is most familiar in the context of magnetic hyperthermia as a potential therapy for cancer, but the neuron-stimulation strategies discussed above avoid triggering cell death and have shifted the research focus toward wireless actuation of cellular activity. Wireless actuation is conceivable if a local temperature increase is sufficient to trigger a targeted, possibly genetically introduced, thermally responsive channel protein. But that temperature increase can't be high enough to cause cell damage.

In 2010 the first scheme for stimulating neurons with heat used low concentrations of magnetic nanoparticles bound to cellular membranes.[10] The researchers employed a fluorescent dye as a thermal probe to show a change in temperature of several degrees Celsius at the surface of the nanoparticles. Since then, others have debated whether a localized temperature increase at the membrane is possible without surrounding bulk

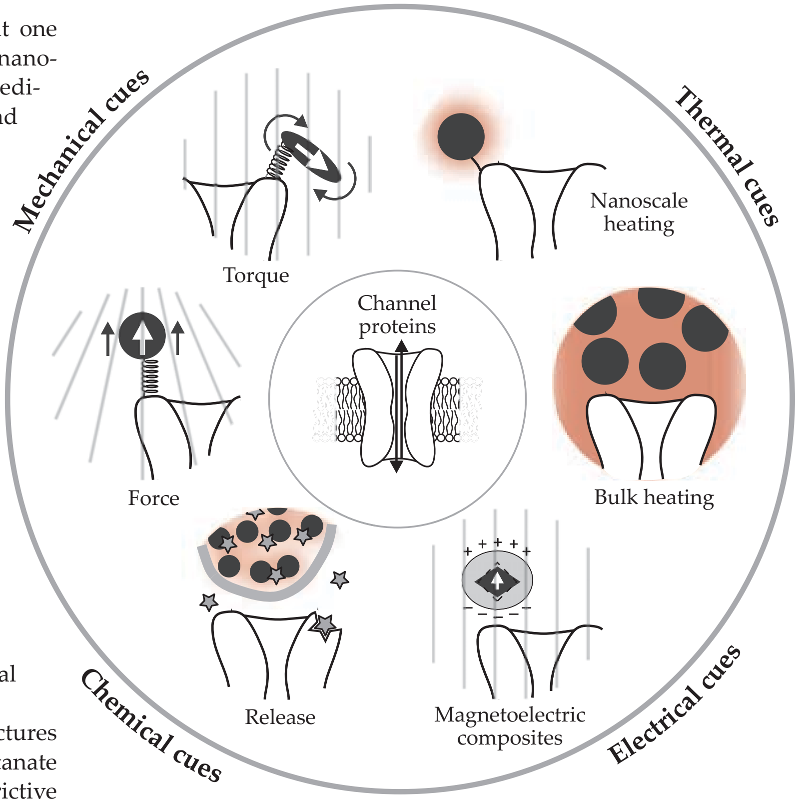

FIGURE 3. SYNTHETIC MAGNETIC NANOMATERIALS can couple to channel proteins, which respond to many types of stimuli, including heat, mechanical strain, electric fields, and chemical interactions. In response, the channels often open and allow the passage of ions, such as Ca^{2+} or Na^{+}. That ion movement then triggers action potentials in neurons. (Adapted from ref. 18 by Michael G. Christiansen.)

heating. The standard heat-transfer equations suggest that the temperature difference between the surface of the nanoparticles and the solution should be more than a million times smaller than some experiments have suggested.

An intriguing clue to explain the discrepancy came nearly a decade later from a study that replicated a comparable methodology.[11] Rather than interpreting similar observations as an increase in surface temperature, the researchers suggested two types of experimental artifacts that may account for the original observation. Their findings and other recent negative results raise questions about the existence of nanoscale heating in similar systems. Nevertheless, heat-transfer effects peculiar to the nanoscale are studied extensively in solid systems and considered in terms of the transport of quantized phonon modes rather than classical heat flow. Moreover, various nanoparticle systems suspended in solution compellingly demonstrate carefully controlled heating effects and offer researchers an opportunity to reexamine physical models of nanoscale heat transport at crystalline-disordered interfaces.

Even without relying on nanoscale heating effects, heat can still stimulate targeted neurons. The classical heat-transport equations allow for bulk heating of concentrated ferrofluid droplets to stimulate neurons sensitized to increased temperature, an effect that has been demonstrated experimentally.[12] One recent paper suggested an extension of those methods based on bulk-heating effects: Known as magnetothermal multiplexing, the approach heats adjacent ferrofluid droplets independently by pairing different types of magnetic nanomaterials with alternating magnetic field conditions that ensure selective heating.[13]

Another method readily extendable to chemical stimuli targeted at particular channel proteins is the magnetically triggered release of chemical payloads from nanoscale carriers. The concept was originally explored primarily for drug delivery and diagnostics. Available carriers include nanoparticle surfaces, thermally sensitive liposomes, and degradable polymer composites. In one instance, researchers controlled neural activity in freely behaving mice by triggering the release of neurochemicals from thermally sensitive liposomes.[14] In the future, chemomagnetic methods could be coupled with superimposed magnetostatic selection fields, which offer spatial control in drug release.

Chemomagnetic methods are a relatively recent development compared with the other approaches highlighted in this section. Such chemomagnetic studies are affected by the uncertainty surrounding nanoscale heating because they are often performed at concentrations of magnetic nanoparticles that are far below that required for bulk heating. Whether the phenomenon triggered by an alternating field and leading to release can be exclusively attributed to heat is a question worth further consideration.

Electromagnetic induction methods

As described by Faraday's law, time-varying magnetic fluxes induce electric fields in conductive media, which generate currents that oppose the change in flux. The effect, already put to wide and varied technological use, offers a basis for neuronal stimulation through effects experienced at the tissue scale or via wirelessly powered devices.

Researchers have demonstrated that neurons in humans can be stimulated using magnetic fields pulsed at millisecond time scales—on the order of 10^4 T/s with a peak amplitude of up to 1 T—to produce rapid variations of the field strength.[15] Figure 4 depicts how placing current-carrying coils close to the scalp stimulates neurons within the first few centimeters of the brain. The technique, called transcranial magnetic stimulation, or TMS, has shown promise for treating depression, neuropathic pain, and other disorders.

But researchers face several challenges when highly targeted stimulation is required. For example, changes in pulse duration and the physical orientation of the neurons can suppress neuronal activity rather than stimulate it. Superficial brain structures receive a stronger stimulus than deeper ones because magnetic field magnitude decreases with the distance from the coils. To improve spatial selectivity in their effects, researchers commonly use figure-eight or butterfly-coil geometries, both of which have two coils wound in opposite directions to focus stimulation effects near the point of overlap.

Others in the research community have suggested employing a similar effect in implanted devices as an alternative to the conventional electrodes used for deep-brain stimulation that apply potentials to inject small currents into their surroundings. The alternative electrodes remain tethered to an external power source and stimulate neurons in surrounding tissue through inductive effects generated by an approximately 1-mm-diameter solenoid.[16] Although still invasive, the approach avoids scarring, in which brain cells called glia accumulate around an electrode and insulate it from its intended neuronal targets.

Inductively powered, untethered miniature devices implanted in the brain take the technology one step further and have been demonstrated for neural stimulation in animal models.[17] Miniaturization is constrained fundamentally by both a device's requirement to reach induced voltages that are physiologically relevant and its reduced cross-sectional area. The most successful of those neural-stimulation devices have a highly permeable miniaturized ferrite core and a tightly wound solenoid. They use a simple circuit that resonantly couples to an alternating magnetic field with a frequency in the low megahertz range and that rectifies the resulting voltages for direct-current stimulation.

The excitation coils can be thought of as the primary windings

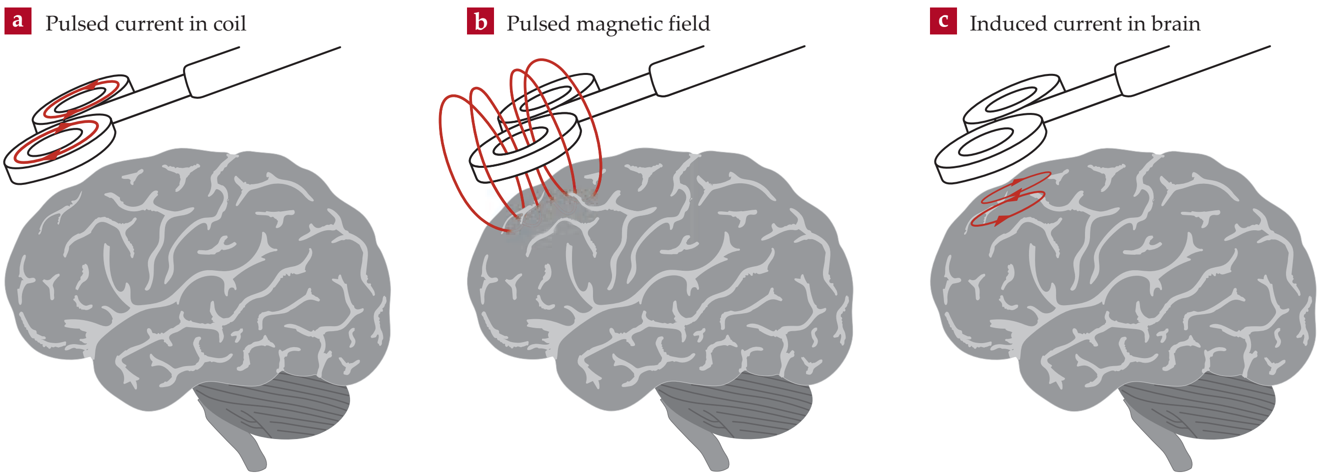

FIGURE 4. TECHNIQUES SUCH AS TRANSCRANIAL MAGNETIC STIMULATION, or TMS, use rapidly varying magnetic fields to induce voltages that trigger the voltage-sensitive channel proteins in neurons. In the representative scheme depicted here, **(a)** a current pulse is delivered to a coil that **(b)** generates a pulsed magnetic field. **(c)** Weaker currents opposing the change in magnetic flux are then induced in the brain tissue and produce neuronal stimulation. (Adapted from ref. 18 by Michael G. Christiansen.)

of a transformer, and the device's inductive pickup acts as the secondary windings. A simple and compact resonant circuit rectifies the induced voltage, which allows the device to inject current into its surroundings and stimulate neurons. The degree of the transformer's inductive coupling is small compared with more familiar transformers optimized for power transfer. But the design of the device enables noninvasive stimulation over a reasonable area in which an animal can freely move. Other technical advantages of the approach include low power requirements for alternating magnetic field generation and the tunable resonance of the secondary coil. With multiple independently addressable devices, researchers may be able to stimulate different sites in the brain.

Accelerating progress

The present efforts to stimulate neurons with magnetic fields serve as a reminder that progress in science is rarely linear. Spurred by the unmet need for a tool useful to neuroscientists and clinicians alike, independent researchers have produced intriguing ideas and strategies to tackle the same underlying problem. Work that garners the greatest attention is the kind that seeks to shift existing paradigms, so perhaps it should be unsurprising when controversy follows closely behind some of the most prominent claims.

In those cases, a noticeable pattern emerges: Objections often center on foreseeable, fundamental explanatory shortcomings. Even when researchers have sought to defend the reproducibility of their results, they have frequently retreated from their initial statements about mechanisms. Arguably, that outcome is more a consequence of mindset than of expertise.

The fundamental orientation toward problem-solving often fostered in the physical sciences allows one to break difficult problems into solvable pieces and to test plausibility with simplified arguments rather than perfectly recapitulate reality. That way of thinking has already led independent researchers to make valuable contributions toward magnetic control over neurons, and additional engagement and dialog with physical scientists could help accelerate progress in neuroscience.

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California Dreamin'

Defense projects made the West Coast the promised land for US physicists after World War II—until the projects dried up.

Stuart W. Leslie

The Cold War decisively shifted the US physics community's center of gravity west, from the elite universities, corporate research laboratories, and high-tech firms in the Northeast and Midwest industrial corridors to the emerging centers of aerospace and defense electronics on the West Coast, particularly in Southern California. Even though universities in New England and mid-Atlantic states continued to award far more PhDs in physics than schools on the Pacific coast, those new physicists increasingly went west to work. (See the article by L. R. Harmon, PHYSICS TODAY, October 1962, page 21.) By 1960, the tipping point, California already employed more physicists than New York, Pennsylvania, and New Jersey combined. Los Angeles, Orange, and San Diego Counties alone employed nearly as many physicists as New York, the leader among the other states.

Aerospace, the quintessential Cold War industry and Southern California's largest single employer, drove the westward tilt in physics. During World War II, Southern California's aircraft companies were magnets for tens of thousands of job seekers. Among them were a large number of women—ultimately 42% of the industry's local wartime workforce—who were drawn to skilled and semiskilled manufacturing jobs for the first time.[1] At its wartime peak, the aircraft industry employed a quarter million workers in Southern California. Scientists and engineers generally made up less than 5% of the workforce.

By the early 1960s, aerospace rather than aircraft had become the major market. Companies originally built on manufacturing know-how became increasingly dependent on scientific expertise to design and build rocket engines and inertial guidance systems for intercontinental ballistic missiles, aircraft and antiaircraft radar systems, ground-to-air and air-to-air missiles, and other high-tech instruments.[2] Established firms such as Northrop and North American Aviation (NAA) added new electronics and aerospace divisions, whereas newcomers that included Hughes Aircraft Company and Thompson Ramo Wooldridge (shortened to TRW in 1965), with their heavy emphasis on R&D, added manufacturing facilities to their laboratories.

To facilitate their transition to aerospace, Southern California's big five—NAA, Lockheed, Northrop, Douglas Aircraft Company, and Convair Astronautics—hired scientists, engineers, and

Hughes Research Laboratories in Malibu, California. (Courtesy of HRL Laboratories.)

technical personnel by the tens of thousands. The new employees accounted for close to a quarter of the companies' total workforce in the mid 1960s. By 1962 Southern California aerospace companies had been awarded a quarter of the nation's prime defense contracts and employed 380 000 workers (although far fewer of them were women or people of color than during World War II). That buildup led to what would be the world's largest concentration of high-technology industry up to the end of the Cold War.[3]

To give themselves an edge in recruiting, hiring, and retaining young physicists and engineers, Southern California's aerospace companies had to project the right image. In their advertisements, they highlighted bold architecture, brilliant colleagues, challenging problems, and "California living at its finest." The companies gave a distinctly Californian flair to what David Kaiser has called "the suburbanization of American physics."[4] As aerospace companies relocated their R&D laboratories and high-tech manufacturing divisions to new research campuses in the emerging "edge cities" of greater Los Angeles, they created aerospace suburbs. Those enclaves of privilege for white, white-collar, and predominantly male workforces reinforced a regional pattern of socially stratified and racially segregated communities.[5]

Shangri-la for deep thinkers

During World War II, the reclusive billionaire Howard Hughes purchased a large tract of land in Culver City, just north of the Los Angeles airport. There he constructed an industrial complex where Hughes Aircraft built planes under contract with other airframe manufacturers. The ensuing Cold War pushed the company's focus from aircraft manufacturing to sophisticated radar and guided missiles. It faced formidable competition for the military electronics market, especially from established eastern firms such as General Electric, Westinghouse, RCA, and Raytheon, all of which were major wartime radar contractors with enormous research laboratories.

In 1946 Hughes Aircraft hired Simon Ramo and Dean Wooldridge as the brain trust for its aerospace group. The two were graduate school classmates in physics at Caltech in the late 1930s. After graduation they had headed east—Ramo to General Electric's research laboratories and Wooldridge to Bell Labs. Though small, the company's aerospace group had one decisive advantage: the essentially unlimited capital of its sole shareholder, Hughes. Ramo and Wooldridge also had the confidence of former air force officers who were in charge of the avionics and missile programs. The company's leaders felt that neither traditional airframe manufacturers, whom they dismissed as Rosie the Riveter–type operations, nor established electronics companies such as General Electric could attract and hold truly top-notch scientists and engineers.

Leaning on its Pentagon connections and the reputation of its technical staff, Hughes Aircraft cornered the market for airborne electronics for all air force interceptors. By 1952 Hughes had air force contracts worth $200 million and 15 000 employees, including 1000 scientists and engineers. Despite the defection of Ramo and Wooldridge to form Ramo-Wooldridge Corp (later TRW) in 1953, Hughes Aircraft became the largest military electronics firm, and perhaps the most innovative, in Southern California.

Ramo and Wooldridge set out to build the Bell Labs of the West, but at one-tenth the size. They offered top salaries, compelling technical challenges, and, as the recruiting posters promised, "luxury living in California," poolside beneath the palms. To give the scientists their own space, literally and intellectually, Hughes built Hughes Research Laboratories (HRL), a stunning complex in Malibu perched on a hill overlooking the beach. The facility, shown in the opening image on page 36, boasted unrivaled views of the Pacific Ocean to one side and the Santa Monica Mountains to the other. Entirely sheathed in glass and with a cantilevered canopy for shade from the intense Malibu sun, the building featured an enormous fieldstone wall near the entrance and a bridge of interlocking concrete slabs crossing a large, landscaped pond. The lobby, furnished with chairs, tables, and couches in the Danish modern style, looked like the entrance to an exclusive country club.

Hughes's namesake lab could be as secretive, glamorous, and seductive as the reclusive billionaire himself. It's no wonder comic master Stan Lee modeled the original Iron Man,

FIGURE 1. A YOUNG AEROSPACE ENGINEER AND HIS FAMILY look for a house in Orange County, California. Autonetics drew physicists and engineers to work at its nearby facility by promising beautiful homes and neighborhoods, good schools, and other amenities. (Courtesy of the City of Huntington Beach Historical Collection.)

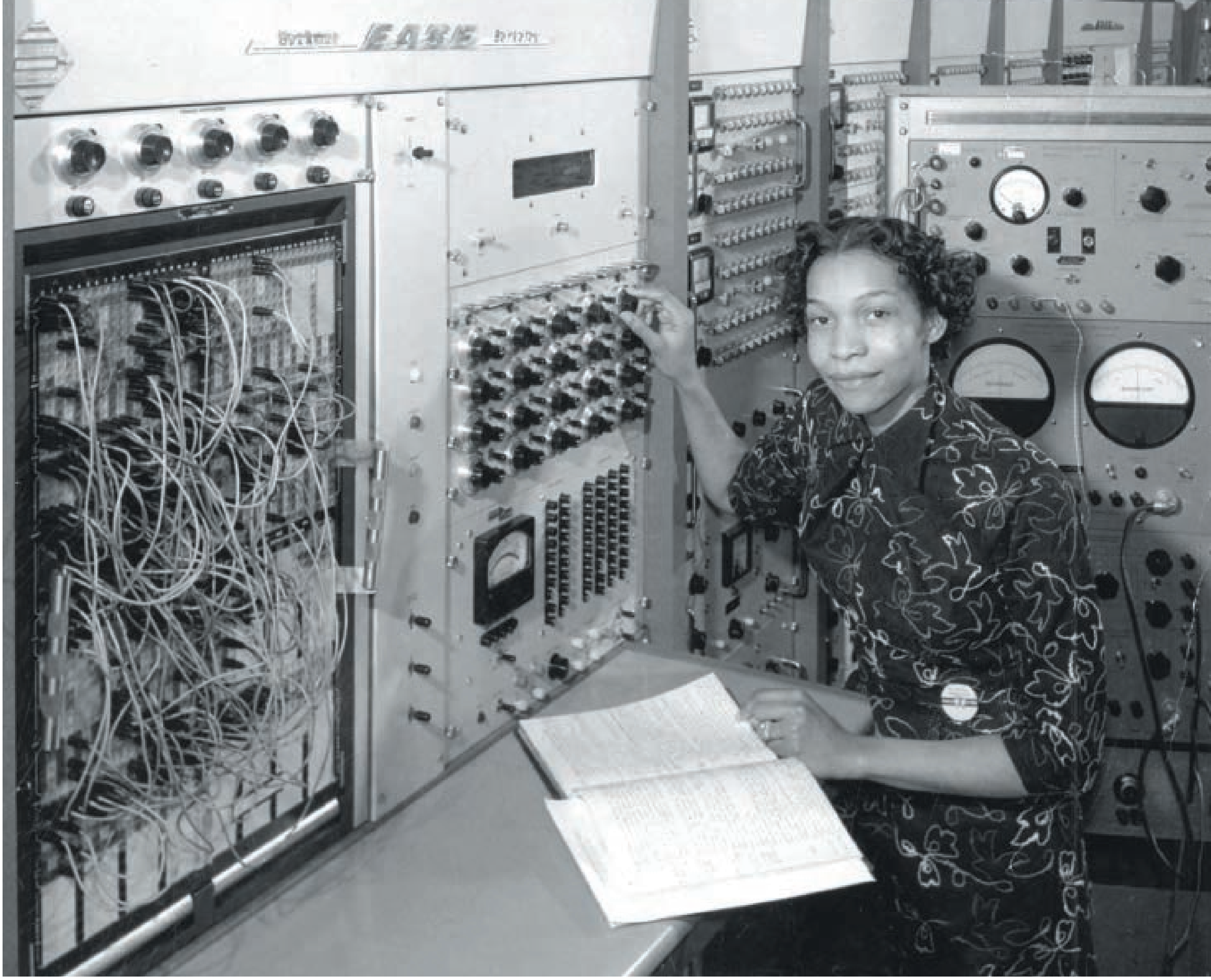

FIGURE 2. PHYSICIST NASIRA WILKINS was a member of Rocketdyne's scientific staff in 1959. Women, particularly women of color, were "hidden figures" at most aerospace companies in the 1950s. (Courtesy of the Valley Times Collection, Los Angeles Public Library.)

Tony Stark, on Hughes. The 2008 film version set Iron Man's clandestine laboratory in the basement of a Malibu mansion that freely borrowed from some of architect John Lautner's futuristic mansions. Hughes, a connoisseur of midcentury modern, surely would have approved.

HRL moved into its new home in early 1960. The facility housed research groups for theoretical physics, quantum physics, computing, and materials science. "Sure it's a long haul," one scientist complained about the commute to HRL in a 1962 *Westways* magazine article. "But it's such a darn pleasant place to work I actually look forward to the drive every morning." HRL repaid the company's investment almost immediately. Theodore Maiman fired up the world's first functioning laser there that May, beating out Bell Labs and its high-powered team of future Nobel laureates and bringing the new laboratory instant international recognition.

The company sought to provide a university atmosphere even though it was a highly classified laboratory. It recruited heavily from Caltech, especially at the PhD level, and many of those alumni moved to its upper ranks. To keep some of that freewheeling graduate-school spirit alive, HRL brought in Richard Feynman to consult and to give a series of popular weekly lectures to the staff. The company advertised for researchers fascinated by "far out" ideas and attracted more than its share. Physicist Robert Forward, for example, spent three decades there working on gravity-wave and gravity mass detectors, ground-based lasers for interstellar propulsion, space tethers, antimatter, and smart structures. He wrote popular science fiction on the side.

HRL became the public face of a company with a reputation for keeping a low profile. It was a place everybody—generals, executives from other companies, even scientific dignitaries—wanted to see for themselves. In 1965 the European press corps was invited to cover the launch of *Intelsat 1*, the first geosynchronous communications satellite. The company's management made sure the journalists saw two Southern California landmarks: Disneyland, with a personalized tour by multilingual guides, and HRL, whose own "imagineers" talked about lasers, ion propulsion, and other real-life science fiction.

HRL set the tone for the company's manufacturing divisions. Hughes's ground systems division built an enormous complex for its ground radar systems in Fullerton, located in Orange County. The ultramodern T-shaped complex featured a glass curtain wall and fieldstone accents on the facade. Fullerton offered the first-rate housing, schools, and lifestyle HRL envisioned for its predominantly male workers, most of whom had stay-at-home wives with young children.

Bolstered by a huge backlog of military contracts for ground-based air defense systems, Hughes continued expanding. The company hired physicists, engineers, and technicians as fast as it could sign them up. By 1961 the Fullerton site had 7000 employees and had essentially become a self-contained city within a city. "With its broad lawns and stands of towering trees, the sprawling Hughes Aircraft aerospace complex looks more like a college campus than an industrial outpost of the Cold War," according to a 1994 *Los Angeles Times* article. Fullerton's mayor made no apologies for saying, "Hughes is Fullerton, and Fullerton is Hughes."

Space-age workers find "home"

Like its competitors, NAA decided after World War II that its future would be in aerospace, not aircraft. Southern California's biggest wartime aircraft manufacturer moved aggressively into missiles, space, and related technologies. In 1955 it established three new aerospace divisions: Rocketdyne for rocket engines, Atomics International for nuclear reactors, and Autonetics for missile guidance and control. All three depended heavily on physicists.

When NAA's original plants became severely overcrowded, it relocated Rocketdyne and Atomics International to Canoga Park in the San Fernando Valley and built a new complex for Autonetics in Anaheim, in Orange County. When the structure was completed in the mid 1960s, it was the nation's largest single military electronics facility, with 3.3 million square feet of floor space and 36 000 workers. The 20-building complex contained everything needed to design, fabricate, assemble, and test complete inertial guidance and flight control systems for a new generation of intercontinental ballistic missiles and advanced jet fighters.

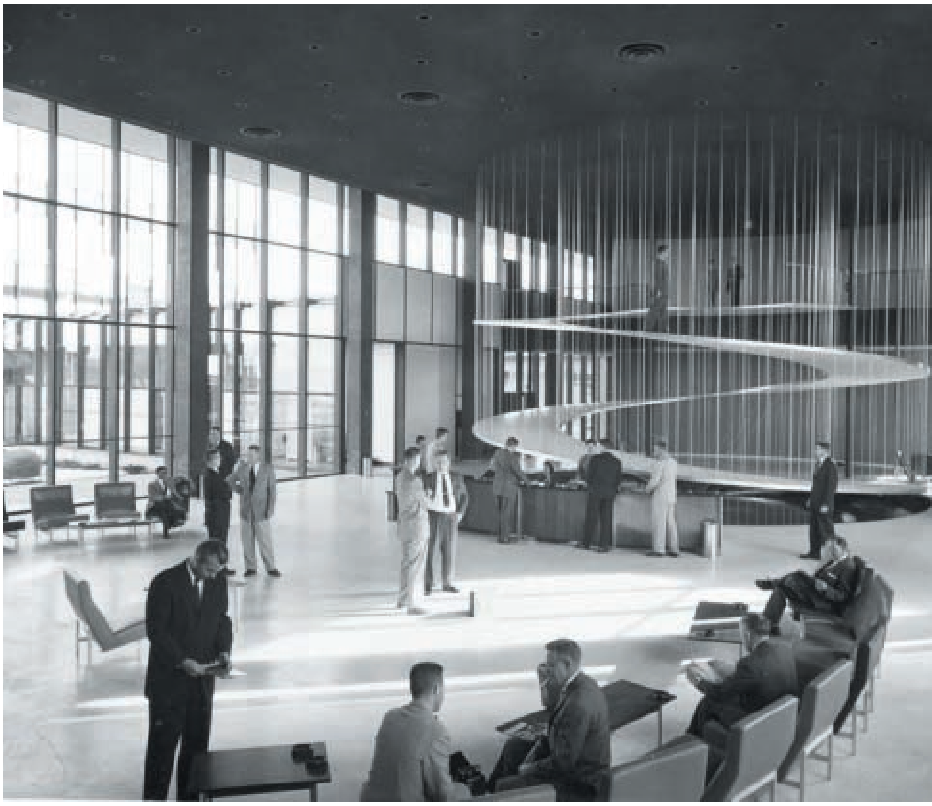

FIGURE 3. THE SUSPENDED ALUMINUM RAMP AT CONVAIR ASTRONAUTICS connected the lobby with the executive offices upstairs. Given that the photo was surely posed, missiles were clearly considered a man's game. (Courtesy of the San Diego Air & Space Museum.)

When it came to new facilities, NAA followed Hughes's lead and designed Autonetics like a university campus so its PhD recruits would feel more at home. The main research laboratory included such touches as tropical gardens in the lobby, lava rock walls, and glass entries screened with artful tile and metal designs. Like its competitors, Autonetics provided its engineers with high salaries, paid postgraduate study, and enviable neighborhoods in which to raise their families (see figure 1). It also built a 20-acre recreation center with a three-section swimming pool, exercise rooms, a steam bath, baseball fields, tennis courts, and a pitch-and-putt golf course that together could have passed for a private country club.

The Rocketdyne and Atomics International facilities in Canoga Park transformed a sleepy San Fernando Valley suburb into a thriving hub of the military–industrial complex. With 10 000 employees, Rocketdyne built rocket engines for the military and for NASA, including the gigantic F-1 engines that powered the first stage of the Saturn V. Atomics International, with 9000 employees, designed experimental sodium-cooled nuclear reactors for electric power stations and compact SNAP (Systems for Nuclear Auxiliary Power) reactors. In 1965, one SNAP reactor, SNAP-10A, was placed in orbit to power a satellite. It remains the only fission reactor power system that the US has launched into space.

Rocketdyne opened in 1955, and within four years it employed 2260 women, a number of whom were scientists and engineers with graduate degrees in mechanical, electrical, and chemical engineering. One of them, Nasira Wilkins (see figure 2), was a bona fide rocket scientist with a physics degree from Howard University. As a Black woman, she was a trailblazer; Rocketdyne's parent company, NAA, refused to hire African Americans for any skilled positions until forced to by federal law in 1941, and then it did so only reluctantly. Predictably, Rocketdyne could not resist calling its female employees "Rockettes." The press release for the opening of its 15-acre Atomics Club featured two model-worthy employees in revealing swimsuits, "setting stage for summer splashing" in the new pool.[6]

An established firm, NAA had a reputation for being a somewhat undesirable place for scientists to work. To change that, the company followed Hughes and built its own basic research laboratory, known as the Science Center. The founding director, Howard Reiss, was the former head of research for Atomics International. He had spent almost a decade at Bell Labs and set out to re-create a smaller-scale version for aerospace. Rather than organizing the Science Center around research themes of direct relevance to NAA's manufacturing divisions—atomic power, guidance and control, propulsion, and aerodynamics—Reiss proposed something modeled after a university with departments of physics, chemistry, physical metallurgy, and mathematics.

Reiss was convinced that an academic style would most appeal to the kind of scientist he hoped to recruit. He thought something like 50 PhDs would be sufficient to start, but as he noted in a memo to corporate officers, each one had to be first rate: "It should be reiterated that such personnel will be attracted to the corporate research center only if the proper image can be created. Everything must be done to produce and maintain this image. Once we acquire outstanding personnel and are provided with proper funding and adequate working conditions, the rest will take care of itself. The essence of this image is the company's display of enthusiasm for good science and the establishment of a permissive atmosphere in which creativity can flourish."

What could convey the right image more forcefully than architecture? Reiss considered Bell Labs' facility claustrophobic, with scientists sequestered like monks in identical 8-by-10-foot cells. He hired Albert Martin Jr to design something contemporary and chic for the Science Center. Martin had recently conceived stunning new corporate campuses for TRW, the Aerospace Corp, and Atomics International.[7] He and Reiss chose a spectacular 66-acre site in Thousand Oaks overlooking a dry creek and adjoining the residential community. Given a generous budget, Martin came up with a laboratory worthy of the site. To blend into its suburban surroundings, he kept the laboratory one story, with tapered concrete stilts in soft white with exposed brown aggregate from a nearby quarry.

The Science Center's architecture and location became an important recruiting tool for Reiss. In a remarkably short time, he pulled together an organization that could compete with Hughes, although not necessarily with the best East Coast laboratories, many of which were 10 or 20 times as big as the Science Center. In one memorable year, the Science Center staff published 600 papers, more than Bell Labs—a rare accomplishment indeed.

Beyond its scientific achievements, the Science Center became a port of entry for bright young scientists who eventually moved into management positions in other parts of NAA. Reiss correctly estimated that perhaps three-quarters of his staff would choose to relocate to Thousand Oaks or nearby suburban communities. Restrictive racial housing covenants meant that no African Americans could live there or in places such as Canoga Park, which had just two Black residents in 1960. Nonwhite employees would have to commute from Pacoima, a town 20 miles to the northeast that had suburban homes for sale to nonwhite residents. In the late 1960s, the town's population was 79% African American.

Atoms for peace, and for profit

Founded in 1955 by defense conglomerate General Dynamics, General Atomics aspired to do for the nuclear age what General Electric had done for an earlier era. Its sister company Convair Astronautics constructed a $20 million self-contained missile factory north of San Diego. There, 20 000 scientists, engineers, and technicians—the vast majority of them white and white collar—designed, manufactured, and tested the Atlas missile. The stunning lobby, the work of architect William Pereira, featured a suspended aluminum ramp rising out of the pool below, shown in figure 3, and epitomized aerospace modernism. Although an iconic image of the lobby depicts a couple ascending the ramp, few women, aside from the secretarial staff, actually worked there.

General Dynamics considered atomic energy a key emerging market and backed its commitment with cash: $10 million in startup funds to make General Atomics a world-class center for studying nuclear power. On the advice of Edward Teller, General Dynamics hired Frederic de Hoffmann to organize and staff its newest division. Along with many of the brightest physicists of his generation, de Hoffmann had spent the war in Los Alamos. After completing his doctorate at Harvard University, he returned to Los Alamos as Teller's assistant on the hydrogen bomb project and was responsible for some of the trickier numerical computations. But it was nuclear power—the quest "to bring the sun down to the earth," as he often put it—that truly captivated de Hoffmann.

With his inside contacts at Los Alamos and the Atomic Energy Commission (now the Department of Energy), de Hoffmann already knew virtually everyone in the field worth knowing. Now he had the money to make them offers they could hardly refuse. Hoping to recapture some of the magic of Los Alamos, de Hoffmann recruited heavily among its veterans. He lined up an all-star team of advisers, including Hans

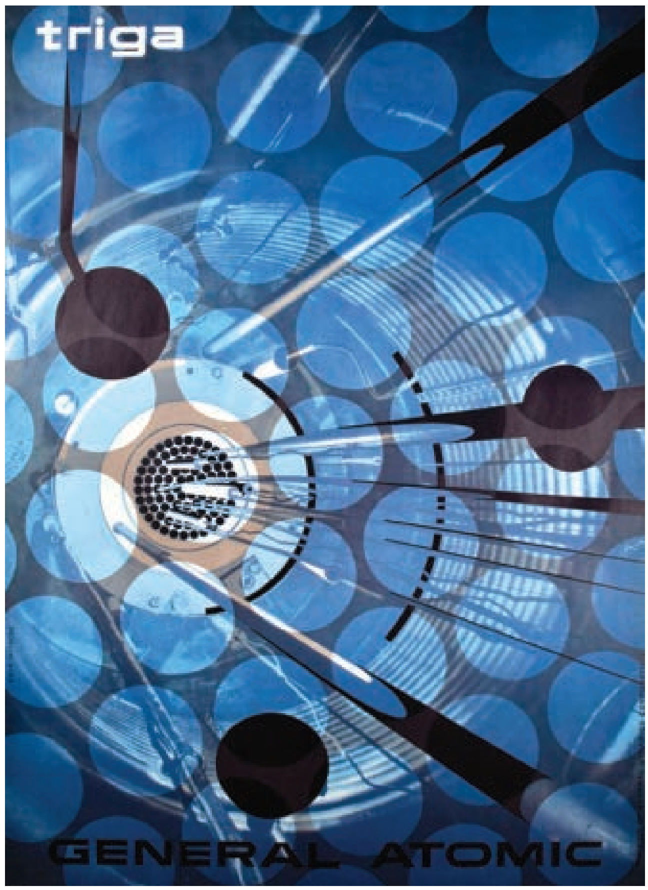

FIGURE 4. ERIK NITSCHE'S ATOMS FOR PEACE POSTERS are now considered design classics. The Swiss graphic artist created this poster of General Atomics' TRIGA reactor for the Second International Conference on the Peaceful Uses of Atomic Energy in Geneva, Switzerland, in 1958. (Image from © The Museum of Modern Art/Licensed by SCALA/Art Resource, NY.)

FIGURE 5. AUTONETICS' NEO-BABYLONIAN ZIGGURAT in Laguna Niguel, California, was designed by William Pereira and completed in 1971. However, the company never occupied the 1-million-square-foot megastructure; instead, they swapped properties with the General Services Administration which placed federal agencies in the building. (Image from © J. Paul Getty Trust/Getty Research Institute, Los Angeles, 2004.R.10.)

Bethe, Richard Courant, Frederick Seitz, and Teller.

For the laboratory's director, he brought in Edward Creutz, a group leader at Los Alamos who had worked on the design of nuclear fuel elements. Creutz had gone on to head the physics department at Carnegie Institute of Technology (now Carnegie Mellon University) and build its synchrocyclotron. Together, Creutz and de Hoffmann would create one of the country's biggest and best physics departments, which boasted the highest percentage of PhD physicists of any corporate laboratory. They envisioned General Atomics as a university without students and without pressure to bring in outside grants.

The city of San Diego donated 320 acres of land on Torrey Pines for the General Atomics laboratory; the site overlooked sandy beaches and the Pacific Ocean. Creutz turned to Pereira to design a one-of-a-kind laboratory for a one-of-a-kind company. Based on his prior experience at universities and national laboratories, Creutz firmly believed that developing complicated new technologies would require interdisciplinary collaboration. Traditional campuses reinforced disciplinary isolation, so he encouraged Pereira to think outside the box. Pereira's hub-and-wheel laboratory ring design looked more like a tethered space station than a corporate laboratory. The central hub housed common areas—the cafeteria, executive dining room, and library—and the main laboratory buildings nearly encircled the hub. With their sky-blue spider leg motif, the laboratories looked like they had just touched down from the future.

Pereira's guiding aesthetic for the General Atomics commission might be dubbed California country club. The facility included tennis courts and an outdoor swimming pool, and the landscaping would have looked right at home at Torrey Pines Golf Course, which opened just west of the General Atomics campus in 1957. The difference between an old-style eastern corporate laboratory and its upstart western rival was epitomized in the contrast between General Electric's red-brick industrial research laboratory in Schenectady, New York, and Pereira's space-age design for General Atomics in San Diego.

Its civilian projects got the press, but General Atomics' defense contracts made the money. The TRIGA (Training, Research, Isotopes, General Atomics) reactor, designed by Los Alamos veteran Ted Taylor and consultant Freeman Dyson, found a large market as a small, safe reactor for universities and hospitals (see figure 4). General Atomics also developed the HTGR (High-Temperature Gas-Cooled Reactor) with funding from a utilities consortium, although it failed to work out all the bugs before orders for nuclear power plants collapsed. A group of Texas utility companies put up $10 million for research on fusion reactors, but nothing commercial came out of that effort either. For pure audacity, it would be hard to match Project Orion, the hydrogen-bomb-powered spacecraft envisioned by Taylor and Dyson for a mission to Mars.[8]

As fascinating as those projects may sound, General Atomics' viability, financially and otherwise, depended solely on US Air Force and Advanced Research Projects Agency funding for ballistic missile defense and other weapons studies. Its reputation was out of proportion to its size—fewer than 600 total employees in its early years and just 1350 by 1962. But the company set a high standard for laboratory architecture in San Diego, against which later icons, such as the Salk Institute, would measure themselves.

Between them, Convair Astronautics and General Atomics employed 224 physicists in 1960, along with some 7000 other scientists and engineers. Virtually all of them chose to live in new suburban developments in Kearny Mesa and La Jolla. Those neighborhoods were worlds (if not miles) away from older working-class neighborhoods like Linda Vista, which was once the largest public-housing complex in Southern California. During World War II, 3000 homes and 750 dormitories were built in Linda Vista for San Diego's aircraft and shipyard workers. After, it was home to 20 000 residents, and it was one of the few neighborhoods in San Diego County where African Americans could buy single-family homes.[9]

The crash of blue-sky California

As the Vietnam War heated up in the early 1970s, the space race wound down and demand shifted from strategic weapons back to conventional ones. California's aerospace industry lost 160 000 jobs, 80% of those in greater Los Angeles. The end of the Cold War brought an even more devastating downturn: Southern California lost 150 000 aerospace jobs from 1988 to 1996, then another 130 000 in the following decade as companies shut down or sold off entire divisions. Household names like Douglas, NAA, and Northrop disappeared in a wave of mergers, and with them entire aerospace complexes.

Many scientists and engineers suddenly found themselves confounded by a world where "Work Close to Home," Rocketdyne's slogan for luring employees to the suburbs of the San Fernando Valley, seemed a cruel irony. In 1995 Hughes closed down its modern-day company town in Fullerton, a place that for four decades had delivered on the promise of "the American dream—a large home with a yard and a pool, nice cars, a stable environment in which to raise children, and some money in the bank," according to a 1994 *Los Angeles Times* article. A real estate developer replaced the Hughes campus with a community of single-family homes and a shopping center.

California has fewer physicists now than it did at the height of the Cold War—still more than any other state, but scarcely more than runners-up Maryland and New Mexico.[10] Boeing bought what was left of the Autonetics complex in 1996 and closed it a decade later; all that remains today is a monument to aerospace workers that was erected by Boeing in 2009. HRL outlived the company that created it and is now a jointly owned venture of General Motors and Boeing. It still attracts top talent for the same reasons as in the past: world-class science and a great location. Almost everyone mentions the ocean views and gorgeous sunsets, although the occasional killjoy rips HRL as an old aerospace company run like it was still 1965.

The NAA Science Center carries on as a division of Teledyne. General Atomics continues to thrive as a scientific workplace, with its midcentury modern style frozen in time and its idealistic founding mission of turning "atoms for peace" into "atoms for profit" long since supplanted by a more pragmatic business plan. Today General Atomics makes its money from Predator drones and their offspring and remains on the cutting edge of Southern California aerospace.

Fittingly, perhaps, no physicists or engineers ever got to occupy the biggest "aerospace" ever built in Southern California. In 1968 Autonetics purchased 1320 acres in Laguna Niguel, in southern Orange County, in preparation for a planned expansion. The company hired Pereira to produce a master plan for its $20 million facility. Instead of a campus, Pereira designed a seven-tiered ziggurat in neo-Babylonian brutalism, the perfect metaphor for the Vietnam War–era bunker mentality of the military–industrial complex (see figure 5).

The building's facade stood as massive, forbidding, and unapproachable as a medieval castle. But with the collapse of its defense contracts, Autonetics found itself with the quintessential white elephant and traded it to the federal government, which found the ideal tenants for such a structure: the Internal Revenue Service and, later, the Department of Homeland Security and its Immigration and Customs Enforcement. Despite the loss of Autonetics, Laguna Niguel flourished as one of the largest and fastest-growing cities in Southern California in the 1980s. Its population was 84% white and less than 2% Black.

Symbolically, Pereira's ziggurat marked the end of the golden age of aerospace in Southern California. Hunter Thompson's 1971 elegy for the radical 1960s, *Fear and Loathing in Las Vegas,* applies just as well to the forgotten cold warriors who believed the sky was the limit and whose scientific contributions, many still classified, have never been fully acknowledged:

> We had all the momentum; we were riding the crest of a high and beautiful wave.
>
> So now, less than five years later, you can go up on a steep hill . . . and look West, and with the right kind of eyes you can almost *see* the high-water mark—that place where the wave finally broke and rolled back.

As the aerospace wave receded, it left behind a unique suburban geography with divisions of labor, class, race, and gender that will long outlast the industry that spawned it.[11]

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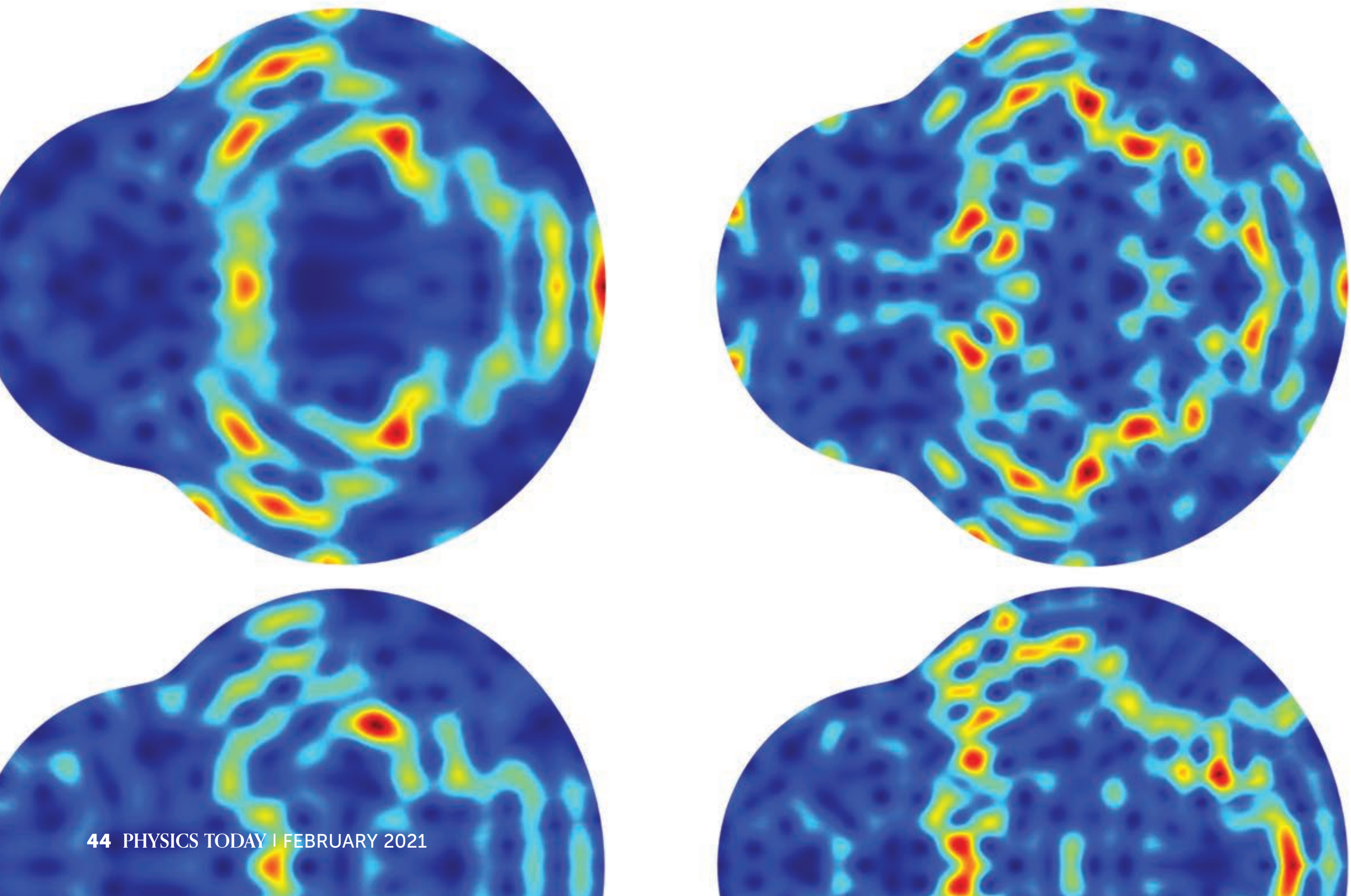
Relativistic quantum chaos in graphene

Hong-Ya Xu, Liang Huang, and Ying-Cheng Lai

Classical chaos gains some additional degrees of freedom in materials with excitations described by the Dirac equation.



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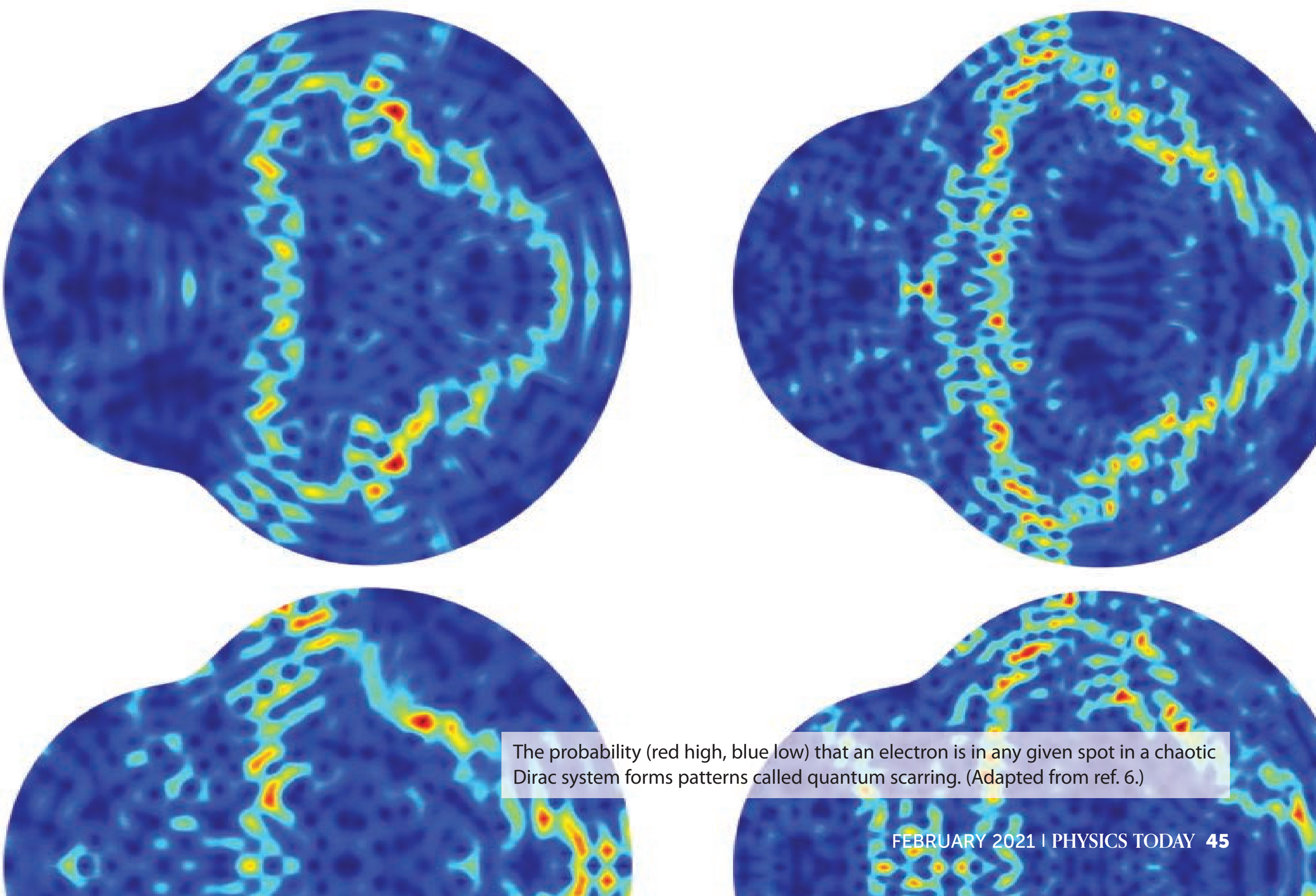
In his 1987 best seller *Chaos: Making a New Science*, science journalist James Gleick wrote, "Where chaos begins, classical science stops." Indeed, after relativity and quantum mechanics, chaos became the 20th century's third great revolution in physical sciences. Chaos results from the sensitivity of a nonlinear system to initial conditions, and it makes classical evolution appear random with time (see the article by Adilson Motter and David Campbell, PHYSICS TODAY, May 2013, page 27). That sensitivity is the origin of Edward Lorenz's well-known butterfly effect[1]—named for the idea that a butterfly flapping its wings in South America could set off a tornado in Kansas—which rules out any hope for long-term weather forecasting.

Chaotic behavior manifests in quantum and relativistic systems, and classical chaos can lead to new manifestations in systems that are both relativistic and quantum mechanical—such as graphene, whose electrons can behave like massless particles. Those novel fingerprints of chaos are of theoretical and practical interest.

Classical chaos emerges in, for example, classical particles bouncing around elastically, similar to a billiard ball. For a billiard system with the usual rectangular boundary, two nearby particles with the same momentum reflect off the boundary with equal momentum. But when the boundary is curved, the reflected momenta of the particles are different, sometimes drastically so. That sensitivity to momentum provides the nonlinearity required for chaos in a simple system geometry, such as an oblong shape that resembles a sports stadium.

Classical light rays imitate a billiard system when confined



The probability (red high, blue low) that an electron is in any given spot in a chaotic Dirac system forms patterns called quantum scarring. (Adapted from ref. 6.)

in a cavity. To produce confinement, the cavity's refractive index must be larger than that of the surrounding medium, so that the rays undergo total internal reflection for angles larger than the critical angle, which is determined by the ratio of the cavity to exterior refractive indices. Unlike the billiard system, however, light rays can escape from the cavity when their incident angle is less than the critical angle.

Figure 1 shows the modeled behavior of two representative light rays in a dielectric cavity formed by two nonconcentric circles that define the boundaries for regions with different refractive indices. The refractive index is largest in the center circle (region III), smaller in the larger ring (region II), and smallest outside the ring (region I). Although the two light rays differ only slightly in their initial angles, the resulting behaviors are remarkably different. That sensitivity is the hallmark of chaos.

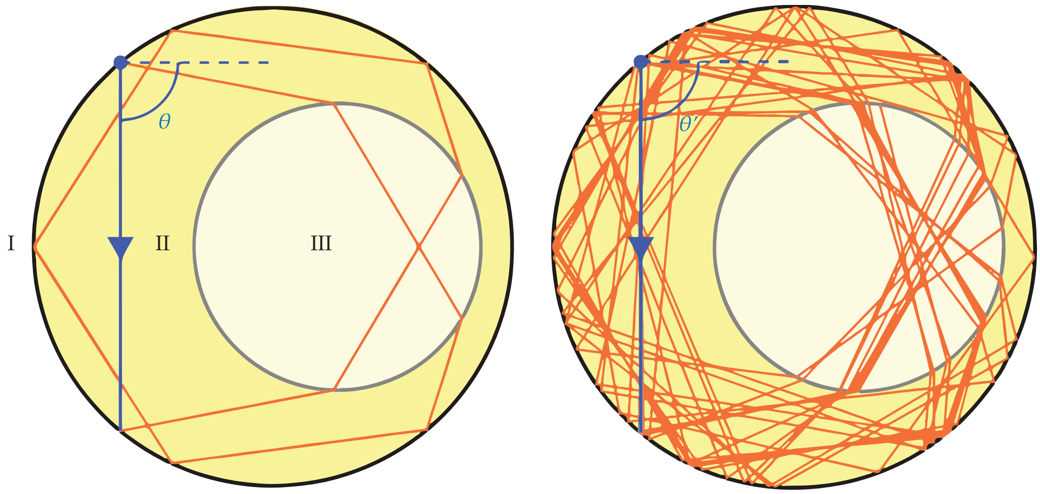


FIGURE 1. LIGHT TRAPPED IN THIS CAVITY displays chaotic behavior. In this dielectric medium the index of refraction is largest in the smallest circle (region III), smaller in the region between the two circles (region II), and smallest in the surrounding area (region I). Two ray trajectories (blue arrows) differ only slightly in their initial angles, $\theta' - \theta = 10^{-4}$, but exhibit drastically different behaviors (orange) inside the cavity. The light in the left illustration bounces in a nearly repeating pattern, whereas the light in the right reflects in an ever-changing, chaotic path. (Courtesy of Hong-ya Xu, Liang Huang, and Ying-Cheng Lai.)

It's all relative

The analogy between classical particles in a billiard system and light rays in a dielectric cavity raises the question of relativity's role. Although both share many features, the particles are nonrelativistic whereas light is relativistic. The difference between them is best described by the dispersion relation, which gives the relationship between the energy and momentum. For a nonrelativistic particle, the energy is proportional to the momentum squared, but for a photon with zero rest mass, the energy is linearly proportional to the momentum.

In quantum mechanics, nonrelativistic particles are described by the Schrödinger equation, which has a quadratic dispersion relation. Relativistic particles, on the other hand, are typically described by the Dirac equation, and for a massless relativistic particle, the dispersion relation is linear. The Schrödinger equation also doesn't include the spin, which is naturally embedded in the Dirac equation.

What happens when quantum mechanical systems are chaotic? The fundamental equations for such systems—Schrödinger or Dirac—are linear and thus rule out real chaotic behavior. As Michael Berry stated in 1989, "There is no quantum chaos, in the sense of exponential sensitivity to initial conditions, but there are several novel quantum phenomena which reflect the presence of classical chaos."[2] Nevertheless, the somewhat inaccurate term "quantum chaos" has taken root to describe the manifestations or fingerprints of classical chaos in a quantum system.[3] In stadium billiards, for example, a classical particle will go through almost every point in the system in the course of evolution, with equal probability of being at any one point. But in quantum mechanics, the wavefunctions concentrate on some unstable classical periodic orbits—so-called quantum scars, shown in the opening image on page 44, which are a distinct quantum manifestation of classical chaos. Traditionally, quantum chaos has dealt almost exclusively with nonrelativistic quantum systems described by the Schrödinger equation.

In the past 15 years, researchers have developed and studied so-called Dirac materials, which host quasiparticles that behave according to the Dirac equation. The most common such material is graphene, a one-atom-thick layer of a hexagonal lattice of carbon atoms.[4,5] After the successful isolation of a single layer of graphene[4] in 2004, researchers have prepared a variety of two-dimensional solid state materials (see the article by Pulickel Ajayan, Philip Kim, and Kaustav Banerjee, PHYSICS TODAY, September 2016, page 38), whose quasiparticles' energy exhibits a linear dependence on momentum. As a result, 2D Dirac materials are described by relativistic quantum mechanics. With available Dirac materials, a viable field has emerged: relativistic quantum chaos,[6] which seeks to discover, understand, and exploit fundamental phenomena arising from the interplay between chaos and relativistic quantum mechanics.

Get to the (Dirac) point

Albert Einstein's theory of special relativity says that a massless particle such as a photon has energy proportional to its momentum, with the speed of light as the proportionality constant. Similarly in graphene and other Dirac materials, quasiparticles have a linear relationship between their energy $E(\mathbf{k})$ and momentum $\mathbf{k}$, $E(\mathbf{k}) = v_F|\mathbf{k}|$, with a proportionality constant $v_F \approx 10^6$ m/s. That constant is the Fermi velocity—the velocity of electrons in the highest occupied energy state at absolute zero temperature, known as the Fermi energy. That linear relation means that electrons' motion in graphene is relativistic despite their velocity being about 1/300 the speed of light.

Graphene's linear dispersion relation is a product of the lattice's geometry and the resulting band structure. Graphene is a honeycomb lattice with two nonequivalent atomic sites in each unit cell, so the entire lattice can be regarded as two triangular lattices, A and B, as shown in figure 2a. About 70 years ago, Philip Russell Wallace calculated the energy bands for the honeycomb lattice structure.[7] His calculation revealed that the

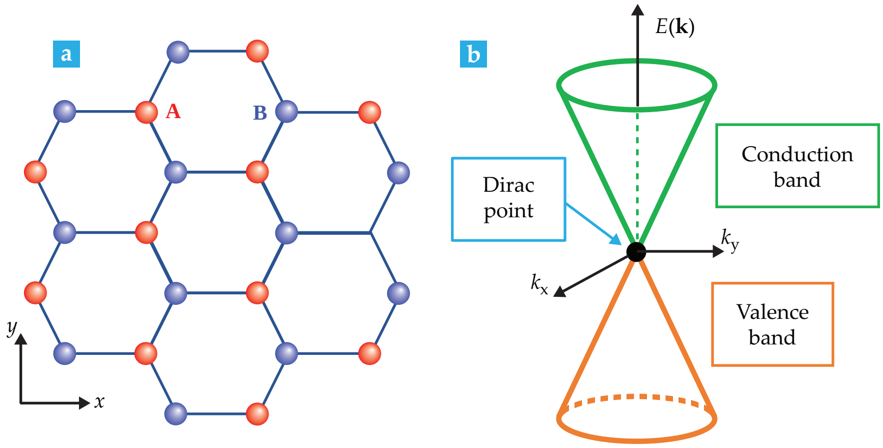


FIGURE 2. GRAPHENE'S LATTICE determines the energy band structure. **(a)** The two-dimensional honeycomb lattice comprises two nonequivalent triangular sublattices, A (red) and B (blue), of carbon atoms. **(b)** That structure determines the relation between an electron's energy $E(\mathbf{k})$ and momentum **k**. Around what's known as a Dirac point, the relation is linear, similar to that of photons and other relativistic particles. (Courtesy of Hong-ya Xu, Liang Huang, and Ying-Cheng Lai.)

first Brillouin zone—the unit cell in reciprocal space—contains two nonequivalent points, the so-called Dirac points, about which the energy–momentum relation is linear. Near a Dirac point, quasiparticles thus behave as massless fermions. Because the momentum vector is 2D, graphene's band structure about a Dirac point consists of a pair of Dirac cones that meet at their tips, as shown in figure 2b.

Graphene and other 2D Dirac materials possess a unique quantum number called the pseudospin degree of freedom.[4,5] The two nonequivalent atomic sites, A and B, provide two independent types of quasiparticle motion. Because the quasiparticles can occupy either A or B, they are said to have pseudospin-½ in addition to the usual real spin-½ (up or down). Without an external magnetic field, the pseudospin Dirac cones are degenerate in the real spin, but in the presence of a magnetic field, the spin degeneracy is broken by the interaction between the field and the real spin.

Because of their shared linear dispersion relation, Dirac fermions behave in a way that is analogous to photons' behavior in optics; reframing relativistic quantum mechanical phenomena in terms of optics is known as Dirac electron optics. For example, Snell's law can predict the behavior of a graphene sheet with a potential difference V_0 between its left and right halves.

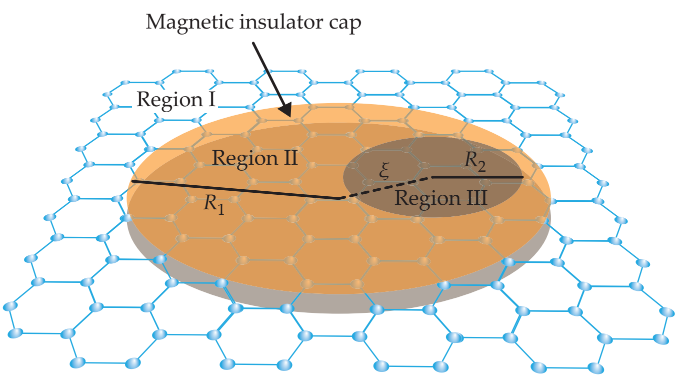


FIGURE 3. A GRAPHENE-SCATTERING SYSTEM analogous to the optical cavity in figure 1. A sheet of graphene is electrically gated in two overlapping circles of radii R_1 and R_2 whose centers are a distance ξ apart. The interactions between the magnetic capping layer in regions II and III and the spin state of graphene's electrons produce different dynamics for those that are spin-up from those that are spin-down. (Courtesy of Hong-ya Xu, Liang Huang, and Ying-Cheng Lai.)

When a plane wave of Dirac electrons with energy $E < V_0$ hits the interface, the angle of the refracted wave can be found by matching the solutions of the Dirac equation in the two halves[8] or through Snell's law for an interface between regions with refractive indices $n_1 \sim E$ and $n_2 \sim E - V_0 < 0$. The half of the graphene that is at the higher electrical potential thus behaves the same as an optical metamaterial with a negative refractive index.

Chaotic graphene

To introduce chaos in a relativistic quantum system, a graphene sheet can mimic the optical cavity from figure 1 through the introduction of localized magnetic and electrical fields, as shown in figure 3. Two circular boundaries divide the graphene into three distinct regions: region I, the graphene around the electrical gates; region II, with radius R_1 and gated with potential ν_1; region III, a distance ξ from the center of region II, with radius R_2, and gated with potential ν_2. A magnetic insulator, such as europium sulfide, caps the whole gated region to form a ferromagnetic–graphene heterostructure.[9] The ferromagnetism in the cap material acts on the electrons' spin, so an electron's energy depends on its spin state. As a result, spin-up and spin-down electrons experience different energy landscapes and display distinct classical ray dynamics.

Figure 4a shows an example in which the spin-up electrons exhibit fully developed chaos (red lines) in the whole gated region, whereas spin-down electrons follow a stable and periodic pattern (blue lines) confined within the small circle. Having electrons simultaneously display both chaotic and nonchaotic behavior is unique to relativistic quantum chaos and only possible because of the fundamental role of spin.

Figure 4b shows how the energy band structure differs by region for the electron spin states. Region I has no magnetic field, so the pseudospin Dirac cones (green) for spin-up and spin-down electrons are degenerate. In the whole gated region, the magnetic field lifts the degeneracy, such that the spin-up and spin-down Dirac cones have a relative energy shift 2μ. In region II, a negative electrical potential $\nu_1 = -\mu$ pulls down both Dirac cones by the same amount. As a result, the Dirac point of the spin-down electrons (blue) is still at zero, but that of the spin-up electrons (red) is now at $\nu_1 - \mu = -2\mu$. In region III, a positive potential $\nu_2 = \mu$ raises the Dirac points of the spin-up and spin-down electrons to zero and 2μ, respectively.

That energy landscape can be reframed in terms of the effective refractive index for the electrons in regions II and III: $n_s^{\mathrm{II}} = 2 + s$ and $n_s^{\mathrm{III}} = s$, where $s = \pm1$ denotes the real spin orientation. For spin-up electrons ($s = +1$), the index values are $n_+^{\mathrm{II}} = 3$

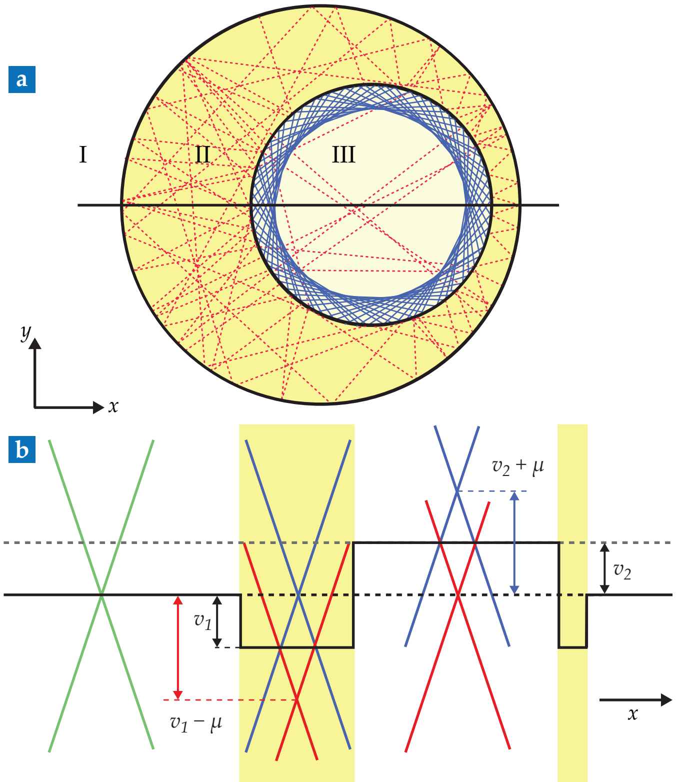


FIGURE 4. RELATIVISTIC QUANTUM CHAOS emerges in the graphene device shown in figure 3. **(a)** Spin-up (red) and spin-down (blue) electrons travel the paths indicated by the lines. Spin-down electrons stay in region III and follow a stable and repeating orbit, whereas spin-up electrons travel chaotic trajectories. **(b)** The energy landscape along the horizontal black line in panel a is indicated in bold black. Region II has an electrical potential v_1, and region III has a potential v_2. Graphene's spin-up and spin-down Dirac cones are degenerate (green) in region I, but that degeneracy is lifted in regions II and III: The magnetic field produces an energy difference of 2μ between spin-up and spin-down Dirac cones. Here, $v_2 = -v_1 = \mu$. (Courtesy of Hong-ya Xu, Liang Huang, and Ying-Cheng Lai.)

and $n_+^{\mathrm{III}} = 1$, so those electrons experience region III as a scatterer in region II, and the ray dynamics can thus be chaotic in region II. For the spin-down electrons ($s = -1$), the refractive index values are $n_-^{\mathrm{II}} = 1$ and $n_-^{\mathrm{III}} = -1$, so those electrons stay in region III and have regular classical ray dynamics.

The two different types of classical dynamics lead to distinct relativistic quantum manifestations for spin-up and spin-down electrons, as illustrated by the differences between the graphs on the left and right of figure 5. For example, in a system with a given R_1 and R_2, the average time τ spent in the system for spin-down electrons can be indefinite (yellow stripes in figure 5a and spikes in 5b), because their ray trajectories can form stable periodic orbits for certain values of ξ and the energy E. For spin-up electrons, because of chaos, no stable periodic orbits exist, and τ is two orders of magnitude lower. In figure 5c, the total quantum scattering cross section $\bar{\sigma}_t$, which is proportional to the rate of the electron scattering off a barrier, has sharp resonances when a spin-down electron has an energy value associated with a large τ—that is, associated with a periodic orbit. For spin-up electrons, no sharp quantum resonances survive the mixing and smoothing effect of chaos. Overall, depending on the real spin of the electrons, the same structure generates completely different quantum scattering behaviors—a relativistic quantum chimera.[10]

Relativistic tunneling

In the past decade, researchers have investigated, mainly theoretically and somewhat experimentally, many topics in relativistic quantum chaos,[6] including relativistic quantum scars, Klein tunneling, superpersistent currents in chaotic Dirac rings, the interplay between chaos and spin, and the suppression of chaos in systems with spin-1 and pseudospin-1. Here, we have presented one concrete phenomenon: spin-dependent, coexistent regular and chaotic scattering. The phenomenon is counterintuitive from the perspective of nonrelativistic quantum chaos: Nonrelativistic quantum particles can't penetrate a potential barrier with probability one, as graphene's electrons do.

That unique phenomenon in relativistic quantum mechanics is called Klein tunneling—named for Oskar Klein, who first discovered the underlying physics in 1929 while studying the scattering of electrons based on the Dirac equation.[11] In general, a particle's wave nature enables the electrons to pass through a classically forbidden region with a finite probability. That tunneling effect is fundamental to quantum mechanics and has significant applications in quantum computing and sensing. In nonrelativistic quantum systems, the tunneling probability typically decreases exponentially with the potential barrier's height and width. But in relativistic quantum mechanics, the linear dispersion relation can allow particles with an internal degree of freedom, such as spin or pseudospin, to penetrate unimpeded through a high and wide potential barrier.

Klein tunneling has been observed experimentally in, for example, graphene and photonic crystals, but it's a somewhat controversial issue with no one accepted model to explain it. For 2D Dirac materials, one explanation for the physical origin of the phenomenon is the charge of the quasiparticles. For a Fermi energy above the Dirac point in figure 2b, the charge carriers are negatively charged electrons, but for a Fermi energy below the Dirac point, they are positively charged holes. And a potential barrier that is repulsive for electrons is an attractive potential well for holes. As the current travels across the potential landscape in figure 4b, the quasiparticles change from electrons to holes when the Dirac point is pushed higher in energy than the Fermi level. That electron–hole transmutation leads to current-carrying hole-like states inside the barrier and an unusually high tunneling probability.

Another way to understand Klein tunneling is through chirality. A massless quasiparticle in a Dirac material possesses a quantum number, known as chirality, which is the projection of its pseudospin in the direction of its momentum. Pseudospin is locked with momentum, so backscattering at normal incidence is possible only if the pseudospin can be reversed simultaneously. Because an electrical potential does not interact with pseudospin, the pseudospin can't be reversed. The quasiparticle thus has a 100% transmission probability at normal incidence, no matter how high or wide the potential barrier is.

Klein tunneling also appears in 2D Dirac materials with pseudospin-1. In such a lattice, the unit cell has three nonequivalent atoms and thus a three-band structure: a pair of Dirac cones and a flat, horizontal band where the cones intersect. Klein tunneling through a potential barrier can be more pro-

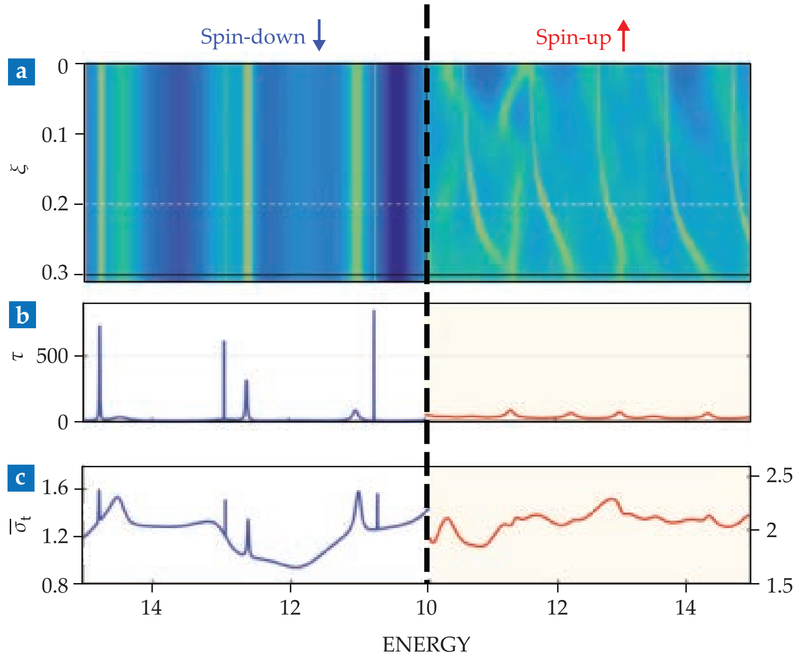


FIGURE 5. SPIN-UP AND SPIN-DOWN ELECTRONS manifest different classical behavior for the system in figure 3. **(a)** The average time τ (yellow high, blue low) electrons spend in the system varies with the distance ξ and the energy E, both given in dimensionless quantities. **(b)** The spectrum in dimensionless quantities along the dashed white line in panel a. Spin-down electrons can form stable periodic orbits, which lead to spikes in τ. For spin-up electrons, because of chaos, no stable periodic orbits exist, and τ is much lower. **(c)** The total quantum scattering cross section $\overline{\sigma}_t$, which is proportional to the rate of the electron scattering off a barrier, has sharp resonances when a spin-down electron has an energy value associated with a large τ. For spin-up electrons, no sharp quantum resonances survive the mixing and smoothing effects of chaos. (Courtesy of Hong-ya Xu, Liang Huang, and Ying-Cheng Lai.)

nounced in pseudospin-1 systems than in pseudospin-½ systems. For example, with the right Fermi energy, the transmission probability is 100% for any incident angle, a phenomenon known as super-Klein tunneling.

How then can an external electric potential confine quasiparticles? Classical chaos can make the task even harder. Because chaos leads to ever-changing trajectories, confined light will frequently hit a barrier at an angle that exceeds the maximum for total internal reflection, and it will escape its confines. According to the ray–wave correspondence, which is fundamental to quantum chaos, quantum particles will behave the same, and long-lived trapping is unlikely. But massless pseudospin-1 quasiparticles defy that intuitive picture.[12] They can be localized through the mechanism of revival Klein scattering resonances, which is analogous to exciting localized surface plasmons at a metal–dielectric interface. The counterintuitive emergence of resonant states of the quasiparticle represents a twist on the Klein tunneling with the new capability of realizing a surface plasmon-like trap in pseudospin-1 Dirac material systems.

Quantum scars

Another pronounced phenomenon in quantum chaos is scarring. In a classical billiard system shaped like a stadium or heart, the particle has an equal and uniform chance of being anywhere in the system because it has infinite possible periodic orbits, none of which are stable. For example, one orbit in the stadium billiard is the particle bouncing back and forth between the apex points of the two curved sides. But an arbitrarily small perturbation will wreck that orbit.

Quantum systems, however, have a discrete spectrum of eigenstates. And about 40 years ago, Allan Kaufman and his then-graduate student Steven McDonald found that the quantum eigenstates, unlike the uniform probability in classical billiards, tend to concentrate on certain unstable periodic orbits,[13] a phenomenon Eric Heller of Harvard University named quantum scarring.[14] Scarring generally arises from wave interference: If, after traveling the complete cycle of a periodic orbit, the total accumulated phase is an integer multiple of 2π, the wavefunction will constructively interfere along the orbit and form quantum scars.

About 10 years ago, two of us (Lai and Huang) and others predicted relativistic quantum scars in chaotic graphene billiard systems.[15] Subsequently, we found a class of quantum scars in Dirac billiard systems—chiral scars that break time-reversal symmetry and have no counterpart in nonrelativistic quantum systems.[16] Examples of chiral scars arising from a chaotic Dirac billiard are shown in the opening image. More recently, researchers have developed a theory to unify scarring in nonrelativistic and relativistic quantum systems through solutions of the spin-½ Dirac equation in different mass regimes.[17]

The interplay between chaos and spin-1 relativistic quantum mechanics is an emerging topic of theoretical interest and with potential applications in electronics, spintronics, and a related device architecture known as valleytronics, which controls a so-called valley degree of freedom associated with different parts of the band structure. For example, researchers could use chaos in an electronic switch to control electrons' spin orientation in spintronic devices.

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NASA IMAGE NO. 70-H-1553

Wearing sombreros, *Apollo 11* astronauts (left to right) Michael Collins, Buzz Aldrin, and Neil Armstrong are swarmed by admirers during a motorcade in Mexico City as part of their international goodwill tour after returning to Earth.

The (soft) propaganda value of lunar exploration

On 20 July 1969, parents around the world sat with their children in front of television sets. Fumbling with their radios, drivers pulled off to the side of the road. Passersby peered at televisions through storefront windows. For a moment, as they watched and listened to Neil Armstrong stepping onto the Moon, audiences across the world felt connected to each other. For many, the shared experience marked the first moments of a global consciousness. That feeling of community was no happy accident: As historian of science Teasel Muir-Harmony explains in her new book, *Operation Moonglow: A Political History of Project Apollo*, the universal kinship many felt was the culmination of a decade of careful public relations strategy.

Muir-Harmony is a curator at the National Air and Space Museum and is well-known for her work on the material culture of space. She helps museum visitors understand the historic context of objects large and small—from space shuttles to space-themed postage stamps. In *Operation Moonglow*, Muir-Harmony provides an excellent analysis of the relationship between policy and political narrative, from the first beeps broadcast by *Sputnik 1* in 1957 to the international goodwill tour made by the *Apollo 11* astronauts in 1969 after their return to Earth. Her work is reminiscent of Kenneth Osgood's *Total Cold War: Eisenhower's Secret Propaganda Battle at Home and Abroad* (2006), which focused on how the Eisenhower administration's "Atoms for Peace" campaign shored up America's international reputation during the 1950s.

Operation Moonglow
A Political History of Project Apollo
Teasel Muir-Harmony
Basic Books, 2020. $32.00

One of *Operation Moonglow*'s many strengths is how Muir-Harmony seamlessly weaves analyses of both the domestic and international contexts into a cogent history of public diplomacy. In the book's introduction, she explains that her doctoral research on NASA's international exhibits was what eventually drove her to write a history of Apollo. Those exhibits, she notes, built on the success of educational displays about nuclear energy that the US Information Agency (USIA) circulated in the 1950s. Other anecdotes highlight public relations strategies in African and Asian nations, such as when the USIA sent African American "space lecturers" to Madagascar and other countries to lecture about American accomplishments in space and to demonstrate racial equality in the US. More ominously, Muir-Harmony also notes that President Richard Nixon attempted to harness the goodwill from *Apollo 11* to influence political leaders during his tour of Southeast Asia at the height of the Vietnam War in summer 1969.

Among the book's highlights are vivid descriptions—including quotations—of the astronauts' international tours. Muir-Harmony successfully argues that the astronaut tours—particularly the one made by the *Apollo 11* astronauts—framed the development of America's aerospace technology as an international triumph. She also notes individual astronauts' agency during those tours. In one example, she describes how the success of John Glenn's visit to Burma in 1966 was entirely because of his own careful messaging. "Glenn was an astute politician," she explains on page 139. "He sold US space exploration by downplaying competition with the Soviet Union, and explaining the local relevance of space exploration to the Burmese people."

Surprisingly, Muir-Harmony's fine-grained analysis shows that President John F. Kennedy's focus on the space race was not just about "beating the Soviets," but also about defining his presidency in opposition to the perceived failures of the Eisenhower administration. He believed that success in the space race would position the Democrats as the party of vision and imagination. Muir-Harmony explains how Kennedy's masterful communication skills aided in that effort: Television appearances regarding the space race were tightly scripted, and larger PR events were deftly orchestrated.

My favorite part of the book is the description of journalist Edward R. Murrow's role in creating the narratives of the space race. For historians of Cold War communication, it comes as no surprise that Kennedy recruited Murrow, a public relations expert, to lead the USIA in 1961. At the time, Murrow was one of the most trusted correspondents in America; his weekly television series *See It Now* was one of the most watched programs in the 1950s.

Kennedy tasked Murrow, as head of the USIA, with developing a global communication strategy to promote the US position in the space race. Murrow was fascinated by science, as I have discussed in my own work, and *See It Now* episodes on topics such as nuclear weapons had boosted his reputation in many scientific circles. Muir-Harmony shows us how he carefully guided the development of press kits, news releases, and films that celebrated the Mercury and Apollo missions. Although other communicators, such as Walter Cronkite, helped guide the public's image of the Apollo years, Murrow played a pivotal role at its inception. I am delighted that *Operation Moonglow* finally gives Murrow his due credit as a science communicator.

Ingrid Ockert
Berkeley, California

An IR image of the nebula W51, one of the most active star-forming regions in the Milky Way, captured by the *Spitzer Space Telescope*.

NASA/JPL-CALTECH/GLIMPSE & MIPSGAL TEAMS

The legacy of a great observatory

More Things in the Heavens
How Infrared Astronomy Is Expanding Our View of the Universe

Michael Werner and Peter Eisenhardt
Princeton U. Press, 2019. $35.00

The *Spitzer Space Telescope* is one of four large astronomical observatories launched by NASA in the 1990s and early 2000s; the others are the *Hubble Space Telescope*, the *Chandra X-Ray Observatory*, and the *Compton Gamma Ray Observatory*. An extremely sensitive telescope, *Spitzer* observed the mid- and far-IR bands of the electromagnetic spectrum. It was the last of the so-called Great Observatories to be launched, in 2003, and it was decommissioned at the end of January 2020. *More Things in the Heavens: How Infrared Astronomy Is Expanding Our View of the Universe* captures *Spitzer*'s scientific legacy.

The book's authors, Michael Werner and Peter Eisenhardt, worked on *Spitzer* for decades (as did this reviewer). Because they wrote *More Things in the Heavens* for a general audience, they did not use equations, but they still lean heavily on technical figures. Along with quantitative graphs, such as spectral energy distributions and color–color diagrams, the authors include many "indicative color" images of astronomical objects in which the IR wavelengths observed by *Spitzer* are mapped to the red, green, and blue that our eyes can see. Those aspects could make the book difficult for nontechnical readers, but most readers of PHYSICS TODAY should have no problems understanding the science.

Most of the book is devoted to the major discoveries made by physicists and astronomers who used *Spitzer*. Perhaps the most important are the observations of star and planetary-system formation in the Milky Way and distant galaxies. The ideal targets for *Spitzer* were stars and planetary systems that formed in nebulae where interstellar dust blocks essentially all visible light yet allows IR radiation to escape. The blocked light also heats the dust, which then produces more IR radiation. Astronomers used *Spitzer* to analyze accumulations of circumstellar dust—commonly known as debris disks—that seemingly are left over after planet formation.

Images from the telescope also yielded star-formation maps of nearby galaxies. Likewise, data gathered by *Spitzer* of IR brightness from distant galaxies were used to derive their total star-formation rates.

Exoplanets were discovered well after *Spitzer* was designed, but the telescope's extremely stable orbit meant that astronomers could use it to precisely study the small dips in stellar brightness that occur when exoplanets transit across stars. Such unexpected applications highlight the value of general-purpose space facilities like *Spitzer*; they can be used to study new phenomena never dreamed of during the mission's planning.

Spitzer was also effective at finding accreting supermassive black holes in the centers of galaxies. They power so-called active galactic nuclei, regions at a galaxy's center that have a high luminosity and include the most luminous known quasars. The radiation from those nuclei has nearly power-law spectral energy distributions, which means they emit more in the long-wavelength IR bands observed by *Spitzer* than stars, whose emission spectra are quasi-blackbody.

Spitzer also observed some of the most distant known galaxies. The *Hubble Space Telescope* first found the galaxies, but it could observe them in only a small segment of the near-IR bands. *Spitzer* provided vital confirmation of the galaxies' ages and distances by showing that the ratio of 3.6 μm light to a shorter wavelength captured by *Hubble* was consistent with the stellar radiation from a young galaxy formed early in the history of the universe.

More Things in the Heavens is a well-written account of the accomplishments of a great observatory over its more than 16-year lifetime. It shows how much patience is needed when working on a space mission. I first heard about the mission that became *Spitzer* at a meeting in 1974, and I made observations with it throughout its life. Fortunately, *Spitzer*'s scientific return was worth the decades of effort by many dedicated scientists and engineers.

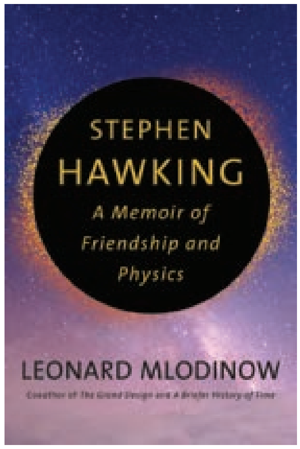
Edward L. Wright
University of California, Los Angeles

NEW BOOKS & MEDIA

Stephen Hawking

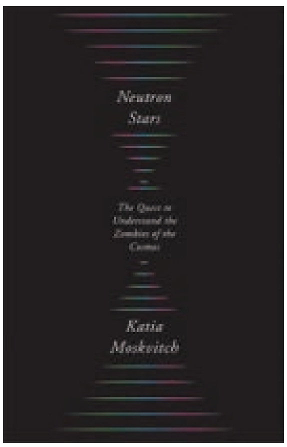
A Memoir of Friendship and Physics

Leonard Mlodinow
Pantheon Books, 2020. $25.00



Theoretical physicist and writer Leonard Mlodinow worked with Stephen Hawking on two books, *A Briefer History of Time* (2005) and *The Grand Design* (2010). In *Stephen Hawking: A Memoir of Friendship and Physics*, Mlodinow reflects on their collaboration and on Hawking's remarkable work as a physicist. He also writes candidly about Hawking's life with amyotrophic lateral sclerosis; by the time the two met in 2003, Hawking was using a wheelchair, typing on a computer to speak, and living with the support of several caregivers. Mlodinow's passages about Hawking's personality, including the challenges of working with his deep-rooted perfectionism and his intense dislike of being compared with fellow Cambridge professor Isaac Newton, are full of affection, humor, and insight.

—MB



Neutron Stars

The Quest to Understand the Zombies of the Cosmos

Katia Moskvitch
Harvard U. Press, 2020. $29.95

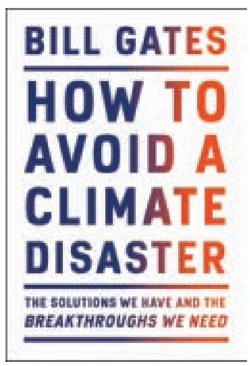
When a dying star larger than the Sun explodes in a supernova, gravitational collapse compresses the stellar material into a dense neutron star some 20 km in diameter. In *Neutron Stars*, science journalist Katia Moskvitch recaps the many astronomical observations that've been made with the help of those remnant stars. From the measurement in 2007 of fast radio bursts—whose origins still remain somewhat mysterious—to the detection in 2017 of gravitational waves by the LIGO and VIRGO observatories, the stories surrounding those discoveries are likely to appeal to just about anyone interested in astronomy.

—AL

How to Avoid a Climate Disaster

The Solutions We Have and the Breakthroughs We Need

Bill Gates
Knopf, 2021. $26.95

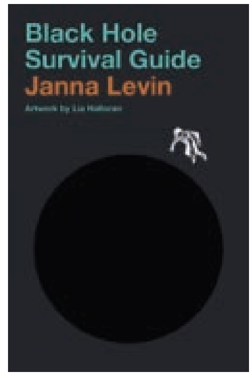


Books on climate change are often full of ominous warnings about what the future will look like if humanity does not change its ways. Billionaire philanthropist Bill Gates briefly outlines such a scenario in his new book *How to Avoid a Climate Disaster*. Spoiler alert: It's not pretty. However, the book focuses primarily on presenting what Gates calls a "concrete" plan for reducing net carbon emissions to zero across the globe by 2050 or shortly thereafter. The proposal involves incentivizing a broad shift to green technologies that are already mature, like electric vehicles and solar panels, while simultaneously investing in new technologies like direct carbon capture and zero-carbon cement and steel. Gates's plan is an optimistic yet realistic how-to guide to solving a global crisis. Unfortunately, he offers no solution to combating disinformation spread by climate change deniers, which is likely the biggest challenge to climate action.

—RD

Black Hole Survival Guide

Janna Levin
Knopf, 2020. $20.95



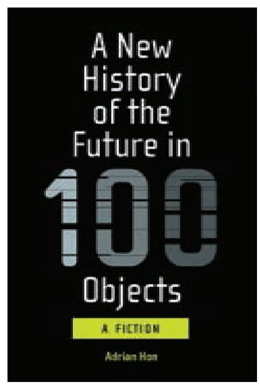
Both a reflection on what is known about black holes and speculation on what is not, *Black Hole Survival Guide* takes the reader on a journey beyond the event horizon. On this thoughtful and imaginative trip, cosmologist Janna Levin explores the properties of black holes and delves into topics such as cosmology, quantum mechanics, the theory of relativity, and entanglement. The use of the word "survival" in the title is a misnomer, however; because of a black hole's gravitational pull, radiation, and warping of spacetime, any foray into one would necessarily be one way—and deadly.

—CC

A New History of the Future in 100 Objects

A Fiction

Adrian Hon
MIT Press, 2020. $21.95 (paper)



Inspired by the BBC and the British Museum's *A History of the World in 100 Objects*, author Adrian Hon has created a fictional equivalent in which he imagines himself to be a curator in the year 2082 looking back on the 21st century. His 100 futuristic objects encompass not just physical things like "deliverbots" and "smart drugs" but also software, technologies, world events, and so forth. For Hon, a game designer and the CEO and founder of gaming company Six to Start, the goal is not to try to predict the future but to imagine its possibilities, both good and bad, and in so doing gain a new perspective on the present. Originally published in 2013, the book has been updated with new and revised chapters.

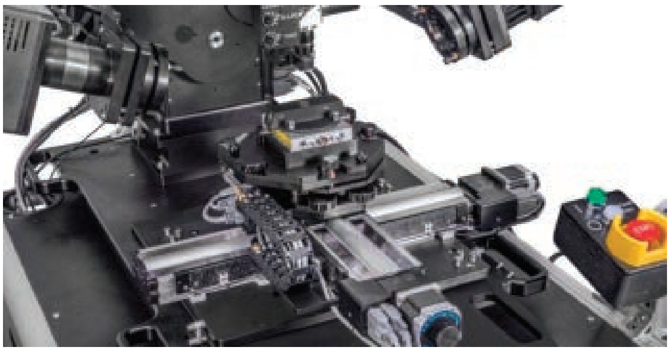
—CC PT

NEW PRODUCTS

Focus on test, measurement, analytical equipment, and instrumentation

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

Andreas Mandelis



Temperature-controlled ellipsometers

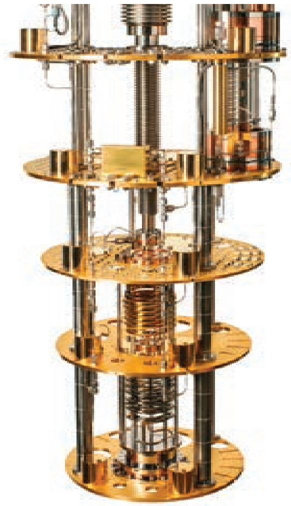
J. A. Woollam has collaborated with Linkam Scientific to bring precise temperature control to its custom ellipsometry instruments. Ellipsometry and thermal analysis are fundamental tools in the study of thin-film materials. Temperature-controlled ellipsometry can be used to characterize a range of properties, such as thermal expansion coefficients, which can be determined by monitoring changes in thickness versus temperature. Linkam has modified its HFS600 heating stage with a special optical adapter so it can be used as an ellipsometer. The adapted temperature controller, known as the HFSEL600, allows temperature-dependent ellipsometry measurements with all J. A. Woollam systems over a wide temperature range. Samples can be quickly characterized by heating them—at a rate of up to 150 °C/min—to within a few degrees of the required temperature and then examining the changes when the heating is slowed to a few tenths of a degree per minute. ***J. A. Woollam Co Inc***, *645 M St, Ste 102, Lincoln, NE 68508, www.jawoollam.com*

Micropumps for small liquid and gas volumes

Innovative Sensor Technology IST AG has unveiled a series of peristaltic micropumps for liquids and gases. The CPP1 pumps provide small flow rates, reliable flow-rate control, and biocompatibility. They enable bidirectional pumping of small amounts of liquids and gases in a controlled stream at flow rates from 150 nl to 800 μl and are therefore suitable for supplying analytes to sensors, among other applications. The CPP1 pumps are designed to be connected to the tubes and pipes of existing fluidic systems, and they can act as valves even when the systems are not rotating. They can withstand a pressure difference of up to 2 bar, which ensures that the media at a pump's inlet and outlet remain separated. The pumps' small size of 9.5 × 11.2 × 31.4 mm is optimal for integration into microfluidic analyzer systems and single-pump desktop and handheld devices. ***Innovative Sensor Technology IST AG***, *Stegrütistrasse 14, 9642 Ebnat-Kappel, Switzerland, www.ist-ag.com*

High-bandwidth midrange signal and spectrum analyzer

Rohde & Schwarz now offers a 1 GHz analysis bandwidth option for its midrange FSVA3000 signal and spectrum analyzer. According to the company, the FSV3-B1000 hardware option makes the FSVA3000 the first such analyzer to cost-effectively feature an internal analysis bandwidth of 1 GHz (previously available only in high-end instruments). Comparable solutions offer just 160 MHz analysis bandwidth. With the new option, available for all models from 7.5 GHz to 44 GHz, the FSVA3000 is suitable for analyzing wideband signals for 5G NR (new radio) and other future wireless standards. It can support the development and production of 5G NR base stations, mobile phones, and components, especially in the 28 GHz and 39 GHz bands; characterize wideband amplifiers; be used for troubleshooting, capturing even very short events; and address automotive, aerospace, and defense applications. ***Rohde & Schwarz GmbH & Co KG***, *Muehldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*



Cryogen-free dilution refrigerator

The Proteox5mK cryogen-free dilution refrigerator from Oxford Instruments Nanoscience is designed to help researchers explore material states at low temperatures and thereby foster the development of next-generation quantum technologies, from early-stage single-qubit research to quantum computer scale-up. The system's high cooling power of 25 μW at 20 mK and low base temperature also make it suitable for such research areas as spectroscopy and quantum annealing. The Proteox5mK uses Oxford Instruments' most powerful dilution unit and active gas gap heat switches to achieve base temperatures below 5 mK. According to the company, that is the lowest continuous base temperature available in any dilution refrigerator. Actively cancelled magnets ensure low eddy current heating to maintain the ultralow base temperatures at high fields. Multiple passive vibration reduction features eliminate the need for costly active vibration solutions. ***Oxford Instruments plc***, *Tubney Woods, Abingdon OX13 5QX, UK, https://nanoscience.oxinst.com*

Integrated platform oscilloscope

Keysight's new Infiniium EXR series of mixed signal oscilloscopes extends the technology of its Infiniium MXR oscilloscope family to users purchasing through the company's global distributor network. Featuring multiple instruments integrated into a single platform, the Infiniium MXR and EXR oscilloscopes reduce test-bench and workflow complexity. A state-of-the-art, application-specific integrated circuit powers seven applications: oscilloscope, digital voltmeter, waveform generator, Bode plotter, counters, and protocol and logic analyzers. The EXR series offers up to eight analog channels that operate simultaneously at 2.5 GHz with 16 independent digital channels. A built-in "fault hunter" feature automatically analyzes the normal signal for 30 s and initiates advanced triggers to find rare or random signal faults. ***Keysight Technologies***, *1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Time-domain terahertz platform

Toptica Photonics has announced the TeraFlash pro, a tabletop time-domain terahertz platform. It achieves a peak dynamic range of 100 dB and a bandwidth of more than 6 THz, and it acquires 60 traces/s at a 50 ps scan range and 95 traces/s at 20 ps. The new "dual" version enables simultaneous measurements in transmission and reflection or in terahertz spectroscopy with orthogonal polarizations. A wide-scan option boosts the scan range from 200 ps to 1000 ps, which translates into a frequency resolution of 1.0 GHz. The TeraFlash pro is suitable for scientific applications, including wide-band spectroscopy, metamaterial analysis, near-field studies, and imaging of cultural-heritage objects. It can also be used in complex configurations that include a cryostat in the beam path and for industrial terahertz applications such as layer thickness gauging and quality control of semiconductors. ***Toptica Photonics Inc***, *5847 County Rd 41, Farmington, NY 14425, www.toptica.com*

Compact high-performance turbopumps

According to Pfeiffer Vacuum, its HiPace 350 and 450 turbopumps are highly efficient, compact, and quiet. They are designed for applications such as mass spectrometry, electron microscopy, metrology, particle accelerators, and plasma physics, but they can also be used for R&D, in coating processes, and in industry. To ensure reliability, the turbopumps have a robust hybrid bearing design that combines ceramic ball bearings on the fore-vacuum side and permanently magnetic radial bearings on the high-vacuum side. An innovative rotor design delivers high-speed pumping for light gases and makes possible high backing pump compatibility, high gas throughput, and excellent compression for light gases. The pumps operate at a speed ranging from 300 l/s to 700 l/s and can be installed in any orientation. ***Pfeiffer Vacuum Inc***, *24 Trafalgar Sq, Nashua, NH 03063, www.pfeiffer-vacuum.com*

Plastic-analysis system

Shimadzu has presented a Fourier-transform IR (FTIR) spectrophotometer for plastic degradation analysis. The system includes proprietary UV- and thermal-damaged plastics libraries to facilitate highly accurate qualification and determine the state of deterioration when analyzing foreign substances, contaminants, and microplastics. It features the company's IRSpirit FTIR spectrophotometer, QATR-S single-reflection attenuated total reflectance attachment, and plastic analyzer method package. The method package includes FTIR spectral libraries for plastics degraded by UV rays and heat. The UV-damaged-plastics library includes more than 200 spectra from the UV degradation of 14 types of plastic, unirradiated and UV irradiated for 1–550 hours. The thermal-damaged-plastics library includes more than 100 spectra from the degradation of 13 types of plastic heated to between 200 °C and 400 °C. ***Shimadzu Scientific Instruments Inc****, 7102 Riverwood Dr, Columbia, MD 21046, www.shimadzu.com*

Smart, remote data logging

Omega, a Spectris company, has developed a smart, flexible way for users to remotely monitor a wide range of applications. Its Layer N products can keep applications running safely in times of social distancing. Temperature, humidity, light, and barometric pressure readings are captured, stored, processed, and transported in real time to the cloud via wireless smart sensors and gateways. Reports can be accessed from anywhere at any time. Layer N sensors, built with edge-control technology, use subgigahertz technology called frequency-hopping spread spectrum, which facilitates long-range communications with a transmission range of up to 3.2 km. The AES-256 encrypted wireless link ensures data security. With the Message Queuing Telemetry Transport protocol for Internet of Things data transport, Layer N products can simply and cost-effectively retrofit and integrate legacy devices and bring them into the digital world. ***Omega Engineering Inc****, 800 Connecticut Ave, Ste 5N01, Norwalk, CT 06854, www.omega.com*

Real-time wideband recording platform

The MUNIN 1005-IF (intermediate-frequency) wideband recording platform from Novator Solutions provides gapless recording of narrowband and wideband IF signals from 2 MHz to 600 MHz bandwidth. The high-speed, configurable platform is suitable for capturing one or more IF channels in real time for device-under-test characterization, spectrum analysis, and setup of repeatable laboratory tests. To ensure correct postprocessing or replay of recorded data, MUNIN records all channels continuously without gaps. A circular pretrigger buffer captures events that happened from a few seconds to multiple minutes before the trigger. With industrial-grade, solid-state drive disks, MUNIN offers a standard redundant array of independent disk configurations from 4 TB to 96 TB. The storage capacity can be expanded beyond 96 TB. Depending on the channel configuration, data can be continuously recorded over time periods ranging from minutes to days. MUNIN 1005-IF comes in several standard configurations with inputs of 70 MHz, 600 MHz, or a combination of both. ***Novator Solutions AB****, Hammarbacken 6A, 191 49 Sollentuna, Sweden, https://novatorsolutions.com*

Software for unlimited-range calibration

Renishaw has released the latest version of its CARTO software suite for calibration products. Because of CARTO 4.2's long-range measurement functionality, users of the company's XM-60 multiaxis calibrator can quickly capture and analyze data from linear axes of any length. The XM-60 allows for direct measurement of all six degrees of freedom—linear, vertical, and horizontal straightness and pitch, yaw, and roll—on any form of linear axis. The CARTO Capture application lets users measure straightness via its dynamic data fit functionality and recalculate the test data to reduce outlying data-points. The improved method offers greater resilience to environmental interference and a better representation of straightness errors for longer axes. Laser users can quickly and easily apply pitch error compensation to Heidenhain machine tool controls. ***Renishaw plc**, 1001 Wesemann Dr, West Dundee, IL 60118, www.renishaw.com*

Digitizer with flexible analog front end

Teledyne SP Devices has announced its ADQ8-4X 10-bit digitizer with software-configurable sampling on two or four channels. It supports sampling at 4 GSPS in the two-channel mode and 2 GSPS in the four-channel mode. Since the ADQ8-4X is available in the PXI Express form factor, different digitizer models can be used in the same system. The digitizer's flexible analog front end features a 1 GHz analog input bandwidth, a programmable DC offset, and a variable input voltage range. A software development kit is included, and the open onboard field-programmable gate array allows for custom digital signal processing. The ADQ8-4X can be used in Thomson scattering (plasma diagnostics), scientific instrumentation design, quantum technology, ultrasound, particle physics, and nondestructive and semiconductor testing. ***Teledyne SP Devices**, 700 Chestnut Ridge Rd, Chestnut Ridge, NY 10977, https://spdevices.com* PT

OBITUARIES

Joan Feynman

Eminent geophysicist Joan Feynman died in Oxnard, California, on 22 July 2020 of a myocardial infarction.

Born in Queens, New York, on 30 March 1927, Joan graduated with a physics degree from Oberlin College in 1948. However, her education and scientific curiosity probably began much earlier, under the guidance and tutelage of her older brother, Richard. She would recount how her first job was as his 4¢-a-week paid assistant, in his sort-of magnetic field and electricity lab, where on occasions she would climb onto boxes to "pull the switch." Her early inquisitiveness into how nature works remained with her throughout her long and distinguished career.

For her PhD, conferred in 1957 from Syracuse University, Joan looked at the IR absorption of diamond-type crystals. After a short period as a homemaker, she started her professional career at Columbia University's Lamont–Doherty Earth Observatory by investigating Earth's magnetic field. That was the beginning of her research in geophysics, particularly in Earth–Sun relationships and climate change.

Joan's contributions to those fields were numerous; some of her most important involved coronal mass ejections (CMEs) from the Sun, their propagation through the solar wind to Earth's magnetosphere, and their effect on the formation of auroras. While working at NASA's Ames Research Center in the early 1970s, she made the significant finding that during the acceleration of solar particles associated with solar flares, the amount of helium in the solar wind increases significantly. Back then, little was known about CMEs, and they weren't easily detected. Now the helium enrichment serves as a method of identifying CMEs. Joan continued her CME research, including coauthoring papers on the clustering of fast CMEs, until her death.

On auroras, Joan's major discovery was that the relative directions of Earth's and interplanetary magnetic fields had to be southward pointing for an aurora to occur. She would tell the story of how in 2012, when she was invited to Sweden to give a talk on auroras, all the conditions were apparently right for one to occur. But when none did, she had to revise her talk to explain why! The reason: The Sun was quiet.

Joan joined NASA's Jet Propulsion Laboratory (JPL) in California in 1985 after stints at the High Altitude Observatory in Colorado; NSF in Washington, DC; and the US Air Force Geophysics Laboratory in Massachusetts.

I first met Joan at JPL when I arrived to lead the Natural Space Environments Group. Its primary function was to provide space missions, such as *Cassini*, with estimates of the environments that the spacecraft would encounter, including the key one of radiation due to high-energy charged particles. In interplanetary space, the main radiation hazard is from solar high-energy protons, which emanate from the Sun during essentially random solar energetic particle events. The models used to predict the total radiation dose from those events were old and based on the concept of anomalously large events, which were thought to occur once every 100 years.

Joan developed a new model, derived from the latest set of spacecraft measurements, and showed that anomalously large events were, in fact, merely part of the overall event distribution and not that rare at all. Her model became the standard model, and it was used in the design of several missions, including *Magellan*. Although *Magellan* suffered from several operational problems, such as solar-array power loss and star-tracker interference, during the large particle events of October 1989, it survived and was extremely successful.

Joan left my group after a couple of years and moved to JPL's space-physics group to continue with her first love, Sun–Earth interactions. She had a permanent job and the freedom to conduct her own research, and in 1999 she joined the elite ranks of JPL senior scientists. A year later she received NASA's Exceptional Achievement Medal for her pioneering contribution to the study of solar causes of geomagnetic and climate disturbances.

In 1992 Joan married another solar scientist, Alexander Ruzmaikin, and they collaborated extensively on solar activity, climate change, and even anthropology. She was proud of the research they did to explain how the late origin of agricultural societies, a puzzle that had worried her from a young age, was caused by climate change.

ALEXANDER RUZMAIKIN

Joan Feynman

The hallmarks of Joan's work were meticulous attention to detail and analyzing data in ways that led to new revelations and discoveries. For Joan, it was imperative that research be fun, and she strived for that throughout her career.

Stephen B. Gabriel
University of Southampton
Southampton, UK

RECENTLY POSTED NOTICES AT
www.physicstoday.org/obituaries

Uri Haber-Schaim
8 February 1926 – 16 September 2020

Richard Strombotne
6 May 1933 – 25 August 2020

Arnold J. Glick
7 November 1931 – 16 August 2020

L. Donald Pearlstein
10 December 1932 – 9 July 2020

Leonid Vladimirovich Lutsev
25 August 1955 – 6 July 2020

Phillip W. Mange
5 June 1925 – 18 June 2020

David Nieman Pipkorn
10 October 1936 – 9 May 2020

Lorenzo Jan Curtis
4 November 1935 – 29 March 2020

Mario J. Molina

Atmospheric chemist Mario J. Molina died on 7 October 2020 in Mexico City. He was the first to demonstrate that industrially produced chlorofluorocarbons (CFCs) decompose and release chlorine atoms in the stratosphere, which lead to catalytic ozone destruction. His research was instrumental to the establishment of the 1987 Montreal Protocol to ban ozone-depleting substances worldwide. Additionally, Molina made contributions to science policy issues related to urban, regional, and global air pollution and climate, and he promoted environmental protection and awareness on climate change. He was a corecipient of the Nobel Prize in Chemistry in 1995 and received the Presidential Medal of Freedom in 2013.

Born in Mexico City on 19 March 1943, Molina earned an undergraduate degree in chemical engineering in 1965 from the National Autonomous University of Mexico, a graduate degree in 1967 from the University of Freiburg in Germany, and a PhD in physical chemistry in 1972 from the University of California, Berkeley. He was an MIT Institute Professor between 1989 and 2003 and a Distinguished Professor at the University of California, San Diego, between 2003 and 2020. In Mexico City in 2003, he established the Mario Molina Center for Strategic Studies on Energy and the Environment to conduct research and advocate for public policy; he headed it until his death. Under Presidents Bill Clinton and Barack Obama, he served on the President's Council of Advisors on Science and Technology.

In a landmark 1974 publication, Molina and F. Sherwood Rowland reported their discovery of the ozone-depletion potential of CFCs. The paper showed that when chemically inert CFCs, once considered miracle compounds because of their versatile industrial applications, reach the stratosphere, the intense solar UV radiation causes them to dissociate, producing chlorine atoms that consequently and efficiently destroy ozone through catalytic reactions. Their results, which predicted that if CFC release into the atmosphere was unchecked then significant depletion of the ozone layer could be possible, were later verified by the discovery of the Antarctic ozone hole.

Molina continued his research on stratospheric chemistry between 1974 and 1995, during which time he published a series of articles that elucidated the chemical properties and the fundamental mechanisms that lead to the breakdown of the stratospheric ozone layer. His foundational research on the CFC–ozone issue demonstrated the vulnerability of the natural environment and promoted public awareness of the potential harmful consequences of anthropogenic activities. His research and effort in galvanizing public opinion led to the negotiation and establishment of the Montreal Protocol to protect the ozone layer by prohibiting the release of gases that destroy it. Nearly 200 countries, including every member of the United Nations, have ratified the protocol, and signs of ozone-layer recovery have recently been documented. The protocol's importance in protecting climate has also been firmly established, since CFCs not only cause ozone depletion but also are key greenhouse gases.

Molina later shifted his research to the chemistry of air pollution in the lower atmosphere. He participated in interdisciplinary collaborations to confront the problem of air-quality deterioration and to advance the knowledge of and solutions for air pollution in urban areas. His latest work was also dedicated to science policy issues related to climate change, and he promoted global actions for sustainable development inclusive of economic growth.

My first encounter with Molina occurred in spring 1990 at MIT, as he patiently explained to me, a first-year graduate student in meteorology, the importance of clouds in the depletion of stratospheric ozone over the Antarctic. That meeting inspired me to pursue a career in atmospheric chemistry and initiated a long-lasting collaboration between us. He was a remarkable mentor to his graduate students, postdocs, and research scientists. I was particularly intrigued by his unique manner of scientific thinking—exploring not only the obvious but also the invisible. I was also fortunate to inherit several instruments from him after his departure from MIT in 2003.

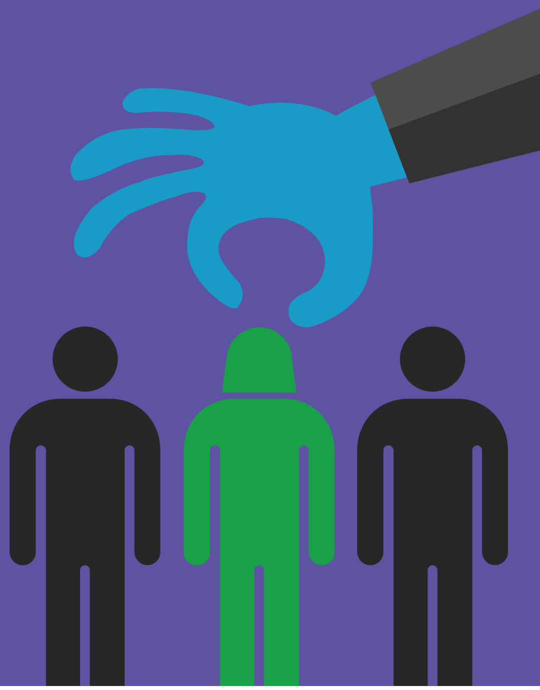
Our collaboration continued until last summer, as he held numerous virtual meetings with my students and me concerning the COVID-19 pandemic. He


Mario J. Molina

wrote personal letters to the head of the World Health Organization and the director of the US Centers for Disease Control and Prevention to communicate our scientific findings on the importance of airborne transmission in spreading the disease and of face coverings in preventing interhuman transmission of it. His last public appearance was on 15 August 2020, when, with allusions to Mexican president Andrés Manuel López Obrador and US president Donald Trump, he insisted that high-level politicians should set an example in the use of masks.

Molina believed that scientists should not claim their authority by labeling their specialty but should make convincing arguments by presenting their evidence. A favorite quotation from him was that "scientists may depict the problems that will affect the environment based on available evidence, but their solution is not the responsibility of scientists but of society as a whole."

Renyi Zhang
Texas A&M University
College Station PT



QUICK STUDY

Stuart Williams is a professor and directs the microfluidic-systems laboratory at the University of Louisville in Louisville, Kentucky.

Whiskey webs: Fingerprints of evaporated bourbon

Stuart J. Williams

When a water-diluted droplet of American whiskey evaporates, it can leave behind a self-assembled web pattern not found in Scotch or brandy.

"Did you know that there are colloids in bourbon?" That question came from a research engineer at Brown-Forman Corporation in Louisville, Kentucky—a state with nearly twice as many aging barrels of bourbon as people—when I was touring the corporation's research facilities a few years ago. Most consumers expect a clear, rich amber color in their bourbon. And to ensure that quality, manufacturers usually monitor their whiskey's turbidity, or cloudiness. Colloids often form when whiskey is diluted with water, though the contents usually remain soluble if the mixture exceeds 46% alcohol by volume (ABV).

Lower dilutions are filtered using charcoal or by what's known as chill filtration. But the process is largely an art, considered part of the whiskey's recipe, and may affect its final color and flavor profile. Interested in learning more, I acquired a variety of aged whiskeys from Brown-Forman to investigate the fundamentals of whiskey colloids. At the time, I was preparing for a sabbatical at North Carolina State University to study with colloid scientist Orlin Velev, and I reasoned that arriving at his lab with a case of whiskey in hand would make a good first impression.

Evaporation dynamics

During our investigations, Velev and I became interested in the behavior of evaporating droplets of whiskey. Howard Stone's group at Princeton University had studied the issue using evaporated Scotch whisky in 2016 and noticed that the evaporated droplets produced uniform films whose formation fundamentally differs from that of coffee-stain rings. The characteristic ring forms because the evaporation of a droplet is faster at its edges. Whereas the dark edges of the ring form as coffee grains drift outward and accumulate at the droplet's pinned meniscus, Stone and his colleagues found that the fluid motion in a Scotch droplet actually counters that outward drift from differential evaporation. The presence of surfactants lowers the whiskey's surface tension, and as the liquid evaporates, the surfactants collect on the droplet perimeter and pull the liquid inward—the so-called Marangoni effect.

We were curious if bourbon evaporation was comparable, as the two liquids are prepared differently. Whereas Scotch is stored in reused wooden barrels, bourbon is a type of American whiskey stored in new, freshly charred oak barrels and has a grain composition, or "mash bill," of more than 50% corn. Furthermore, we had samples of different ages and wanted to see if we could distinguish them by their films.

We evaporated microliter droplets at 45% ABV, and they formed uniform films, just as in the Scotch study. Next, we evaporated droplets of various dilutions. Some whiskey enthusiasts believe that adding water enhances whiskey's aroma and taste, but it's more universally known to hasten the transport of congeners—aldehydes, esters, phenols, and other fermentation products—to the surface and modify the whiskey's interfacial properties. We prepared a collage of evaporated-droplet images at different proofs, shown in figure 1. At alcohol concentrations of 20–25%, strange patterns emerged; none had appeared in the Scotch study. Ever since, we have dubbed those evaporation patterns whiskey webs.

We spent the following months exploring the fundamental physics behind whiskey webs. First, we wanted to know when those structures formed. A 1 μl droplet of diluted whiskey takes approximately 10 minutes to evaporate, during which several fluid-dynamic mechanisms occur, as illustrated in figure 2. In the first minute or so, Marangoni flows produced by the differential evaporation of ethanol in the droplet drive colloidal clusters—aggregates of insoluble congeners—to the liquid–air interface. There, the clusters break open into distinct chains that start forming a self-assembled monolayer.

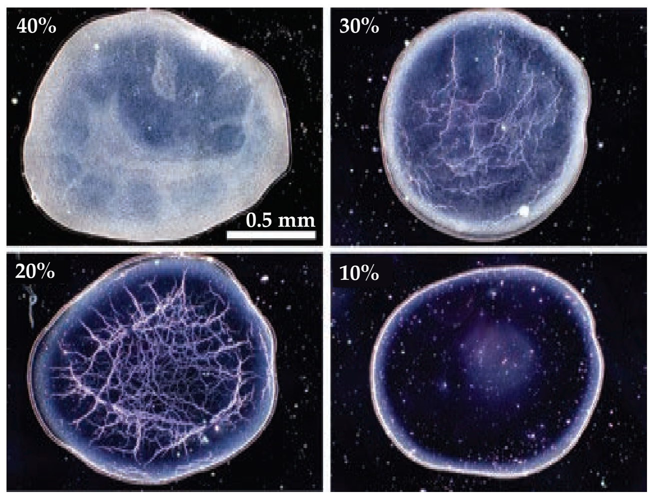


FIGURE 1. WHISKEY WEBS. Some of our first images, created from the evaporation of 1 μl of diluted Jack Daniel's bourbon on a clean glass coverslip. At high proofs—that is, high alcohol by volume—the evaporated drop forms a uniform film; at intermediate proofs of 20–25%, the intricate folds of a whiskey web forms; and at low proofs, coffee-ring patterns form. Brightly lit lines indicate the collapsed folds in a self-assembled monolayer of water-insoluble chemicals in the bourbon. (Images from Stuart Williams.)

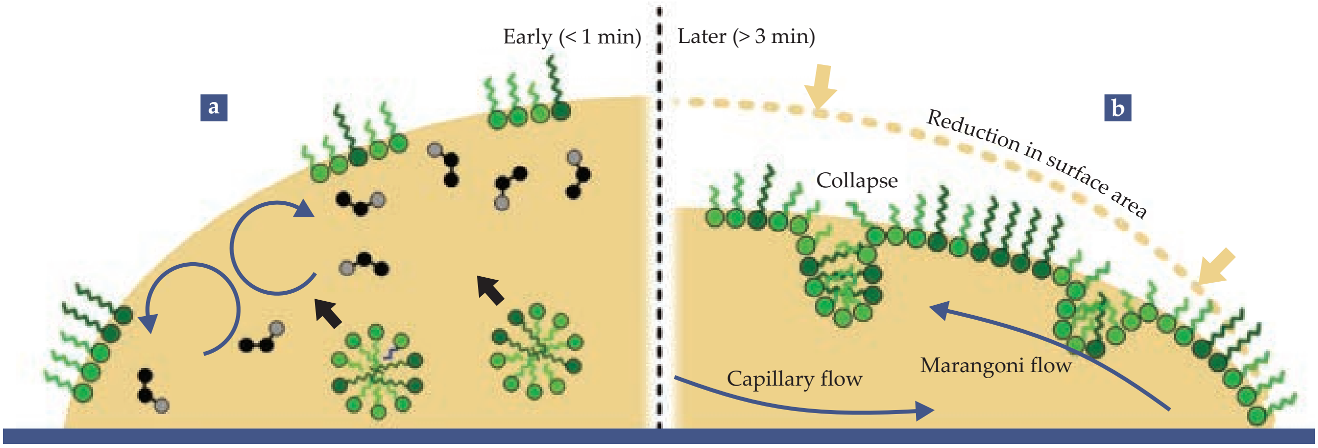


FIGURE 2. FLOW, SELF-ASSEMBLY, AND COLLAPSE. As whiskey is diluted in water and deposited on a glass coverslip, it starts evaporating. **(a)** Marangoni flow initially dominates, driven by the differential evaporation of ethanol (black). The flow and concomitant erratic vortices (blue) carry colloidal clusters to the surface–air interface, where they open into chains of fatty acids (green) that start assembling into a monolayer. **(b)** As evaporation continues, the droplet's surface area decreases by 30% or so and stress on the monolayer causes parts of it to fold and eventually collapse. (Adapted from A. D. Carrithers et al., *ACS Nano* **14**, 5417, 2020).

To visualize the bulk fluid motion, we added fluorescent microparticles to the sample and monitored them during evaporation. Erratic vortices typical of ethanol–water mixtures also emerged during that first minute or so. In the second phase of evaporation, surface-tension-driven Marangoni flow is still at work, along with capillary flow toward the droplet's edge. Liquid evaporates more quickly there, and capillary flow compensates by driving fluid from the bulk to the perimeter. (See the article by Roberto Zenit and Javier Rodríguez-Rodríguez, PHYSICS TODAY, November 2018, page 44.)

Visualization, tests, and reproducibility

The web structures began to form at the droplet's liquid–air interface about halfway through evaporation. Seeing the patterns was easiest with scattered light, and we were able to monitor their formation using phase-contrast microscopy. The webs did not translate or rotate; the rigid structures remained on the surface during evaporation. Web density also increased as the surface area dropped. We hypothesize that a chemical monolayer forms at the liquid–air interface and subsequently folds and collapses from stresses imposed by the reduced surface area.

We tested 66 off-the-shelf American whiskeys, 56 of which were bourbon whiskeys. All but a 42-year-old sample formed webs at 25% ABV. The exception likely had elevated levels of surfactants, which are known to reduce the rigidity of monolayers. Indeed, no whiskey webs formed when we added a common surfactant (sodium dodecyl sulfate) to our bourbon. And some of our older whiskeys had fewer collapsed structures near the perimeter, behavior we believe is caused by a local elevated concentration of surfactants. Such surfactant gradients are known to drive Marangoni flow.

Unaged whiskey did not form webs in our experiments, nor did other non-American whiskeys. Because they are aged in charred oak barrels, American whiskeys typically have about twice the mass of suspended solids as other whiskeys. That aspect of production is likely key to understanding the uniqueness of American whiskeys in forming web patterns. Nonetheless, preliminary results suggest that other whiskeys *can* form webs, albeit under different conditions: A Canadian whisky and an Irish one, for instance, formed structures in a 2 μl droplet at 40% ABV. Using a lower dilution with a hydrophobic surface increases the concentration of water-insoluble interfacial species and thus the likelihood of monolayer formation and subsequent collapse.

The complex flavor profile of whiskey is the result of its intricate composition of chemicals and congeners. That heterogeneity is also responsible for distinctive web patterns. For example, more lines form when a whiskey is spiked with lignin—a chemical associated with maturation in oak barrels. Other distinct modifications in the pattern emerged with the addition of other chemicals associated with flavor and maturation.

Those distinct patterns can be used to identify samples and counterfeits. As a demonstration, my group created 10 whiskey-web patterns from the same batch of whiskey and used digital image processing to map web density as a function of radial location in the droplet. We then repeated that process for two other whiskeys to generate a digital library. To test how well a pattern matched the whiskey used to create it, 15 droplets of each whiskey were evaporated, photographed, and compared to the library. Remarkably, a successful match was made 90% of the time. We believe that more robust digital-image algorithms—perhaps incorporating machine learning—may improve the technique.

What's more, those whiskey-web images can be acquired using a smartphone camera. They might even provide distillers with an inexpensive means to conduct quality control.

To learn more and for advice on reproducing our results, see whiskeywebs.org.

Additional resources

▶ H. Kim et al., "Controlled uniform coating from the interplay of Marangoni flows and surface-adsorbed macromolecules," *Phys. Rev. Lett.* **116**, 124501 (2016).

▶ B. C. G. Karlsson, R. Friedman, "Dilution of whisky—the molecular perspective," *Sci. Reports* **7**, 6489 (2017).

▶ S. J. Williams, M. J. Brown VI, A. D. Carrithers, "Whiskey webs: Microscale 'fingerprints' of bourbon whiskey," *Phys. Rev. Fluids* **4**, 100511 (2019).

▶ A. D. Carrithers et al., "Multiscale self-assembly of distinctive weblike structures from evaporated drops of dilute American whiskeys," *ACS Nano* **14**, 5417 (2020). PT

Neon's electronic blueprint

The European XFEL, the 3.4-km-long x-ray free-electron laser facility in Schenefeld, Germany, can generate some 27 000 x-ray flashes per second, with a brilliance about a billion times that of the best conventional x-ray sources. The picture here shows the inside of the Atomic-like Quantum Systems station, one of three stations of the Small Quantum Systems instrument. The wires at the top of the image belong to a velocity-map-imaging spectrometer; the conical objects near the bottom are the electron time-of-flight spectrometers, which provide the capability to measure the energy of electrons that carry information about an atom's transient states.

Tommaso Mazza, a research scientist at the facility, and his colleagues investigated ultrafast decaying states in the electronic structure of a neon atom before any relaxation of the system occurred. The neon atom was first photoionized by a single x-ray photon. That kicked one electron out of the atomic core and left a hole. Then a second x-ray photon from the same pulse probed the transient electronic state of the core-excited atom, which lasted for only about 2.5 femtoseconds. With high-resolution electron spectroscopy, the researchers then observed Rydberg resonances and unraveled the details of the subsequent decay of the hollow atom. (Image courtesy of the European XFEL; T. Mazza et al., *Phys. Rev. X* **10**, 041056, 2020.) —AL

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