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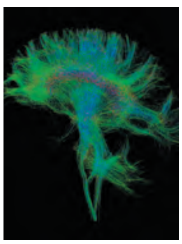
FEATURES



ON THE COVER: By using magnetic fields to manipulate nuclear spins, magnetic resonance imaging excels at revealing subtle features in soft tissue. In this image of the human brain, a specific sequence of magnetic pulses yields an image whose contrast arises from the diffusion of water molecules in the tissue. To read about other clinical MRI applications, such as mammography and radiation therapy, see the article by David Jordan on **page 34**. (Image by Callista Images/Cultura Creative (RF)/Alamy Stock Photo.)

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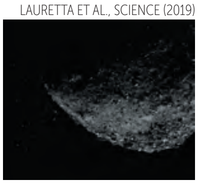
LAURETTA ET AL., SCIENCE (2019)



▶ Asteroid mystery

Rocks are flying off an asteroid, and astronomers want to know why. Using images from NASA's *OSIRIS-REx* spacecraft of pebbles escaping the near-Earth asteroid Bennu, researchers have now pinned the particle ejection on some combination of mineral dehydration, meteoroid impacts, and thermal stress.
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▶ Girls and science

In her latest column, PHYSICS TODAY's Johanna Miller recalls the Christmas during her childhood when she received both a doll and a science kit and reflects on the clashing messaging she received as a young woman interested in science. Miller's columns are published online once or twice a month.
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▶ Bring back the OTA

Last year several lawmakers led an ultimately unsuccessful effort to revive the Office of Technology Assessment (OTA), which advised Congress on science and technology matters from 1972 until it was defunded in 1995. PHYSICS TODAY's David Kramer makes the case for reopening the OTA's doors.
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Open access for and against

Charles Day

In 2013 the Obama administration mandated that scientific papers reporting the results of federally funded research be freely available one year after publication. This past December rumors spread that the Trump administration is considering reducing the embargo time to zero. Although the White House has yet to confirm a new mandate, the rumors were sufficiently substantiated that two coalitions of scholarly publishers promptly sent letters to President Trump urging him to reconsider.

The case for immediate open access (OA) is strong. NASA, NSF, and other federal agencies disburse research grants that are funded by US taxpayers. Tuition revenue and state taxes fund scientists at public universities. Why, having helped pay for a research project, should a US taxpayer face the choice of either waiting 12 months to read the corresponding paper or paying for prompt access?

Whether immediate OA becomes mandatory will depend in part on the opposing arguments. How persuasive are they?

The 18 December letter to Trump organized by the Association of American Publishers (AAP) and signed by 135 professional societies builds its case around upholding US leadership in science. While I accept that invoking patriotism is sometimes necessary when appealing to politicians, I find the practice unsavory. Science is an international enterprise.

Still, how strongly is a country's scientific prestige tied to its homegrown journals? Weakly, in my view. None of the top physics journals is Japanese, yet Japan is a physics powerhouse. In 1994 Stuttgart-based Holtzbrinck Publishing Group bought a controlling stake in London-based Macmillan Publishers, owners of *Nature*, arguably the world's foremost scientific journal. *Nature* and its swelling number of stablemates remain under German ownership. The UK's standing in science has not fallen nor has Germany's risen as a result.

The AAP letter asserts that peer-reviewed articles are "licensed to users in hundreds of foreign countries, supporting billions of dollars in U.S. exports." The United Nations recognizes 195 countries. Given that "hundreds" is an exaggeration, I suspect "billions" is too. Still, the authors of the AAP letter are right to point to the economic impact of immediate OA. The question of who pays is paramount.

An 18 December letter to Trump signed by 62 scholarly publishers points out that scientific societies use subscription revenue to fund worthy activities. "One particular area of importance," the letter says, "is strengthening U.S. STEM infrastructure through education, career, and outreach programs." The transfer of money from libraries to societies is defensible. But it seems to me unfair to expect, say, the University of Tokyo or the Max Planck Society to subsidize programs that benefit the US.

In its 2018 industry overview, the International Association of Scientific, Technical and Medical Publishers reported that its members incur expenses of around $4000 to publish a peer-reviewed paper in an archival journal.[1] When publishers offer authors the option to make their papers freely and instantly accessible, the fee is also around $4000. Journal subscriptions are of the same order. Online-only subscriptions to the two biggest astronomy journals by volume, *Astrophysical Journal* and *Monthly Notices of the Royal Astronomical Society*, cost $2175 and $10 249 a year. (*ApJ* levies page charges to offset publishing expenses; *MNRAS* does not.)

With those numbers in mind, you can see how the impact of immediate OA depends on how prolific an institution's researchers are. If an astronomy department publishes more than four or so papers a year, buying subscriptions could be cheaper than paying author fees. Kent Anderson made that point last year in *The Scholarly Kitchen*: The subscription model, he contends, is significantly more cost-effective than the OA model because publishing expenses are borne by both readers and authors.[2]

Despite its advantages, the subscription model is overstretched. As diagnosed by Aileen Fyfe and her coauthors,[3] the underlying problem is that academics are evaluated on research published in traditional journals despite the existence of alternative outlets. So they publish more, and scholarly publishers, whether for-profit or nonprofit, respond by launching more journals. Libraries' bills keep going up.

Immediate OA would bring relief to libraries and compel researchers to be more judicious in what they publish, but at what cost?

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PT

Commentary
High journal acceptance rates are good for science

Scientists occasionally complain that journal standards are too low and that journal acceptance rates are too high. The American Astronomical Society (AAS) journals that I publish in most frequently, the *Astrophysical Journal* and the *Astronomical Journal*, have an acceptance rate above 85%, as do the journals of many other professional societies. Therefore, nearly all significant astronomical results submitted to those journals that are not obviously fatally flawed are likely to be published. I am pleased with that state of affairs; it is the sign of a healthy culture of science, and astronomy is better for it.

One problem with the argument for lowering the acceptance rate is that it reduces the several dimensions of quality—correctness, importance, impact, flashiness, and others—to just one. The reduction inevitably leads, for instance, to researchers having difficulty publishing null results and similarly "boring" work. Such concerns are the source of the well-known issue of publication bias, in which the unlucky experimenter who gets a surprising (and spurious) result is more likely to get their work published. Thus the corpus of published work becomes skewed toward erroneous conclusions and makes for less reliable metastudies.

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Indeed, a common perception in some subfields of astronomy is that *Nature* articles tend to be flashy but much less likely to be correct than papers in less selective journals.

The argument for higher standards also presumes that the editorial and refereeing processes are good measures of quality and that it is the poorer-quality papers that will end up being rejected. My experience with the refereeing process and discussions with scientists in other fields suggests that papers are at least as likely to be rejected for other reasons—among them scientific taste, politics, professional advantage, and science's inherent conservatism.

A favorite example of such conservatism is a referee's comment on Raymond Davis Jr's 1955 work that set one of the first upper limits on neutrino production in the Sun.[1] The referee complained, "Any experiment such as this, which does not have the requisite sensitivity, really has no bearing on the question of the existence of neutrinos. To illustrate my point, one would not write a scientific paper describing an experiment in which an experimenter stood on a mountain and reached for the moon, and concluded that the moon was more than eight feet from the top of the mountain."[2] Such a critique must have seemed quite reasonable at the time. In retrospect, though, the paper marks an important milestone in our understanding of the neutrino and on Davis's road to receiving the 2002 Nobel Prize in Physics.

In some fields, faculty positions and tenure are contingent on getting first-author papers published in extremely selective journals such as *Nature* or *Cell*. That puts tremendous pressure on researchers to cater to the perceived tastes of those journals' editors and has even led to dramatic cases of scientific fraud, such as the Schön scandal (see PHYSICS TODAY, November 2002, page 15). It also gives too much power for shaping the field to those editors, who have no fiduciary obligations to the discipline or its members. Astronomers and physicists are fortunate that our premier journals are largely run by professional societies, which are guided by such an obligation and where power to shape those fields properly lies.

Another issue is where a field puts its efforts. In fields with very low acceptance rates, researchers spend (and, in my opinion, waste) a huge amount of time both refereeing their peers' papers and revising and resubmitting their own. The system especially disadvantages graduate students and other junior researchers, who need to be published quickly to establish their careers and whose talents are best spent on their next project, not their last one.

Science is also best served when researchers feel comfortable taking chances and being wrong. In the words of legendary UCLA basketball coach John Wooden, "If you're not making mistakes, then you're not doing anything." A pub-

GERHART FRIEDLANDER (left) AND RAYMOND DAVIS JR work in the pump room of the Homestake detector in Lead, South Dakota, ca. 1967. Davis's 1955 paper that helped secure a Nobel Prize for him was panned by an early reviewer. (Photo courtesy of Brookhaven National Laboratory.)

lication scheme that attempts to prioritize correctness is less likely to produce the sorts of inspired, unlikely, and foundational results science valorizes. In other words, it's important that scientists be allowed to be wrong in the literature, as long as they have made no errors. Referees and editors do well when they respect the distinction.

To those who think journals should be more selective, I ask, Who is served by those ostensibly poor papers not being published? Gone are the days when scientists received and read entire paper copies of journals, and so might have had to waste time and shelf space on "bad" papers. Today, researchers who get papers rejected have no shortage of "lesser" journals to submit to, and they will eventually get published, including on arXiv.org, regardless of how much gatekeeping any individual journal does.

I do acknowledge the view that "prestigious" journals in science are important—for instance, as a signal to the public or media that a paper is especially noteworthy. Indeed, AAS has reoriented *Astrophysical Journal Letters* to serve that niche in the marketplace of scientific journals and to better compete for high-impact papers with *Nature* and other prestige publications. I appreciate that in making that business decision, AAS has preserved the character of its other journals, so that it can cater to both markets.

I believe journals serve their disciplines best when they serve as journals of record, allowing scientists to document the work they have done. I also believe referees best serve when they act not as gatekeepers but as editorial consultants and independent voices that offer constructive criticism that improves submitted papers. High acceptance rates in the high-impact journals of the physics and astronomy professional societies help make those fields more efficient, fair, and productive. May it be so across science.

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Jason Wright
(astrowright@gmail.com)
Pennsylvania State University
University Park

LETTERS

Modern discovery in soft-matter physics

The 90th anniversary of *Reviews of Modern Physics* (*RMP*) is well celebrated in the February 2019 issue of PHYSICS TODAY—for example, in the excellent review of the late 20th-century topic of soft matter (page 38) popularized by the authors of its references, notably Pierre-Gilles de Gennes. The authors of the last two *RMP* references worked in numerous European countries and in Turkey, India, and North America. Even so, I was struck by the article's omission of a spectacular South American discovery in the 21st century, a discovery that in my view extends biologists' 20th-century qualitative considerations far up to the quantitative level sought by physicists.

Although the discovery of fractals associated with the solvent-accessible surface areas of folded protein segments was made by two Brazilian physicists, Marcelo Moret and Gilney Zebende,[1,2] Lars Onsager's 1944 work had shown that long-range interactions at phase transitions are best described with fractals.[3] Online protein data bases, including especially the genomic sequences data base, are by far the largest ever assembled.[4,5] The Moret–Zebende discovery of 20 precise fractals in complex protein structures has far-reaching implications, including the demonstration of Darwinian evolution in protein families.[2] Such high precision immediately suggests that physicists may be able to achieve results of great medical value.

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James Phillips
(jcphillips.physics@gmail.com)
Rutgers University
Piscataway, New Jersey PT

Ultracold chemistry: No longer a disappearing act

Until now, researchers have struggled to study reactions whose products they couldn't see.

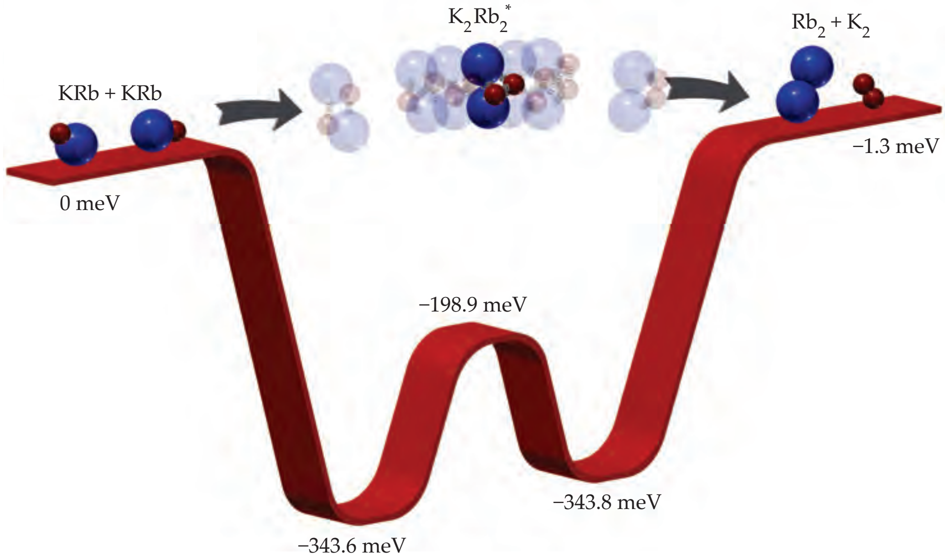

FIGURE 1. MOLECULES OF POTASSIUM–RUBIDIUM (KRb) can react to form $K_2 + Rb_2$ by means of a four-atom intermediate complex $K_2Rb_2^*$. Because the reaction releases energy and has no initial energy barrier, it's energetically allowed even at submicrokelvin temperatures. But until now, the reaction products had never been observed. (Courtesy of Ming-Guang Hu.)

A chemical reaction can be divided into three stages: the initial encounter of the reactants, the final emergence of the products, and everything in between. The middle stage—which involves all the making and breaking of chemical bonds, the rearrangement of atoms, and the surmounting of energy barriers—is difficult (although not impossible) to directly observe. Much of it can be reconstructed, however, through a combination of theoretical calculations and a careful look at the speeds, directions, and quantum states of the reaction products. (See, for example, PHYSICS TODAY, February 2019, page 14.)

In the submicrokelvin regime, the nature of the experiments means that that product information is usually inaccessible. Researchers prepare a gas of ultracold molecules—for example, potassium–rubidium, or KRb—in an optical dipole trap, monitor the rate at which the molecules disappear, and infer that the disappearance must be due to a chemical reaction. The trap has an energy depth of less than a nano-electron volt. The presumed reaction products, K_2 and Rb_2, are produced with far more kinetic energy than that, so they're lost from the trap and from the experiment.

Now Harvard University's Kang-Kuen Ni and colleagues, including PhD student Yu Liu and postdoc Ming-Guang Hu, have found a way to fill that information gap. By adapting velocity-map imaging (VMI), a standard technique of chemical physics, into the ultracold regime, they've detected both K_2 and Rb_2 fleeing from a trapped ultracold KRb gas.[1] And they've caught a glimpse of $K_2Rb_2^*$, the transient intermediate complex that precedes the product formation. Because of the reactants' low energy and ground quantum state, the intermediate has a lifetime of nanoseconds to microseconds, not femtoseconds, so it can be detected without special ultrafast techniques.

Sticky molecules

The field of ultracold chemistry stemmed from an unintended discovery just over a decade ago. In the first experiments on ultracold heteronuclear molecules, which Ni worked on as a graduate student under Jun Ye and Deborah Jin at the University of Colorado Boulder, the aim wasn't to study chemical reactions at all.[2] Rather, the researchers hoped to investigate the many-body physics of quantum gases (Bose–Einstein condensates or, in the case of $^{40}K^{87}Rb$, degenerate Fermi gases) with dipole–dipole interactions among the particles. Atoms are readily cooled to temperatures at which quantum effects prevail, but they lack permanent electric dipole moments. So do homonuclear molecules. But heteronuclear molecules fit the bill.

Because direct cooling of molecules proved too much of a challenge, the researchers cooled gases of two different atoms, then used lasers and magnetic fields to coax them together into molecules. Those techniques are best suited to pairs of alkali atoms, such as K and Rb, and bialkali molecules remain the most commonly studied ultracold molecular systems. Experiments on KRb reached 150% of the Fermi temperature[2] in 2008 and 30% of the Fermi temperature last year.[3]

From the many-body physics perspective, the loss of molecules from the trap is a bug, not a feature, because it limits the duration of the experiments. But the researchers noticed that the rate of loss was proportional to the square of the density of the KRb gas—that is, to the rate of bimolecular collisions. They concluded that the losses must be due to molecules colliding and reacting.

The work presented an opportunity to study chemistry in a new quantum regime. In a sense, all chemistry is quantum mechanical because the electrons that make up interatomic bonds must be described by their quantum wavefunctions. But at ambient temperatures, atomic nuclei are well approximated as classical billiard balls; at ultracold temperatures that approximation breaks down. A new medley of quantum chemical effects—for instance, the requirement that when two identical fermionic molecules react, they must do so via an overall antisymmetric wavefunction—came into play and observably influenced reaction rates.[4] (See the article by Debbie Jin and Jun Ye, PHYSICS TODAY, May 2011, page 27.)

Despite the interest in ultracold chemistry, researchers still hoped to study long-lived molecular gases in which reactions were suppressed. And there seemed to be a way to make them: Whereas the KRb reaction releases 1.3 meV of energy, as shown in figure 1, other bialkali molecules, such as rubidium–cesium or sodium–potassium, must consume energy to react. Because ultracold molecules have little energy to consume, gases of those molecules should be stable. However, experiments soon showed that even those putatively unreactive species disappeared from their traps at almost the same rate as KRb and other reactive molecules.[5]

Theorist John Bohn and colleagues, also at the University of Colorado, have proposed an explanation for that mysterious effect.[6] When two bialkali molecules (such as RbCs) collide, they cling together in a four-atom complex ($Rb_2Cs_2^*$) that persists for long enough that it might collide with a third molecule or absorb a photon from the optical trap.[7] Either of those interactions could break the complex into products with enough energy to escape the trap.

It's a plausible hypothesis, but without any way of observing the complexes or the reaction products, experimenters have had a hard time definitively testing it. And it's raised the question of how well the KRb reaction is really understood: Does it proceed as a direct bimolecular reaction, as previously presumed, or does it rely on Bohn's sticky-complex mechanism as well?

Products and intermediates

Ni and coworkers' initial idea was to use mass spectrometry to characterize the masses of molecules escaping the trap. But colleagues in physical chemistry urged them to consider VMI. "They convinced us that it was 'easy' and would give us a wealth of information," she says. "We've found the VMI complements mass spec and has been crucial for all of our studies thus far."

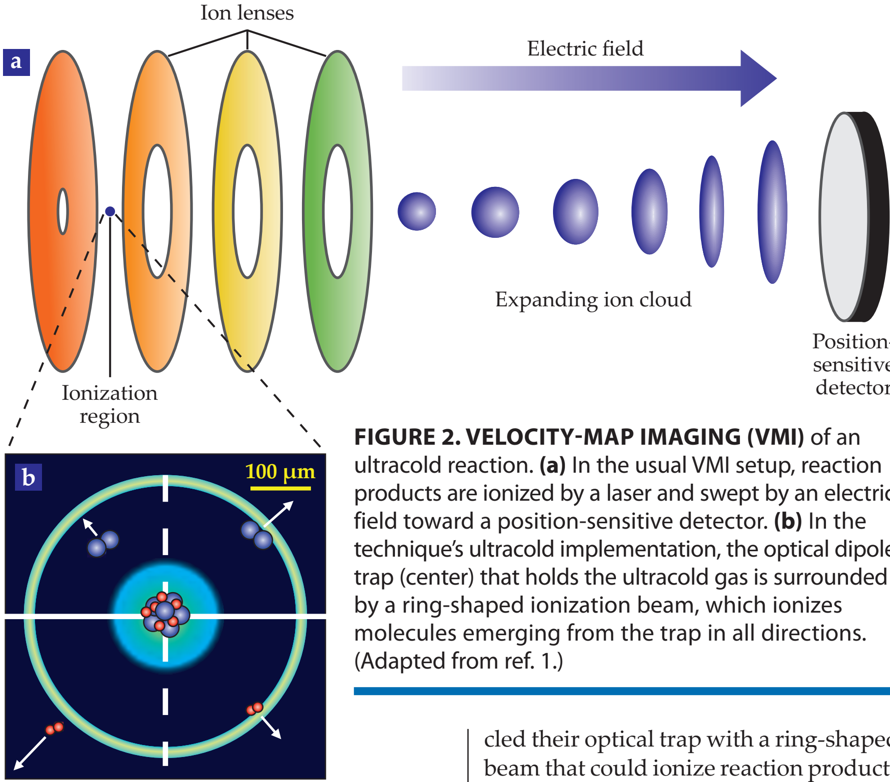

FIGURE 2. VELOCITY-MAP IMAGING (VMI) of an ultracold reaction. **(a)** In the usual VMI setup, reaction products are ionized by a laser and swept by an electric field toward a position-sensitive detector. **(b)** In the technique's ultracold implementation, the optical dipole trap (center) that holds the ultracold gas is surrounded by a ring-shaped ionization beam, which ionizes molecules emerging from the trap in all directions. (Adapted from ref. 1.)

Figure 2a shows the structure of a typical VMI experiment. Molecules formed in a reaction are ionized, usually by a pulsed laser, and then swept by an electric field toward a position-sensitive detector. Their time of flight between ionization and detection gives their mass-to-charge ratio, and their positional distribution on the detector gives the transverse component of their velocity. A series of charged plates focuses the ions so that ions created in different locations but with the same velocity strike the same point on the detector. (For more on VMI and its applications, see PHYSICS TODAY, October 2013, page 15.)

Typically, the reacting molecules in a VMI experiment come from molecular beams—thin jets of gas squirted into the reaction chamber—and are continuously supplied by the quadrillions. In contrast, an ultracold KRb gas, which takes the better part of a minute to prepare, contains just a few thousand molecules that react into nonexistence over the course of several seconds.

To make the most of their limited potential signal, Ni and colleagues used an unconventional optical setup, as shown in figure 2b. Rather than focusing their ionization beam to a point, they encircled their optical trap with a ring-shaped beam that could ionize reaction products emerging in any direction.

The mass-resolved data showed clear signatures of both K_2 and Rb_2. But were they the result of a direct reaction or of a more complicated process involving additional molecules or photons? To find out, the researchers turned to the product velocities extracted from the VMI data. A reaction between two cold, ground-state KRb molecules must conserve both momentum and energy: K_2, at just under half the mass of Rb_2, should emerge from the reaction at just over twice the velocity, and the sum of the product kinetic energies shouldn't exceed the 1.3 meV released in the reaction. The experimental data revealed that both those constraints were satisfied—good evidence that the reaction proceeds directly, as expected.

But that wasn't all. The mass spectra also showed small peaks corresponding to the masses of K_2Rb and KRb_2. The researchers knew those molecules couldn't be formed in a direct reaction: Both product channels $K + KRb_2$ and $Rb + K_2Rb$ are energetically forbidden by hundreds of meV. They suspected the triatomic signals might be the result of the four-atom intermediate complex, $K_2Rb_2^*$, with one of its atoms expelled by the ionization laser. Sure enough, when they lowered the ionization photon energy to just above the complex's ionization threshold, the K_2Rb and KRb_2 disappeared and were replaced by a peak at the mass of $K_2Rb_2^*$.

More to come

"We were really just hoping to see products," says Ni, "and were not even considering the intermediates at first. But now that we've seen them, there's a lot more to explore." Although she naturally wonders what products VMI might detect emerging from a gas of NaK, RbCs, or any of the other bialkali molecules whose direct reaction is energetically forbidden, Ni notes that those experiments aren't on the agenda—at least not for her group. "All our lasers are specifically optimized to work with rubidium and potassium," she says. "We'd need a whole new set of lasers to study sodium or cesium." But, she notes, further experiments on KRb could provide insight into the reaction mechanisms of other molecules.

The feasibility of Bohn's proposed sticky-complex mechanism, after all, depends critically on how long-lived the $Na_2K_2^*$ and $Rb_2Cs_2^*$ complexes really are. Theory offers a way to predict the lifetime of a molecular complex as a function of the density of states of its available decay channels, but the method remains to be tested in the quantum regime. A direct experimental measurement of the $K_2Rb_2^*$ complex lifetime would be a valuable benchmark for understanding the decays of other similar complexes.

So far, Ni and colleagues have just an order-of-magnitude estimate of the $K_2Rb_2^*$ lifetime—between 350 ns and 3.5 μs—based on the strength of their measured $K_2Rb_2^*$ signal and their best guess of the complex's photoionization cross section. With technical improvements to their experiment, they hope to be able to measure the lifetime directly based on the elapsed time between when the complexes escape the trap and when they're ionized.

Johanna Miller

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Spin waves control the magnetization around them

The quasiparticles essential for proposed magnonic devices exert a spin-transfer torque of the same magnitude as that of electrons.

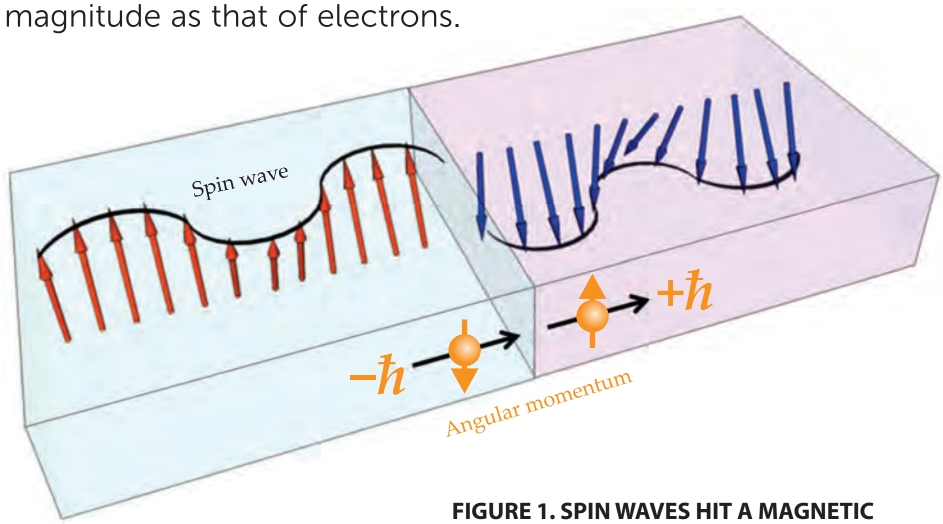

FIGURE 1. SPIN WAVES HIT A MAGNETIC DOMAIN WALL (the boundary between the blue and pink boxes) in a magnetic film. As it moves from left to right, the spin wave carries spin and angular momentum (orange) and comprises the collective precession of electron spins (red and blue arrows). At the domain wall the phase and angular momentum of the spin wave flip. (Adapted from ref. 2.)

As electronics get faster and smaller with more densely packed elements, Joule heating from electron motion and the resulting collisions becomes more prominent. Heat limits the performance of electrical devices and requires built-in cooling methods—from fans to heat sinks. A device that transports information without moving electrons would avoid such power dissipation, and so-called magnonic devices would do just that.

In magnonics, spin waves embody and transfer information through the collective precessions of electron spins that transport angular momentum while the electrons stay put. Although related, magnonics is distinct from spintronics, which uses the electron spin as an additional degree of freedom but still relies on electron motion in the form of electrical spin currents.

The spin-wave quasiparticle, known as a magnon, flows and carries spin angular momentum in much the same way that electrons do. In a well-prepared sample, it can propagate as far as centimeters—three orders of magnitude farther than electrical spin currents—and spin waves have already performed as logic gates.[1]

Despite their advantages, magnons are trickier to direct and measure than electrons are. A step toward making magnons more manageable has now been taken by two groups—one led by Luqiao Liu of MIT and the other by Hyunsoo Yang of the National University of Singapore. Their experiments have revealed how magnons both control and are controlled by their magnetic environment. The results suggest a design for all-magnon devices that are free from Joule heating and prove that magnons are capable of applications like manipulating magnetic memory.

Generating spin waves

The key for both studies was producing strong spin currents. A few techniques can generate spin waves, but they share a basic scheme: Take a material with the electron spins aligned in one direction and flip or disturb one spin state. The interaction between the flipped electron and its neighbors starts the electron spin precession and sends spin waves through the material. Techniques use different methods for disturbing the electron spins and different materials for magnon propagation.

Each group chose a different magnon-generation strategy and material system. Liu and his colleagues were interested in how spin waves respond to the interface between two magnetic domains, or a domain wall, as a possible method to manipulate the waves.[2] Because an external magnetic field could destroy the domain wall, the researchers required an alternative method to nudge the electron spins into a spin wave. They also needed a material that isn't too magnetically damping—otherwise it will extinguish spin waves—and that is thick enough to host a strong spin-wave signal. It's also easier to introduce spin waves in a material with strong magnetic anisotropy.

Liu and his colleagues settled on a cobalt–nickel multilayer film. In their device, the spin wave is set in motion by an embedded microwave antenna, which provides an alternating local magnetic field that induces spin precession. Microwave antennas are the classic technique for creating and detecting spin waves, and their dimensions set the resulting spin wave's wavelength.

In the second study, Yang and his colleagues opted for a newer strategy that requires two specialized material layers: One turns an electrical signal into a strong electrical spin current, and the other efficiently transports spin waves.[3] The electrical spin current in the first layer induces spin waves in the second layer through the spin Hall effect. (See PHYSICS TODAY, May 2010, page 13.)

For the electrical spin-current layer, a topological insulator—such as Yang's selection, bismuth selenide—is a natural choice. Although insulating in its bulk, it has surface states that are metallic and have distinct channels based on the spin. (For more on topological insulators, see PHYSICS TODAY, April 2009, page 12.) For the spin wave layer, the group selected nickel oxide, an antiferromagnetic insulator with a few crucial advantages. Insulators in general are more efficient than conductors at carrying spin waves because insulators don't have conduction electrons bumping around and disrupting the waves. Antiferromagnets have the added benefit of hosting spin waves that are in the terahertz range, which allows data to be transmitted at high speeds.

Changing the domain wall

With their spin-wave sources selected, the groups were ready to explore how spin waves interact with magnetization. Two of Liu's graduate students, Jiahao Han and Justin Hou, built a setup capable of simultaneous imaging in two modalities. Microwave transmission imaging tracks the amplitude and phase of the spin wave; magneto-optical Kerr effect (MOKE) imaging maps the magnetization through changes in the phase and intensity of light reflected off the sample.

Liu set up the Co–Ni films with an up magnetic region (blue box in figure 1) and a down magnetic region (pink box). As the spin wave moved from the up to the down domain, or vice versa, its amplitude shrank, and its phase shifted by 175° consistently across different devices. Their observed phase shift is close to the 180° phase shift predicted back in 2004 by Jürgen Kirschner of the Max Planck Institute of Microstructure Physics in Halle, Germany.[4] A 180° phase shift is particularly well suited for logic gates in potential wave-based computing.

Kirschner also predicted that the domain wall would move because of conservation of angular momentum. At the wall, the magnon's angular momentum changes by $2\hbar$ from spin down to spin up, and there's no reflection. The momentum is thus transferred to the domain wall, and the torque from that spin transfer drives the wall in the opposite direction of the spin wave.

When Liu and his group mapped the magnetization, they saw the domain wall shift a few micrometers after the spin wave passed through. Other groups have observed a magnetic domain wall shift from the electron spin-transfer torque,[5] but Liu and his group are the first to see the behavior from magnon torque.

Spin waves flip the switch

Yang and his postdoc Yi Wang were initially interested in electron spin-transfer torque in Bi_2Se_3 and ferromagnet heterostructures as a method to switch magnetization. They investigated how the torque exerted by electrons as they flow into a magnet changes with the thickness of a NiO layer inserted below

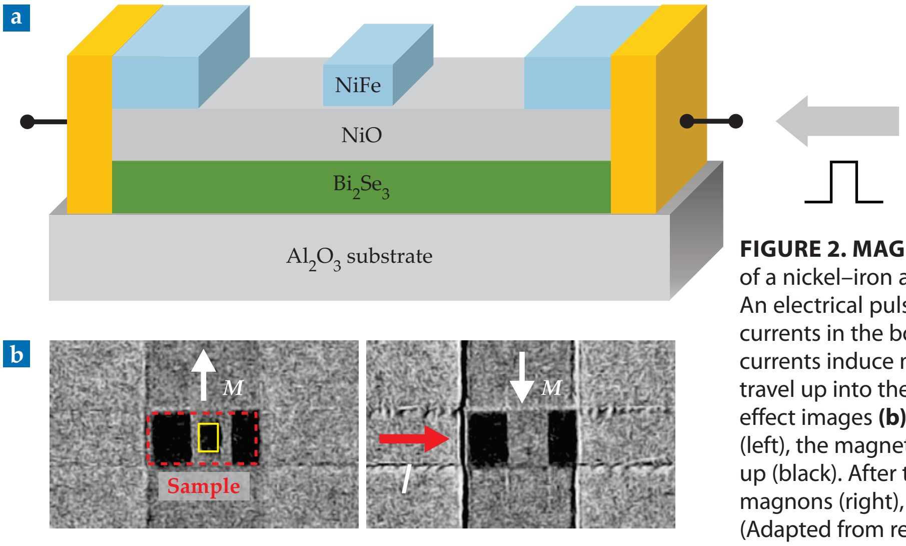

FIGURE 2. MAGNONS FLIP THE MAGNETIZATION of a nickel–iron alloy magnet in the device shown in **(a)**. An electrical pulse (gray arrow) creates electrical spin currents in the bottom bismuth selenide layer, and those currents induce magnons in the nickel oxide layer that travel up into the NiFe magnet. In magneto-optical Kerr effect images **(b)**, before the magnons are introduced (left), the magnet's magnetization *M* (yellow rectangle) is up (black). After the electrical pulse *I* (red arrow) induces magnons (right), its magnetization is down (gray). (Adapted from ref. 3.)

the magnet (see figure 2a). The additional layer should diminish the electron torque simply because a current can't pass through an insulator. Other researchers had found, however, that the electron torque was enhanced[6] with the addition of a 1- to 2-nm-thick layer of NiO, and Yang and Wang planned to replicate those results.

Yang and his group didn't see the enhancement for reasons not yet clear. For thicknesses up to 10 nm, the electron torque did decrease for thicker NiO layers, as expected. They were surprised to find that spin torque experienced by the magnet increased monotonically as the thickness increased from 10 nm to 25 nm, peaking at about half the maximum value. That was their first indication that magnon spin torque was present and nearly as strong as the electron torque.

The group's MOKE maps revealed that magnon spin-transfer torque is strong enough to flip the magnetization of an entire magnet (yellow rectangle in figure 2b). When the spin wave flowed into a nickel–iron alloy magnet, it flipped the 6-nm-thick layer's magnetization from up (black) to down (gray) and then from down back to up. In a future all-magnon device, spin waves may be a way to program magnetic bits without Joule heating—in fact, Yang's next step is to design a device without any electrical components.

Up next for magnons

Spin-wave control of magnetization offers many potential applications. For example, in an all-magnon device, spin waves could modulate the transmission of subsequent ones by moving the domain wall. Or they could be detected through changes in the magnetization rather than through small changes in the electrical resistance.

But first, the process of creating spin waves in a material needs to become more efficient. According to Liu, the solution for efficiently inducing spin waves will come down to developing easy-to-fabricate materials with the right properties, such as low damping and high magnetic anisotropy, and new techniques, such as voltage-controlled magnetic anisotropy.

Heather M. Hill

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A broad acoustic bandwidth helps listeners understand fragmented speech

High-frequency audibility is critical for understanding speech in crowded social settings.

Fortunately for the 50 million Americans who experience hearing loss, hearing aids have improved since the cumbersome, hand-held trumpets of the late 18th century. Back then, mechanically amplifying any and every sound frequency was the only option.

Today, audiologists know that loss of sensitivity to sound first becomes measureable at frequencies around 4000–8000 Hz—much higher than the dominant frequencies in normal speech, which range from around 100–1000 Hz. Most modern hearing aids work by providing frequency-dependent amplification based on the severity of an individual's loss at each frequency. That approach works well in quiet settings.

However, in noisy settings, listeners also need to distinguish competing talkers and interpret speech based on a few heard fragments—a problem that extends beyond amplification alone. (See the article by Emily Myers, PHYSICS TODAY, April 2017, page 34.) Even for people with normal hearing, understanding a conversation in a noisy train station or a crowded bar can be challenging. For those who can no longer make out high-frequency sounds, it's even more difficult.

The importance of extremely high-frequency sounds may not be immediately apparent in daily life, but even mundane speech contains important information at high frequencies. For example, the fricative consonants "th," "s," and "f" have energy beyond 4000 Hz when spoken, so words containing those consonants may be difficult to distinguish for someone who is beginning to experience high-frequency hearing loss. Luckily, speech is a highly redundant signal; robust information in one frequency band can compensate for lost information in another, and the brain can often fill in the gaps from what's left.

How the brain uses high-frequency cues to understand speech in noisy settings remains a puzzle. However, Virginia Best and colleagues at Boston University have made a new and significant observation: Systematically removing sound energy at high frequencies can have

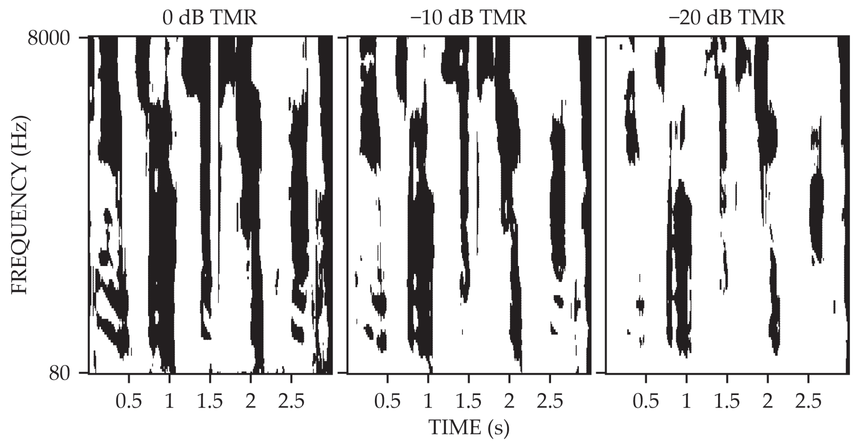

FIGURE 1. LISTENERS IDENTIFIED WORDS based on glimpses of target sentences that were masked by two competing sentences, for a total of three overlapping sentences, at target-to-masker ratios (TMRs) of 0, −10, and −20 dB. The black regions indicate the times and frequencies at which the target speech was more intense than the competing speech. (Adapted from ref. 1.)

a dramatic impact on understanding speech that's partially masked by competing talkers.[1]

Sounds of silence

When multiple people talk simultaneously, coincident sounds lead to portions of time at which the speech of interest is blocked at some or all frequencies. The remaining moments, during which the speech of interest stands out in the acoustic mixture, are known as "glimpses." Glimpses arise when the background noise decreases or when the volume of the talker of interest increases. Listeners use glimpses, along with contextual information, to fill the gaps in acoustic information and construct a complete audible picture.[2]

Most of audiology researchers' understanding about glimpsed speech comes from studies that measure a subject's comprehension of speech that is periodically interrupted by silence or disturbing sounds. In those studies, listeners with hearing loss performed poorly compared with those with normal hearing.

Comprehending speech that includes competing talkers presents a special challenge because extraneous speech sounds very similar to the target. In recent studies, subjects listened to the fragments of conversations in which the target talker's voice dominated the acoustic mixture.[3] Those studies suggested that the main auditory difficulty arises not from isolating the target speech, but from understanding the target message based on a version with bits and pieces missing.

Other auditory studies have investigated the importance of high frequencies on a listener's ability to understand uninterrupted speech.[4] Those studies determined how many syllables a listener could correctly identify in sentences with various frequencies filtered out. The results suggested that speech intelligibility is aided by a broad bandwidth that includes frequencies above 3000 Hz.

A few words

Best and her colleagues hypothesized that a loss of audibility at high frequencies would influence a listener's ability to understand glimpsed speech more readily than uninterrupted speech. To test the hypothesis and understand why hearing loss has such a dramatic effect in multi-talker environments, the researchers gave normal-hearing adults recordings created from three sentences presented simultaneously. Unlike previous work, the recordings preserved only the glimpses of the target sentence that remained after filtering out segments that were masked by the competing talkers.

To vary the number of available glimpses, test subjects were presented with portions of target speech that were created from competing talkers. Progressively louder competing sentences produced increasingly negative target-

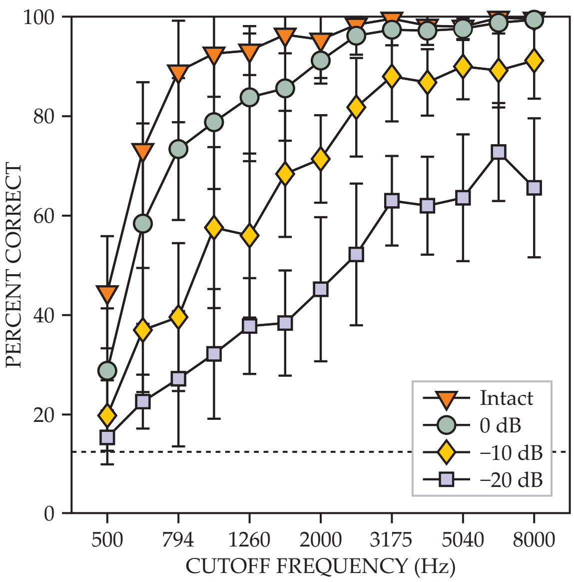

FIGURE 2. FOR INTACT AND GLIMPSED SPEECH at three different target-to-masker ratios, listeners reported the words that they heard. The percent correct began to decline at cutoff frequencies that were higher for the glimpsed speech than for the intact speech. Cutoff frequencies were chosen by dividing the range 500–8000 Hz into third-octave steps. (Adapted from ref. 1.)

to-masker ratios (0, −10, and −20 dB) that corresponded to how much quieter the target was than the competition. In the loudest mixture, the speech of interest rarely dominated the acoustic mixture—that is, the glimpses were short and few; in the quieter mixtures, the glimpses were longer and more numerous, as illustrated in figure 1. To test the effect of bandwidth, the recordings were low-pass filtered at 13 frequency cutoffs between 500 Hz and 8000 Hz, meaning that sound frequencies higher than the specified cutoff were eliminated from the acoustic mixture.

In each listening situation, Best and colleagues measured speech intelligibility by scoring the listeners on the words that they reported hearing. The researchers used those scores to determine the bandwidth at which a loss of high-frequency information affected intelligibility. The "minimum bandwidth" describes the bandwidth required to obtain a specified level of performance, defined by Best's team as understanding 90% of the words. A lower minimum bandwidth corresponds to better intelligibility.[5]

Analysis of available speech information confirmed that the proportion of time filled by glimpses declined as the magnitude of target-to-masker ratio increased and as the high-frequency content decreased. Speech intelligibility, in turn, declined systematically with increasingly negative target-to-masker ratio or with lower cutoff frequencies, as shown in figure 2. Importantly, for all conditions, intelligibility dropped rapidly for bandwidth cutoffs below 1000 Hz. Generally, as a greater proportion of the signal was blocked and glimpses were lost, higher frequency components (1000–8000 Hz) became increasingly important for making sense of what remained. Those frequencies did not affect the intelligibility of intact, unmasked speech.

Hearing loss often starts at the highest frequencies and works its way down. The new findings suggest that those high frequencies are more important for comprehension in the presence of competing talkers than in quiet situations. The results may be an important consideration for improving hearing aid design. Unfortunately, although providing more gain at high frequencies can improve audibility, the added loudness can also cause aural discomfort. Further research could help identify new ways of providing customized amplification that are adapted for different people and listening situations; such customization should result in both better comprehension and greater comfort.

Rachel Berkowitz

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Goal: Double the number of African Americans in physics and astronomy

The recommendations of a new AIP report aim to catalyze and guide a huge cultural shift.

Over the past two decades, the numbers of bachelor's recipients in physics and astronomy in the US have rocketed to record highs. Yet even as the increase in African Americans earning bachelor's degrees across all fields has outpaced the overall population, the percentage of physics and astronomy bachelor's degrees earned by African Americans has stalled at around 4%, according to data from the Statistical Research Center at the American Institute of Physics (AIP, publisher of PHYSICS TODAY).

Other underrepresented groups have made larger gains. For example, from 1995 to 2018 the percentage of physics bachelor's degrees earned by women grew from 17% to 21%; for Hispanics that percentage rose from 2.7% to 8.8%. Across the physical sciences, technology, engineering, and mathematics, African Americans made up just 5.3% of bachelor's recipients in 2018. They made up 9.2% of bachelor's recipients across all fields. And in recent years they have made up 14–15% of high school graduates from US public schools. (Data are from the US Department of Education's Integrated Postsecondary Education Data System and its National Center for Education Statistics.)

The reasons for the paucity of African American students in physics and astronomy are complex and long-standing. But two factors stand out: the lack of a supportive environment in many departments and the enormous financial challenges many of these students face.

Fostering a sense of belonging is essential for African American student persistence and success.

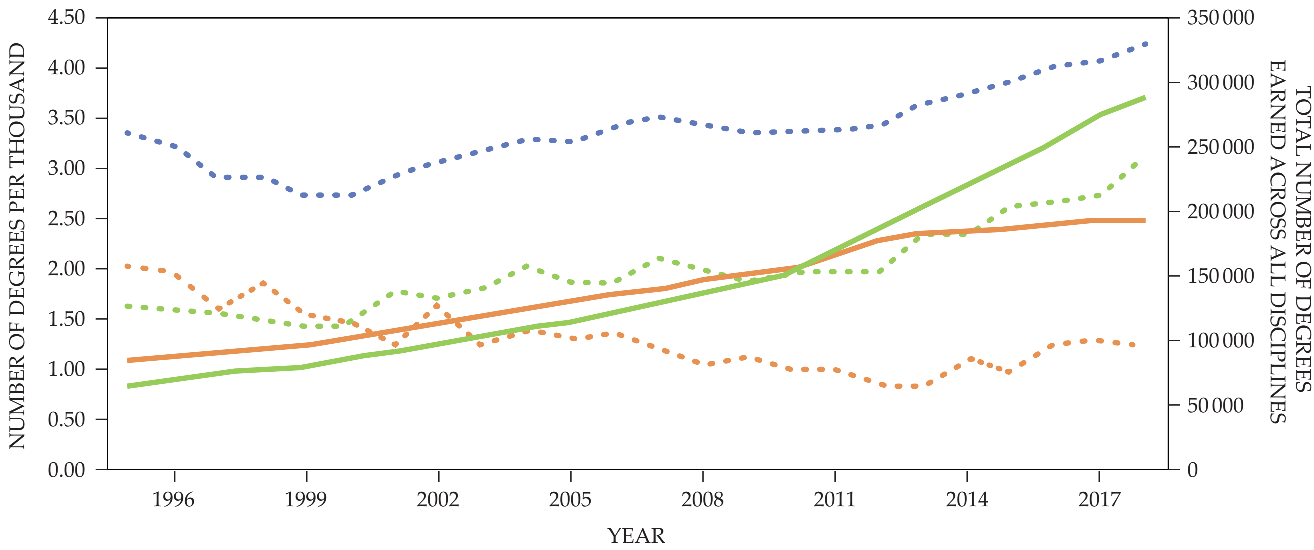
JEDIDAH ISLER (LECTERN), EDMUND BERTSCHINGER, and other members of the task force to elevate African American representation in undergraduate physics and astronomy unveiled their roughly 200-page report at the American Astronomical Society's January meeting in Honolulu. (Courtesy of AIP.)

That's according to TEAM-UP, the national task force to elevate African American representation in undergraduate physics and astronomy, which AIP convened in 2017. On 5 January 2020, at the American Astronomical Society's annual meeting in Honolulu, AIP unveiled the results of TEAM-UP's investigation into the persistently low representation of black students in physics and astronomy. In a nearly 200-page report, the task force, a panel of 10 physicists, astronomers, and social scientists plus two AIP employees, lays out recommendations to effect sweeping cultural change in the physics and astronomy communities—and to double the numbers of African Americans earning bachelor's degrees in those fields by 2030. (The red callouts are summaries of some of the report's findings.)

"The physics community is looking very deeply at itself," says Shirley Malcom, a senior adviser at the American Association for the Advancement of Science and director of the association's STEMM Equity Achievement (SEA) Change, who wrote the foreword to the TEAM-UP report. "I hope people are willing to look past the defensiveness that often emerges when you talk about these issues. There is no reason to be defensive. We were born into a society that tends not to value black people. Let's get over that and change behaviors that keep African Americans from thriving in our colleges and universities and contributing to the advancement of physics."

Cultural shift

TEAM-UP surveyed and interviewed students and department chairs; conducted department site visits; and consulted the literature on African American students in science, technology, engineering, and math and on women of color in physics. The task force's findings and recommendations are presented along six themes: Belonging, physics identity, academic support, personal support, leadership and structures, and change management. "Change management" refers to the need to understand the broad social context and the systemic changes sought, including the roles of individuals, orga-



AFRICAN AMERICANS EARN DISPROPORTIONATELY FEWER physics and astronomy bachelor's degrees. Over the past quarter century, the total number of bachelor's degrees (not shown) earned in the US has grown from 1.1 million to 2.1 million. The number earned across all fields by African Americans has more than doubled, from 85 856 to 193 567 (—), and for Hispanics has grown even more (—). But in physics and astronomy, neither group keeps pace with the proportion of degrees earned by the population as a whole, as shown by the dotted lines, which represent the numbers of degrees per 1000 degrees earned in those fields (••• all students, ••• African Americans, and ••• Hispanics). In 2018 African Americans earned a total of 223 degrees in physics and 10 in astronomy. (Plot created by the AIP's Statistical Research Center using data from the Department of Education's Integrated Postsecondary Education Data System.)

nizations, and society. Boosting participation of African Americans in physics and astronomy, the report says, "requires not only changing the way physicists train students, but how they *think* about training students."

Efforts at every level of the physics and astronomy communities are necessary. So are will and money. "African American students have the same drive, motivation, intellect, and capability to obtain physics and astronomy degrees as students of other races and ethnicities," the report notes, but many African Americans choose majors that "are perceived as being more supportive and/or rewarding, resulting in a loss of talent to physics and astronomy."

The goal of doubling the number by 2030 is intended to put African Americans' representation in physics and astronomy on a par with their participation in engineering and other physical sciences. African Americans got left behind in the huge increases that physics has seen in the past two decades, says task force chair Edmund Bertschinger of MIT. "We want to rectify that omission."

The task force did not identify a simple how-to list for achieving its goal. Instead, it crafted recommendations that individual faculty members, department chairs, professional societies, and funding agencies can turn to for guidance.

Still, the report does set priorities. For individual physicists and astronomers, the top priority is to read and discuss the TEAM-UP and related reports as a means to "consider their role in establishing their departmental culture and commit to creating an environment where African American students and those from other marginalized communities can thrive."

To persist, African American students must perceive themselves, and be perceived by others, as future physicists and astronomers.

Department chairs should identify and tap into resources on and off campus that can help meet students' financial and other needs. Next, they should "begin the hard work of culture change," by setting norms and values of inclusion and belonging; recruiting, developing, and supporting a diverse faculty; and overseeing policies and practices that enhance the success of African American students.

For their part, professional societies should start by encouraging discussion in their organizations. And they should raise a $50 million endowment. That figure would provide an estimated annual $2.4 million from the endowment's presumed interest earnings.

Half the money would be used to cover the roughly $8000 a year in unmet needs for 150 students. The student total is not arbitrary. If the growth in physics degree production that didn't happen in the past 20 years at historically black colleges and universities had matched that of other campuses, 150 more black students would graduate annually with that major by now. African American students at any campus could apply for money to pay for tuition, fees, books, living expenses, conference travel, and the like. The other half of the money would be available to departments to implement the TEAM-UP recommendations that require funding. For example, a department might apply for money to hire extra lecturers so as to free up faculty to spend time on mentoring or to introduce new programs.

AIP's next steps will be to present and discuss the report at conferences and to convene workshops of department chairs, interested faculty members, representatives from diversity-related committees of professional societies, and other stakeholders. "We will take deep dives on the recommendations and conclusions and start a dialog on how the community can respond," says AIP chief executive officer Michael Moloney. "The goals are ambitious and challenging, so an ambitious response is appropriate." (The report is available at www.aip.org/teamup.)

The large number of findings and recommendations could be overwhelming, acknowledges Bertschinger. The idea, he says, is for people to go through the recommendations and prioritize for themselves. "We didn't want to be too specific, because not every individual and department will be in the same situation." Implementation could take years, he adds. The report also includes suggestions for faculty training, self-assessment tools for individuals and departments, a rubric for prospective students and their families to evaluate physics and astronomy departments, and more.

Black physicists matter

Unsurprisingly, TEAM-UP finds that African American students are more likely to persist in physics and astronomy if they feel a sense of belonging to their academic community. Interactions with faculty and peers, encouragement and inclusion in activities, and recognition of school and nonschool problems a student may be confronting all contribute, positively or negatively, to students' sense of belonging.

For sustainability, academic and disciplinary leaders must prioritize creating environments, policies, and structures that maximize African American student success.

Positive examples include praise about work, invitations to study or socialize, and high expectations for success. Negative examples include the slights and indignities that African American students in physics and astronomy encounter—everything from "Are you lost?" when they head to a basement lab for their research to "You should switch majors."

Sharon Fries-Britt, a task force member and University of Maryland professor of higher education who studies the experiences of black students in academia, says that they are consistently being "advised out" even before they have had a chance to display their skills. Those types of comments add up and contribute to feelings of isolation, she says.

African American students face challenges that other groups may not have to deal with as much. Harold Johnson, a second-year graduate student in theoretical physics at the University of Texas at Austin, grew up on Chicago's South Side. "It's a different reality," he says. "People don't talk about physics. Our priorities are how to stay out of prison and not become a statistic." One big factor is math, he adds. "If you don't get a good math grounding in school, then you are behind by the time you get to college. It would also encourage black kids if they saw more black people in college. It's a layered issue." (See why Willie Rockward switched from football to physics in the interview at http://physicstoday.org/rockward.)

The TEAM-UP report cites financial data from the US Federal Reserve Board: In 2016 the median wealth of white families in the US was $171 000, 10 and 8 times more than that of black families ($17 600) and Latino families ($20 700). As a result, African American students disproportionately juggle work and financial or medical problems while in school. The TEAM-UP report recommends that physics and astronomy department staff familiarize themselves with campus resources, such as counselors to address stressful situations, and with funding sources to mitigate financial emergencies. An African American student may be selected for a research internship, for example, but be forced to decline due to lack of travel money. Physics and astronomy faculty members should help identify opportunities for African American students to work in areas related to their studies, the TEAM-UP report says.

It's not enough to invite students into the field, the report says, "especially if their social identity does not conform to stereotypes of who is a physicist." Underrepresented minority students "must continually navigate the incongruity of their social and physics identities." According to Fries-Britt, that challenge affects black students staying in the sciences. "They don't want to park other aspects of their identity outside the door, but when they bring those other things up, they often feel that they are perceived as being less serious scientists." That perception can be stronger in physics than in other fields, she adds, perhaps because it's often considered the toughest major. One way departments can help, the report says, is by creating opportunities "for students to discuss broader societal issues of concern such as gun violence, immigration, hate crimes, and protest movements." (See also PHYSICS TODAY, October 2019, page 24.)

Bertschinger notes that African Americans tend to be socially minded. "Giving back to the community is highly valued." The tendency goes back to the history of supporting each other in the face of systemic discrimination, racism, and hate crimes, he says, and that social context provides important grounding to the African American experience. Faculty may not realize that a physics degree provides a strong background to work in areas that undergraduates are interested in, such as climate change or how technology can enhance or diminish civil rights, Bertschinger says. "But physics training provides rigorous methodology for problem solving. We as physicists could do a better job if we recognized connections beyond our discipline." Along those lines, the report recommends that departments discuss career options for physics bachelors.

Many African American students need support to offset financial burdens and stress.

The TEAM-UP financial challenges are more straightforward than the cultural ones, says Bertschinger. It may not be easy to raise $50 million, but the objective is clear. Shifting attitudes is harder, he says. "Faculty may feel ill-equipped to deal with the issues, or that it's not their responsibility, but I am optimistic because there is so much awareness these days of the inequities in society and on campuses." S. James Gates, a theoretical physicist at Brown University and task force member, agrees: "This report comes at a fortunate time, as academics are already dealing with harassment issues." Partly because of the #MeToo movement, there are more "woke" people walking around, he adds. "I think we can make a difference."

Toni Feder

Weapons labs to build costly new device to better understand plutonium

Scientists say subcritical experiments with plutonium will eliminate the need for nuclear tests, a promise that was first made in 1995.

The pockmarked Nevada National Security Site, where more than 900 nuclear blasts were set off during the Cold War, will be host to a new billion-dollar-plus experimental weapons test facility located more than 300 meters underground. But the observations of how plutonium behaves under the extreme pressures that occur during detonation of a nuclear weapon will be made without those blasts.

The Enhanced Capabilities for Subcritical Experiments (ECSE) facility will capture x-ray images of the dynamics occurring during the implosion of scale models of plutonium pits, which are at the heart of a nuclear weapon's primary stage. When completed in 2025, the ECSE will consist of two major components. The most critical, and by far the most expensive, is Scorpius, a 20 MeV accelerator that will produce x rays from bremsstrahlung radiation generated by decelerating electrons as they hit a heavy metal target. The photons will capture images of the hydrodynamics occurring during the implosions. A second instrument, in an earlier stage of development, will probe the behavior of neutrons as the plutonium samples approach, but never attain, a critical assembly capable of sustaining a chain reaction.

The ECSE will work analogously to how aircraft manufacturers develop new planes, says Los Alamos National Laboratory (LANL) director Thomas Mason: "We can't fly the aircraft, but we can put the model in the wind tunnel." The results will be used to validate the codes that have been developed on high-performance computers to simulate nuclear blasts, "to fly the planes, if you will."

Scientists at LANL and Lawrence Livermore National Laboratory (LLNL) already have several devices for studying implosions. Both labs have aboveground machines that can create x-ray images of imploding targets. LANL's Dual Axis Radiographic Hydrodynamic Test (DARHT) facility is the more advanced of the two, capable of generating four images at 2 MHz of the hydrodynamics of imploding materials. Scorpius will at a minimum have the same imaging capability, but its design may be upgraded to capture eight images at 5 MHz, says David Funk, LANL senior director for the advanced sources and detectors project in Nevada, of which Scorpius is a part.

The aboveground devices have a major drawback: For environmental and safety reasons, they can experiment only on surrogate materials such as tungsten, lead, copper, and gold. Surrogate materials help validate some model properties, but "in the end, plutonium is a unique metal," Funk says. For example, it has seven phases that can be created in a lab without exotic equipment. "At very high pressures and temperatures its behavior may not be very well represented by surrogates."

Since the US halted nuclear tests in 1992, plutonium implosion experiments have been carried out in the U1a tunnel complex at the Nevada National Security Site. The high-explosive-driven experiments are done within containment vessels with quantities designed to remain subcritical.

Funk says the existing pair of 2.2 MeV accelerators located in the U1a complex produce photons with enough energy to

LOS ALAMOS NATIONAL LABORATORY

THE U1A TUNNEL COMPLEX, 330 meters beneath the Nevada National Security Site, will house the Enhanced Capabilities for Subcritical Experiments facility, which will probe the behavior of plutonium under conditions that occur in nuclear detonations.

record only the early stages of implosion. "For quantities of interest—I won't say anything about the scale or size of experiments—it's very difficult to look through a dense metal like plutonium with 2.2 MeV. We need much higher energy photons."

Holding the experiments underground avoids generating a new transuranic waste stream, Funk says. Instead, the waste is simply entombed in the U1a complex. The subterranean environment also is inherently safe and secure, he asserts.

The Department of Energy's National Nuclear Security Administration (NNSA) established in 2014 the need for an ECSE-like capability to ensure proper functioning of the weapons stockpile. The ECSE will also likely be used to evaluate new weapons designs. No new warheads have entered the stockpile since the 1980s, but a replacement warhead for US land-based intercontinental ballistic missiles is now in the design phase.

Fuzzy cost estimates

A preliminary ECSE design, expected by March 2021, will include a cost baseline with a confidence level of at least 80%. Until then, the estimate ranges from $500 million to $1.1 billion. Extending the U1a tunnels to accommodate the device will cost another $111 million to $175 million, Funk says. Congress included $145 million for the project in the current fiscal year's appropriations.

Scorpius is named after Scorpius X-1, the first cosmic x-ray source to be discovered, and the brightest. The accelerator will produce x rays sufficient for producing images of the latter, denser phases of implosions. The x rays will also be able to capture images of targets that more closely resemble pits in size and shape compared to current implosion targets. The cameras and other diagnostics at the ECSE will be comparable to those located on DARHT, but with some improvements, he adds.

A second ECSE component, now in the R&D phase, will probe the neutron reactivity of the plutonium as it implodes. In a stand-alone mode, a pulsed-power device known as a dense plasma focus will produce 14 MeV neutrons from a deuterium–tritium plasma. Those neutrons will be directed onto the plutonium target and the decay rate of the reaction measured. Scorpius will serve as the neutron source for combined radiographic–neutronic experiments. That's because neutrons created by the accelerator via photofission will vastly outnumber the neutrons produced by the dense-plasma-focus device. The ECSE's neutronic components are estimated to cost around $90 million.

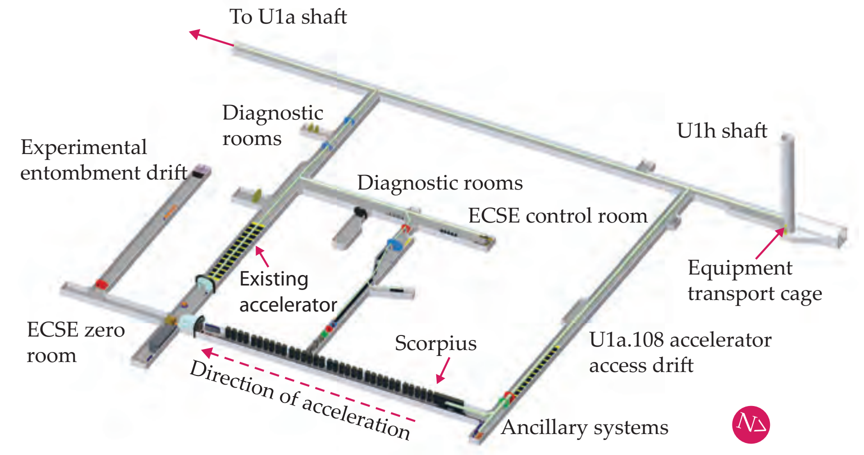
The combination of radiographic and neutronic experiments "should preclude the need to do any kind of testing in the future of an underground type," Funk says. That same promise was made by the lab directors a quarter century ago. In that light, what's happened since then to justify the ECSE's costly new capabilities?

Aging concerns

Each year since the cessation of nuclear tests in 1992, the directors of the three US weapons labs—LANL, LLNL, and Sandia—have been required to assure the president that the weapons are safe, reliable, and secure. But lab scientists continue to have concerns over the aging of pits and their interactions with other weapon components. That's despite studies that have concluded that the pits, which date to the 1980s, should function properly for decades to come.

For example, researchers at LLNL applied accelerated aging techniques to the primary fissile material in warheads, plutonium-239, which has a half-life of 24 100 years. The study found that the material, will "age gracefully" for at least 150 years. That research discounted concerns that phase changes or helium bubbles caused by alpha decay in the metal's lattice might change the shape or strength of the pits.

A 2007 report by JASON, the secretive group of scientists who advise federal



A SCHEMATIC OF THE U1A TUNNELS shows the locations of the proposed Scorpius electron accelerator and one of the two existing accelerators. Scorpius will produce x rays to image the hydrodynamics of plutonium as it implodes. The smaller accelerator will generate high-energy neutrons to probe time-dependent neutron reactivity during implosions. Both types of experiments occur inside containment vessels located in the zero room at the lower left. Spent vessels are entombed in the vertical tunnel at the far left. (Courtesy of Los Alamos National Laboratory.)

agencies, also found little age-related reason for concern—at least in the unclassified summary. Nonetheless, Congress last year ordered JASON to take another look. The group's November report provided no estimates for pit lifetimes. It recommended that the labs continue with plutonium aging research. Mason says the ECSE will be an important component of the "focused program to understand aging" that the study called for.

Mason says the 2007 JASON review included a number of important caveats that often get lost in the slogan "we don't have to worry about plutonium aging." The report, he says, "has a much more nuanced view of that," although those details are classified.

Apart from assessing aging concerns, Funk says the ECSE will help evaluate whether weapons will be affected by new manufacturing methods and the addition of new safety and security devices.

Mason points out that the NNSA plans to ramp up production to 80 new pits per year by 2030 in response to a directive in the 2018 *Nuclear Posture Review*. Those pits will be cast instead of wrought, as was the case for manufacturing all but a handful of pits in the current stockpile. The wrought pits were proven to work in full-scale nuclear tests. In the absence of testing, the ECSE will help certify the performance of the new pits to be manufactured at LANL and DOE's Savannah River Site, Mason says.

Critics argue that the ECSE is unnecessary. In fact, LANL manufactured more than two dozen cast pits over a decade ago that were certified for submarine-launched ballistic missiles. "All of this is about the future stockpile and future heavy modifications, if not outright new designs," says Jay Coghlan of the watchdog group Nuclear Watch New Mexico.

Budget documents for the current fiscal year indicate that all 141 pits scheduled to be fabricated from FY 2023 through FY 2030 will be used for a new warhead rather than as direct replacements for aging weapons. Designated W87-1, the new warhead is to replace the W78 that tops most of the US Air Force's Minuteman III intercontinental ballistic missiles. The W87-1 will be the first new warhead design to be certified without the need for underground testing.

Coghlan and others worry that facilities such as the ECSE are being created to support increasingly major modifications to existing weapons systems. The changes are creating "code drift," he says, by moving the remodeled weapons further away from the simulations that were validated by nuclear testing. That will degrade rather than improve their reliability, he argues.

David Kramer PT

IOWA'S agriculture IS LOSING ITS Goldilocks CLIMATE

Eugene S. Takle and
William J. Gutowski Jr

Climate conditions for growing corn and soybeans have improved, but current trends indicate they will not last.

CHARLIE NEIBERGALL/AP/SHUTTERSTOCK

Eugene Takle is an emeritus professor in the department of agronomy, and **William Gutowski** is professor of meteorology in the department of geological and atmospheric sciences, both at Iowa State University in Ames.

The Iowa landscape is endowed with rich, deep, dark soils that have high water-holding capacity. Because most of the state's land is flat or gently rolling, agriculture can be practiced with large, efficient machinery. Historically, Iowa's average climate is characterized by a growing season of about five to six months with favorable sunshine and warm temperatures. Its crop-dormant season has low enough temperatures to prevent overwintering of detrimental pests and pathogens. The seasonal cycle of precipitation has a spring–summer maximum and a winter minimum that generally provide a sufficient and timely supply of water to support high crop densities without the need for irrigation.

Iowa's climate, along with its rich soil, has made the state the national leader in producing corn and raising animals that feed on corn—namely, hogs and laying hens. Iowa is also second in the nation in soybean production.

More sophisticated and automated machinery, large amounts of fertilizer and pest-management chemicals, and improvements in crop breeding have made Iowa's agriculture more productive. However, those changes have driven up production costs and reduced diversity to two crops. They have also depopulated vast areas of the state and made profits dependent on a favorable climate for those two products.

Iowa's climate is experiencing increased humidity, early-season rainfall, as well as a reduction in mid- to late-summer maximum daily temperatures. Evidence is mounting that the multidecadal trend of increases in Midwest corn yields, generally attributed to improved technology and management, may also have been partially attributable to the climate becoming more favorable. Midwest agricultural production is important to the national and global food supply and, more recently, to biofuels; its importance motivates us to take a closer look at recent climate trends, future projections of climate for the region, and how the climate will impact agriculture.

One change that has likely contributed to higher yields is humidity high enough to prevent extreme plant desiccation but not so high that it consistently fosters detrimental fungus and mold. Other probable contributions are abundant rains that reliably recharge the deep-soil water reservoir in spring but not so extreme or persistent that they delay or prevent spring tillage and planting; and abundant sunshine with high summer temperatures but not so high as to limit crop growth or reproduction.

Those climate changes have led Iowa to a Goldilocks period with just the right measure and timing of humidity, rainfall, and heat. But it will likely not last. Without major technological advances, by the mid 21st century climate change could decrease Midwest agricultural productivity to 1980s levels.[1]

The physical link between the greenhouse gas heating of our planet and food production in a particular region can be captured by mathematical models; see the box on page 31.

Climate change and Iowa's crops

Iowa's summer daily maximum temperatures over the past 30 years have not followed the upward global trend. Nighttime minimums have increased, but higher humidity, overcast skies, rainfall, and the resulting wet soil have decreased the fraction of solar radiation converted to sensible as opposed to latent heat. More latent heat causes even higher humidity and limits warming, which has led to a so-called warming hole in the central US.[2]

Water stress on crops is measured by the water-vapor deficit—the difference between the saturation vapor pressure of water in a leaf and the ambient water-vapor pressure. Rising dew-point temperatures due to enhanced moisture flow from the Gulf of Mexico, coupled with steady or declining maximum daily temperatures, mean that the

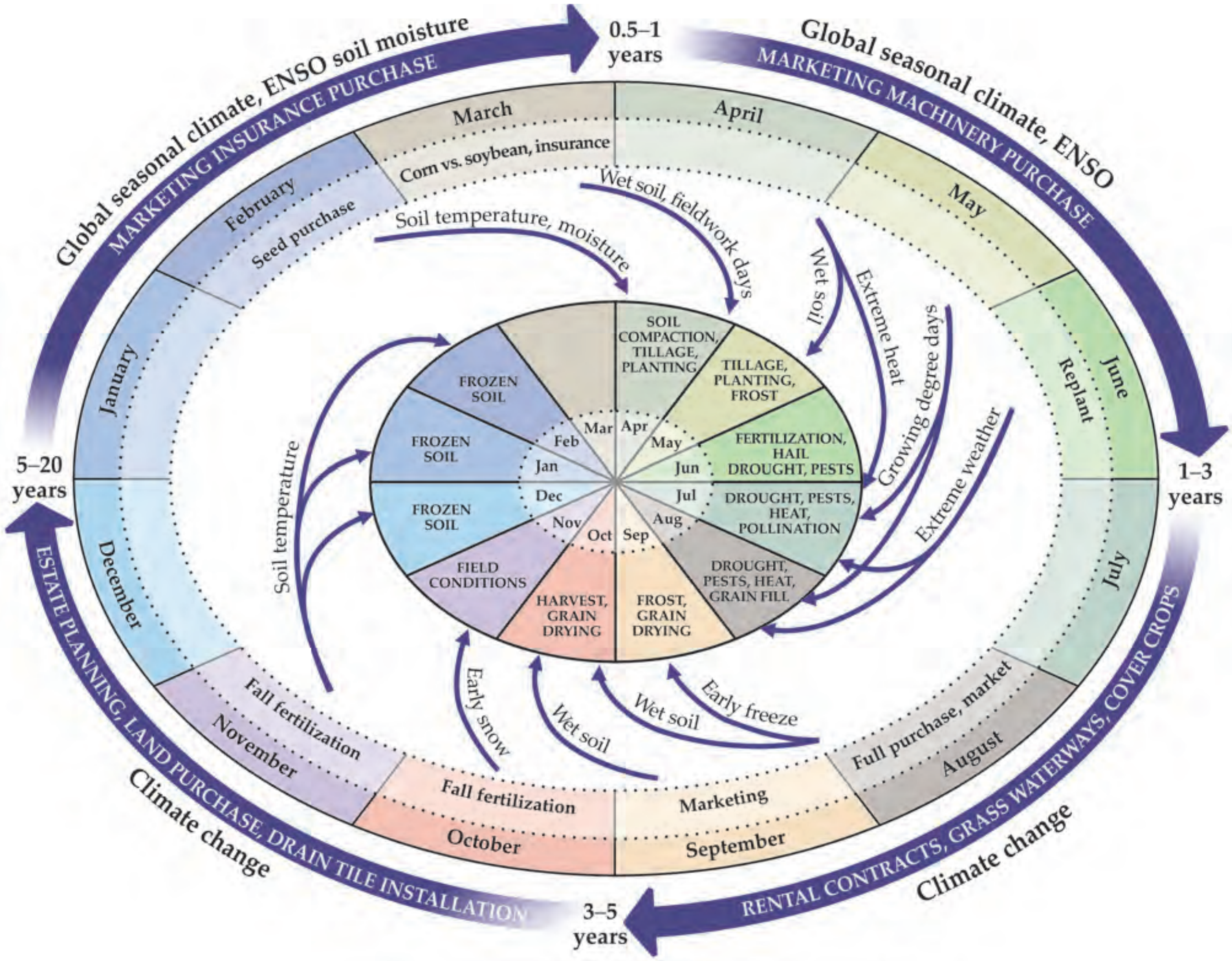


FIGURE 1. A DECISION CALENDAR for Midwest corn producers showing climate forecast lead times. The outer monthly ring shows the timing of typical decisions producers make; the inner monthly ring shows the activities and climate outcomes related to those decisions. The lengths of arrows connecting the rings indicate the time lapses, or climate forecast lead times, between decisions and their impacts; the labels on the arrows show the relevant climate condition. The outer ring of arrows indicates decisions farmers make that are affected by seasonal to decadal climate conditions and changes. For instance, producers in Florida might use a six-month forecast of the El Niño/Southern Oscillation (ENSO) conditions to estimate soil moisture levels over the growing season. Farmers in Iowa might use forecasted decadal trends in growing season precipitation to decide on whether to install subsurface drainage tile. (Adapted from ref. 18.)

daytime vapor-pressure deficit, and hence crop stress, has decreased. Those factors lead to the counterintuitive conclusion that climate change has decreased, not increased, water stress in plants in Iowa. The lack of new irrigation systems in the state suggests that farmers are not having a problem with water stress in crops.

The water supply for the spring recharge of the agricultural soil-moisture reservoir has increased over the past 30 years. But now moisture is more frequently impeding tillage and planting operations and is increasing soil erosion. In 2013 the US Department of Agriculture reported that more than 1100 square miles of corn and soybean cropland in northwest Iowa were not planted because of persistent rains during the planting season.

Rising humidity from Gulf moisture, increased spring rain, and subsequent increases in soil surface evaporation in late spring and summer are leading to longer periods of rain and dew remaining on foliage. Those conditions increase the growth of molds and fungi and contribute to increases in infections and mycotoxin contamination in both preharvest and stored grain.

Greater humidity and cloudy skies trap more IR radiation, which suppresses nighttime cooling of near-surface air. By midsummer corn plants have reached their maximum height; for the remainder of the growing season, they convert atmospheric carbon into seed mass. Cooler nighttime temperatures lengthen that so-called grain-filling period, and warmer ones shorten it. Therefore, higher nighttime temperatures from climate change reduce carbon mass accumulation in grain and tend to lower yields.[3]

The most favorable temperature range for vegetative development of corn is the high 70s to low 90s °F; soybeans grow best in the mid 70s to mid 90s. Pollination and seed formation peak in cooler conditions:[4] Corn favors low 60s to mid 70s, and soybeans do best in mid 60s to mid 80s. At temperatures above 100 °F, vegetative development and reproduction pause in both crops. The reduction of daytime temperatures in Iowa because of generally wetter conditions has improved both plant development and seed formation for corn and soybeans.[5]

Other results of recent global climate change have been favorable for agricultural production in Iowa. The longer growing season allows for planting of longer-season hybrids that capture more carbon and thus have higher yields. More seasonal rainfall and stored water, along with fewer extreme heat events, have prompted farmers to plant more seeds per acre—30 000 or more now compared with less than 20 000 per acre 40 years ago for corn. Those favorable changes, and farmers' adaptations to them, have been credited with a 28% greater yield, approximately 1.2 metric tons per hectare, or 19.3 bushels per acre,[5] since 1981.

Adapting to climate change

Arguably the strongest passion of a Midwest farmer is the vernal urge to get seeds planted once the soil temperature reaches 50 °F. It is no surprise then that farmers have been some of the first to detect a subtle but systematic shift in that long-awaited launch point. Warmer average spring temperatures caused by global warming and a rise in humidity—water vapor is a strong greenhouse gas, so higher humidity increases IR absorption—have enabled farmers to begin planting in Iowa, on average, about 10 days earlier in the past 20 years than they did in the 20th century.[4]

Farmers know that the current climate is not the same as that in the last quarter of the 20th century. Over many generations, they have learned to adapt to challenges: pests, price swings, market volatility, and the costs of machinery and fertilizer. Farmers also adapt to persistent adverse weather conditions by, for example, planting on multiple dates and planting multiple corn varieties that have different pollination periods. That approach spreads out the risk of losing an entire crop from a single heat wave.

Seed providers have improved the drought tolerance of hybrid corn, but tolerance to extreme heat and waterlogged soil remains elusive. More frequent and intense rain events have left narrower windows for crucial spring fieldwork, so farmers are purchasing larger planters that can be pulled across fields faster. A 90-foot-wide corn planter is currently being marketed in Iowa; it can plant an area the size of a football field in less than 46 seconds, at least doubling the planting speed of two decades ago.

Intense spring rains on bare soil would enhance soil erosion were it not for the recent increased use of mitigation techniques. Those include fall-planted cover crops to protect the soil, no-tillage practices that leave more surface detritus, perennial grass cover in shallow gullies, water management to reduce runoff, row crops planted on landscape contours rather than up and down slopes, and narrow perennial-grass prairie strips that suppress surface runoff.

Increased occurrences of water-logged soil such as that shown in the opening image have prompted more installation of subsurface drainage tile—perforated pipe that captures and transports soil water to streams and rivers—at closer spacing and even on sloped surfaces. It is estimated that more than 2 million miles of drainage pipe lies under the Iowa landscape.

Higher humidity has driven increased spraying for pathogens and delays in harvesting soybeans. The legumes do not separate well from wet pods, so some farmers have purchased larger, faster bean-harvest equipment to compensate for shorter dew-free harvest periods.

Precision agricultural equipment and more climate analysis technologies are being implemented in the field. Most Midwest farmers make decisions based on short-term weather information; far fewer use seasonal or long-term climate projections. The site-specific and temporally resolved nature of seasonal to annual weather conditions needed for agricultural decisions demand forecast accuracy beyond current levels. Figure 1 shows the relationship between when producers make weather and climate-related decisions and when the impacts of those decisions are seen.

The long lag time between the events highlights the need for improved climate forecast products that farmers will use to estimate crop-relevant conditions weeks to years or even decades into the future. For example, crop inputs, such as seeds, fertilizer, and pest-control chemicals, are purchased months before they are used. If planting is delayed from mid-April, which is optimum for corn in Iowa, until the end of May or beyond, as in 2013 in Iowa and 2019 in both Iowa and Illinois, the reduced growing season may be too short for the longer-season seed variety that was purchased. So even though adaptations may be available, they can come at a price.

Projected trends and agricultural impacts

The conditions underlying recent increases in Midwest humidity and, consequently, high spring and early summer rainfall

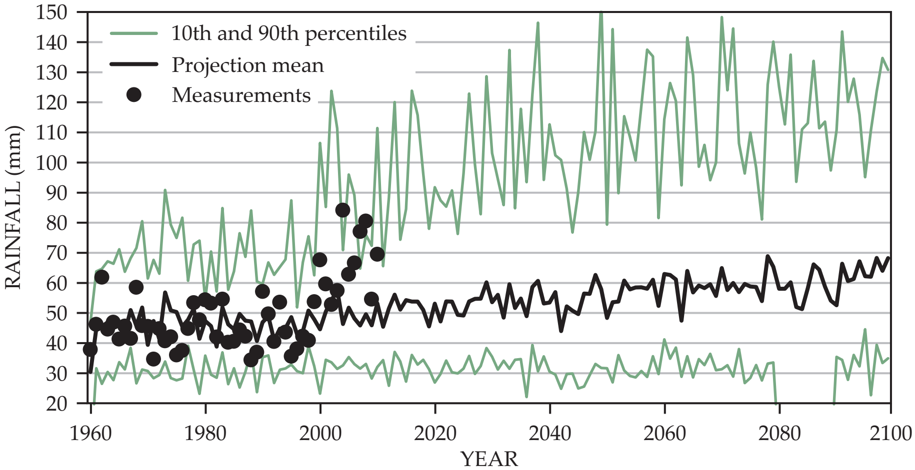


FIGURE 2. BASIN-AVERAGE ANNUAL MAXIMUM DAILY PRECIPITATION (AMP) for the Cedar River Basin at US Highway 30 as represented by the average of 19 global climate simulations for the period 1960–2100 and an ensemble of emission scenarios. The black line is model average AMP, and green lines are the 10% and 90% boundaries of AMP. Black dots are measured values from 1960 through 2009. (Adapted from ref. 8.)

are closely linked to the rise in global mean temperatures.[6] They are therefore likely to persist over the coming decades.[7] A study of average annual maximum daily precipitation (AMP) for a large basin in eastern Iowa comprising 14% of the area of the state revealed that global climate models can capture the increase in AMP between the 20th and early 21st century.[8]

Modeled average AMP values for the Cedar River Basin (figure 2) rise slightly from 1960 through the end of the 21st century. The trend of the 90th percentile line, however, shows that models project a rise in extreme rainfall beginning around 2000 and then a leveling off to a value about 2.5 times the almost-constant 20th century value. The upward trend in the models' extreme high rainfall is borne out by the data and likely to continue for a couple of decades. In that case, the extreme high precipitation over large areas of the state would range from 2.5 to 3.0 times the amounts recorded in the 20th century. The short period of observed data for the 21st century contained no years of low AMP values to validate the once-per-decade low AMP projections.

Heavy spring rains creating waterlogged soil will likely decrease the number of acres planted with corn or soybeans. Rain events exceeding 1.25 inches will also become more frequent and thus worsen soil erosion. The prevalence of bacterial plant diseases and the number and intensity of fungus and disease outbreaks are expected to rise with the higher temperatures and heavier spring rain. Warmer soil and more moisture will lead to more loss of soil carbon and poorer surface-water quality through eroding soil particles and nutrients. Riverine nitrogen levels are particularly exacerbated by alternating years of extreme drought and flood.

According to the US National Climate Assessment, temperatures during five-day summer heat waves are projected to increase more in the Midwest than in any other region of the US.[9] Higher August temperatures reduce the length of the grain-filling period for corn. Higher extremes can also interfere with reproduction.[3] Current average temperatures for a five-day heat wave in Iowa are about 92 °F; by the mid 21st century, that is projected to rise by 5 °F if future greenhouse gas emissions are low and 11 °F if they're high. Even under a medium-emission scenario, projections indicate that, on average, by the mid 21st century one year out of two in Iowa will have at least one summer five-day period when pollination of corn and soybeans will fail.

Increases in growing-season temperature in the Midwest are projected to be the largest factor contributing to declines in the productivity of US agriculture.[1] The suppression of summer daytime maximum temperatures that created the warming hole in the central US is projected to abate, at which point the underlying warming—particularly under higher carbon emission scenarios—will be unmasked and create a "warming hill" and a spatial peak in vapor-pressure deficit, both centered over Iowa[10] (see figure 3).

Biophysical crop-growth models that include future climate scenarios from global models project yields of commodity crops to the middle and end of the 21st century.[10–13] In regions where corn is currently grown, results typically show that yields could drop by 5% to more than 25% below extrapolated trends; that figure is more than 25% for soybeans in the southern half of the region. The models project new areas coming into production outside the northern borders of the corn belt and loss of production on the western edge.

Warming winters with higher soil temperatures are expected to promote the survival and reproduction of insect pests. A northward expansion of new insect pests and crop pathogens into the Midwest already has been observed.

Recent simulations for the high carbon emission scenario suggest that increased droughts between high-rainfall years will be the largest threat to US rainfed corn production in the short term. However, beyond midcentury, high temperature and heat stress will be the dominant constraints. Elevated atmospheric CO_2 can have a fertilizing effect that will partially, but not entirely, offset crop-yield declines caused by climate extremes. That effect is greater for soybeans than for corn.[10]

Adapting for the future

Farmers have used various adaptation strategies over the past four decades. Some were aimed at preventing yield reductions due to adverse weather, and others took advantage of favorable climate changes. Identifying which adaptation strategies to use moving forward will depend on availability and cost.

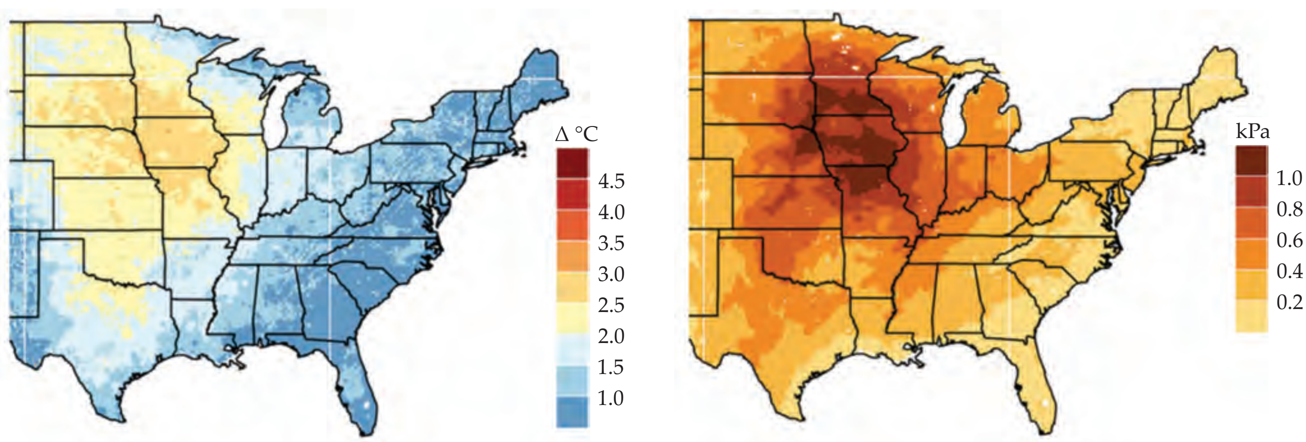
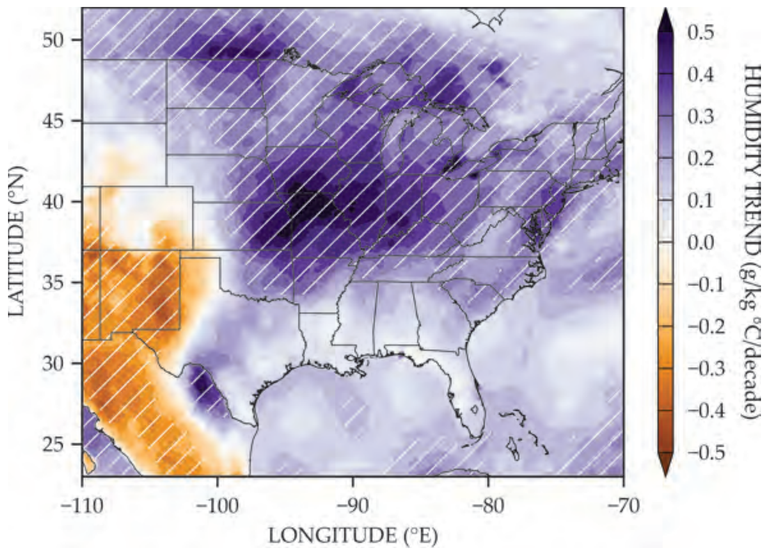


FIGURE 3. PROJECTED CHANGES IN MAXIMUM GROWING-SEASON TEMPERATURES (left) and maximum water-vapor-pressure deficit (right) by the end of the 21st century. The changes are downscaled by use of the Weather Research and Forecasting climate model for the medium-carbon-emissions, or RCP 4.5, scenario. (Adapted from ref. 10.)

THE PHYSICAL BASIS FOR CLIMATE CHANGE IN IOWA



Surprises can emerge from a mathematical description of moist gas circling a rotating planet. The physical system's dynamics and thermodynamics are governed by a set of nonlinear second-order partial differential equations. In Iowa, the most notable climate changes have been higher humidity, more frequent and intense rain events, and a reduction in the daily range of temperatures. Those changes are linked, since higher humidity—especially in spring and early summer—creates more intense rain events and cloudiness that, in turn, reduce daily maximum temperatures and increase daily minimums.

Most of Iowa's warm-season rainfall can be traced to moisture flowing from the Gulf of Mexico. In spring and summer, northward moisture transport is produced by a west-to-east pressure gradient created by a strengthened high-pressure region over Bermuda and a low-pressure region over the Rocky Mountains.[6] The local force of that pressure gradient, in balance with the local Coriolis force of Earth's rotation, creates a northward flow known as the Great Plains low-level jet (GPLLJ) about 1.5 kilometers above the surface.

Mesoscale convective systems (MCSs) are long-lived, heavy-rain-producing weather systems that generate 30–70% of the warm season precipitation in the central US.[6] The GPLLJ provides MCSs with a nocturnal supply of latent heat and moisture that allows convection—and therefore thunderstorms—to persist through the night without solar radiative forcing. That makes the central US unique; it's the only region of the country to have a nocturnal maximum in daily precipitation in the spring and summer.

Zhe Feng and coworkers at Pacific Northwest National Laboratory, using data from about 1.5 kilometers above Earth's surface,[6] traced the increase in Iowa's April-May-June (AMJ) rainfall during MCS occurrences over the period of 1979–2014. The map shows trends in specific humidity—the mass of water vapor per unit of dry air mass—over that period; hatched areas indicate greater than 95% confidence. The researchers attribute the changes to a warmer Gulf of Mexico, which has created a dome of higher-moisture air over the north central Gulf and adjacent southern states. That dome fuels the GPLLJ and, in turn, MCSs, which convert the moisture into more frequent and intense precipitation across the Midwest.

Surface observations in Iowa and across the Midwest corroborate a rise in the AMJ atmospheric water vapor, or absolute humidity, a measure that does not require a concurrent atmospheric pressure measurement. According to the Clausius–Clapeyron relationship, global atmospheric water vapor increases by about 6–7% per degree Celsius of warming. Between 1985 and 2014, the global mean temperature has risen by about 0.56 °C, so global background absolute humidity has risen by 3.6%, or 1.2% per decade. By contrast, surface measurements reveal a rise in absolute humidity in Iowa of about 4.4% per decade. As an outcome of that increase, Iowa AMJ precipitation over the 20th century averaged 11.6 inches but has increased by 2.2 inches, or 19%, over the past three decades, with the attendant impacts discussed in this article.

The GPLLJ and MCSs have long been recognized as central elements of Iowa's AMJ climate that until recently have provided just the right amount of rain at just the right time to be beneficial for Iowa's agriculture. However, enhanced Gulf temperatures and a strengthened GPLLJ that we have traced to global climate change from increased global atmospheric greenhouse gas concentration[2,7] have created significant problems for Iowa's agriculture that are likely to increase in the future.

Climate adaptations may increase production, but an important question for farmers is, Will they increase productivity? Xin-Zhong Liang and coworkers at the University of Maryland used total factor productivity—the ratio of outputs to inputs—as a measure of productivity rather than production.[11] Under the medium-carbon-emissions future climate scenario, they conclude that all the productivity gained by US agriculture from 1981 to 2010 will be reversed by 2035.

Other research concludes that known and practiced adaptations will have marginal benefits under moderate climate change for some crop systems, but their effectiveness will be limited under more extreme conditions of medium- or high-emission scenarios.[14] Developing a more resilient agricultural landscape and agrarian society of land managers and agribusiness providers to cope with climate change will require socioeconomic, cultural, and institutional restructuring, which must be guided by informed policies and implemented at scales beyond the farm.[15]

Agriculture can be more than just crop production; it can also be a carbon-management tool for climate change mitigation. Land use change by humans—in particular, the repeated tillage of agricultural soil—has resulted in substantial loss of carbon from soils. But by returning that carbon, the soil could also serve as a land reservoir for carbon capture and storage.

Roughly half of the carbon in Iowa soils has been lost through tillage of the native tall-grass prairies, so theoretically, that carbon could be returned if economically viable sequestration methods were developed. Such practices would be beneficial for grain production because the recarbonized soil would have a better texture for reducing compaction and holding water and nutrients. Alternative land management practices, such as use of prairie strips in row-crop fields, can also contribute to carbon sequestration. Deep-rooting prairie plants provide ecological and environmental benefits without an overall production penalty.

Healthy soil effectively holds water and nutrients needed to maintain a rich and diverse microbial population that, in turn, sustains plant life. One way to rebuild agricultural soil quality is with organic carbon material that resists decomposition, such as biochar. Such treatment would not only bring back the nutrient- and water-holding capacity of higher soil carbon,[16] but also place agriculture in a leading role in mitigating climate change. Long-term studies show that a one-time biochar application of 10 tons per acre can increase crop yield by 13 bushels per acre. The response is highly variable depending on the soil and year, and the effect is larger on degraded and otherwise poor-quality soils.

Positive outcomes from the use of biochar prompted the "4 per 1000" initiative at the 2015 Conference of Parties meeting in Paris; the conference is held annually under the United Nations Framework Convention on Climate Change. The initiative calls for increasing stored organic carbon in soils by 0.4% per year. If achieved, that would store carbon at a rate of about 6 gigatons per year, a significant fraction of the roughly 10 gigatons per year emissions rate in recent years. However, that's an ambitious goal; closer to 1 gigaton per year might be more realistic.

The physics of coping with climate change

Iowa's climate underscores the danger in jumping to conclusions about the impact of climate change on a particular location. Earth's climate system is a huge thermodynamic engine that takes in solar energy and transforms it into sensible heat, latent heat, and, through photosynthesis, chemical energy that leads to the formation of plant carbon. Sensible and latent heat help establish pressure gradients that team up with Coriolis forces to distribute heat around the spinning planet. Energy is expelled as IR energy back to space in amounts comparable to incoming solar radiation.

Spatially inhomogeneous heating caused by the different radiation absorptivities of land, water, vegetation, and ice creates a complex climate that defies simplistic predictions of how future seasons will play out at any fixed point. Iowa's crop-favorable moisture conditions are the end product of a sequence of time-sensitive dynamic and thermodynamic processes that link Iowa to the Gulf of Mexico and to global rises in atmosphere and ocean temperatures.

Recently, the cascading effects of atmospheric moisture transport to Iowa have led to moisture levels that are neither too high nor too low and that occur at the right time of year. But Iowa's agriculture has a fragile Goldilocks relationship to global climate change. A continued increase in moisture transport will lead to an excess of the humidity, precipitation, and flooding that has begun to affect the state in the past 30 years. A decrease in moisture transport, which is projected to occur in the latter half of the 21st century, will reduce critical spring and summer rainfall and lead to markedly higher daily summer maximum temperatures that exceed the vegetative and reproductive limits of Iowa's current crops.

Science-based policies and agronomic research are needed to maintain grain production for food and feed supplies in the current half of the 21st century.[4,14] The research would provide information about managing carbon-cycle dynamics through soil amendments, tillage, and the use of perennials; controlling water through drainage, storage, and irrigation; and understanding the root structures, water- and nitrogen-use efficiencies, and declining nutritional values of plants. Beyond midcentury, increases in growing-season heat[10] are projected to lead to substantial crop-yield reductions.[13] That level of disruption calls for transformative developments in agriculture[13] and broader societal recognition of the threats of climate change.[17]

We dedicate this paper to the memory of our friend and colleague, Ray Arritt, from whom we learned so much about the Great Plains low-level jet and convective precipitation in the central US.

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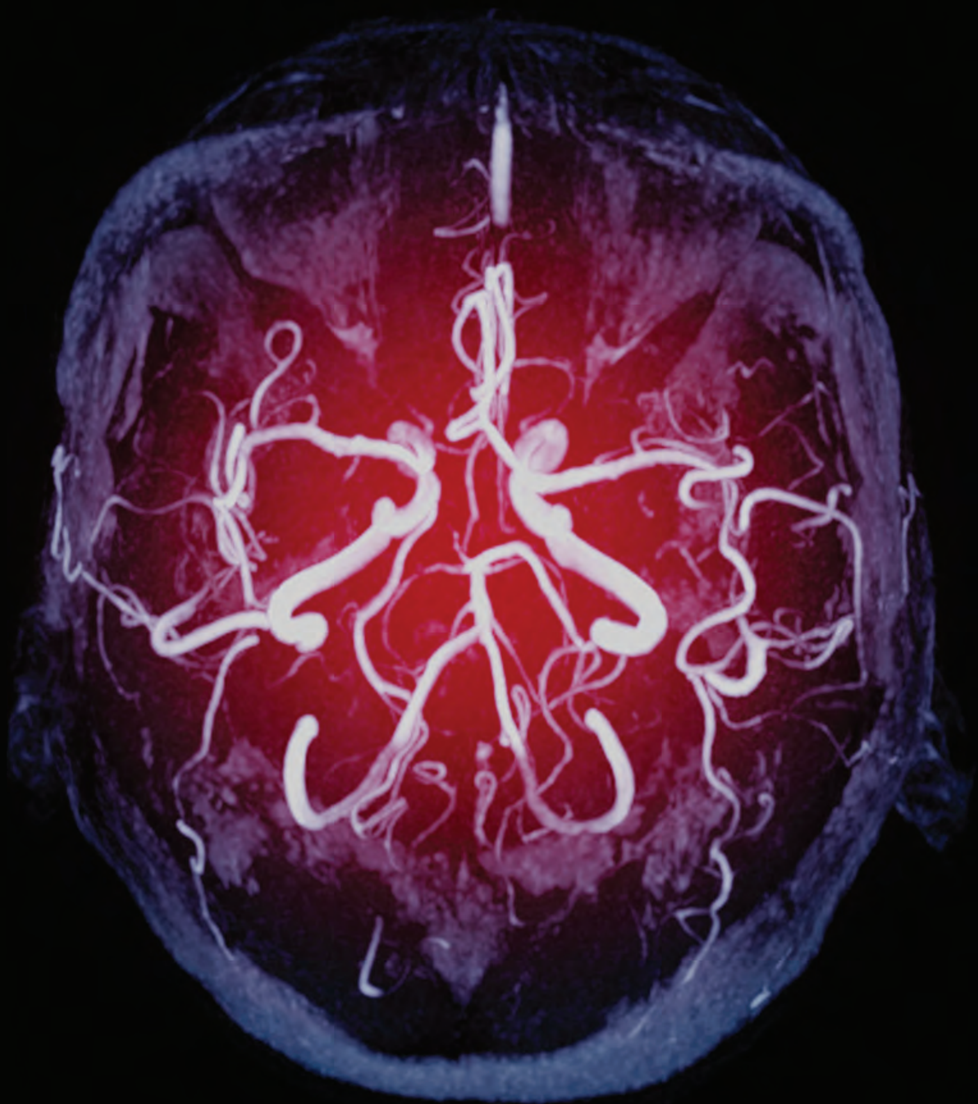
STATE OF THE ART IN MAGNETIC RESONANCE IMAGING



ISTOCK.COM/MR.SUPHACHAI PRASERDUMRONGCHAI.

David Jordan

As a clinical technology, MRI offers unsurpassed flexibility to look inside the human body.

Dave Jordan is chief medical physicist at University Hospitals and associate professor of radiology at Case Western Reserve University, both in Cleveland, Ohio.

In 1977, inspired by the observation that cancerous and healthy tissues produced different nuclear magnetic resonance signals, Raymond Damadian, Michael Goldsmith, and Lawrence Minkoff performed the first MRI scan of a live human body.[1] In the early days of clinical MRI, scans took hours and provided low spatial resolution, but they have become essential for distinguishing between healthy and diseased tissues. By its 40th anniversary, MRI was a must-have tool in hospitals and clinics of all sizes. And it has found applications in image-guided interventions and surgeries, radiation therapy, and focused ultrasound. Advances in technology, meanwhile, have pushed the envelope of scanner performance with improvements to speed and spatial resolution.

At the frontiers of MRI development, work is focused on fast, quantitative imaging. Clinical needs increasingly demand functional information—on heart-muscle contractions,[2] brain activity,[3] chemical concentrations in tumors,[4] and blood flow in and out of tissue[5]—in addition to anatomical structures. New approaches must also maintain a patient's comfort and safety; MRI is well-known for sparing patients any exposure to ionizing radiation, yet it is not without hazards.[6]

How MRI works

When biological tissue is placed in a magnetic field, nuclei with magnetic moments become magnetized. RF pulses are then applied that match the resonance, or Larmor, frequency of the nuclei, causing them to tip out of alignment with the external magnetic field and precess about it. The precessing nuclei, in turn, induce oscillating magnetic fields at the Larmor frequency; those oscillations are detected via Faraday induction of an electromotive force in a nearby coil of wire.[7]

In practice, many nuclei must precess in phase with each other to produce a detectable signal. The loss of phase coherence among precessing nuclei over time is called T2 relaxation. And the orientations of the nuclei eventually return to their equilibrium orientation in the external magnetic field—a process called T1 relaxation. Early NMR experiments revealed that various tissues have distinct T1 and T2 relaxation times. For certain diseases, including cancer, changes in either time can distinguish between diseased and healthy tissue. That feature is useful in the case of lesions whose absorption of x rays is similar to that of surrounding healthy tissue, which makes them difficult to detect using radiography or x-ray computed tomography.

In NMR measurements, the timing of the applied RF pulse and of the RF readout signal from the tissue can be chosen so that the strongest signal is produced by tissue with the shortest T1 relaxation time. A measurement whose timing is chosen that way is called a T1-weighted measurement. Alternatively, the sequence timing can be chosen so that the strongest signal comes from tissue with the longest T2 relaxation time, a T2-weighted result.

In tissue, the hydrogen nucleus is the most abundant magnetizable nucleus. Its gyromagnetic ratio is 42.56 MHz/T, which results in operating at Larmor frequencies of roughly 64 MHz and 128 MHz for 1.5 T and 3 T MRI scanners, respectively. Magnets with a range between 0.2 T and 7 T are used for clinical scanning, and human scanning up to 10.5 T is currently available in research settings.

Spatial encoding

Using the NMR signals from tissue for clinical diagnosis requires that they be localized in three dimensions to form images. Three sets of electromagnetic gradient coils in the MRI scanner accomplish that task. Each produces a linearly varying magnetic field along one of three orthogonal axes. And each gradient can be switched on and off to produce different strengths depending on the current applied; the gradient fields are superimposed on the main magnetic field—usually 1.5 T or 3 T—to create a spatially dependent variation in Larmor frequency. If a gradient is applied for some time and then turned off, all signals have the same frequency, but their relative phase shifts, accumulated while the gradient was on, vary according to position along the gradient axis.

Frequency encoding—collecting the NMR signal while a gradient field is applied—produces a spatially dependent variation in resonant frequency along one spatial dimension. Phase encoding is applying a gradient field along one axis for some time and then removing it before collecting the NMR signal. In MRI, frequency encoding and phase encoding are performed along perpendicular axes to localize the signal in two dimensions.

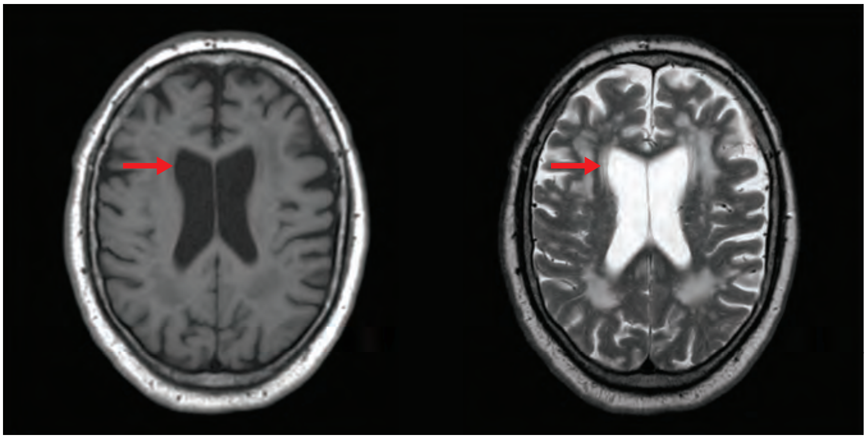


FIGURE 1. MRI OF A BRAIN with T1 (left) and T2 (right) weighting. T1 refers to the time required for precessing nuclei in tissue to relax to their equilibrium orientation in a magnetic field, and T2 refers to the time it takes the nuclei to lose their phase coherence. The timing of RF pulses can be chosen so that the MRI signal comes from tissue with the shortest T1 times or the longest T2 times. Images taken with those different timings demonstrate how MRI can be tuned to produce different signal intensities in the same tissue. Fluid-filled ventricles (red arrow) are darker than the brain tissue on the T1-weighted image and brighter on the T2-weighted image. (Images by David Jordan, University Hospitals Cleveland Medical Center.)

Gradients also allow tomographic slices of tissue to be imaged selectively. By applying an orthogonal gradient through the slice plane, the resonant frequencies of nuclei can be shifted so that only those in the slice of interest are matched to the frequency of the incident RF magnetic pulse used to excite the tissue. Much clinical MRI uses that method. When the in-plane frequency and phase encoding and data readout are subsequently performed, only those nuclei at the desired location and within the selected slice thickness produce signals.

In early MRI, various techniques were used to arrange signals spatially to produce images. But the spatial-encoding approaches developed by Paul Lauterbur and Peter Mansfield, for which they shared the Nobel Prize in Physiology or Medicine in 2003 (see PHYSICS TODAY, December 2003, page 24), have become the standard for clinical MRI.[8–10] Magnetic resonance scanning is usually an iterative procedure. It involves slice-selective excitation followed by phase encoding, frequency encoding, and signal detection repeated a few hundred times to produce an image of one slice of tissue. Each time, a clinician uses a different phase encoding gradient strength, collects the RF waveform emitted by the tissue during each cycle, and then stores it in one row of an array called *k* space—so named for the wavenumber or spatial frequency.

The gradient spatial encoding has the effect of decomposing signal variations from the tissue into a Fourier series of spatial frequencies. The collected RF waveforms represent the spatial frequencies of the signal intensities, and a 2D inverse Fourier transform of the *k*-space data produces a two-dimensional image of the tissue. Using fast-Fourier-transform techniques, MRI image reconstruction can be performed quickly and efficiently, and dozens or even hundreds of images appear onscreen virtually instantaneously upon completion of a scan.

In an MRI scan, the number and relative timings of activations of the RF transmitter, receiver, and gradient coils make up the pulse sequence. That sequence is the recipe that determines the amount of signal that's collected and the type of NMR information, such as contrast weighting, encoded in the image.

Qualitative evaluation of weighted images by a trained radiologist is an effective diagnostic tool (see figure 1 for an example), but interest is growing in quantitative measurements of tissue parameters to improve diagnosis. Water diffusivity and chemical concentrations can be measured quantitatively. The signal intensities in T1- and T2-weighted images are usually relative, however, and do not inherently represent absolute quantitative measurements of T1 or T2 relaxation times in the imaged tissue. Such measurements are possible, and efficient techniques to do so are an active area of research. Figure 2 shows an example of differences in quantitative T1 measurements for normal and diseased lung tissue in cystic fibrosis. Lung tissue is difficult to image using qualitative MRI because the signal level is inherently low, but quantitative T1 maps provide a clear visualization of disease.

Contrast enhancement

In x-ray imaging, radiologists can use contrast agents such as barium and iodine to fill blood vessels, bowel loops, and other structures that are otherwise difficult to see. Contrast dye flowing in the bloodstream strongly attenuates radiation and makes it much easier to image the vessel itself and determine where in the tissue blood is being delivered.

In MRI, the workhorse contrast agent is gadolinium, chelated to various molecules to prevent toxic interactions with the human body; the free Gd^{3+} ion competes with Ca^{2+} metabolism.[11] The paramagnetic Gd nucleus induces a strong local magnetic field and substantially shortens the T1 relaxation time of nearby hydrogen nuclei. As a result, Gd dye in a fluid or tissue increases the local brightness on T1-weighted MRI, as illustrated in figure 3.

Several commercial, Gd-based contrast agents are commonly used in MRI exams of all body parts and diseases. The two main safety concerns are the stability of the chelate and retention of the agent in tissue. Most chelates eventually break down and release free Gd^{3+} ions over a long time period; that process is not a safety concern if it happens on a time scale much longer than the time it takes dye to be cleared from the body. However, toxicity does become a concern if dye is retained in tissue long enough for the chelate to break down.

Recent research indicates that some tissues may retain Gd-based contrast agents much longer than previously suspected.

Fast imaging

In MRI, it takes time to acquire images, typically two to five minutes for each. Patients must lie still, often in unnatural poses, while the scan data are collected. Some scans are influenced by involuntary (cardiac or peristaltic) motion; to capture clear images of those moving structures, fast scanning is essential. Patients can be coached to control their breathing and swallowing, but there are limits to how long they can reliably hold their breath or lie still.

Many image-quality parameters can be sacrificed to reduce scan time, but doing so may limit the physician's ability to make a confident diagnosis. Reducing scan time can also reduce spatial resolution and produce grainy, speckled images. So-called parallel-imaging techniques increase scan speed by using a phased array of RF receiver coils positioned at different locations around the anatomy of interest. To reduce time, fewer data points are collected than would normally be needed to scan the field of view at the desired spatial resolution.[12]

In one family of parallel MRI techniques, a radiologist maintains the spatial resolution but undersamples the data to save time, a process that produces a smaller field of view. He may combine a collection of small fields of view to produce a larger one, in which case each coil in the array needs calibration. Those sensitivity encoding (SENSE) methods provide a new feature to spatial encoding—the relative signal that tissue produces in multiple receiver coils—and supplement the frequency- and phase-encoding information. In another family of parallel techniques, some *k*-space data are omitted during the scan to save time and are synthesized prior to reconstruction.

Parallel imaging speeds up the process of collecting all the samples needed to achieve good spatial resolution. Compressed sensing can further accelerate scanning. In that technique, a portion of the sampling is omitted entirely to save scan time.[13] The data are processed with discrete cosine and wavelet transforms, which are used extensively for image compression in digital photography and video. The transforms generate MR images with the required spatial resolution but from a fraction of the measured data that would normally be required. In essence, the smaller data set contains a compressed version of the MR image, which is decompressed using those transforms during image reconstruction.

By combining parallel imaging with compressed sensing, high-quality scans of the liver or lungs are becoming practical without requiring the patient to hold their breath. Images of the beating heart can now be scanned faster and with higher quality than ever.

MRI mammography

Recently, x-ray mammography for breast-cancer screening has become controversial as government and medical professional bodies have diverged on recommendations for screening various populations of women. MRI has long been used to refine a breast-cancer diagnosis, and in high-risk populations—women with dense breasts or a family history of breast cancer—it has been a successful screening strategy.

MRI can typically detect cancers at an earlier, more treatable stage and those that start small but are aggressive, fast growing, and more likely to metastasize. X-ray mammography is best for imaging tumors that are denser than surrounding tissue, contain calcifications, or distort the surrounding tissue. Those gross structural changes are less likely to be evident in early cancers, and some evidence suggests that aggressive cancers may not even develop the changes in tissue before spreading. With injected Gd contrast dye, MRI can highlight microscopic tissue changes in early cancer, such as changes in T2, water diffusivity, or blood flow to certain locations.

The high sensitivity of breast MRI would be a boon to all patients who need screening, but widespread tests have never been feasible because of cost and time constraints. Clinics that perform breast MRI screening typically use protocols borrowed from their diagnostic problem-solving work. That means spending 20–40 minutes scanning a patient to get images with several different contrast weights and images after contrast dye has been injected into the tissue to best determine the location, size, type, and prognosis of the lesion.

Those scans produce a large and complex data set. From each image series, the radiologist identifies a given lesion as malignant or benign and estimates its aggressiveness. In an hour, breast radiologists can typically interpret dozens of mammograms but only a handful of MRI exams.

Researchers have been working to overcome those limitations and bring breast MRI screening to a wider population. The breakthrough in feasibility for large-scale screening came from redesigning the imaging protocol to focus on detection sensitivity and speed while eschewing the additional scans usually needed to characterize a tumor.

In fast-screening breast MRI, a single scan is performed on both breasts simultaneously; Gd dye is injected and the same scan is then repeated. The first image is subtracted from the second, which ideally removes all the tissue from view except for the locations containing dye

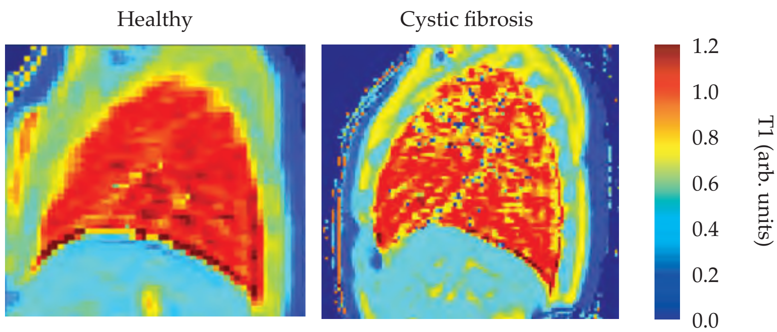


FIGURE 2. QUANTITATIVE T1 MRI MAPPING of the lungs of healthy volunteers (left) and cystic fibrosis (CF) patients (right). Low T1 values (blue, green, and yellow regions) in the lungs of CF patients indicate reduced blood flow to scarred lung tissue. Researchers hope to use those measurements of T1 to monitor the progression of disease and the effectiveness of treatment. (Courtesy of Chris Flask, Case Western Reserve University.)

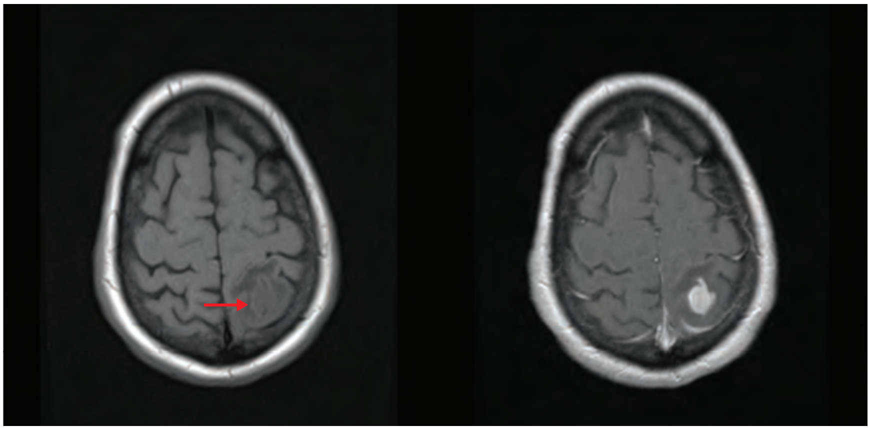


FIGURE 3. T1-WEIGHTED IMAGES OF A BRAIN without (left) and with (right) gadolinium contrast dye. The tumor (red arrow) is only subtly visible without the contrast; new blood vessel formation in the tumor results in high uptake of the dye, which makes the tumor much more visible in the contrast-enhanced image. (Images by David Jordan, University Hospitals Cleveland Medical Center.)

in the second scan. Individual slices of imaged tissue are fused together into a volume using the so-called maximum intensity projection technique. The fusion allows the radiologist to view all the dye-flow information in a pseudo-3D slab without having to scroll through images of individual slices (see figure 4 and the image on the title page of this article). She can thus easily detect tumors that recruit new blood flow in a matter of seconds following a three-minute MRI scan.[14]

Fingerprinting

Magnetic resonance fingerprinting (MRF) is a recent advance that takes a fundamentally different approach to quickly acquiring and processing signal data.[15] Conventionally, MRI scans are often used only to detect and localize possible disease, whereas the ultimate diagnostic judgment follows a biopsy and histopathological analysis. With more robust tools to characterize tissue, radiologists could make definitive diagnoses directly from MRI scans, and that could reduce the need for invasive biopsy. The practice would save time, cost, pain, and potential complications.

The MRF technique is conceptually similar to fingerprinting techniques used by law enforcement agencies to identify people. The pattern of ridges on someone's fingertips does not contain particularly interesting or useful details about the person. But it is unique, and if it can be matched to the person in a database, the match provides access to a much richer set of identifying details.

Here's how it works: A pulse sequence is synthesized with a pseudo-random variation in such parameters as the repetition time between pulses and the RF power applied to tissue. (In conventional MRI, it is critical to keep those parameters constant while generating and reading out spatially encoded signals.) A computer models the signal that a theoretical tissue would produce in response to the pulse sequence, given the T1 and T2 relaxation times of the tissue. The responses are then calculated using the NMR Bloch equations, which describe the magnetization of the tissue over time.[16]

A library of responses is created from the signal models for a wide range and numerous combinations of T1 and T2 values. The responses may not represent real physical tissues, but each mathematically represents the physical response of a unique combination of T1 and T2 values. The MRF scan uses the synthesized MRF pulse sequence to scan a patient (with spatial encoding to produce images), and the real MRF signals are recorded and compared with the library responses. For each pixel, the best match is determined between the recorded MRF signal and a response in the library, and the library match's T1 and T2 values are assigned to the pixel.

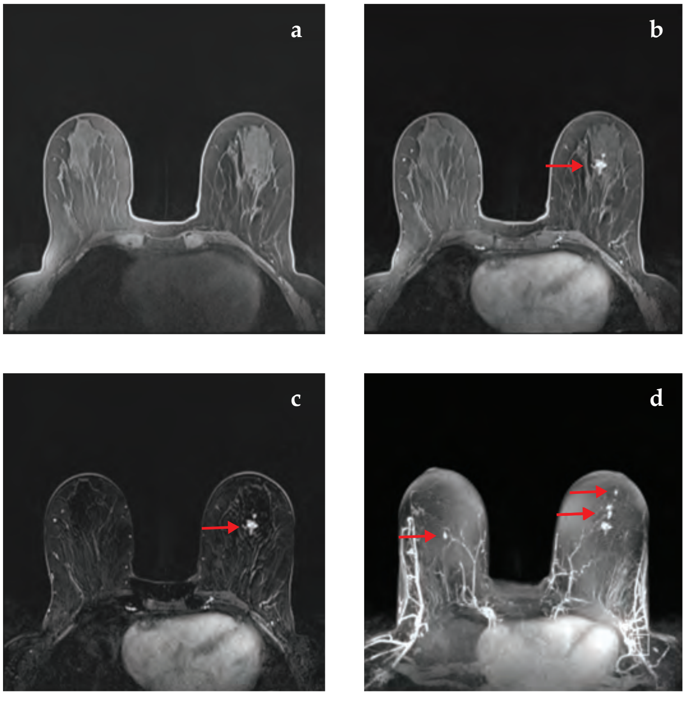


FIGURE 4. FAST-SCREENING BREAST MRI. (a) In this T1-weighted image without contrast dye, no abnormalities are apparent. **(b)** With contrast dye injected into the tissue, this T1-weighted image shows a large lesion (red arrow) that's easily seen. **(c)** This subtracted image, panel b minus panel a, improves the tumor's visibility and the brightness of dense glandular tissue. **(d)** A so-called maximum intensity projection of *all* subtracted slices (such as panel c) reveals other small lesions (red arrows), including one in the contralateral breast. A radiologist can much more rapidly detect all suspicious lesions by viewing a single image of this type than by individually reviewing dozens of image slices. (Images by David Jordan, University Hospitals Cleveland Medical Center.)

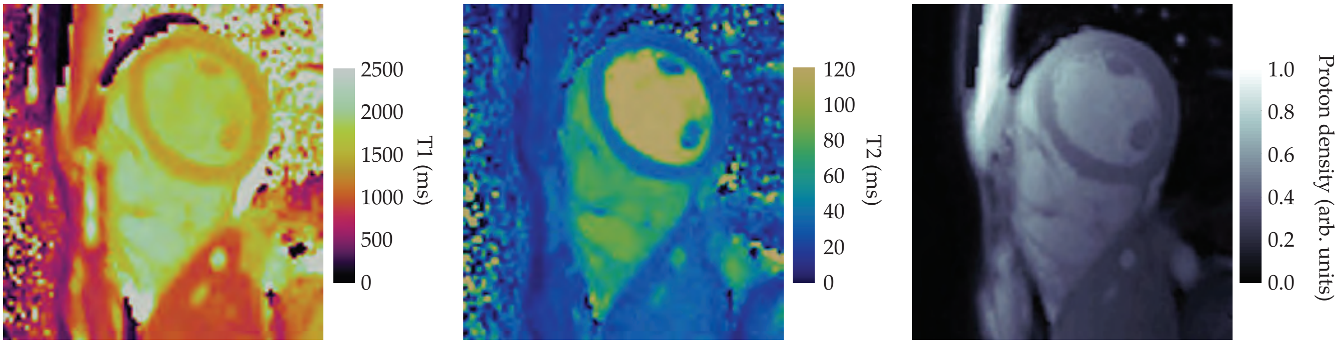


FIGURE 5. MAGNETIC RESONANCE FINGERPRINTING. In this image of a human heart, the technique provides quantitative maps of T1, T2, and proton density. All three images come from a single scan, whereas conventional MRI would require at least three separate scans to collect the same information. Clinical MRF research is underway to measure the effect of diseases and injuries on the three parameters. (Courtesy of Nicole Seiberlich, University of Michigan.)

That approach allows clinicians to determine the absolute T1 and T2 values from a single scan. Matching the tissue response to a library profile is relatively insensitive to noise; therefore, very fast MRF acquisitions can reliably provide robust quantitative results without the need for longer scans to achieve high signal-to-noise ratios.

Once the T1 and T2 values for each voxel have been extracted from the MRF library, the values can be displayed as quantitative maps. (Figure 5 shows an example.) In addition, the response of each voxel to traditional MRI pulse sequences can be calculated, so the MRF data can be used to synthesize traditional T1- or T2-weighted images without having to spend additional scan time to acquire them.

Using quantitative images of tissues, clinicians can potentially supplement their qualitative evaluations of the appearance of anatomy and pathology on conventional weighted images. With additional research, it is likely that they will use MRF to definitively identify specific disease signatures directly. That process would simplify the task of identifying a disease or judging its severity on the basis of its qualitative appearance and quantitative measurements.

Radiation therapy

Image-guided radiation therapy relies increasingly on MRI in treating cancer and other disorders. Two key roles are treatment planning and online image guidance during treatment.[17] Treatment planning uses images scanned before treatment to determine the placement of radiation beams to deliver a targeted dose and destroy a lesion. In online guidance, modern treatment machines use images taken during treatment to modify the targeting and account for the patient's motion and changes in tumor shape and position.

To deliver a large, precise radiation dose to a tumor while sparing healthy tissue, radiation therapy requires detailed information about the tissue environment. Computed tomography (CT) is useful in that regard since its image is a map of photon attenuation. A clinician measures a scanner's response by scanning calibration phantoms—reference objects with known size and electron density—and uses the patient's CT image to model where a treatment will deposit energy. The treatment can then be simulated and optimized to destroy the tumor and spare damage to the surrounding tissue. (See, for example, the article by Paul Moran, Jerome Nickles, and James Zagzebski, PHYSICS TODAY, July 1983, page 36.)

CT images are a good model for determining radiation-dose deposition in the treatment area, but they often fail to show a clear view of the tumor itself. Yet the tumor's visibility is crucial when the radiation oncologist defines how to target the treatment. MRI overcomes that difficulty: With many contrast-weighting options available to control how bright or dark the tissue appears, there is almost always a way to distinguish the tumor from surrounding soft tissue.

Unfortunately, no straightforward way exists to interpret MRI images as maps of radiation attenuation. NMR signals arise from the nucleus's magnetic behavior, which correlates poorly with the orbital electron behavior that governs x-ray absorption and scattering. Thus it is extremely difficult to accurately model the radiation-dose distribution using MRI images that best show the target lesion.

Radiation oncologists seek the best of both worlds by scanning patients with both CT and MRI. Although image-fusion techniques align multiple images using rigid structures such as bones, small differences in patient positioning or breathing motions between two scans can produce errors when the target, defined on an MRI image, is projected onto the CT image set for radiation planning. In radiation therapy, millimeters of misalignment can severely injure healthy tissue or leave part of an aggressive tumor untreated.

To resolve the problem, physicians and scientists are turning to machine-learning techniques to extract information from multiple MRI image sets and to determine the radiation attenuation of tissue without x-ray images. Many of those algorithms reconstruct "pseudo CT" images—maps of photon attenuation—from the MRI data. That approach provides both tumor visibility and the radiation-dose distribution from a single scan, without the risk of errors introduced by repositioning the patient on another scanner.

Tumors that are difficult to see using x-ray imaging during treatment planning are also difficult to monitor during live treatments. The trend in radiation therapy is to deliver higher, more focused doses to tumors in each treatment session. Doing so reduces the spatial margin for error and places greater importance on techniques for managing moving structures. Imaging and tracking the target in real time during treatment is a powerful way to do that, and MRI offers distinct imaging advantages.

Performing MRI on a patient during a radiation-treatment session also introduces fundamental challenges. A linac is the common tool for modern radiation therapy, but magnetic fields interfere with its operation; indeed, strong magnetic fields can cut off the electron beam entirely. For the first commercial MRI-guided treatment machine, engineers turned to an earlier mainstay of radiation treatment—the cobalt-60 teletherapy machine. The presence of a magnetic field doesn't affect gamma-ray production in ^{60}Co, and instrument designers were able to focus on other issues, such as integrating the imaging and treatment devices and customizing how mechanical elements functioned inside the magnet.

Putting the system into clinics and hospitals allowed radiation oncologists to treat patients using MRI scans acquired in the treatment room, while medical physicists worked on the problems of measuring and calibrating therapy beams in the strong magnetic field and understanding changes in dose distribution. In particular, when the treatment beam is absorbed or scattered in tissue, energetic electrons are released; they are usually absorbed in nearby tissue, a consequence accounted for in the treatment plan. In a magnetic field, the paths of those electrons are deflected, and the deflection must be modeled in the treatment plan to determine accurate radiation doses.

MRI-guided ^{60}Co therapy opened the door to MRI-guided treatment, but many treatments performed using linacs can't be done on ^{60}Co systems. The quest to develop integrated MR-guided linacs has led to innovative systems in research centers around the world, and commercial systems are now coming to market.

Physicists have managed to produce a strong, uniform magnetic field for real-time MRI in the treatment room while eliminating magnetic interference with the attached linac.[18] There is still much to learn about optimizing MRI scanning during radiation treatments to give the best therapeutic results, but the technology has broad applications for radiotherapy and radiosurgery of all body regions and types of disease.

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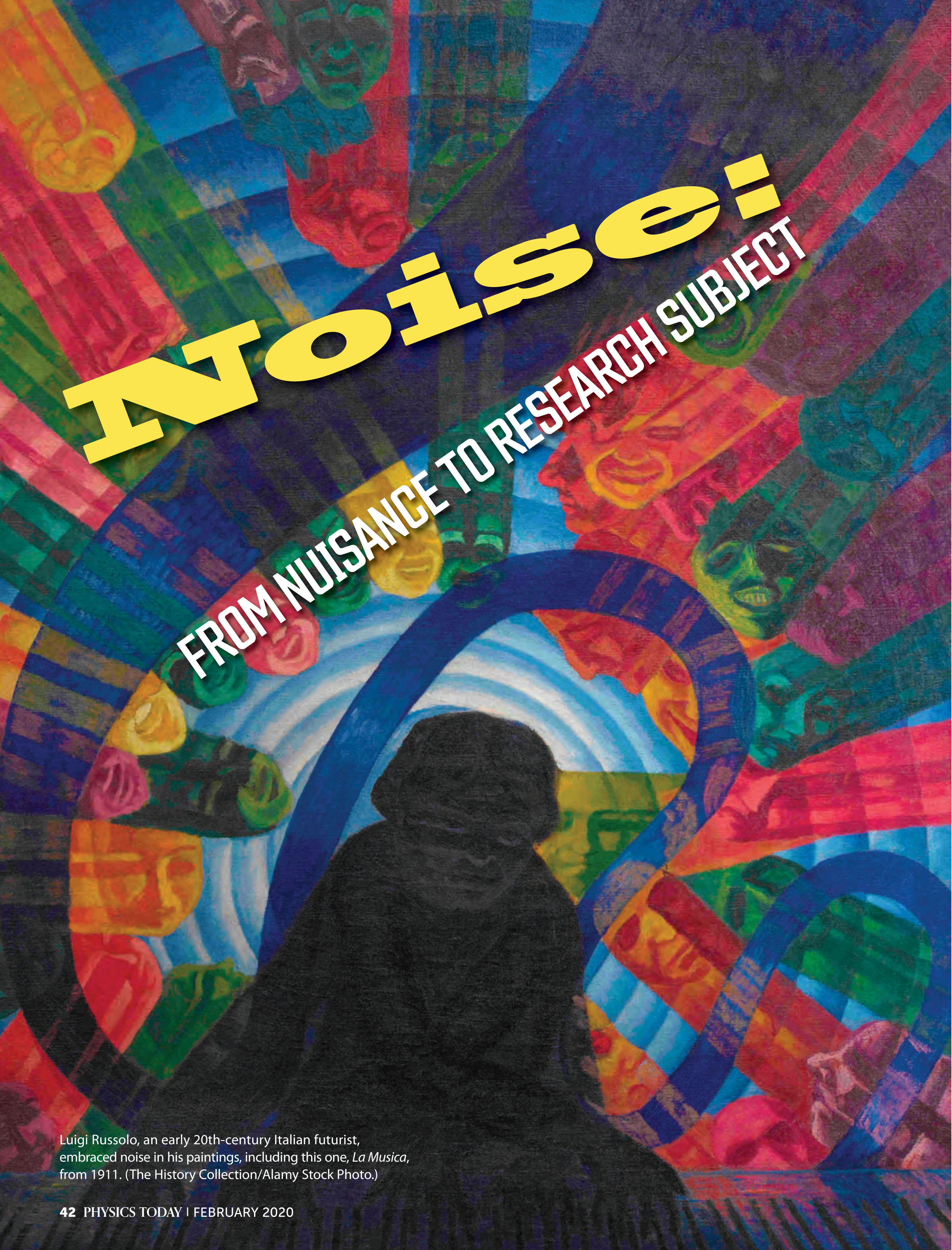
Noise:

FROM NUISANCE TO RESEARCH SUBJECT



Luigi Russolo, an early 20th-century Italian futurist, embraced noise in his paintings, including this one, *La Musica*, from 1911. (The History Collection/Alamy Stock Photo.)

Roland Wittje is an associate professor in the history of science and technology at the Indian Institute of Technology Madras in Chennai.

Roland Wittje

The definition has evolved through history from an acoustical term informed by music to a plurality of meanings. Today one person's noise may be someone else's signal.

Noise is associated with various phenomena, ranging from unwanted sounds to random fluctuations in thermodynamic systems. Beyond it being an acoustic property, scientists now regard noise as a limiting factor in information theory and measurement processes. How have so many meanings arisen? The history of noise over the past 150 years shows that its definition has undergone a series of semantic and conceptual shifts and extensions.

The shifts and extensions of noise concepts were accompanied by a fundamental transformation of acoustics research. The science of sound has been closely related to the human sensation and perception of hearing and discourses on speech and music. Consequently, acoustics has never been reduced to physics alone; it resides among several disciplines and between science and culture.

People have complained about noise as a nuisance in urban settings at least since antiquity, according to records from ancient Rome.[1] But physicists turned their attention to noise at a relatively late date. It only became a target of study during World War I. The neglect of noise as a subject of acoustics was related first to researchers' focus on musical sounds and second to the idealization of music as inherently harmonic—a relationship that scholars have traced back to Pythagoras. For example, in his 1619 book, *Harmonices Mundi* (*The Harmony of the World*), Johannes Kepler established a correspondence between the harmony of music and the apparently perfect movement of celestial bodies. (See the article by Aviva Rothman, PHYSICS TODAY, January 2020, page 36.)

Ernst Chladni, Hermann von Helmholtz, Lord Rayleigh, and other 19th-century physicists continued to treat acoustics as a science of music and harmony and relegated noise to nonmusical sounds and disharmonic oscillations. For physicists, listening to sound was synonymous to listening to music, and that remained the ruling paradigm in acoustics research until 1914.

Two important developments changed physicists' engagement with noise: electroacoustics—the application of electricity concepts to acoustics as a research field—and measuring

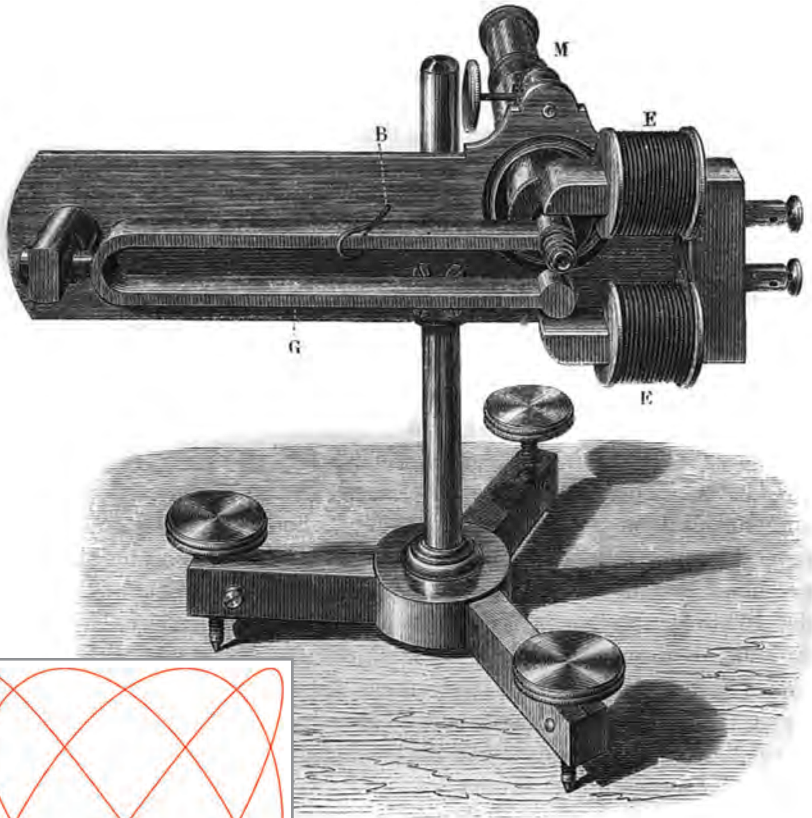
One of the most fascinating topics in science is the development of the various, sometimes even contradictory, meanings and concepts of noise. Yet not much has been written about its history. That might be because researchers often view noise negatively, and associate it with what to get rid of, such as distortions in data that need to be eliminated, suppressed, or filtered. But not all definitions amount to what is unwanted. Noise is a factor, if not the focus of scientific concern, in the more complex scenario between disturbance and signal. To understand the multiple meanings and definitions, researchers must understand the different contexts in which they emerged.

The notion of noise originates from the perception of sound phenomena, which has been used to categorize and distinguish certain sounds from others. Such phenomena may be classified differently across languages. This story draws heavily on episodes from the physics communities in Germany, the UK, and the US. But local and national developments can be understood only in an international context, especially regarding the rapid spread of acoustical knowledge and mass-media technologies. For example, radio and sound film spread across political and cultural boundaries where English became a lingua franca.

sounds from battlefields in World War I. For the first time, acousticians moved beyond music and became interested in the complex noises of battlefields. War also advanced telephony, wireless, and electric-amplification technologies. In the interwar period, mass media, especially sound motion pictures and radio broadcasting, became the main drivers of acoustics research.

Concepts from electrical engineering were integrated into acoustics research. Scientists and engineers learned that electric oscillations with waveforms identical to acoustic vibrations could be described by using the same mathematical equations and substituting the equivalent electric variables for acoustic ones. Acousticians started using circuit diagrams to represent sound fields, which provided them with a new way to think and talk about sound.[2]

Researchers also translated ideas from acoustics into electrical engineering. Originally a parameter of acoustics, the definition of noise was expanded to disturbances in electrical circuits, which limited the intelligibility of communication through telephone and telegraph systems. Using electrical industry research about those systems, Claude Shannon and others introduced signal-to-noise ratios into information theory.[3]



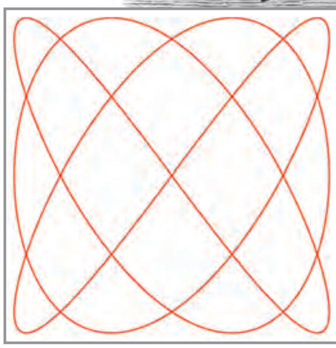


FIGURE 1. THE VIBRATION MICROSCOPE was adapted by Hermann von Helmholtz to observe rapid oscillations of violin strings. He examined the various forms of Lissajous patterns (see the inset) that he saw through the microscope for different vibrations of the strings. Irregularities in the patterns (not shown) would have indicated scratching noises from the violin bow or low-quality instruments. (Image from ref. 4; inset by Alessio Damato, CC BY-SA 3.0.)

The acoustics of Helmholtz and Rayleigh

Two highly influential works on acoustics were published in the second half of the 19th century. One is Helmholtz's 1863 *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik*, published in English in 1875 as *On the Sensations of Tone as a Physiological Basis for the Theory of Music*.[4] The other is Rayleigh's *The Theory of Sound*,[5] published as two volumes in 1877 and 1878. Helmholtz's and Rayleigh's respective works laid the foundations for and, until the outbreak of World War I, set the standards and approaches to acoustics research. Helmholtz primarily addressed not physicists but musicologists and aestheticians in an attempt to connect physics, philosophy, and art, which, he argued, had drifted too far apart.

Helmholtz and his contemporaries considered only musical sounds: One would look in vain for the notion of noise as nuisance in his book. The distinction between irregular sounds as noise and harmonic sounds as music was central to his work. In the first chapter of *Sensations of Tone,* Helmholtz distinguishes noises from musical tones: "The [sounds] of the wind, the splashing of water, the . . . rumbling of carriages, are examples of the first kind, and the tones of all musical instruments of the second. Noises and musical tones may certainly intermingle . . ., but their extremes are widely separated" (page 11).

Helmholtz idealizes the sound of musical instruments as "perfectly undisturbed, uniform . . . which remains unaltered as long as it exists . . . whereas in a noise many various sensations of musical tone are irregularly mixed up"(page 12). He concludes that the "sensation of a musical tone is due to a rapid periodic motion of the sonorous body; the sensation of a noise to non-periodic motions" (page 13).

Helmholtz merges the physical definition of noise as a non-periodic motion with an understanding of it as unmusical sounds. After the first chapter, he never returns to discuss noises, though he does point out that musical tones are always accompanied by them. Far from being annoyances, noises from an instrument, such as the scratching or rubbing of a violin bow and the rushing air in a flute or organ pipe, contribute to the instrument's character and make the music more interesting. Figure 1 shows the microscope that Helmholtz used to investigate the vibrations of violin strings.

In contrast, Rayleigh considered his audience to be mathematically trained physicists. Nonetheless, he followed Helmholtz's distinction, and classified sounds "as musical and unmusical; the former for convenience may be called *notes* and the latter *noises*. The extreme cases will raise no dispute; everyone recognizes the difference between the note of a pianoforte and the creaking of a shoe. . . . Although noises are sometimes not entirely unmusical, and notes are usually not quite free from noise, there is no difficulty in recognising which of the two is the simpler phenomenon . . . no combination of noises could ever blend into a musical note"(volume 1, page 4). After that short passage, Rayleigh also never returns to the topic of noise. His statement that he is providing "the reader a connected exposition of the theory of sound" (volume 1, page v) implies that Rayleigh and his contemporaries only dealt with musical sounds and ignored noise as a topic of scientific concern.

Helmholtz's and Rayleigh's treatises continued to set the tone for acoustics research until the outbreak of World War I, but several developments foreshadowed the breakdown of the dichotomy between musical sounds and noises. Helmholtz wanted to place consonance and dissonance—whether listeners find certain sounds pleasant or unpleasant—in the realm of physics and physiology. But one of his strongest critics, philosopher Carl Stumpf, opposed the move. In the following decades, the debate migrated from physics to the emerging disciplines of experimental psychology and comparative musicology. Luigi Russolo, a member of the Italian futurism movement in the early 20th century, wrote a manifesto in 1913 titled *L'Arte dei Rumori* (*The Art of Noises*) that constituted a full-fledged attack on the dichotomy between musical sounds and noises.

Whereas the futurists embraced industrial noises and the soundscape of the city, some citizens of metropolises in Europe and North America started to organize noise-abatement societies to battle the din of modern urban living. However, neither the Italian futurists nor the noise-abatement societies managed to turn acousticians' attention away from musical sounds and toward noise. That happened when physicists were employed in large numbers during World War I to detect the sounds of heavy artillery, aircraft, and submarines.

Sounds of the battlefield

The long list of physicists involved in sound-detection and sound-ranging activities during World War I includes Nobel laureates Max Born, William Henry Bragg, William Lawrence Bragg, Ernest Rutherford, and Erwin Schrödinger. Few of the scientists had worked in acoustics before the war because it had been a rather dormant discipline since the late 19th century. But many did have experience with wireless telegraphy and electrical precision measurements. Rather than study musical sounds in concert halls, the new acousticians had to locate and analyze industrial sounds in the cacophony of the battlefields.

In the beginning, they listened to the sounds of war with funnels or the unaided ear. But those methods were soon found to be unreliable, especially considering a listener's uneven reaction time for recording sound events from artillery ranging. Scientists worked feverishly to substitute subjective human listeners with so-called objective methods, including microphones, string galvanometers, and mirror oscillographs. But the microphones developed for those methods were not meant to record

FIGURE 2. A HYDROPHONE OPERATOR, aboard a US minelayer in 1918, listens in his headphones to the various sounds recorded by a drifter hydrophone to identify their origins. (Image from the National Maritime Museum archive, London.)

every sound. For example, the hot-wire microphone invented by William Tucker of the UK was specially designed to record only one signal—the low-frequency firing of heavy artillery—amid all the disturbing noises of the battlefield.

The work of German physicist Erich Waetzmann is in many ways synonymous with the transformation that acoustics underwent during the war. Having first worked in the tradition of Helmholtz, Waetzmann turned toward studying how to locate aircraft noises. He employed instruments like tuning forks and pitch pipes but found that they were inadequate for the task. Emily Mary Smith and Frederic Charles Bartlett of the Cambridge Psychological Laboratory had similar experiences with Politzer acoumeters and soon shifted to using a buzzer circuit and a telephone for training submarine hydrophone operators.[6]

Although acousticians did not require sound amplification to locate artillery, they did need radio-tube amplifiers to listen underwater and to detect aircraft. Such technology became available around 1917 to the Entente Powers of France, Britain, and their allies and to the Central Powers—Germany, Austria–Hungary, and their allies. Initially, highly resonant hydrophones were developed for underwater sound signaling to communicate with submarines. But hydrophones could also be used to detect enemy vessels. “U-boat warfare created the need for a second type of [noise] receiver, which was mainly designed to record the noises of ship propellers or alien submarines,” Austrian physicist Franz Aigner explained in his 1922 book *Unterwasserschalltechnik* (*Underwater Sound Technology*). The hydrophone can “record equally both the on-board noises of a nearby ship and the working of the ship engine, pumps, electric machines, and the grinding of the propeller. All these noises have a characteristic timbre for the listener, so that with practice he will be able to determine from the noises with absolute certainty the type of ship.”[7] Figure 2 shows a hydrophone operator on a US ship listening to the sounds picked up by a drifter hydrophone.

The resonant hydrophone for underwater sound signaling and the nonresonant noise receiver represent notions of signal and noise that were quite different from the dichotomy of musical sounds and nonmusical noises. In Aigner’s account, the noises of the enemy ship were not irksome; rather, they contained highly valuable information about the vessel and its operation. The hydrophone operator had to tune in to the noise.

Even as acousticians realized that they could detect enemy submarines and aircraft by their noise, they also knew that enemy scientists were using the same methods, so they began to silence their machinery. For Waetzmann, studying aircraft sounds was as much about detecting enemy aircraft as it was about eliminating noise to build a “soundless aircraft.” For submarines and aircraft, propellers appeared to be the main source of noise, and the aerodynamic testing laboratory headed by Ludwig Prandtl in Göttingen, Germany, carried out investigations to make them quieter.[6]

Warfare finally achieved what the citizen initiatives had not: It turned acousticians’ attention to industrial noise and its abatement. Silencing aircraft wasn’t the result of noise-abatement societies or noise-pollution regulations: It was a military demand.

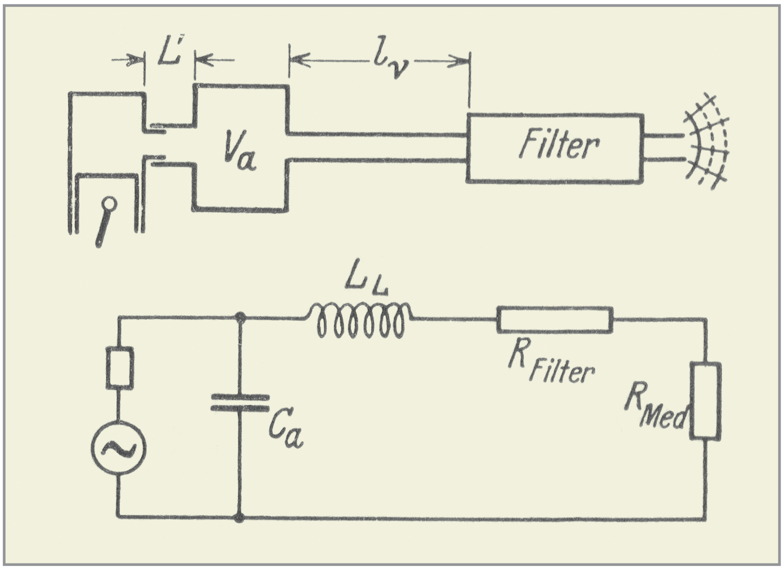


FIGURE 3. THIS DIAGRAM of an automobile exhaust silencer is similar to an electric circuit diagram. Even though the automobile exhaust silencer does not contain any electrical components, diagrams like this one became useful analytical tools for engineers designing an acoustic filter analogous to an electric one.[16]

Interwar electric circuits, noise abatement, and mass media

After the war, military applications were no longer the main driver for acoustics research. Instead of returning to music as the leading paradigm, scientists moved to electroacoustic media and communications technologies, especially radio broadcasting, sound motion pictures, and telephony, as the new framework in which they operated in the 1920s and 1930s. Although the telephone had already been invented in the 19th century, it was mostly seen as an electrical technology and had little effect on acoustics research before the war. The mass employment of scientists in warfare had boosted industrial research, and electrical industry research companies, such as Bell Labs in the US and the Siemens & Halske laboratories in Germany, became the largest employers of physicists and the main actors in acoustics research.

With the advances made to electroacoustic technologies and radio-tube amplifiers during the war, acoustics was transformed from a subfield of mechanics to an electrotechnical discipline. Electroacoustic measurement became the new standard of the field, and acousticians needed proficiency in radio technology rather than in musical listening. That shift was technological and epistemological, as it created a new way of thinking and talking about sound. Terms such as the sound field, antenna, and transmitter were introduced to the acoustic literature. Similarly, acoustic parameters were translated to electric ones, and equivalent circuit diagrams were used to analyze and represent acoustic systems, even if there was nothing electrical about them. For example, Martin Kluge, an electrical engineer in Dresden, Germany, used electric-filter theory to translate the exhaust silencer of an automobile to an electric-circuit diagram, as shown in figure 3.

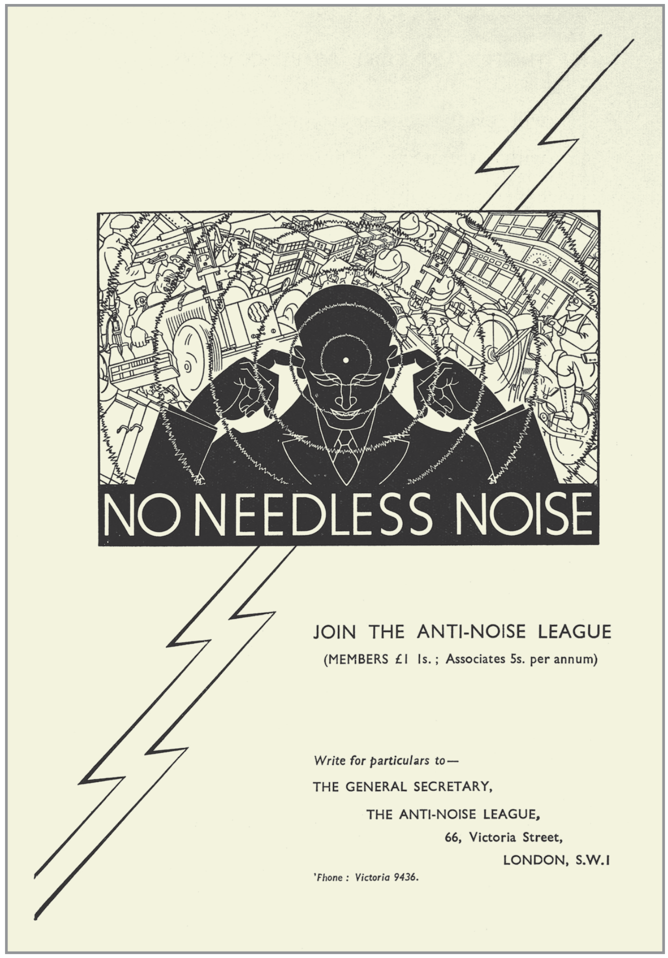


FIGURE 4. THIS ADVERTISEMENT for the Anti-Noise League in London highlights the noise-abatement concerns of some citizens during the 1920s and 1930s. During that time, acousticians started to systematically study the noise environment in European and US cities. (Image from the *Noise Abatement* exhibition, Science Museum, London, 1935.)

In the context of electroacoustics, noise became a category for random fluctuations and disturbances in electrical systems. Many disturbances originated from a circuit's components, such as the carbon microphones used at the time. Wireless telegraphy and radio operators dealt with static interference, the atmospheric disturbances of radio waves. Radio-tube amplifiers could strengthen weak acoustic signals until they were drowned out by noise created in the amplifier circuit itself.

The crucial device for advancing electroacoustics was the amplifier tube. Theoretical physicist Walter Schottky had worked on it at the Siemens & Halske labs during the war. His innovation of screen-grid vacuum tubes in 1915–16 improved their performance considerably, and in 1918 he published a groundbreaking paper in which he identified the lower limit of thermal disturbances in amplifier tubes.[8] At the time, listening to those disturbances from a telephone or loudspeaker was the only way to detect them. That made Schottky's choice of acoustic terminology for describing the electric disturbance—buzzing—a natural one; his lab colleague Carl Hartmann labeled it a shot-effect tone in 1922. Later, in 1925, John Bertrand Johnson of Bell Labs finally called it a noise.[9]

Importantly, the discovery and categorization of shot noise shifted the semantic and conceptual idea of noise and introduced it as one of random thermal fluctuations and as a parameter of electrical systems. How did noise as an aperiodic fluctuation relate to noise as a nuisance? In the late 1920s and 1930s, acousticians and public institutions started to participate in the noise-abatement campaigns of metropolitan cities such as New York, London, and Berlin. Figure 4 shows an advertisement of the Anti-Noise League in London. Frederic Charles Bartlett, who contributed to the 1935 *Noise Abatement* exhibition of the Science Museum in London and who served on the UK's Industrial Fatigue Research Board, argued that "the physical definition of noise as sound resulting from stimuli which cannot be resolved into periodic vibrations is hopeless."[10] Many of the sounds that Bartlett and his colleagues identified and categorized as noise were highly, if not strictly, periodic.

Bartlett's German-speaking colleagues would point out that noise as a nuisance, *Lärm*, should not be confused with noise as a nonperiodic sound, *Geräusch*. The German commission for units and formulae drafted instructions in 1933 detailing how to demarcate the two. According to the instructions, noise as a nonperiodic sound was a purely objective, physical value, and its measurement should be straightforward, at least in principle. In contrast, noise as a nuisance was an inherently subjective value and could only be measured indirectly.[11]

Did demarcating noise as either an entirely objective or inherently subjective concept work in practice? Harvey Fletcher, the collaborator to Robert Millikan in the famous oil-drop experiment, became in 1928 Bell Labs' leading acoustician. In his 1929 book *Speech and Hearing*, Fletcher wrote that "when transmitting speech or music . . . over . . . a radio or a telephone system, there is always an interference to the proper reception of such speech and music, due to other sounds being present. These extraneous sounds which serve only to interfere with the proper reception are designated by engineers as 'noise.' With such a designation, the sound may be either periodic or non-periodic as long as it is something that would be better eliminated."[12]

Fletcher's account reveals that a clear-cut definition of noise as a nonperiodic fluctuation was not practical for the electrical-communication engineers at Bell Labs. Ferdinand Trendelenburg, then the chief acoustician of Siemens central research lab, also found it difficult to clearly separate harmonic sounds from noises. In his 1935 book *Klänge und Geräusche* (*Sounds and Noises*), he found that "the compound tone of a piano, for example, is not strictly periodic, in the moment of strike [of the piano string], the compound tone is mixed with the noise of the hammer . . . ; nevertheless, in linguistic usage we would always call the sound of the piano a compound tone, for the ear in this case the tone-like characteristic is the preeminent characteristic."[13]

A universal concept

The history of noise underlines the relevance of acoustics in the evolution of modern physics during the 20th century.[6] Rayleigh's *Theory of Sound* was an important resource for the development of Maxwellian electrodynamics and, to a lesser extent, of quantum mechanics and the theory of relativity (see the article by Carlo Beenakker and Christian Schönenberger, PHYSICS TODAY, May 2003, page 37). Advancements in acoustics research performed by industrial scientists in electrical-industry laboratories were instrumental to the formulation of information theory and the transmission of noise from acoustics to other research fields.

By the 1950s, the definition of noise as random or unwanted fluctuations in all kinds of physical systems had been firmly established, and its acoustic origins had become almost invisible. Since then, noise has experienced a transition to a digital-information paradigm that is closely related to data transmission over telephone lines and early computers.[14] Although definitions have moved from music to information, researchers continue to operate with notions of noise that lie somewhere between random fluctuations without a pitch and unwanted sounds or data, whether harmonic or not.

Today concepts of noise are used in a broad range of scientific fields, including statistical mechanics, applied mathematics, quantum electronics, computer science, and even the humanities and social sciences.[15] I hesitate to question the relevance of categories like applied and pure science or classical and modern physics, but the history of noise exemplifies how fluid and porous such categories are, how they transform, and where they might break down. Although scientists have created more refined categories of noise, one person's noise may be someone else's signal. As the hydrophone operators of World War I did, one must tune in to the noise to extract information from it. Far from noise becoming more objective, it remains deeply entangled with the focus of an investigation and the goals of the researchers.

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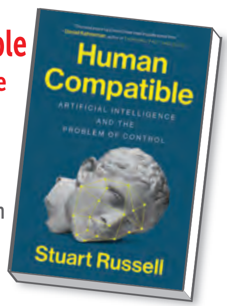
GADO IMAGES/ALAMY STOCK PHOTO

Can artificial superintelligence match its hype?

At a recent meeting of the World Economic Forum, someone asked Stuart Russell, a professor of computer science at the University of California, Berkeley, when superintelligent artificial intelligence (AI) might arrive. He loosely estimated it to be within his children's lifetime, and then he emphasized the Chatham House rules of the meeting and that his conjecture was "strictly off the record." But, he writes in his new book *Human Compatible: Artificial Intelligence and the Problem of Control*, "Less than two hours later, an article appeared in the *Daily Telegraph* citing Professor Russell's remarks, complete with images of rampaging Terminator robots."

Human Compatible
Artificial Intelligence and the Problem of Control
Stuart Russell
Viking/Penguin Random House, 2019. $28.00



Hyperbole by many media outlets has made it challenging for experts to talk seriously about the dangers of artificial superintelligence—a technology that would surpass the intellectual capabilities of humans. Nonetheless, many experts have written books on the subject. Nick Bostrom's 2014 book *Superintelligence: Paths, Dangers, Strategies* raised eyebrows for its passages on embryo selection and modification as a potential path to superintelligence. Murray Shanahan provided only a short introduction to the field in his 2015 book *The Technological Singularity*. And Max Tegmark's 2017 book *Life 3.0: Being Human in the Age of Artificial Intelligence* focuses mostly on ways in which an artificial superintelligence might be horrible to us.

Human Compatible has a more practical and down-to-earth approach, if one can say that about a book on superintelligent AI. Calmly taking the fearmongering headlines in stride, Russell starts at the beginning with a thorough explanation of intelligence, what AI is and does, and how we might reach superintelligence. Then he explains how humanity can and should make sure that its eventual arrival will be beneficial for humanity.

Russell has been one of the foremost academics in the field of AI since the late 1980s, and many would say that a popular book on AI by him is long overdue, especially considering his decades of public advocacy. He is known for two major achievements. First, Russell pioneered inverse-reinforcement learning in 1998, which he explains clearly in *Human Compatible* without trumpeting his own achievements. Second, he has educated generations of AI researchers with *Artificial Intelligence: A Modern Approach*, the textbook he coauthored with Peter Norvig in 1995; the fourth edition is due in 2020.

For those seeking a more accessible introduction to AI, *Human Compatible* provides one of the clearest explanations of the underlying concepts. The scope of the book underscores the vast, interdisciplinary field. Russell explains concepts from computer science, robotics, psychology, economics, mathematics, and politics. Readers without a degree in AI can follow his descriptions, although his definition of intelligence might cause head-scratching: Russell claims that "machines are *beneficial* to the extent that *their* actions can be expected to achieve *our* objectives." It is a confusing utilitarian view that translates better to computer programming than to human behavior.

Russell's excellent writing is, at times, surprisingly funny and sets his work apart from that of his peers. He has a knack for eminently quotable turns of phrase. The chapter on AI misuses begins with a warning of "the rapid rate of innovation in the malfeasance sector." The elegant writing highlights my main contention: Too many people are writing about the dangers of superintelligence rather than more pressing issues such as algorithmic injustice.

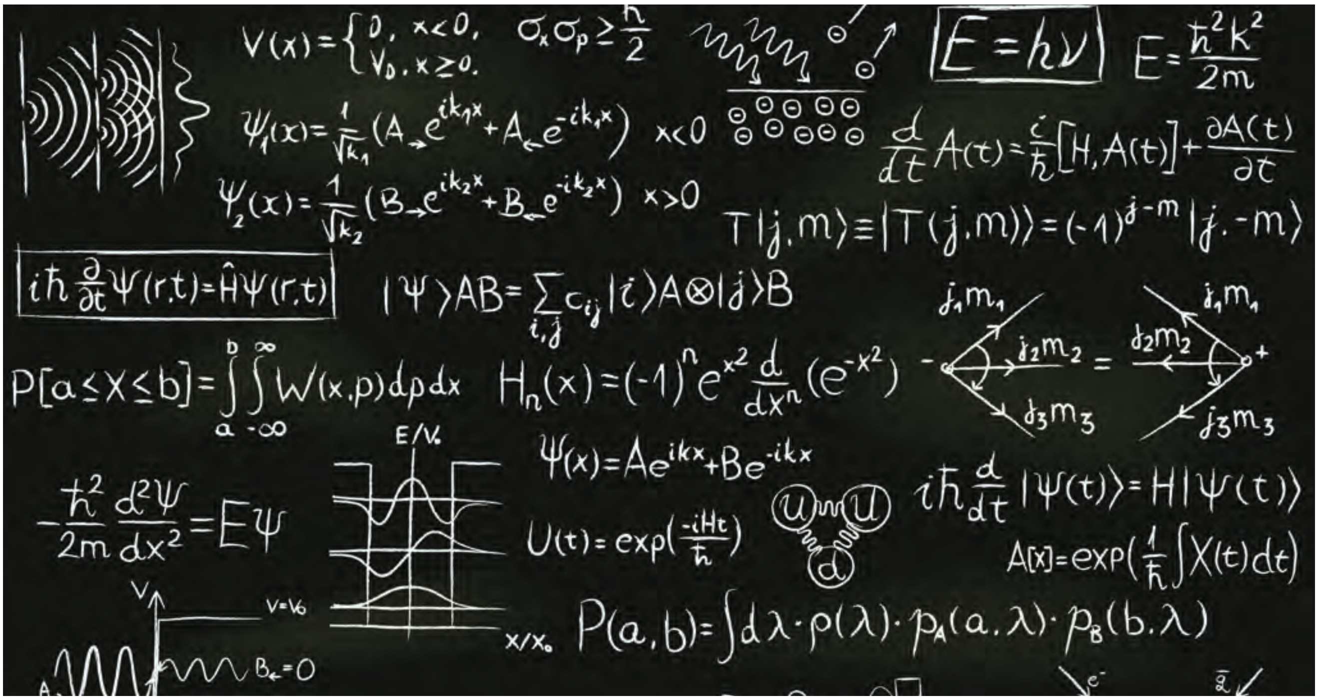
In a later chapter, "The Not-So-Great AI Debate," Russell debunks the arguments against taking the risk of superintelligence seriously. He starts with an easy one—calculators and horses haven't taken over the world, so we don't have anything to fear from superhuman intelligence. He moves on to refuting more sophisticated arguments, such as the assertion that AI won't have destructive emotional traits if we don't build them into it. He concludes the chapter with a quote by *Slate Star Codex* blogger Scott Alexander: "We should probably get a couple of bright people to start working on preliminary aspects of the problem."

Notably, that chapter is one of the few times that Russell addresses the beneficial uses of AI. Whereas his treatment of contemporary AI ethics issues is commendable, he unfortunately pays little attention to the technologies that are beginning to show promising results. For example, short-term weather forecasts and long-term climate change projections are both improving because of AI technologies that can crunch vast amounts of data.

I would have loved to see Russell take on a question central to the current "not-so-great AI debate," as he calls it: Should we be paying so much attention to superintelligence when humanity is creating enough problems for itself with existing AI? The relentless growth of contemporary AI technologies, such as driverless cars that require electricity-hungry computer servers to store and process data, threatens the climate, our physical safety, and our privacy. Achieving superintelligence within our children's lifetime poses a significantly lower risk than the possibility that they will be rubbing sticks together for fire after surviving catastrophic global warming or a world war.

Russell concludes that researchers should study superintelligence but that focusing too much attention on it may leave other threats in the AI sector understudied and underfunded. Yes, superintelligence skeptics and activists alike would agree that a few brilliant people should think about superintelligence, but this skeptic thinks the emphasis should fall on "a few."

Kanta Dihal
University of Cambridge
Cambridge, UK



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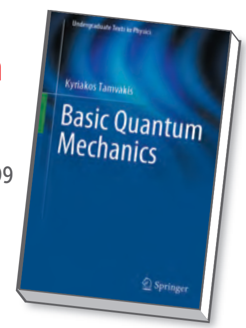
Quantum mechanics textbook teaches through examples



Basic Quantum Mechanics
Kyriakos Tamvakis
Springer, 2019. $74.99 (paper)

At the turn of the 20th century, experimentalists began uncovering mysterious phenomena that were unexplained by classical theories. Physicists put forward groundbreaking new ideas, the consequences of which we are still trying to fully comprehend. The modern version of quantum mechanics was developed in the 1920s through pioneering works by Erwin Schrödinger, Werner Heisenberg, Max Born, and other contemporaries. Since then quantum mechanics has become an integral part of standard academic curricula for university physics, and several canonical textbooks exist on the subject.

Quantum mechanics has gained a reputation for being a difficult subject due in part to both its conceptual differences from classical physics and its difficult mathematical machinery. To deal with those challenges, most students learn about quantum mechanics from multiple sources, each of which provides different insights.

Kyriakos Tamvakis's new book, *Basic Quantum Mechanics*, offers an alternative to the classic textbooks on the subject, such as those by Albert Messiah and Jun John Sakurai. Tamvakis is an emeritus professor of theoretical physics at the University of Ioannina in Greece and author of another textbook, *Problems and Solutions in Quantum Mechanics* (2005). In his new book, he draws on more than 30 years of experience teaching quantum mechanics and tackling cutting-edge scientific questions at CERN, and he doesn't shy away from detailed calculations. The book is helpful both for students beginning their journey into the fascinating world of quantum mechanics and for lecturers preparing courses. The student-friendly text covers in detail the usual topics in a core undergraduate course and more specialized topics in graduate courses.

The first three chapters form the basic quantum toolbox typically included in an introductory course. Tamvakis starts with the famous double-slit experiment, which, as Richard Feynman eloquently stated, "has in it the heart of quantum mechanics." That example introduces the fundamental notion of the wavefunction and the superposition principle. Once the elementary concepts have been introduced, the main emphasis is on solving Schrödinger's equation. Throughout the book, discussion of theory is followed by detailed examples to help readers develop and hone their problem-solving skills. In total, the book presents about 60 worked examples and 200 exercises.

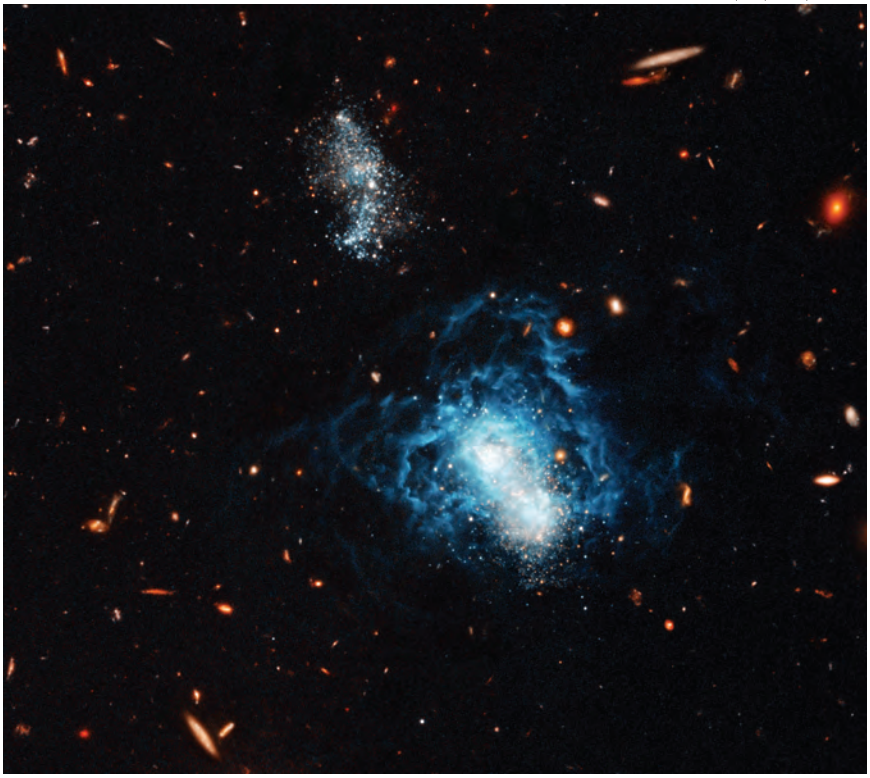
The middle of *Basic Quantum Mechanics* begins with the mathematical framework and terminology of Hilbert spaces. After introducing state vectors and observables, Tamvakis presents some essential examples, such as the ubiquitous quantum harmonic oscillator, the two-state system, and the particle in a periodic potential. Across seven chapters that cover angular momentum, spin, and central potentials, he discusses three-dimensional motion in detail. The following chapters introduce many-body problems, which are preludes to atomic and molecular physics.

The last few chapters examine approximation methods, symmetry considerations, and scattering theory. Additionally, two of the chapters introduce the quantization of electromagnetic fields and their interactions with matter. The book thus gives a decent overview of the most common laboratory phenomena and basic methods of analysis. The book also digresses on the Aharonov–Bohm effect, Bell's inequality, and Feynman's path-integral formulation. Those advanced topics are likely to stimulate students' interests and curiosity and reward their hard work in learning the foundation.

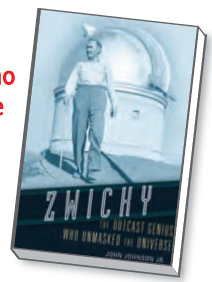
Basic Quantum Mechanics presents a comprehensive modern alternative to classic books on the topic. Readers will appreciate the balance between theory and worked examples. The detail of the analysis and the self-contained structure make Tamvakis's book a good companion for independent study and a serious candidate for either the primary textbook or supplementary material for undergraduate courses.

Marko Toroš
University College London
London, UK

NASA/ESA/STSCI/A. ALOISI



Astrophysicist's personality outshines his scientific legacy



Zwicky
The Outcast Genius Who Unmasked the Universe
John Johnson Jr
Harvard U. Press, 2019. $35.00

Today the term "rocket man" has become associated with President Trump's 2017 characterization of North Korean dictator Kim Jong Un. But in the 1950s, it would have referred to Fritz Zwicky, the brilliant yet controversial astrophysicist. In *Zwicky: The Outcast Genius Who Unmasked the Universe*, science reporter John Johnson Jr details Zwicky's contributions to jet engineering and rocket science during and after World War II. As head of research at the Aerojet Engineering Corp beginning in 1943, Zwicky became a leader in the US Air Force's rocket program and earned the Medal of Freedom in 1949. Yet his status in the history of science is primarily associated not with his work in rocketry but with his important contributions to astronomy and astrophysics.

Although he was born and raised in Varna, Bulgaria, Zwicky was a Swiss citizen and spent most of his career in the US. He graduated from the prestigious ETH Zürich, where he specialized in physical chemistry, specifically the quantum theory of crystals and electrolytes. Years after arriving at Caltech in 1925, he shifted to astrophysics; one of Zwicky's first papers was a critical response to Edwin Hubble's announcement of the law that was subsequently named for him.

Strangely, Johnson ignores Zwicky's 1929 paper introducing the now debunked "tired light" hypothesis as an explanation for galactic redshifts. Johnson's chapter on the early expanding universe is uninformative and sometimes misleading—for example, when he characterizes astronomer James Jeans as a "leading advocate for what came to be known as the steady state theory." Jeans died in 1946, two years before the steady-state cosmological theory was introduced, and he never supported the idea of an eternally expanding universe with continual matter creation. Johnson also incorrectly states that Georges Lemaître, the physicist who in 1927 proposed an expanding universe model, had "no proof," by which he presumably means a lack of redshift–distance data. The book contains several similar errors, exaggerations, and questionable statements.

Zwicky's resistance to the expanding universe was clearly a mistake, although he never admitted it. But he did publish a series of remarkably prescient papers, which secured his reputation as one of the most innovative astrophysicists of the 20th century. His now-famous prediction of dark matter in the Coma cluster dates from 1933, when it appeared in a Swiss journal. That paper was followed by a collaborative work with Walter Baade, in which they introduced the radical idea of neutron stars. And in a short article in 1937, Zwicky explained that Albert Einstein's predicted gravitational lensing effect was more useful for observing galaxies rather than stars. Much later, with the help of several collaborators, Zwicky completed an impressive and heavily used six-volume catalog of galaxy clusters. Johnson's book covers all that work—but only briefly and with little emphasis on the science.

The book's focus is more on Zwicky's peculiar character and involvement in countless feuds and controversies. With a big ego and a well-deserved reputation for abrasiveness, he deliberately fell out with many of his colleagues, including Baade, J. Robert Oppenheimer, Allan Sandage, and Subrahmanyan Chandrasekhar. Zwicky had no tolerance for people who did not recognize his genius or otherwise disagreed with him.

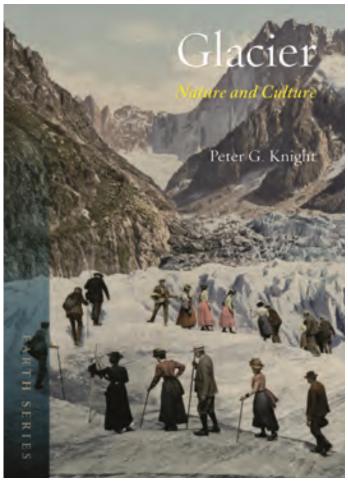
As Johnson points out, Zwicky's greatest weakness was his unwillingness to compromise or listen to critics. That stubbornness was the reason that he never accepted the expanding universe and, after World War II, that he adopted strange ideas, such as pelting the Moon with missiles and artificial meteors and turning the Sun into a spaceship. He justified some of those claims with his so-called morphological philosophy, a variant of empiricism. Zwicky insisted that his morphological method applied not only to science but also to society. Most scientists and philosophers ignored his ideas, and posterity hasn't been kinder to the morphological gospel.

Johnson's biography is well researched, drawing from interviews, articles from local newspapers, and, not least, material from the Fritz Zwicky Foundation archive in Glarus, Switzerland. However, many of the sources are anecdotal reminiscences, which make the book an enjoyable read but questionable as a scientific biography. Johnson doesn't discriminate properly between what is interesting and relevant and what is not. The book is filled with sometimes charming but still trivial details about the life of Zwicky and his family. In short, Johnson's work about the outcast genius who allegedly unmasked the universe is primarily aimed at a broad audience, and as such it is recommended. But it may not satisfy physicists and astronomers with a serious interest in the history of 20th-century science.

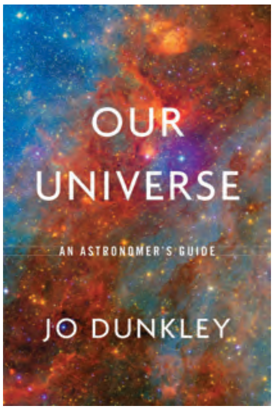
Helge Kragh
University of Copenhagen
Denmark

NEW BOOKS & MEDIA

Glacier
Nature and Culture
Peter G. Knight
Reaktion Books, 2019. $24.95 (paper)



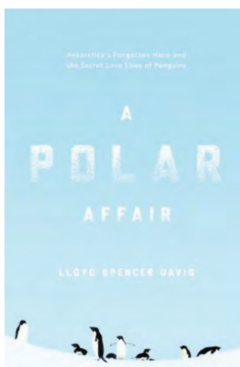
Among the many victims of climate change are glaciers. The huge bodies of dense ice that form on land and are constantly moving from the force of their own weight no longer cover as much of Earth's surface as they once did. In *Glacier: Nature and Culture*, geographer Peter Knight discusses not only the science of glaciers but also their importance and influence on the environment, weather, and even art and culture. Featuring more than 100 illustrations, *Glacier* pays homage to one of Earth's most majestic, yet fragile, features. —CC



Our Universe
An Astronomer's Guide
Jo Dunkley
Harvard U. Press, 2019. $29.95

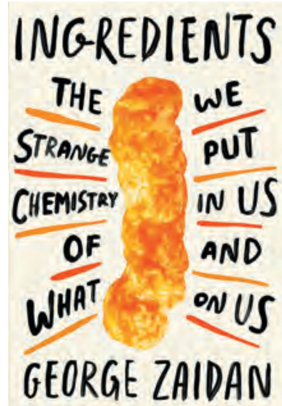
Written for a general audience, *Our Universe: An Astronomer's Guide* aims to instill in readers a sense of the wonder and mystery of the cosmos and whet their appetites for future discoveries. Starting with an overview of Earth and the solar system, astrophysicist Jo Dunkley continues outward, explaining star formation, black holes, and dark matter and finishing up with what the author calls a "whistle-stop history" of the universe. Discussions of major scientific theories, their evolution, and the ever-improving technologies used to peer deeper into space lead to an inspiring epilogue on the many mysteries that remain to be solved, such as whether extraterrestrial life exists and what the invisible part of the universe is made of. —CC

A Polar Affair
Antarctica's Forgotten Hero and the Secret Love Lives of Penguins
Lloyd Spencer Davis
Pegasus Books, 2019. $29.95



Only recently come to light is the first scientific study of penguin sexuality in Antarctica, written by George Murray Levick, who served as physician for Robert Scott's Antarctic expedition of 1910–13. Contrary to popular belief that penguins are monogamous and mate for life, Levick observed them committing a number of what he considered to be sexual depravities and misbehaviors. Indicative of the Victorian mores of the times, the manuscript was marked "NOT FOR PUBLICATION" and hidden away. Those long-forgotten pages serve as the impetus for *A Polar Affair*, a combination of adventure and natural history by modern-day penguin expert and Antarctic explorer Lloyd Spencer Davis, who discusses the life and times of the scientist who wrote them, drawing parallels between Levick's findings and his own research, carried out almost a century later. —CC

Ingredients
The Strange Chemistry of What We Put in Us and on Us
George Zaidan
Dutton, 2020. $27.00



From eating cheese puffs to smoking cigarettes to applying sunscreen, humans ingest, breathe, and absorb numerous chemicals every day. What's harmful, and what isn't? In *Ingredients*, science communicator George Zaidan delves into what science can and cannot tell us about the potential dangers of those and other commonplace products. Aimed at a popular audience, the book presents the latest scientific research in a lighthearted and occasionally irreverent manner. —CC

Archaeology from Space
How the Future Shapes Our Past
Sarah Parcak
Henry Holt and Co, 2019. $30.00

When you think of an archaeologist, you may picture someone bent over in the dirt carefully uncovering a fragment of ancient history. Space archaeology, though, is a newer and complementary specialty that employs aerial photography and satellite imagery to reveal undiscovered sites and other topographical features on Earth that wouldn't be readily visible from the ground. In *Archaeology from Space*, archaeologist Sarah Parcak provides a comprehensive review of the new subfield. She covers the science's history from the first attempts in which balloons and satellites were used to some of today's endeavors with the newest tools, such as unmanned drones. In addition to explaining the science of remote sensing, Parcak constructs historical narratives for the sites she's studied across 12 countries and 4 continents. —AL PT

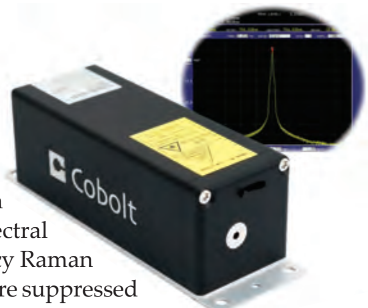
NEW PRODUCTS

Focus on analytical equipment, sensors, and instrumentation

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

Andreas Mandelis

Laser for Raman applications



Hübner Photonics has introduced the model 08-NLDM 785 nm ESP to the Cobolt 08-01 series of high-performance, single-frequency, narrow-linewidth lasers. The 08-01 series covers the broad 405–1064 nm range for high-resolution Raman processes. ESP, which stands for enhanced spectral purity, is particularly beneficial for low-frequency Raman applications. It defines how well the side modes are suppressed relative to the main laser peak and how close to the main peak the level of side-mode suppression is. Thanks to a patent-pending optical design, the spectral purity of the 08-NLDM 785 nm ESP is greater than 60 dB as close as 0.3 nm from the main peak. The multi-transverse-mode laser has an output power of less than 400 mW with fully integrated electronics in a single compact, hermetically sealed package. ***Hübner Photonics Inc****, 2635 N First St, Ste 228, San Jose, CA 95134, www.coboltlasers.com*

Real-time cell analyzer

According to Agilent, its multimode real-time cell analyzer (RTCA) is the first of its kind: It combines noninvasive biosensor measurement with live-cell imaging to deliver deep insight into cellular function. The xCELLigence RTCA eSight continuously monitors cells at predefined temporal resolutions for days or weeks, in a well-controlled, physiologically relevant environment. It provides label-free, real-time biosensor measurements and kinetic imaging of the same live-cell populations independently or simultaneously and monitors cell health, adhesion, morphology, proliferation, and cytolysis in primary or native cells alone or in co-culture. The analyzer supports three fluorescence channels, various well-plate formats and reporter reagents, and flexible user-defined schedules. It reads a 96-well plate in 15 s. ***Agilent Technologies Inc****, 5301 Stevens Creek Blvd, Santa Clara, CA 95051, www.agilent.com*

Mixed-mode option for digitizers and AWGs

An optional module for Spectrum Instrumentation's latest 16-bit digitizers and arbitrary waveform generators (AWGs) adds 16 synchronous digital lines to the analog data. Combined with the four multipurpose XIO lines already standard on those digitizer and AWG cards, the module offers, in total, 20 fully programmable XIO lines. The lines can run as synchronous digital inputs for a digitizer, synchronous digital outputs for an AWG, or asynchronous input and output lines, status lines, or additional trigger inputs. The modules fit on the 16-bit digitizers of Spectrum's M2p.59xx series, which offers 20 different PCIe cards with 1–8 channels and 20–125 MS/s. They also fit on the 16-bit AWGs of the M2p.65xx series, which consists of 8 PCIe cards with 1–8 channels and the choice of 40 MS/s or 125 MS/s. ***Spectrum Instrumentation Corp****, 401 Hackensack Ave, 4th Fl, Hackensack, NJ 07601, https://spectrum-instrumentation.com*

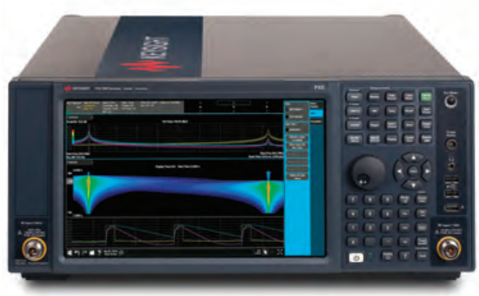
Fluorescence spectrometer add-on

PicoQuant has launched the FluoMic add-on for its FluoTime 300 time-resolved fluorescence spectrometer. The add-on enhances the FluoTime 300's accessibility and versatility by allowing users to perform spectroscopy on samples located outside the spectrometer. The FluoMic is easy to operate as it does not require lengthy alignment or coupling procedures. Using a special microscope coupler unit, the FluoMic's prealigned fibers guide excitation light from both pulsed and steady-state spectrometer sources to a microscope, such as the Olympus BX43. Emission is collected from a small sample area (down to 2 μm spatial resolution) and sent via a fiber to the detection arm of the FluoTime 300. The FluoMic add-on easily extends the state-of-the-art spectrometer's spatial resolution so the instrument can be used for performing a wide variety of steady-state and time-resolved measurements. ***PicoQuant****, Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

Low-current, high-capacitance measurements

Tektronix has produced two source measure unit (SMU) modules for the Keithley 4200A-SCS parameter analyzer. The 4201-SMU and 4211-SMU modules can perform low-current measurements even in the presence of high load capacitance caused by long cables and complex test setups. Excessively high test-connection capacitance can make low-current measurements unstable. Because the new modules can function with longer cables or more connection capacitance than traditional SMUs, they can save researchers and test engineers the time and cost of troubleshooting and reconfiguring test setups. At the lowest supported current-measurement range, the 4201-SMU and 4211-SMU can source into and measure a system that is 1000 times as capacitive as what is currently possible. ***Tektronix Inc***, *14150 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com*

High-frequency emissions receivers



Keysight has extended its N9048B PXE electromagnetic interference (EMI) receiver from 26.5 GHz to 44 GHz. The PXE EMI receiver has the sensitivity to detect small signals close to the noise level—common in electromagnetic compatibility testing—so users can identify unwanted emissions caused by their devices and ensure they comply with worldwide and regional standards. Its time domain scan (TDS) and accelerated TDS capabilities meet dwell measurement requirements and reduce receiver scan and test time from hours to seconds. The device offers full signal visibility, where the real-time scan provides gapless signal capture and analysis in up to 350 MHz bandwidth and simultaneously displays the frequency domain, time domain, and spectrogram. ***Keysight Technologies Inc***, *1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Multispectral research spectrometer

Bruker has expanded its Invenio Fourier Transform IR R&D platform by launching its Invenio X system for research in molecular spectroscopy. The intuitive, modular spectrometer retains features of the original Invenio platform, such as FM functionality for simultaneous mid- and far-IR spectroscopy, and offers new advanced capabilities. The Invenio X is available with an automated three-position beamsplitter changer, and its novel, wear-free Integral interferometer combines high spectral resolution of less than 0.09 cm^{-1} with the accuracy of cube-corner mirrors. The highly automated, multispectral spectrometer features up to seven software-controlled detectors and multiple light-source options. Users can measure from the far-IR to the UV and visible range without needing to exchange optical components manually. ***Bruker Corporation**, 40 Manning Rd, Billerica, MA 01821, www.bruker.com*

Microscope for atomic tomography

Ametek Cameca has unveiled its Eikos-UV atom-probe microscope. It uses standard microscopy sample-preparation methods to deliver nanoscale structural information to materials researchers and product developers. According to the company, it is both easy to use and economical. The base Eikos system, which incorporates a reflectron spectrometer design with a voltage-pulsing setup, ensures high data quality for metallurgical applications. It is field-upgradable to the Eikos-UV, which adds an integrated, automated laser-pulsing module with a computer-controlled focused-spot design. The Eikos-UV provides higher signal-to-noise ratio and access to a larger application range, including metals, semiconductors, minerals, functional and nuclear structural materials, thin films, and coatings. ***Cameca Instruments Inc**, 5470 Nobel Dr, Madison, WI 53711, www.cameca.com*

Test and measurement app

Liquid Instruments has updated the iPad app for its all-in-one Moku:Lab platform for test and measurement. Users of version 1.9 can sort, filter, and mark devices as favorites on the device-selection screen. Signal-fidelity improvements have been made in the spectrum analyzer and frequency response analyzer. The Moku:Phasemeter can now show frequency and amplitude values simultaneously, and reference traces can be displayed in the Phasemeter and all embedded oscilloscopes. Optimizations have improved the app's performance and responsiveness on older iPad models. The new version also fixes bugs and provides enhanced stability and interface upgrades. ***Liquid Instruments**, 740 Lomas Santa Fe Dr, Ste 102, Solana Beach, CA 92075, www.liquidinstruments.com*

Van der Pauw and Hall coefficient measurements

Quantum Design's van der Pauw–Hall option expands the transport capabilities of its physical property measurement system (PPMS) family of instruments. The van der Pauw technique allows for the determination of a material's resistivity for a uniformly thick sample of arbitrary shape. The van der Pauw–Hall option, which enables the efficient measurement of both the van der Pauw resistivity and the Hall coefficient, automatically measures and averages multiple unique permutations of the current and voltage leads, and it yields highly accurate resistivity measurements as a function of temperature or magnetic field. With the application of sufficiently strong magnetic fields, the same switching and measurement hardware can further be leveraged to acquire the Hall coefficient and charge-carrier concentration. Once both the resistivity and the Hall coefficient are known, the carrier mobility μ is readily calculated as a function of temperature across the full PPMS range. ***Quantum Design**, 10307 Pacific Center Ct, San Diego, CA 92121, www.qdusa.com* PT

OBITUARIES

Charles B. Duke

Charles B. Duke, a remarkably versatile theoretical physicist, passed away on 28 June 2019 in Webster, New York. Charlie's contributions to science extended far beyond his work at Xerox Research, where he spent much of his career. A leading solid-state physicist, he did pioneering science in industry, academia, and national laboratories; held many leadership positions; launched and led prestigious scientific journals; was a consummate teacher; and volunteered extensively in service to the scientific community.

Born on 13 March 1938 in Richmond, Virginia, Charlie obtained his BS from Duke University in 1958, with majors in math and theology. In 1963, under Eugene Wigner at Princeton University, he received his PhD in physics for explaining nuclear-surface-peaked energy absorption in nucleon scattering from nuclei. That same year he became a research scientist at General Electric's Corporate Research Laboratory, applying his many-body-theory skills to solid-state physics, including the tunneling of electrons across semiconductor diodes.

In 1969 Charlie went to the University of Illinois at Urbana-Champaign, where he became one of its youngest tenured faculty members. Cementing his scientific reputation, he leveraged the understanding he had gained in his thesis work by creating a way to derive crystalline surface structure parameters from low-energy electron diffraction data. That feat took place in the early days of surface science, when preparing clean, well-characterized surfaces was nontrivial; when computers were unimaginably slow; and when there was much contention over whose ideas came first and whose numbers were most reliable. Still, Duke's results, with Charlie Tucker, George Laramore, and others, contributed substantially to establishing a database of silicon and other semiconductor surface structures that were key to characterizing the behavior of electronic materials.

In 1972 Charlie moved to the Xerox Webster Research Laboratories, rising through research management until his retirement in 2006. His contributions to Xerox included spearheading the electronic devices and materials study that reshaped much of the corporation's R&D in the 1990s, for which he received Xerox's highest honor, the President's Award. Other notable achievements included the color imaging science thrust and the tribology and xerography initiative linking fundamental charge-transfer processes to the core processes that make Xerox machines work.

Charlie maintained strong connections to the academic community, as an adjunct professor at the University of Rochester, and by assuming pivotal leadership roles in scientific societies. He served the American Vacuum Society (AVS) as its president in 1979 and on its board, driving the group's evolution to a concentration on fundamental and applied surface science. Charlie strengthened the reputation of the society's *Journal of Vacuum Science and Technology*. He also served on the Materials Research Society Council, strengthening the organization's publication portfolio by founding the *Journal of Materials Research* and serving as its first editor-in-chief from 1985 to 1986. For over a decade, beginning in 1992, he was editor of *Surface Science* and *Surface Science Letters*, the most prestigious journals in the field.

Charlie interrupted his career at Xerox to serve in 1988–89 as deputy director and chief scientist at the Department of Energy's Pacific Northwest National Laboratory. That afforded a close-up view of the national laboratory complex, which he used to broaden his lectures and consultations on research career management.

Over his career, Charlie earned much recognition. He is one of few to be inducted into both the National Academy of Engineering (1993) and the National Academy of Sciences (2001). AVS bestowed on him its most prestigious prize, the Medard W. Welch Award, in 1977 for work on electron scattering. The American Physical Society (APS) awarded Charlie the George E. Pake Prize in 2006 for contributions to understanding tunneling in solids and electron-surface scattering and to Xerox Corp. From his retirement until his death, Charlie served as a professor of physics at the University of Rochester, where he continued to pursue broad scientific interests and also returned to studying theology.

During Charlie's long career at Xerox, he promoted the endeavors of early-career

Charles B. Duke

AMERICAN VACUUM SOCIETY, COURTESY AIP ESVA PHYSICS TODAY COLLECTION

scientists and engineers, particularly in industrial research. To that end, from governance positions with the American Institute of Physics (publisher of PHYSICS TODAY) and APS, Charlie organized task forces and outreach initiatives.

With her selfless support and social graces, Ann, Charlie's wife, was integral to Charlie in sustaining his legendary work ethic.

Many of our colleagues count Charlie as an essential mentor, career counselor, and scientific critic. We three benefited immensely from his counseling and incisive critiquing over some three decades. The intensity of his intellect, force of his convictions, and sincerity of his friendship have enabled Charlie's lifelong lessons to transcend time. In his own words: "You have to find people who are doing similar things, who are going to mix it up and call each other nuts and have some real good wars and so on—get everybody to think, which is … my philosophy of research."

What a colleague! We will sorely miss the next "war."

Leonard J. Brillson
Ohio State University
Columbus
H. Frederick Dylla
American Institute of Physics
College Park, Maryland
Peter J. Feibelman
Sandia National Laboratories
Albuquerque, New Mexico

Alfred Guillou Redfield

Alfred Guillou Redfield died on 24 July 2019 in Alameda, California. He was a major figure in the development of nuclear magnetic resonance (NMR) and its applications to problems in solid-state physics and biophysics.

Al was born in Milton, Massachusetts, on 11 March 1929 and raised in Cambridge and Woods Hole, where his father, the eminent oceanographer Alfred Clarence Redfield, worked at the Oceanographic Institution. The younger Al graduated from Harvard University in 1950 with a BA in physics and received his MS in 1952 and PhD in 1953, both in physics, from the University of Illinois at Urbana-Champaign. His thesis focused on experimental Hall effect measurements of electron mobilities in photoconductors and the associated theory. His thesis adviser was Robert Maurer, but the publications from his thesis work list Al as the sole author.

For postdoctoral research, Al returned to Harvard. There his interests shifted to magnetic resonance, most likely because of his interactions with Charles Slichter at Illinois and with Nicolaas Bloembergen, John Van Vleck, and others at Harvard. Al's 1955 *Physical Review* paper entitled "Nuclear magnetic resonance saturation and rotary saturation in solids" was a major conceptual breakthrough. In it, he focused on NMR signals from a coupled many-spin system in a solid that is subjected to continuous RF irradiation near the NMR frequency. He showed that the signals could be understood by applying principles of quantum statistical mechanics and thermodynamics to the spin system in a frame of reference that rotates around the static field direction at the frequency of the RF field.

Al's 1955 paper introduced ideas about spin temperature in the rotating frame, dipolar spin order, and spin locking that were essential for many developments in NMR of solids over the next 50 years. Without those concepts, NMR techniques that are widely used in studies of the structure and dynamics of biological and nonbiological materials would be inconceivable. In his book *Principles of Magnetic Resonance*, Slichter called Al's article "one of the most important papers ever written on magnetic resonance."

After taking a position in 1955 at the IBM Watson Laboratory at Columbia University, Al published his next big contribution: a general theory for the rates of relaxation of an out-of-equilibrium spin system in response to randomly fluctuating interactions with surrounding degrees of freedom. Using a quantum mechanical density matrix formalism, he showed that the approach to equilibrium can generally be described by a relaxation rate matrix, with elements that depend on spectral densities of the fluctuating interactions. The formalism, often referred to as Redfield theory, was published in the *IBM Journal of Research and Development* in 1957. In NMR of condensed matter, Redfield theory is commonly used to extract rates and amplitudes of molecular motions from linewidths and spin relaxation times.

Although Redfield theory was originally motivated by phenomena in magnetic resonance, it has broad applicability in condensed-matter physics and physical chemistry. Al's 1957 paper still receives about 50 citations per year, most recently in papers on topics as diverse as electron transfer in photosynthesis, light propagation in quantum dot lasers, and effects of magnetic fields on electrical currents in graphene.

Al was also a creative experimentalist. His work at Watson Lab included measurements of spin-lattice relaxation in metals at very low temperatures, measurements and analyses of spin relaxation in solids driven by translational diffusion, and the first demonstration of NMR as a method for characterizing the vortex lattice in a type II superconductor. Al also developed an indirect detection method for rare spin species that was an intellectual ancestor of contemporary indirect detection methods in NMR.

In 1969, during a sabbatical with Daniel Koshland at the University of California, Berkeley, Al began applying NMR to biological problems. In 1972 he joined the faculty of Brandeis University, where he remained for the rest of his career. Among his many contributions to biomolecular NMR are early studies of electron transfer in cytochrome c, the introduction of frequency-selective composite RF pulses for exciting hydrogen-1 NMR signals of biomolecular solutes without interference from much stronger solvent signals, and studies of tRNA structure by NMR-detected hydrogen–deuterium exchange. They also include an early ^{1}H-detected two-dimensional NMR technique for observing ^{15}N–^{1}H chemical shift correlations, closely related to 2D techniques that are now a mainstay of biomolecular NMR.

Alfred Guillou Redfield

LAWRENCE BERKELEY NATIONAL LABORATORY

For his outstanding achievements, Al received many honors. They include the International Society of Magnetic Resonance's ISMAR Prize in 1995 and the Max Delbruck Prize in Biological Physics from the American Physical Society in 2006.

Al was a modest man who did not like to call attention to himself. He was a scientist's scientist, with phenomenal mathematical and theoretical abilities, outstanding experimental skills, an exceptionally broad knowledge of physics and biology, and a love for research. He was universally respected and is deeply missed.

Robert Tycko
National Institutes of Health
Bethesda, Maryland
Robert G. Griffin
Massachusetts Institute of Technology
Cambridge PT

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QUICK STUDY

Jonah Botvinick-Greenhouse is a junior mathematics major at Amherst College in Massachusetts, and **Troy Shinbrot** is a professor in the department of biomedical engineering at Rutgers University in New Jersey.

Juggling dynamics

Jonah Botvinick-Greenhouse and Troy Shinbrot

With complex throwing patterns of multiple objects, jugglers seemingly defy human limits of reaction time and throwing accuracy.

In 1993 Claude Shannon, founder of information theory, wrote a popular analysis of juggling, and he even accompanied the article with a working model of a juggling robot. Building such a robot—in fact, juggling at all—is remarkable, because it seems to require faster reaction times than most of us can muster. Speed jugglers can achieve nearly 500 catches in a minute, a rate that allows just 120 ms per catch. Yet typical human reaction times are 250 ms, and even experts in high-speed sports such as tennis take 200 ms to adjust their responses.

So how do jugglers with reaction times no better than 200 ms catch balls every 120 ms? In part, multitasking may allow multiple balls to be processed simultaneously, though how that is done with 11 balls—the Guinness world record—is far from clear. And in part, balls are not thrown to random locations, so each ball need not be tracked and caught independently. Indeed, up to five balls can be juggled while the juggler is blindfolded. Jugglers rely on making accurate throws and predictions of where the balls will travel. The accuracy required is a measure of how unstable—and thus how difficult—a particular juggling pattern is.

Showers and cascades

Figure 1 shows two five-ball juggling patterns above plots that define their sensitivities to deviations in throw speed and angle. On the left is the most common pattern, the cascade, in which each hand catches and throws balls to equal heights across the body's centerline. Hand motions in the cascade are left–right antisymmetric—that is, 180° out of phase. It is an amusing exercise to prove what all jugglers know—that only an odd number of balls can be juggled in the cascade. It's impossible to juggle an even number of balls in a cascade without breaking the antisymmetry—for example, by throwing with both hands simultaneously or by throwing balls to different heights.

The shower pattern (shown on the right), by contrast, lacks symmetry and can be performed with either even or odd numbers of balls. Although the pattern is dynamically simpler, it's also less stable—and thus more difficult—than the cascade. To appreciate why, consider the sensitivity plots (figure 1b) for both cascade and shower.

Both panels show the results of simulated parabolic trajectories under gravity. Figure 2a illustrates the ideal positions: The trajectories define throws that leave the exact center of the throwing hand and land precisely in the center of the catching hand. The hands move in ellipses, centered 50 cm apart and 180° out of phase, with horizontal radius 10 cm and vertical radius 5 cm. In simulations we add Gaussian deviations in initial speed v_0 and angle θ_0 to the throws and record how rates of

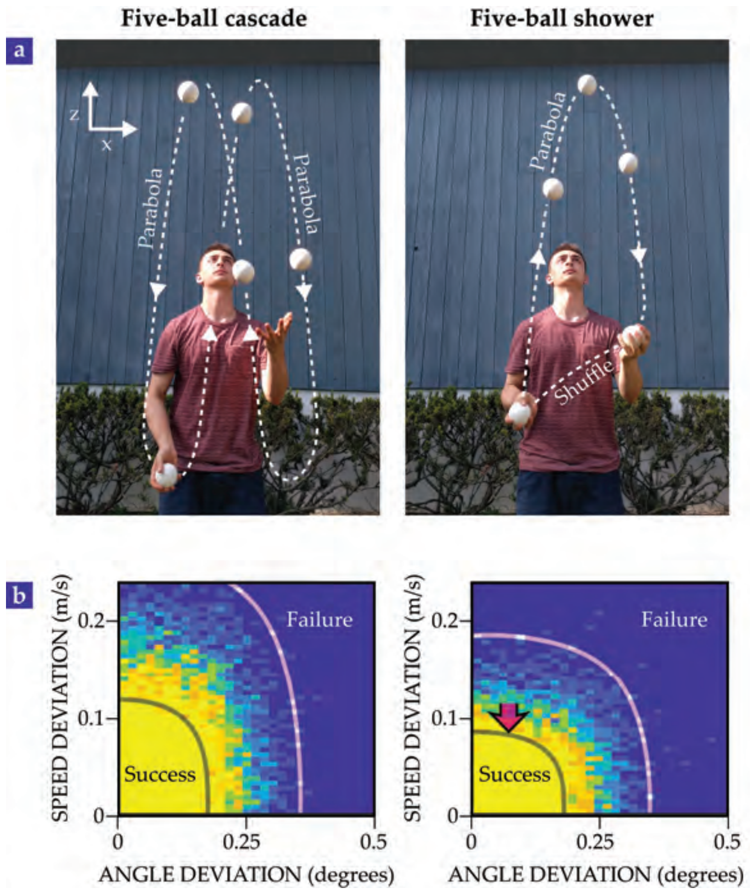

FIGURE 1. TRAJECTORIES AND SENSITIVITIES. (a) Two common juggling patterns are shown, each with five balls thrown to nearly identical heights. In the cascade (left), the five balls follow two parabolic trajectories, whereas in the shower (right), they follow one. **(b)** The seemingly more complicated cascade pattern is significantly less sensitive to deviations in speed than the shower, as indicated by the red arrow. Gray and red lines delimit the bounds within which juggling will always be a success and beyond which it will always be a failure.

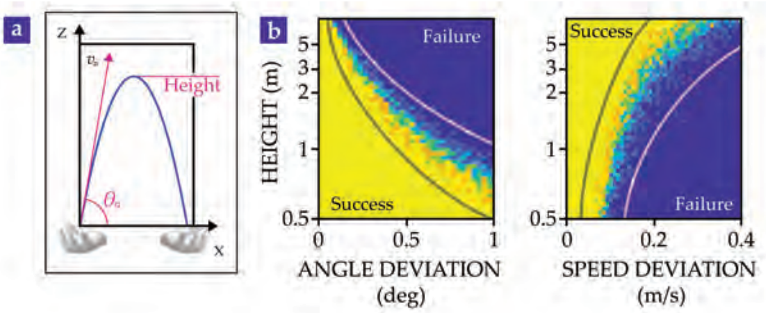

FIGURE 2. AN IDEAL THROW AND CATCH (a) with initial speed v_0 and angle θ_0. **(b)** Successful and failed catches occur in yellow and dark blue regions, respectively, for five-ball cascade patterns that include deviations in throw angle (left) and throw speed (right). At large heights, a juggler can tolerate large deviations in speed but little deviation in angle, whereas at low heights, the opposite is true.

catch success depend on throw deviations. Those rates are determined by counting the number of failures from 15 trials. Each trial comprises 50 throws for each combination of v_0 and θ_0 in the plots. Any throw in a trial that misses a catching hand 10 cm in diameter counts as a failure.

The take-home message of figure 1 is that the success region is larger for the cascade than for the shower. Cascade patterns can evidently tolerate greater variability in throw speed than can the shower, with balls thrown to the same height. For that reason, balls in a shower are typically thrown higher than those in a cascade. The higher throws provide more time between catches, but at the expense of requiring tighter control over the angle, as we'll see.

For throws to the same height, the two patterns are indistinguishable in sensitivity to throw angle. That feature makes sense in terms of the dynamics of the problem. The trajectories of both patterns are parabolic and nearly identical, so changing the throw angle produces the same displacement of a catch from its expected location in both.

In the shower pattern, each ball travels first through a parabola and then through a quick shuffle, whereas in the cascade, each ball must travel through two parabolas to return to its starting point. So hands must move nearly twice as rapidly in the shower as in the cascade, which makes catches in the shower much more sensitive to timing.

The different effects of throw angle and speed can be quantified by plotting sensitivities of throws to independent deviations in the two parameters, shown in figure 2b for a five-ball cascade. Notice that throws to greater heights permit less angle deviation but more speed deviation than throws to lower heights. That phenomenon occurs because errors in throw angle produce variations in catch location that worsen as throws become higher.

Initial speed, on the other hand, chiefly affects the timing of the catch. And because greater heights are produced at lower hand frequencies, higher throws provide more tolerance to time variation. So for high, nearly vertical throws, it's speed, not angle, that largely determines the time between throw and catch. The effects—particularly for higher throws—are that throw angle determines the location of a catch, whereas throw speed determines its timing. This distinguishes juggling from darts and other throwing games in which targeting accuracy does not depend on the relative timing between two hands.

The distinction between angle and speed is complicated by so-called siteswaps, juggling patterns defined by the order in which successive balls are manipulated, often resulting in throws to varying heights. When balls are thrown many meters high, throw angles must be accurate to within 0.1 degree. That's more than an order of magnitude tighter than is achievable by world-class athletes, and the time between successive catches is shorter than human reaction times. For an analysis of sensitivity plots for several siteswaps, see the online supplement.

Keep your eyes on the flies

It's unclear how jugglers achieve accuracy and response times beyond apparent physiological limits. But two experiments offer clues to how people can successfully juggle despite these limitations. In 2004 researchers presented evidence that both human and monkey brains can compute trajectories using an internal representation of equations of motion. According to that picture, jugglers keep track of the locations of their balls—and so effectively extend their reaction times—using dynamical prediction. Just as an outfielder predicts where a fly ball will land, a juggler predicts trajectories from how balls are thrown.

A second clue lies in the well-known but poorly understood phenomenon of muscle memory: A practiced sequence of movements can be recalled and repeated (see PHYSICS TODAY, November 2018, page 16). Human physiologists have long known that the brain's motor cortex contains somatotopic maps such that when particular locations are briefly stimulated electrically, specific muscles contract. In 2002 neuroscientist Michael Graziano and his colleagues showed that by prolonging the duration of stimulation, they could produce—at least in monkeys—complex, coordinated motions involving multiple muscles. They concluded that the brain appears to have developed a clear-cut and hierarchical way to encode complex tasks.

Complex tasks like juggling can be successfully performed without understanding the physiology behind motor control, although a deeper understanding is both intriguing and useful. Feedback-controlled robots can juggle a small number of balls by tracking them at 60 Hz. Physiology has apparently found ways to do the same, but with many more balls tracked at the slower rate of just 5 Hz. Unraveling the secrets behind how our nervous systems pull that off may pave the way for more dexterous robots.

Additional resources

▶ C. E. Shannon, *Claude Elwood Shannon: Collected Papers*, Wiley (1993).

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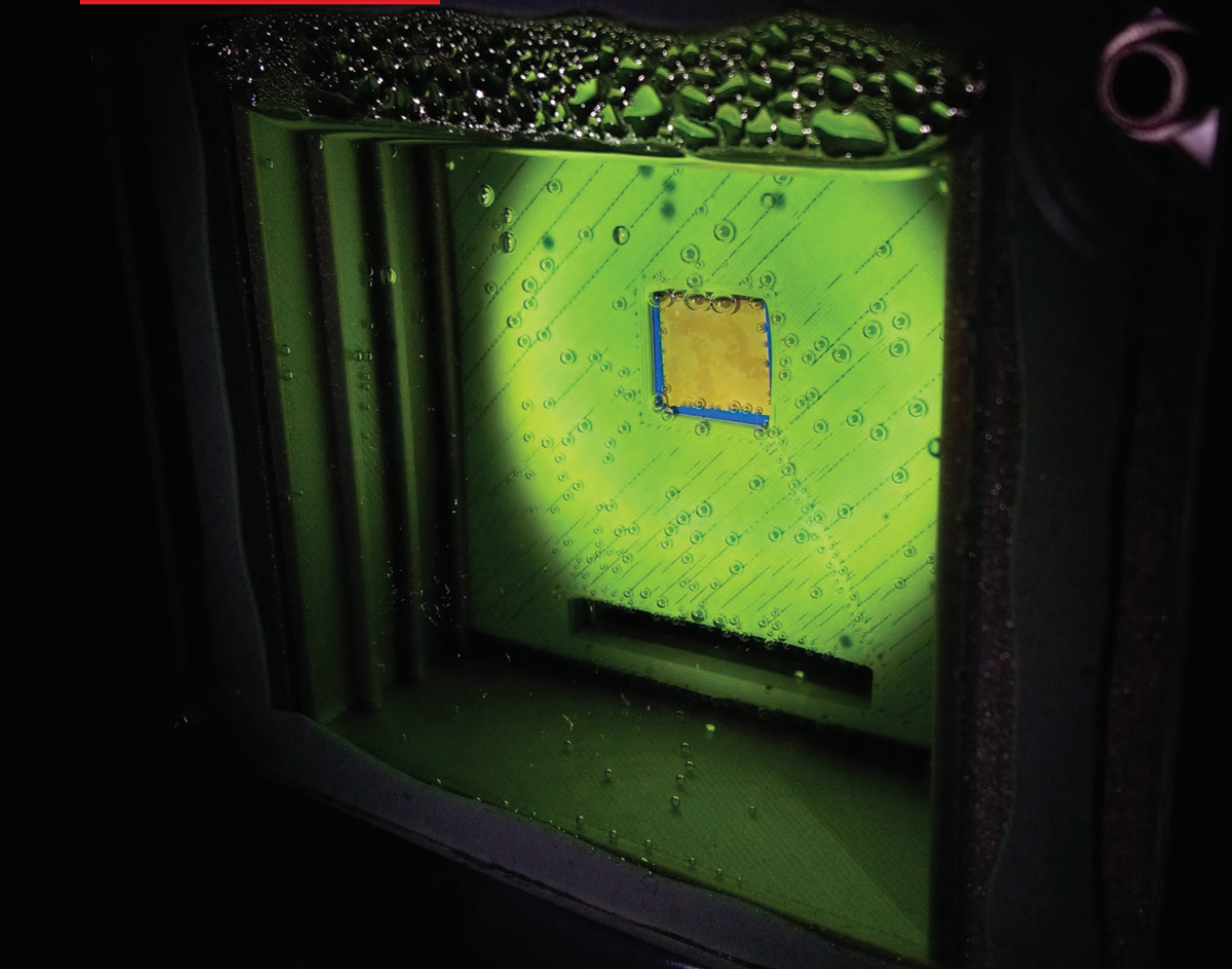

Lab leaf recycles carbon dioxide

Syngas, an intermediate product in the manufacturing of synthetic liquid fuels and methanol, is a mixture of mostly carbon monoxide and molecular hydrogen. Generating the two ingredients typically involves exposing fossil fuels to high temperatures and pressures, so researchers have been studying alternative solar-driven processes to make syngas more cleanly and with a lower thermodynamic burden. Rather than use the photovoltaic cells and noble metals that other researchers have tried, Virgil Andrei, Bertrand Reuillard, and Erwin Reisner at the University of Cambridge turned to photoelectrochemical devices inspired by plant photosynthesis. The molecular catalyst they chose, a cobalt atom surrounded by an organic frame, allows them to produce syngas from a standalone device.

The image, courtesy of Andrei, shows the researchers' artificial leaf immersed in water. It's composed of a yellow bismuth vanadate photoanode coupled to a perovskite-based photocathode. When illuminated by sunlight, the photocathode reduces aqueous CO_2 and water in a neutral pH solution to CO and H_2 gas. The leaf can maintain constant syngas production and water oxidation for several days. Andrei and his colleagues experimented further with the light source and found that the perovskite photocathodes yield CO with as little as a tenth of the Sun's intensity. Although commercialization is far off, the device's potential to operate throughout the day could improve its economic feasibility. (V. Andrei, B. Reuillard, E. Reisner, *Nat. Mater.*, 2019, doi:10.1038/s41563-019-0501-6.)

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