PHYSICS TODAY

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Negative CARBON DIOXIDE emissions

Acoustic ecology

Rethinking student evaluations

Kepler's pursuit of harmony

PHYSICS TODAY

January 2020 | volume 73 number 1

FEATURES

ON THE COVER: Carbon dioxide emissions are expected to reach record levels this year, even as the need for dramatic reductions is becoming more obvious. Beginning on **page 44**, PHYSICS TODAY's news editor David Kramer reviews some of the ways to remove CO_2 directly from the atmosphere. Shown here is a Climeworks plant that uses direct air capture. The Swiss company is the first to commercially deploy the technology. (Photo courtesy of Climeworks.)

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▶ Best of 2019

Take a look at PHYSICS TODAY's most popular stories from last year, including several that can be found only online. Topics include a baffling crystal that melts at two different temperatures and an explanation of why Mercury is, on average and most frequently, the nearest planet to Earth.
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PXFUEL, PD-US

▶ Sound of solutes

Recently a research team was able to distinguish between sand from different beaches by analyzing the sound of a stirrer mixing the samples into an acidic solution. David Adam explains how a cup of hot chocolate led to the development of a technique that characterizes solids via acoustic measurements.
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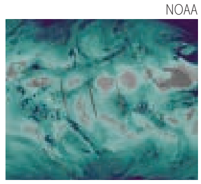
NOAA



▶ 5G and weather

In November an international delegation agreed on an emission standard for 5G telecommunication networks operating at 24 GHz. PHYSICS TODAY's Alex Lopatka reports that many meteorologists think the limits aren't strict enough to avoid contaminating the data collected by moisture-tracking weather satellites.
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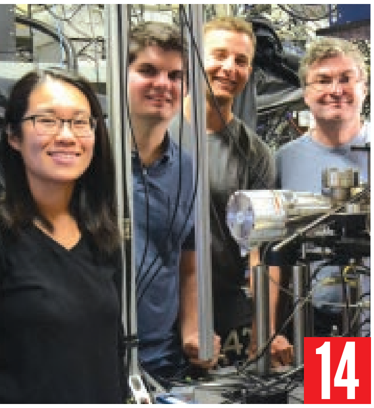
DEPARTMENTS



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FROM THE EDITOR

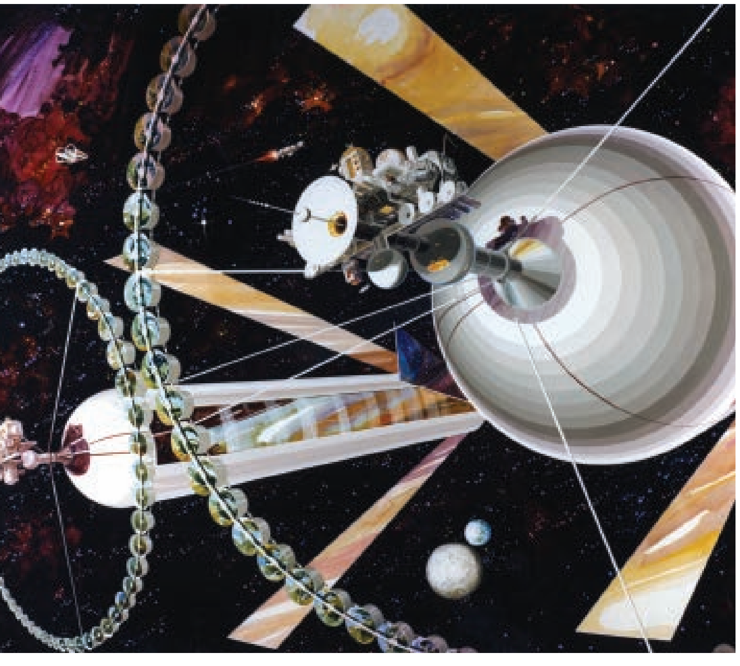
Running out of energy

Charles Day

The cover of the November 2019 issue of *The Atlantic* highlights a 15-page article by Franklin Foer entitled "What Jeff Bezos wants: His master plan, and what it means for the rest of us." The cover image shows the Amazon founder's shaven head in profile. To convey his mental preoccupations, the cover artist has superimposed a patchwork of quasi-hand-drawn zones with labels such as "tax avoidance," "more Jeff-bots," and "Prime day!" By far the largest zone, at the top of the mogul's head, is "colonize outer space."

The apportionment seems justified, and it reflects Bezos's long-held, undimmed enthusiasm for space. In his article Foer recounts that long after Bezos had graduated high school, reporters tracked down his high school girlfriend. "The reason he's earning so much money is to get to outer space," she told them. Foer also notes that as an undergraduate at Princeton University, Bezos attended seminars given by particle physicist Gerard O'Neill.

In 1956 O'Neill published a proposal for a device, a particle storage ring, that could accumulate particles from an accelerator for release later in an intense beam.[1] CERN's Large Hadron Collider, Fermilab's Tevatron, and Brookhaven National Laboratory's Relativistic Heavy Ion Collider all use, or used, particle storage rings. But by the time Bezos attended Princeton, O'Neill had shifted his attention to space. His September 1974 article in PHYSICS TODAY (page 32) outlined the design of vast rotating space habitats.



GERARD O'NEILL proposed building vast cylindrical space habitats whose rotation provides artificial gravity. (Rick Guidice, NASA's Ames Research Center.)

Bezos has invested at least $500 million of his fortune in Blue Origin, a company he founded in 2000 to develop technologies for private access to space. Part of his motivation lies in the glamorous promise of life and travel in space. He is an avowed fan of utopian science fiction, such as the *Star Trek* franchise and the Culture, the post-scarcity civilization in the novels of Iain M. Banks. But Bezos also worries that Earth will run out of energy. "We have to go to space to save Earth," Foer quotes him saying.

As soon as I encountered the notion of running out of energy, my curiosity as a physicist was aroused—and not just because energy, being conserved, doesn't run out. I am perhaps less pessimistic than Bezos is about humans' ability to invent new ways to make energy. That said, I realized that I had yet to encounter an estimate of how quickly new fossil fuels are being made. All the estimates I remembered seeing had addressed a different question: How long would Earth's existing supply of the fuels last.

It proved surprisingly difficult to find estimates of the fossil-fuel replacement rate. The best and most plausible I came across was a 2003 study[2] by ecologist Jeffrey Dukes, who is now at Purdue University. Oil starts off as the decomposing bodies of aquatic algae. Pressure, heat, and time convert it to natural gas and crude oil. Dukes recognized that each step adds inefficiency—to the point, he calculated, that a US gallon of gasoline originates from 90 tons of ancient organic matter. Earth's vast reserves of oil and gas correspond to an even vaster amount of plant material squashed and cooked for eons.

By 1888, Dukes estimated, humanity's rate of consumption of plants in the form of fossil fuels exceeded the rate at which new plants were produced. Given how inefficiently plants are converted to fossil fuel, our rate of using fossil fuels likely exceeded their production rate soon after we started using them.

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The usefulness of GRE scores

Many US physics departments are considering dropping the use of Graduate Record Examinations (GREs) in making admissions decisions (see, for example, the commentary by Alexander Rudolph, PHYSICS TODAY, June 2019, page 10). They are concerned that the exams contribute to the profession's nonrepresentative demographics. The American Physical Society (APS) Panel on Public Affairs is looking at adopting a similar position. Those decisions may be influenced by a widely publicized *Science Advances* paper entitled "Typical physics Ph.D. admissions criteria limit access to underrepresented groups but fail to predict doctoral completion," by Casey Miller and coauthors.[1]

Although that paper uses data provided by many physics departments, I found some serious statistical flaws in its analysis. Contrary to its conclusions, proper statistical analysis of even the incomplete published features of the data indicates that an equal-weight sum of the quantitative and physics GREs is somewhat better than undergraduate grade point average at predicting who will graduate.[2]

I believe the key issues raised include the need for more transparency and statistical literacy in handling data, but the effects of graduate admissions policies themselves are also important. Systematic uncertainties in estimating the effects of using GREs in admissions decisions would remain even after a proper analysis of more complete data,[2] as is typical for any attempt to estimate causal parameters from observational data.[3] Therefore, it may be worth trying a more robust way to get information on those effects.

Given the fairly large number of physics departments that are uncertain about what the GRE's role in the admissions process should be, APS could ask for departments to volunteer in a randomized controlled trial. Some departments would be assigned to GRE-aware admissions and others to GRE-blind admissions. Ideally, the assignments would be switched after a year. Beyond graduation rates, various other outcomes of interest could be tracked. Departments could participate in long-term follow-up even if they committed to only two years of randomized admissions policy. Incremental costs above the already labor-intensive selection procedures should be small, perhaps even negative, if one counts the time saved in decision making.

Although the information obtained might be inconclusive, at least the setup could be a model for approaching policy issues scientifically and honestly. That's important when we consider that our credibility on the really big issues—climate, for example—has been challenged by people who wrongly claim we are just pushing political positions disguised as science.

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Alexander Rudolph's commentary correctly notes that achieving greater diversity in physics requires revamping admissions criteria: You only get what you select for. However, the recommendation against using Graduate Record Examination (GRE) scores draws heavily on a study by Casey Miller and coauthors.[1] That study has three major problems:

- The study measured performance with a binary variable: completion. Eliminating gradations of performance obscures relationships that may be present in more granular data. A large meta-analysis examined student performance with fine-grained measures—for example, research productivity, faculty ratings of student work—and found significant predictive power in GRE scores.[2]
- The work by Miller and coauthors included program rank as an explanatory variable, despite its being strongly correlated with GRE scores. When two or more such variables are strongly correlated, a regression routine cannot easily determine which variable should get the larger coefficient; different coefficient choices could fit the data similarly well. Consequently, coefficient estimates will have large uncertainties.[3] Thus the estimated coefficient of GRE score will almost certainly have a magnitude comparable to the estimate's uncertainty.

A model of efficient competition in admissions: The more desirable programs attract students who are more likely to succeed.

- The predictive power of program ranking actually fits a model of efficient competition in admissions: The more desirable programs attract students who are more likely to succeed. Moreover, a student who is weak by one measure can gain admission by demonstrating strength in another measure. Such cases may camouflage correlations between student performance and other explanatory variables.[4] Of course, there are other plausible explanations for the predictive power of program ranking, but nothing in the cited work enables readers to choose among explanations.

Admissions criteria are ultimately about values, and it is wholly appropriate to include diversity of backgrounds among them. However, if performance is also valued, then valid predictors of performance should also be included. The Miller study does not demonstrate that GRE scores lack predictive power, and it should not be cited uncritically.
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Adjunct educators in a profit-driven arena

To the Issues and Events story about contract lecturers (PHYSICS TODAY, November 2018, page 22), I would like to add a significant concern that we have seen arise with instructors and adjuncts over about the past two decades. During that time the numbers of private and public community colleges and universities have skyrocketed while funding has declined. Those facts, combined with the profit motive and less stringent admissions practices at the freshman level, have led to many displeased academics, particularly in the hard sciences.

Nowadays a significant number of students entering these institutions are not well prepared to succeed in hard-science courses. In search of profits, institutions of learning have loosened entrance requirements. As a result, some admitted students have no motivation to continue in science but either need to take these courses for a career in other fields or are bent on receiving high grades without doing the necessary work.

As test and exam dates draw near, some students realize that they cannot make the high grades, and they complain to the dean or department chair, who rarely offers the teacher an opportunity to make a defense. If the teacher is present, then the students are less likely to embellish their performance or tell lies or denigrate the teachers. Student complaints often get lodged without rebuttal or evidence and become part of the teacher's record. And even if the complaints are true, institutions should have a protocol established for instructors to be able to improve their performance or correct the record. That rarely happens. Now instructors, realizing that they could be fired, may jack up grades in the hope of calming the complaints. One has to think twice to fail a student who might file a complaint.

Often the result is that the complaining students receive better grades than their work deserves and teachers—even research leaders with broad teaching experience—may lose their positions. Their loss leads to a decline in academic standards. In the past decade or so, maybe as a result of this, many failures of high-tech manufacturing products, services, and air travel, some of which have been life threatening, have been in the news.

Colleges and universities must change their policies regarding admissions standards and quality of education, particularly in the hard sciences. Having school administrators require that an instructor be present when a complaint is lodged will minimize students' opportunity to present only their side of the situation, and supporting the professors once they are hired should also help maintain ethical standards. Administrators could also encourage the complainers to first try to settle with their teachers before they lodge an administrative grievance.

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Notes on superconducting hydrides

In their article "The quest for room-temperature superconductivity in hydrides" (PHYSICS TODAY, May 2019, page 52), Warren Pickett and Mikhail Eremets commented that "in the late 1960s William McMillan of Bell Labs extended the [Bardeen-Cooper-Schrieffer] analysis to moderately strong coupling," which is measured by the electron–phonon coupling constant, λ. According to Pickett and Eremets, the McMillan "equation for T_c was extrapolated beyond its regime of validity to fortify claims that 30 K would be the upper limit for electron–phonon coupling."

The above comment may not be entirely fair if its subject is the analysis McMillan made in a 1968 article,[1] in which he doesn't mention 30 K as a possible maximum value of T_c but does list 9.2, 22, 28, and 40 K as possible maximums. None of those temperatures are the upper limit of electron–phonon coupling in general. Rather, they are upper limits of T_c in classes of materials represented by lead, niobium, and niobium–tin and vanadium–silicon alloys, and they have not exceeded the regime of validity of the McMillan equation. In particular, McMillan does not exclude higher T_c in other classes, provided that λ does not exceed 2 in his equation.

Specifically, McMillan realizes that T_c from his equation declines when, on average, the phonon frequency becomes either too large or too small and searching for maximum T_c leads to $\lambda = 2$. Since in 1968 it was believed that $T_c = 7.2$ K and $\lambda = 1.3$ in Pb, McMillan concludes that T_c may reach 9.2 K in a Pb alloy when $\lambda = 2.8$. In that case, T_c was found numerically and therefore was not subject to the $\lambda < 2$ limit. Had, say, McMillan found $T_c = 203$ K with $\lambda = 1.3$ from a material in his day, he likely would have concluded that T_c could be higher still in a similar material with $\lambda = 2.8$.

In recent work,[2] we extended the McMillan equation for $0.6 < \lambda < 2.67$. We found that the original McMillan equation is indeed highly accurate if $\lambda < 2$. We also predicted that T_c can reach ~44 K in a beryllium–lead alloy, when the Be to Pb ratio is 0.58 to 0.42 ($\lambda = 1$ and Debye temperature is 871 K). Our result may be useful to experimenters because it not only shows that T_c may be high in a class of alloys, but it also gives the exact composition of the alloy, hopefully without extreme pressure.

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The article by Warren Pickett and Mikhail Eremets on room-temperature superconductivity in hydrides had me thinking about the role of specific heat in superconductivity research.

Heike Kamerlingh Onnes and Gilles Holst reported in 1914 that "with respect to the specific heat, nothing peculiar happens" at mercury's superconducting transition,[1] which Kamerlingh Onnes had discovered three years earlier. Twenty years later, after technical advances in cryogenics and thermometry, Kamerlingh Onnes's former student, Willem Keesom, and J. A. Kok discovered a specific heat jump at the critical temperature T_c, without latent heat.[1] It was misinterpreted as a sudden drop in Debye temperature, which assumes phonons are the predominant contributor to specific heat, even though the free electronic model for electronic specific heat ($C_e = \gamma T$) had been proposed before then. It took almost another 20 years for the superconducting-state electronic specific heat (C_{es}) to be identified, but still erroneously concluded as having a T^3 dependence. Eventually, experimental data covering a wider (T_c/T) range confirmed the exponential-temperature dependence of its electronic origin.[2]

In their 1957 article, John Bardeen, Leon Cooper, and J. Robert Schrieffer opened with the statement, "The main facts which a theory of superconductivity must explain are (1) a second-order phase transition at the critical temperature, T_c, (2) an electronic specific heat varying as $\exp(-T_0/T)$ near $T = 0$ K and other evidence for an energy gap."[3] The rest is now history.

In my opinion, superconducting hydrides may provide opportunities for studying C_{es} in detail over an exceptionally broad (T_c/T) range. Intuitively, the near-room-temperature transition would make it impossible to delineate the electronic and the lattice contributions from total specific heat ($C = C_e + C_\ell$) being obtained calorimetrically. That appears to be a valid concern for cuprate superconductors with T_c near or above 90 K. In contrast, for metallic hydrogen with an exceedingly high Debye temperature[4] of approximately 3500 K, the lattice specific heat C_ℓ at 280 K can be estimated to be approximately 1 J/mol K. The same amount of normal-state $C_e = \gamma T$ would also prevail at 280 K if the coefficient $\gamma = 3.6$ mJ/mol K^2, which is comparable to that of many conventional superconductors.

The difficulty rests with the high-pressure aspect in calorimetric measurements. A standard pressure-cell approach was successfully employed on superconducting uranium some 50 years ago,[5] but only at 10 kbar. Researchers are designing and developing diamond anvil cells, but they face challenges regarding pressure limits and heat leak. However, as we look back, after 1911 it took more than 40 years of improving cryogenics and low-temperature calorimetry to finally reveal exponential-temperature dependence of C_{es}, which was important to the Bardeen-Cooper-Schrieffer theory. We now need to overcome another technical hurdle—in pressure instead of temperature.

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▶ **Pickett and Eremets reply:** X. H. Zheng and J. X. Zheng focus on McMillan's classic 1968 paper to address the decades-studied but unresolved question of maximum T_c. The last short section of his paper was on issues of maximum T_c. Though he carefully stated that his equation for T_c "was derived for $\lambda \leq 1$," he nevertheless extrapolated from it to consider possibilities for higher, and maximum, T_c. He recognized that λ and ω (the coupling strength and characteristic frequency) were coupled via the relation $\lambda = \eta/M\omega^2$ in terms of the McMillan–Hopfield electronic stiffness η (more often referred to as the Hopfield parameter), which indicates that λ and ω are strongly intertwined. Within a class of similar materials, it was conjectured, η might be considered to change very little, so one might consider $T_c(\eta,\lambda)$ without explicit dependence on ω. Conversely, one might consider $T_c(\eta,\omega)$. That approximation of constant η has been found, over the years, to be poor in several classes of materials, including hydrides.[1]

But having supposed that, McMillan reported that extrapolation of his equation outside the range of derivation indicated a broad maximum around $\lambda = 2$, or $\omega^2 = \eta/2M$. Studies conducted a few years after McMillan's, by Philip Allen and Robert Dynes,[2] established rigorous results, but their relevant result here is that the McMillan equation is *not* accurate around $\lambda = 2$ or greater (unlike the claim by Zheng and Zheng). It is widely understood, as pointed out by McMillan and again by Zheng and Zheng, that any "maximum T_c" is material class dependent.

We do not recommend using any T_c equation beyond that of Allen–Dynes to give realistic values of T_c, given the necessary input.

Jim Ho has emphasized the important role that the specific heat $c_V(T)$ continues to play in the understanding of superconducting properties. In 1957, $c_V(T)$ data recorded every 2–3 degrees,[3] and tabulated but not plotted, just missed showing the structure in $c_V(T)$ near 40 K in magnesium diboride that would have led to the discovery of its paradigm-breaking superconductivity. Instead it remained hidden until its discovery[4] in 2001. Specific heat is a crucial probe in the understanding of low-temperature superconductivity and of system changes as the superconducting state is entered.

Even in MgB_2, with $T_c \sim 40$ K, the signal in $c_V(T)$ at T_c is small because the lattice contribution grows so much more rapidly than the electronic contribution. In hydrides at T_c of 200–260 K, the signal relative to the lattice specific heat will be smaller still. Ho suggests that it may still be observable. More to the point, and recognized by Ho, the diamond anvil cells that are necessary to study very high pressure require a cell of size and mass orders of magnitude greater than the sample, so the signal due to the sample is difficult to obtain. Researchers have measured $c_V(T)$ to pressures[5] of 10 GPa, but the challenges in extending such measurements to the 200 GPa range are considerable.

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A powerful interferometer works by holding, not dropping, its atoms

After 20 seconds in an optical lattice, the gravitational potential-energy difference between two wavepackets separated by micrometers generates megaradians of phase.

Photons and atoms are both described by a wavefunction, whose phase defines a natural ruler that can be used for measuring fields and forces. But when made ultracold, atoms can offer far greater precision. They also have gravitational signals imprinted on their interference pattern, which can resolve changes in Earth's gravity to one part in 10^{11}. That's sensitive enough to detect such features as oil wells, caves, and tunnels; changes in the local water table; and glacial melting. (See the article by Markus Arndt, PHYSICS TODAY, May 2014, page 30.)

Conventional atom interferometers measure gravity by throwing atoms upward and watching them fall. Light pulses tuned to particular resonance frequencies in the atoms serve as beamsplitters and mirrors. The pulses deliver momentum kicks that split the atoms into two wavepackets, send them along separate paths, and then recombine them. At a detection port, the matter waves interfere according to the phase difference between the kicked and unkicked wavepackets—the two arms of the interferometer.

But that approach has two related limitations. An atomic fountain takes up a lot of space—the atoms are launched to a height of several meters in a vacuum. Even with such heights, the duration of the atoms' free fall, which determines the interferometer's sensitivity, lasts only a few seconds. In 2013 Stanford University's Mark Kasevich and collaborators reached a milestone, obtaining 2.3 seconds of interrogation time using a 10-meter fountain.[1] Work is now underway to build fountains measuring up to 300 m. But their sensitivity to vibrations, exacerbated by the increased height, requires elaborate inertial stabilization.

Holger Müller and his group (shown in figure 1) at the University of California, Berkeley, have now demonstrated an alternative method[2] that extends the interrogation time to as long as 20 seconds—the longest coherence time ever obtained for a spatially separated quantum superposition. The achievement came from holding the two wavepackets in an optical lattice after the matter waves were split and separated by light pulses. Without the lattice to hold the atoms against gravity, interrogating them for that long in free fall would require a vacuum system a half kilometer tall.

The Berkeley system takes just 1 meter of vertical space in the researchers' lab. The compact geometry makes it attractive for a mobile atomic gravimeter that can take data in the field. Indeed, Müller already has a project planned to place the system on a drone.

An optical lattice in an optical cavity

A schematic of the new interferometer is

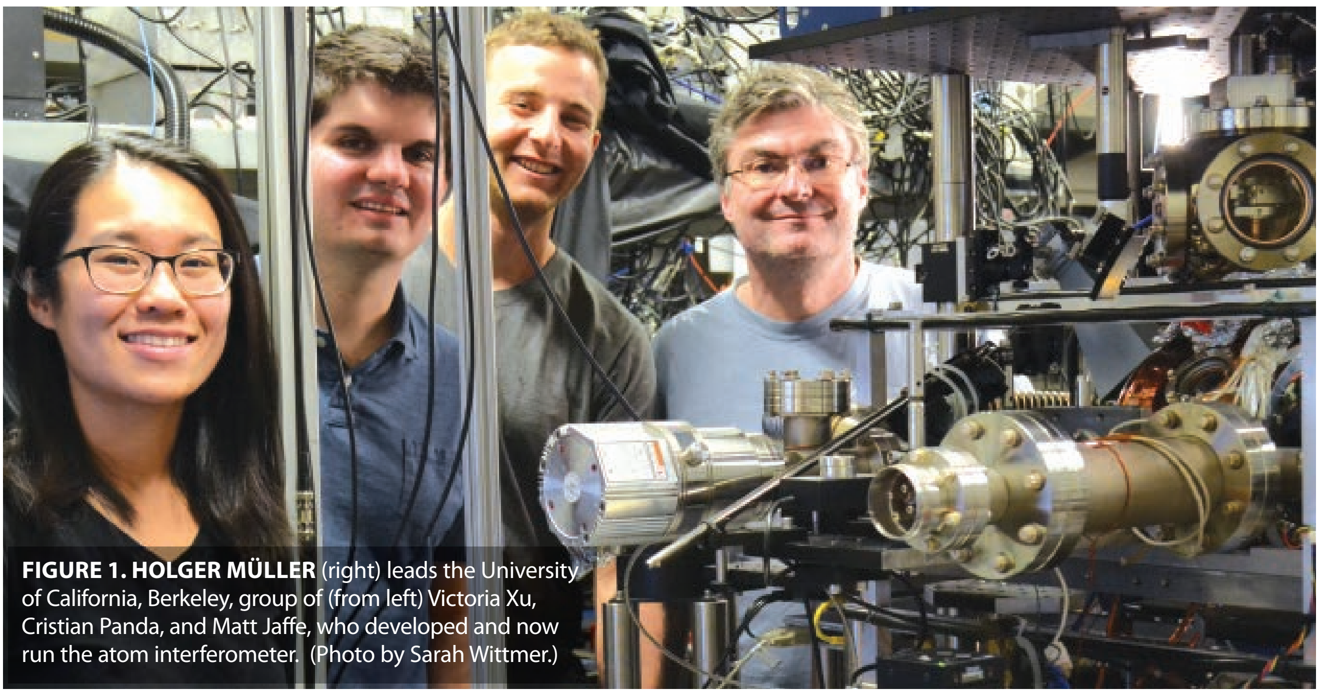

FIGURE 1. HOLGER MÜLLER (right) leads the University of California, Berkeley, group of (from left) Victoria Xu, Cristian Panda, and Matt Jaffe, who developed and now run the atom interferometer. (Photo by Sarah Wittmer.)

shown in figure 2. To make a gravity measurement, the researchers launch a cloud of cesium atoms chilled to 300 nK upward a few millimeters into the center of an optical cavity. As in conventional interferometers, the atoms can be steered in free fall by using Raman transitions: Two counterpropagating laser beams, whose frequency difference corresponds to a hyperfine transition, irradiate the atoms and transfer momentum to them, with each pulse's intensity tuned to kick the atoms with 50% probability.

Four of those $\pi/2$ pulses accompany the atom cloud through the interferometer. The first pulse places each Cs atom into a coherent superposition of two states—one that receives a momentum kick and one that doesn't. The two clouds form localized partial wavepackets traveling along distinct trajectories at different momenta, and the two trajectories form the upper and lower arms of the interferometer.

The second pulse provides another kick, designed to rematch the wavepackets' momenta as they continue rising. At their apex, an optical lattice is turned on to suspend the wavepackets in vacuum. In the lattice, only the two wavepackets' different heights and thus potential-energy difference in the gravitational field distinguish them. After a time t, a second pair of $\pi/2$ pulses steers the wavepackets so that they can interfere according to the phase difference accumulated between the upper and lower arms.

Placing a vertical optical lattice inside an atom interferometer isn't new. Yannick Bidel, now at the French aerospace lab ONERA, and coworkers built nearly the same configuration in 2012. So did Guglielmo Tino and his group four years later at the University of Florence. In both cases the optical lattice trapped the clouds of cold atoms, but imperfections in the free-space laser beams limited the interrogation times to just 0.1 seconds and 1.0 second, respectively.[3]

What makes the experiment so challenging—and the newly achieved 20-second hold time so astonishing—is that the trapping potential must be strong enough to overcome gravity but gentle enough to preserve the atoms' de Broglie–wave phase. Says NSF program director Alex Cronin, "Before this demonstration, I was skeptical that an atom interferometer could ever work with traps turning on and off in the middle of it." The trap has to grab the spatially separated components of each atom's wavefunction without ever changing its quantum state. "Catching matter waves midflight without scrambling their coherence is an exquisite example of quantum mechanical engineering," he says.

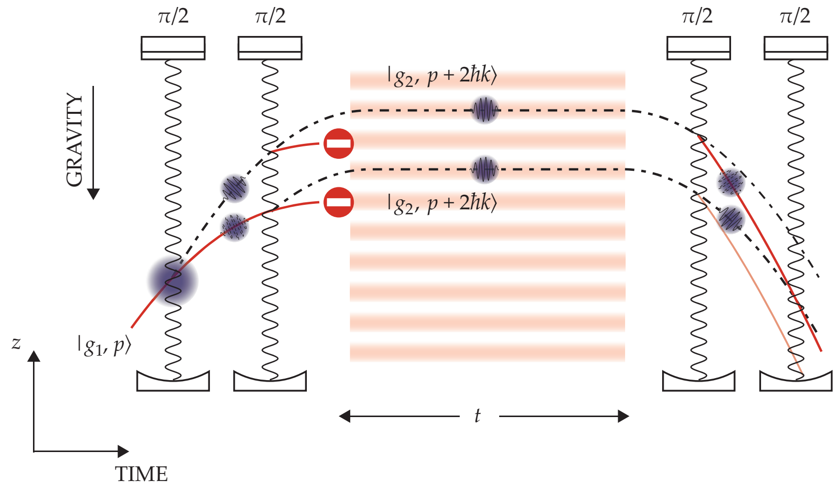

FIGURE 2. SPLITTING ATOMS. The Berkeley interferometer uses two pairs of so-called $\pi/2$ light pulses to manipulate a cloud of ultracold cesium atoms in an optical cavity. Each pulse splits the cloud and produces a superposition of entangled electronic and momentum states. The first pair divides the cloud into four distinct wavepackets and four potential paths (red solid and black dashed lines). The red paths are blocked, leaving two wavepackets at different heights but with the same ground state and momentum, $|g_2, p + 2\hbar k\rangle$. The second pair of pulses recombine the wavepackets so that they interfere and are detected. At the apex, atoms are held for a time t in an optical lattice formed by the mode of an optical cavity and detuned far from resonance with any atomic transition. (Adapted from ref. 2.)

Even at 300 nK, the atoms shake in the antinodes of the standing waves that hold them. To minimize the light scattering and avoid exciting any atoms above the ground state, the researchers detuned the frequency of their trapping lasers to 866 nm, far from any of the atoms' transition frequencies. Even so, a realistic laser beam can never generate an optical lattice with perfect translational invariance. To solve that problem they incorporated a key feature in their setup—an optical cavity that bounds the optical lattice between two highly reflective mirrors.

The marriage between atom interferometry and cavity optics was made four years ago by Müller, his then postdoc Paul Hamilton (now at UCLA), and his current postdoc Matt Jaffe[4] (see PHYSICS TODAY, April 2015, page 12), and the cavity's presence is paramount for achieving long coherence times. For one thing, the cavity mirrors spatially filter the trapping light because only the fundamental Gaussian mode of the cavity is resonant with it. The hundred or so reflections between the mirrors reinforce that mode and improve the uniformity of the optical traps. They also suppress the effect of laser speckle, mirror dust, and any other inhomogeneities in the laser's wavefront.

What's more, the reflections enhance the power of laser light in the cavity by some 40-fold. Years earlier the enhancement led to the group's discovery that gravity measurements could be made at a precision comparable to that of conventional atom interferometers but with far less power—milliwatts instead of watts. The lower power demand helps keep the system compact and reduces stray light generated at external lenses and mirrors that could otherwise distort the lattice sites.

Toward state of the art

Being able to sustain the coherence of the wavepackets for long times confers another advantage to the new interferometer: vibration suppression. Whereas atomic fountains measure the wavepackets' phase at just three positions—at the beginning of their trajectory, at their apex, and when they interfere—the Berkeley interferometer integrates the phase continuously as long as the atoms are suspended in the lattice.

The longer the hold time, the more the vibrations average out. The 20 seconds that Müller achieved reduces the interferometer's phase sensitivity to vibrations by up to four orders of magnitude. He was surprised to discover that as the lattice hold times kept increasing, his team stopped needing any vibration isolation.

Despite its advantages, the new device still falls short of state-of-the-art atom interferometers. In the Berkeley group's proof-of-principle demonstration, the gravitational potential-energy difference from just 4 μm of vertical separation generates 1.6 megaradians of phase accumulated in the two arms. But there's room to improve that performance. An interferometer's precision increases with both longer hold times and larger wavepacket separations.

The 4 μm separation between the arms was achieved using the momentum kick from just a single two-photon Raman transition. In a separate experiment, Müller and coworkers have demonstrated laser pulses strong enough to generate 10-photon momentum kicks and almost 9 mm of separation. No fundamental barrier limits increasing the separation and hold times, but maintaining the coherence of such large spatial superpositions remains a huge technical challenge.

The compact nature of the new interferometer makes it ideal for measuring short-ranged interactions, such as Casimir forces and those hypothesized to be responsible for dark energy. And the different nature of the new approach—holding atoms to probe the potential-energy difference rather than dropping them to measure accelerations—has Müller particularly intrigued.

Measuring the phase of atoms from different gravitational potentials but in a gravitational-force-free setting—for example, inside a spherical shell of uniform mass—would be tantamount to observing the gravitational analogue of the Aharonov–Bohm effect. The experiment, which Müller proposed with the University of Vienna's Anton Zeilinger in 2012, would constitute the first demonstration of a force-free gravitational redshift.[5] It would also provide a new measurement of Newton's constant G, the least accurately known fundamental constant in nature.

Mark Wilson

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A supercooled protein refolds unexpectedly

A small simulated peptide's structure is shaped by the surrounding water's anomalous dynamics.

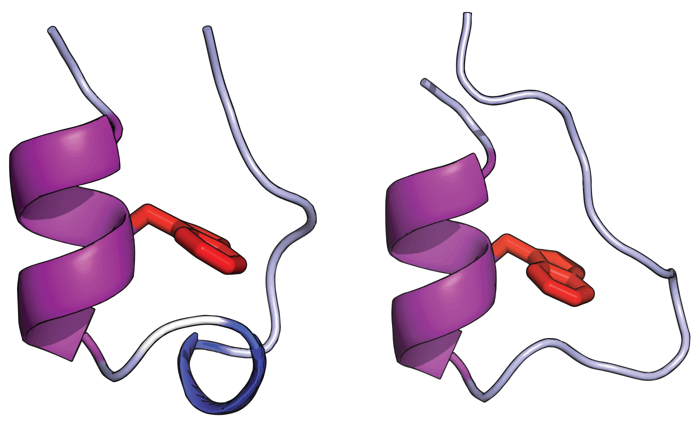

FIGURE 1. AMBIENT AND LOW-TEMPERATURE STRUCTURES for the protein Trp-cage reflect its cold denaturation. The α-helix (purple) remains stable, but the 3_{10}-helix (blue) seen at ambient temperatures unfolds at 224 K. A tryptophan amino acid (red) sits in the protein's core. (Adapted from ref. 1.)

Human bodies have a narrow range of temperatures at which they function properly. Proteins behave similarly: At ambient temperatures they fold as needed for their biological purposes, but if they get too hot or too cold, their structures unravel. The details of what happens to proteins away from their conformational sweet spot and how or why they denature could provide insight into how they manage to find their functional forms at physiological conditions in the first place.

Proteins found in nature don't exist in a vacuum, and the molecules surrounding them affect their behavior (see the article by Diego Krapf and Ralf Metzler, PHYSICS TODAY, September 2019, page 48). It's therefore not enough to consider only how interactions within a protein change with temperature; to fully understand a protein's behavior, the dynamics and structure of the solvent—typically water—must also be taken into account.

At the intersection of protein folding and water's molecular dynamics Daniel Kozuch, Frank Stillinger, and Pablo Debenedetti of Princeton University noticed something unexpected in their simulations.[1] Earlier work[2] led by Debenedetti had investigated the cold denaturation of Trp-cage, a 20-amino-acid model protein, in liquid water supercooled to 210 K. Those simulations, as expected, had shown a peak in the fraction of folded proteins at room temperature followed by a steep drop-off as the temperature decreased. But when the researchers lowered the temperature even further in their latest study, they found a surprising result: At 194 K, the proteins refolded.[1]

The well-tempered ensemble

Experimental studies of protein folding

are challenging because of the short length and time scales on which the folding occurs (see PHYSICS TODAY, October 2019, page 21). Molecular dynamics simulations and theory—the tools employed by Debenedetti's group—are therefore indispensable because they can provide otherwise inaccessible details.

Fast folding may be an impediment for experiments, but it's a boon for simulations because it makes them more time efficient and less computationally expensive. Trp-cage, illustrated in figure 1, normally folds in less than 4 μs, which is relatively fast. For comparison, melittin, a similarly sized protein, folds on millisecond time scales.

Molecular dynamics simulations mimic the stochastic motion of a physical protein; they evolve a protein from an initial to a final configuration by navigating through the protein's free-energy landscape and finding a global minimum. Each computational step represents a small, random physical fluctuation in the protein's conformation that happens on the femtosecond time scale. But a protein's free-energy landscape is vast and complex. If the simulated protein randomly explored that entire space in femtosecond steps, it would take an impractically long time to find its final state.

To bridge the gap between experimental and simulation time scales, computational scientists use enhanced sampling methods that guide the protein's steps through the free-energy landscape to help it explore more efficiently.[3] In their 2016 paper on simulating Trp-cage, Debenedetti and his group used parallel tempering—a technique originally developed to deal with slow dynamics in simulations of low-temperature spin glasses—to sample the protein's conformational states. Also known as replica exchange molecular dynamics, parallel tempering helps the evolving protein access more states by running multiple copies of the simulation simultaneously and by periodically exchanging configurations at different temperatures. Basically, it helps each copy avoid getting stuck.

Parallel tempering enabled the researchers to simulate the protein at temperatures down to 210 K. But, says Debenedetti, "at low enough temperatures it was just impossible to equilibrate the system in reasonable times." Thermal fluctuations had just gotten too small. He and his collaborators therefore turned to an enhanced version of parallel tempering that employs the well-tempered ensemble.[4] The updated technique reweights configurations to help the simulated protein overcome large free-energy barriers in fewer, more efficient steps.

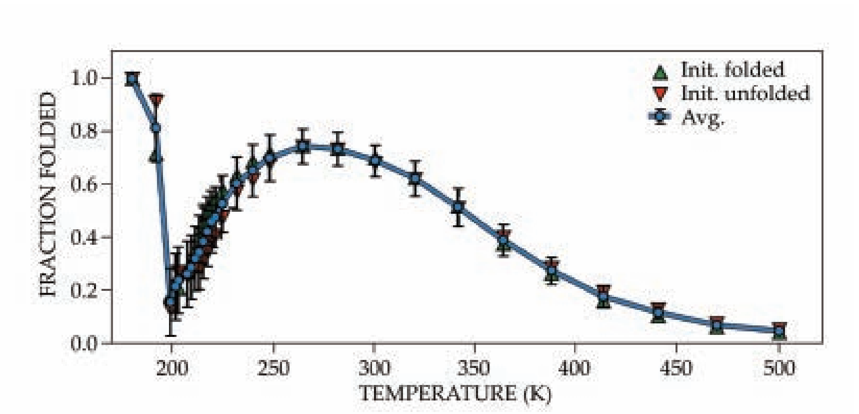

FIGURE 2. LOW-TEMPERATURE REFOLDING OF SIMULATED TRP-CAGE occurs below 200 K as the surrounding water molecules become increasingly tetrahedrally coordinated. Above that temperature, the simulated protein behaves as expected: The fraction of proteins in folded states peaks at ambient temperature decreases as the protein gets too hot or cold. (Adapted from ref. 1.)

Protein variations

Debenedetti's previous study of the cold denaturation of Trp-cage showed the unfolding of the small helix (blue) shown in figure 1. The process was quantified by the average distance between the protein structure and a reference structure, the latter determined by NMR. If the distance was less than 0.3 nm, the protein was deemed folded; otherwise, it was considered unfolded.

Proteins are known to denature at low temperatures, so that result wasn't a surprise; the researchers were focused on delineating the protein's low-temperature thermodynamic properties, such as the free energy of unfolding and the heat capacity. But when Kozuch and coworkers looked at the fraction of folded proteins at even lower temperatures, things unexpectedly changed. The cold denatured configuration from the previous simulations appeared again, but at the lowest temperatures the folded fraction quickly increased, from around 10% at 200 K to nearly 100% at 180 K, as shown in figure 2.

The results of Kozuch's simulations were initially met with skepticism. "I really pushed back," says Debenedetti. "This study took a long time. I had Daniel repeat the calculations many times." But the results were robust. That the protein arrived at the same state regardless of whether it began folded or unfolded confirmed that the result reflected the underlying energy landscape and was not just an artifact.

The supercooled folded structure was remarkably similar, though not identical, to that at ambient temperature. Water molecules hydrated the folded protein's core at room temperature, whereas the supercooled structure had a more compact hydrophobic core.

To seek an explanation for that structural difference, the researchers turned to the surrounding water molecules. Unlike most liquids whose densities increase as they get colder, water reaches its maximum density at 4 °C and then becomes less dense with cooling. The formation of short-lived hydrogen bonds at low temperatures generates transient connections between molecules, thereby increasing the average volume per molecule. By the time water reaches its minimum density, nearly all of the molecules are tetrahedrally coordinated. In the simulations, water's minimum density and the protein refolding occurred synchronously at 195 K. (For more on the unusual behavior of supercooled water, see the article by Pablo Debenedetti and Gene Stanley, PHYSICS TODAY, June 2003, page 40.)

It's no accident that the protein's cold refolding coincided with water's evolution to that low-density state. The researchers attribute the compact core's formation to water's increased order. Although the simulated water remained liquid and had no long-range order, on short length and time scales, the molecules were tetrahedrally coordinated. Solvating the protein's core would have disrupted that order, so instead the water was expelled; hence the core's collapse. Water's role in reforming the helix is less clear, but it's likely a factor. "Biology happens in water," points out Debenedetti. "I would be really surprised if water played no role."

Aqueous oratorio

Accurately capturing water's low-temperature dynamics is a challenge. Many computational models for water exist, and although none are perfect, the TIP4P/2005 model used by Kozuch and coworkers is considered one of the best among classical models. It still has its shortcomings; for example, it places the water's ambient-pressure melting temperature at 252.1 K, more than 20 K below its actual value. That means the researchers' simulations at 200 K are actually only 52 K below freezing, not 73 K. But, importantly, the model has been shown to capture much of water's known behavior—particularly its anomalous dynamics far from ambient conditions—and its complex crystalline phase diagram.

The researchers knew water could influence the protein's behavior, which is why they wanted to capture its dynamics as accurately as possible. In fact, Debenedetti originally wanted to study how Trp-cage's behavior would change around a liquid–liquid phase transition that has been seen in previous simulations of water.[5] But simulating the protein at the low temperature and high pressure necessary to reach that transition was unexpectedly difficult because the system took an extraordinarily long time to equilibrate. Luckily for the researchers, decreasing only the temperature was enough to uncover unexpected and intriguing behavior.

Although proteins don't run the risk of becoming supercooled *in vivo*, the simulated temperatures and cooling rates are physically relevant for preparing cryo-electron microscopy and cryopreservation samples. Now that they know where to look, the researchers are repeating their calculations on other proteins to see whether the refolding effect is more general.

Christine Middleton

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Twisted bilayer graphene enters a new phase

Improved device quality is the key to seeing a whole series of superconducting, correlated, and magnetic states in two layers of graphene assembled at a magic angle.

For years many graphene researchers pursued superconductivity. In 2018 Pablo Jarillo-Herrero of MIT and his colleagues found it in so-called magic-angle bilayer graphene (see PHYSICS TODAY, May 2018, page 15). A single layer of graphene, a two-dimensional sheet of carbon atoms, is not superconducting on its own. But two sheets (blue and black in figure 1) vertically stacked at just the right, "magic" angle θ—about 1.1° with respect to each other—have a superconducting transition around 1.7 K.

Now Dmitri Efetov of the Institute of Photonic Sciences in Barcelona, Spain, and his colleagues have replicated Jarillo-Herrero's results and discovered a rich landscape of competing states in magic-angle graphene.[1] By preparing a more homogenous device, Efetov's team could establish and resolve previously hidden electronic states.

Quest for superconductivity

Researchers long suspected graphene could have correlated states, described by collective rather than individual charge-carrier behavior. Those states, such as superconducting and Mott insulating states, are likely to occur in materials with many electrons sharing the same energy. Such conditions occur in flat regions of the band structure—around a saddle point, for instance. Monolayer graphene has a saddle point in its band structure, but it's several electron volts higher in energy than the Fermi level, the highest occupied state of the material. Raising the Fermi level up to the saddle point isn't feasible with an applied voltage alone. In his graduate work from 2007 to 2014 with Philip Kim, then at Columbia University and now at Harvard University, Efetov tried electrolytic gates, and other groups investigated intercalation to reach higher levels of charge-carrier doping. But none quite reached the saddle point.

A different route to correlated behavior[2] was proposed by Rafi Bistritzer and Allan MacDonald at the University of Texas at Austin back in 2011. Two layers of graphene at different relative angles form a quasiperiodic structure, or moiré lattice, at a larger length scale than graphene's lattice constant—see the larger hexagons in figure 1, in which the graphene sheets nearly align at their centers and increasingly misalign toward their edges. The periodicity of the moiré lattice tunes the band structure from that of independent monolayers for large angles to that of normal bilayer graphene, which is also not superconducting, when the layers are aligned.

For two layers of graphene misaligned by 1.05°, the largest of a series of magic angles, Bistritzer and MacDonald calculated the emergence of a flat horizontal band, which varies by less than 10 meV as a function of momentum. More importantly, the flat band was at the Fermi level. In effect, the creation of a moiré lattice in bilayer graphene drags the high-energy saddle point from monolayer down to an accessible energy.

Jarillo-Herrero and colleagues assembled twisted bilayer graphene devices with relative angles near 1.1°. They first observed insulating behavior below 4 K. Although the density of states doesn't have a gap, the strong interaction between charge carriers keeps them from moving. At even lower temperatures, increasing or decreasing the number of charge carriers leads to superconducting states. Those states can be summoned in and out of existence by changing either the angle between the graphene sheets during assembly or the charge-carrier density with an applied voltage.

Beyond that tunability, magic-angle graphene's superconductivity is interesting because the transition temperature's relationship with the carrier density—the so-called superconducting dome indicated by orange dashed lines in figure 2—resembles that of high-T_c cuprates. Magic-angle graphene could serve as a convenient platform for studying unconventional superconductivity.

Since Jarillo-Herrero's paper came out, other groups have tried their hands at making twisted graphene devices. Four groups performed scanning tunneling spectroscopy on magic-angle graphene to visualize the moiré lattice and measure the density of states in the flat band.[3] Cory Dean of Columbia University and his colleagues applied more than 1 GPa of hydrostatic pressure to induce superconductivity in a twisted bilayer device with a larger twist angle of 1.27° that did not otherwise show any correlated behavior.[4] Feng Wang of the University of California, Berkeley, and his colleagues found superconductivity in twisted trilayer graphene.[5] In the busting field of twisted bilayer graphene research, Efetov has produced the most uniform magic-angle graphene to date and thus measured many previously unobserved correlated states with diverse properties.

Improving the device

The group's thorough electrical phase diagram of magic-angle graphene was largely possible through the development of improved devices, which were fabricated by Efetov's postdoc Xiaobo Lu. In a normal layer of graphene, the electrical mobility is limited by impurities. In twisted bilayer graphene, an additional impediment comes from local variations in the angle, which broaden the features in electrical measurements and obscure small energy gaps. A sample with a more uniform angle will reveal behaviors not distinguishable in measurements on other devices.

To realize the magic angle, Lu uses the established tear-and-stack technique: He tears one sheet of graphene in two. He then rotates one piece just past the magic angle, by about 1.2°, to account for the small decrease in the angle when the layers settle. He then stacks the rotated layer on top of the other. In most electrical devices, the final step is annealing to clean the sample and get rid of any air bubbles between the layers. But in magic-angle graphene, with the layers misaligned by such a small angle, heating the sample snaps the layers back into alignment. So instead of annealing, Lu rolls the top layer down gradually, starting from one edge, rather than dropping the second layer directly down onto the first. That method, called mechanical cleaning, squeezes out any air bubbles as they form.

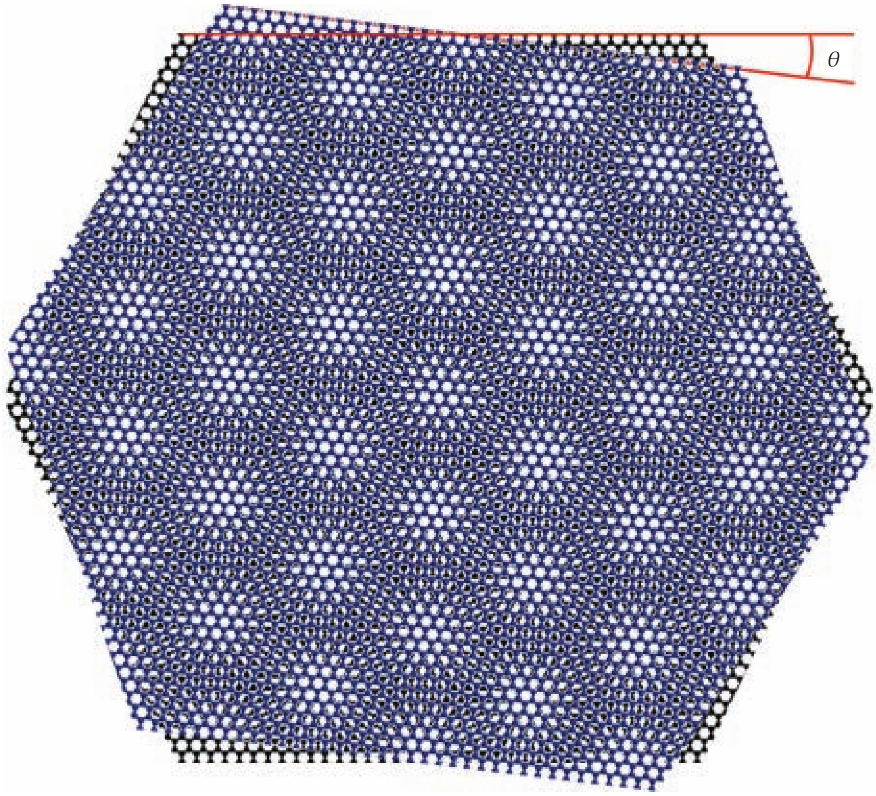

FIGURE 1. THE MOIRÉ LATTICE from two layers of graphene (blue and black hexagonal patterns) is the larger quasi-periodic hexagonal pattern formed by regions where the graphene lattices nearly align. The relative angle θ between the layers determines the periodicity of the moiré lattice. (Courtesy of ICFO/Xiaobo Lu.)

Mechanical cleaning hadn't been used for magic-angle graphene before because it frequently causes the twist angle to deviate from the intended angle. But Efetov regards the higher failure rate as worth the better device quality. The result is a relative angle that varies by only 0.02° over a 10 μm device, a record for magic-angle graphene. The fabrication overall is tricky; in the first three months, just 2 of the 30 devices worked. Now their success rate is closer to 20%.

Counting the states

Efetov and his group measured the electrical resistance over a wide range of charge-carrier densities and were surprised to find a host of states, shown in figure 2. When the device had a carrier density of about -2×10^{12} cm^{-2}, below the charge neutral point, they saw the same superconducting state as Jarillo-Herrero, plus three new superconducting states at carrier densities as low as 0.5×10^{12} cm^{-2}, a record low absolute value for a super-

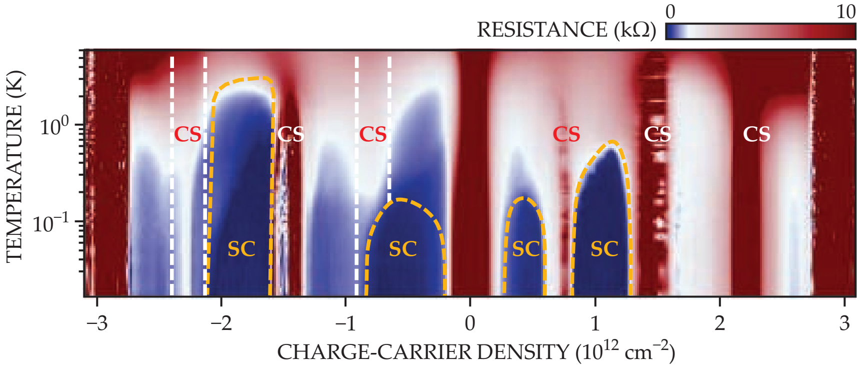

FIGURE 2. IN THIS ELECTRICAL PHASE DIAGRAM of magic-angle graphene, the orange dashed lines indicate the 50% resistance value of the phase transition to a superconductor (SC) with the highest transition temperature of 3 K. Between the SC states, the magic-angle graphene is in a correlated state (CS). (Courtesy of ICFO/Xiaobo Lu.)

conducting state. For the original superconducting state, Efetov and his colleagues found a nearly two times higher transition temperature, 3 K, than previously reported—perhaps due to their improved sample quality. The three new superconducting states had much lower transition temperatures in the hundreds of millikelvin.

At charge-carrier densities between all superconducting regimes, magic-angle graphene showed resistance peaks from correlated states, such as the insulating behavior Jarillo-Herrero saw. Three of the correlated states were insulating, and three seemed semimetallic. Two of the noninsulating states were also topologically nontrivial: A charge carrier that traveled in a closed loop in the band structure wouldn't return to its original state. The topological states were characterized by invariants, known as Chern numbers, of 1 and 2. (For more on Chern numbers, see the article by Joseph Avron, Daniel Osadchy, and Ruedi Seiler, PHYSICS TODAY, August 2003, page 38.) The correlated states occurred whenever the carrier density supplied an integer number of carriers, from one to four, for each moiré unit cell (the larger hexagons in figure 1). Those densities correspond to filling each of the four valence and four conduction bands; the eight bands arise from lifting the valley and spin degeneracies.

Efetov and Lu also found a ferromagnetic state, similar to one observed previously by David Goldhaber-Gordon of Stanford University.[6] With the application of an external magnetic field, monolayer graphene and magic-angle bilayer graphene exhibit the Hall effect. The conventional Hall resistance varies linearly with the magnetic field, but some materials show a hysteresis loop from the anomalous quantum Hall effect, which indicates magnetization of the material. After the application of a large enough field—3.6 T—magic-angle graphene shows a combination of conventional and anomalous Hall effects and thus has an induced magnetic state. Most magnetic states arise from the spin of the charge carriers, but twisted bilayer graphene's magnetism is from the orbital angular momentum.

The outstanding question is, what are the mechanisms behind all the superconducting and correlated states? Electron–electron interactions can't account for all of them. Electron–phonon interactions could explain magic-angle graphene's superconductivity, but its proximity to correlated insulating states suggests a more exotic pairing mechanism. Efetov plans to shed light on the correlation mechanisms by investigating how the varied states' behaviors change due to the dielectric environment around magic-angle graphene. If a change in the surrounding dielectric function kills the superconducting state but not the correlated insulating states, they arise from different mechanisms. Says Efetov, "There will be a lot of surprises in the next year."

Heather M. Hill

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Controversy continues to swirl around uranium enrichment contract

A little-used nuclear fuel may be the foot in the door for a US company hoping to snag a far bigger prize.

The chairs and ranking members of two House Science, Space, and Technology subcommittees have asked the Department of Energy to justify the October award of a $115 million contract to Centrus Energy to demonstrate technology for producing a specialized nuclear fuel for advanced reactors. The bipartisan quartet questioned DOE's decision to bypass competitive bids for the work; expressed skepticism over the need for the fuel, known as high-assay low-enriched uranium (HALEU); and asked why DOE's civilian nuclear program was tapped to pay for a program that ultimately will be of far greater benefit to defense applications.

HALEU is enriched in isotope uranium-235 up to 19.75%—just below the 20% threshold that defines highly enriched uranium (HEU). Some designs for advanced reactors would require enrichment levels above the 4–5% that fuels the existing fleet of US commercial reactors.

DOE insists that Centrus is the only company qualified to produce the HALEU because it is owned and operated by a US entity and will use a domestically developed enrichment technology. Under existing US regulations, that qualifies Centrus HALEU to be used in advanced reactors that may be acquired by the military, the agency's notice of award said. No domestic-origin requirements are necessary for uranium that is used for civilian purposes.

"We note that the entire decision to issue the award to Centrus on a sole-source basis seems organized around outcomes that would advantage the Department of Defense exclusively, which has neither contributed financially to the demonstration nor articulated a formal requirement or needs assessment concerning HALEU," the lawmakers said in their 13 November letter to then Energy secretary Rick Perry and his successor Dan Brouillette. The letter was signed by Representatives Mikie Sherrill (D-NJ) and Ralph Norman (R-SC) of the subcommittee on oversight and investigations and Conor Lamb (D-PA) and Randy Weber (R-TX) of the subcommittee on energy.

A DOE spokesperson said the department will respond to the lawmakers' questions. The spokesperson did not reply to PHYSICS TODAY's questions about the contract award, and Daniel Poneman, Centrus president and CEO, declined to be interviewed. Poneman, who was deputy energy secretary from 2009 to 2014, has argued previously that the US should not become dependent on foreign sources of uranium for its defense needs. Further, he has said nonproliferation policy requires a strict divide between civilian and military programs and materials.

In a response to emailed questions from PHYSICS TODAY, a Centrus spokesperson said that the company has invested $3 billion in shareholder funds to develop the centrifuge technology and will incur a loss in performing the new contract. DOE's support for the company's technology "reflects its unique importance to meeting US national security and nonproliferation requirements as well as advancing American nuclear leadership," she wrote.

The Centrus contract calls for construction of a small demonstration plant with 16 of its AC100M centrifuges by October 2020 and production of a "small quantity" of HALEU by September 2021. In budget documents for fiscal year 2020, DOE says it will not pay for any subsequent expansion of the plant's capacity.

In parallel, however, DOE's National Nuclear Security Administration (NNSA) formalized plans last year to acquire a far larger uranium enrichment plant to produce both LEU for tritium production and eventually HEU for naval propulsion reactors. Although the NNSA hasn't formally requested proposals from industry, Centrus is considered the leading contender for that plant because of domestic-origin requirements. The agency said it would decide by the end of 2019 whether to use the AC100M or a smaller centrifuge in development at Oak Ridge National Laboratory. No announcement had been made at press time.

In a 2015 report to Congress, the NNSA said a plant meeting defense enrichment needs would require 1660 centrifuges and cost anywhere from $3.1 billion to $11.3 billion. The 2015 report found there was sufficient LEU on hand to meet NNSA tritium requirements until at least 2038 and enough HEU to meet naval reactor needs until 2064 (see PHYSICS TODAY, March 2019, page 28). The Government Accountability Office has said the NNSA cost estimates don't meet GAO reliability standards.

Conflicting interpretations

The Defense Department is expected early this year to solicit industry proposals to

CENTRUS ENERGY

CENTRUS ENERGY'S 120-centrifuge uranium enrichment demonstration plant was in operation from 2013 to 2016 in Piketon, Ohio. The 12-meter-tall AC100M centrifuges have been decommissioned, but Centrus has continued developing the technology under contract with the Department of Energy.

build a prototype of a portable advanced reactor for powering remote military bases that now require periodic fuel deliveries. Such compact reactors are expected to require HALEU fuel. But the fact that DOD has dedicated no funding to microreactors to date "is a strong indication that [DOD] does not have a near-term need for HALEU to support any defense applications," the four lawmakers wrote.

US policy stipulates that uranium used for any military purpose, including nuclear fuel, must be enriched using US-origin technology. A corollary would seem to require that all US commercial reactor fuel be enriched using US technology, since US military bases draw power from a commercial grid that gets nearly 20% of its power from nuclear plants. But in fact, two-thirds of the uranium supplying US commercial reactors in 2018 was enriched abroad, much of it in Russia.

The Nuclear Energy Institute, an industry trade group in the US, estimated in 2018 that industry would require 53 tons of HALEU by 2025 and 590 tons by 2030. But the lawmakers noted that the only advanced reactor design presently undergoing US licensing approval—that of NuScale Power—doesn't need HALEU, and it isn't even expected to achieve commercial operation until 2026. Advanced reactor designs requiring HALEU are "extremely unlikely" to need a supply of HALEU in the time frame spelled out in the Centrus award, they said.

The last Cold War–era enrichment plant was permanently closed by Centrus's bankrupt predecessor in 2013. Since then, no domestic enrichment plants have employed US-developed technology. Centrus now is a uranium broker to nuclear utilities. Its main source of enriched uranium is the Russian state-owned TENEX.

The sole enrichment plant in the US today is operated by Urenco, which is owned by a Dutch-German-UK consortium that developed its centrifuge technology abroad. No one currently enriches HALEU commercially, but Urenco announced plans last year to add HALEU capability to its New Mexico plant. The Urenco partner governments have said their 1995 agreement with the US does not prohibit the company from providing HALEU for military reactors or LEU for tritium production. The agreement does limit Urenco's uranium product to "peaceful non-explosive purposes," but it doesn't cover tritium. It's worth noting that tritium, a vital component of all US nuclear weapons, is produced in a civilian reactor as a by-product of electricity generation. That arrangement crosses the purportedly red line between weapons and civilian nuclear facilities.

Unlike DOE, the Pentagon apparently hasn't dismissed the possibility of using Urenco HALEU. A 2018 report commissioned for the US Army noted that for a "modest- to large-scale deployment" of portable reactors, Urenco is the lowest-cost HALEU source. Urenco has estimated the up-front cost to meet HALEU demand at $300 million to $500 million, and company officials told the army that production could begin in five to seven years. DOE's timeline for a new enrichment plant with sufficient capacity to meet anticipated demand for those reactors is in the late 2030s or later, the army report stated.

Although adjustments to the agreement between the US and Urenco governments would be required, "it is possible however, that the [Urenco] owners could approve fuel enrichment to support military electrical power production," the report said.

In the July–August 2019 issue of *Arms Control Today*, Frank von Hippel and Sharon Weiner noted that the strict US interpretation of the peaceful-use restriction was established in 1998, when the US still operated enrichment plants employing domestic technology. The authors said that the production cost of LEU for the proposed NNSA plant would be up to 40 times as much as the current market price. The authors also noted that the Dutch and UK governments and the two German utilities that own Urenco have expressed interest in selling the company, which had an estimated market value of $10 billion in 2013. That's within the upper bound of the NNSA's cost estimate for a new plant that would have only 1/50 of Urenco's enrichment capacity. And those estimates don't allow for the large cost overruns that typically occur on DOE nuclear facility construction.

Other supply options

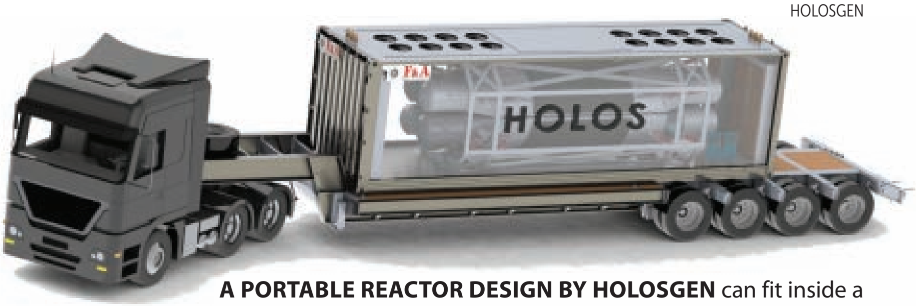
In a report last year, DOE's Nuclear Energy Advisory Committee (NEAC) was sharply critical of the agency for reallocating $23 million in FY 2019 funding from the nuclear energy research program to pay for the Centrus plant. That decision left only $10.6 million for academic research on the nuclear fuel cycle last year. The funding cut occurred just prior to the due date for academic research proposals, after "massive efforts" had been expended on proposal preparation, the committee said.

The report said other "very promising routes" could provide HALEU. DOE has set aside a portion of its surplus of HEU to be diluted to HALEU. By 2023 the agency plans to recover another 5 tons of HALEU in spent fuel from a decommissioned experimental breeder reactor in Idaho. And Congress appropriated $20 million in FY 2019 to recover HEU from spent naval reactor fuel stored in Idaho for potential conversion to HALEU. The NEAC report also suggested that 34 tons of surplus weapons-grade plutonium slated for disposal under a bilateral agreement with Russia could be diluted to provide the equivalent of 170 tons or more of US-origin HALEU. DOE plans instead to render the plutonium unusable and store it permanently at its Waste Isolation Pilot Plant in New Mexico.

Terms of the award call for Centrus to match 20% of the federal funding, the lawmakers' letter stated, in apparent contravention of 2005 legislation that requires no less than a 50–50 share.

David Kramer

HOLOSGEN



A PORTABLE REACTOR DESIGN BY HOLOSGEN can fit inside a standard shipping container and generates 13 MW of power for 12–20 years. The reactor would use high-assay, low-enriched uranium containing up to 15% ^{235}U.

Reevaluating teacher evaluations in higher education

Relying on students to rate professors is convenient, cheap, and problematic.

For decades student evaluations have been the mainstay of attempts to measure the quality of teaching at colleges and universities across the US and beyond. Now, as part of a growing focus on teaching in higher education, and because of mounting evidence of student biases, those evaluations are increasingly in the crosshairs. A smattering of institutions have begun revamping their approaches to student evaluations of teaching (SETs), and those independent efforts are fueling momentum on a national scale.

SETs have become the norm in higher education because they are convenient and cheap. The questions and scoring vary by discipline and institution, but typically before they see their final grade, students are asked to fill out a survey about the course and the instructor. Department heads or other campus officials calculate averages and often compare a given teacher's ratings to others' in the department and across the institution. The ratings inform promotion and tenure

DOUGLAS WARD/UNIVERSITY OF KANSAS

FACULTY MEMBERS BRAINSTORMED how to improve teaching and teaching evaluations last April in Boulder. Gabriela Weaver (in turquoise), Ann Austin (in purple), and Noah Finkelstein (with fingers at the board) are principal investigators on a multi-institutional, cross-disciplinary project that looks at teaching effectiveness.

decisions and are often the deciding factor in renewing teaching contracts for instructors who are not on the tenure track (see PHYSICS TODAY, November 2018, page 22).

The trouble is in what the ratings say—or don't. In 2009 the faculty union at Ryerson University in Toronto filed a grievance with the university over SETs being an unfair measure of teaching effectiveness. Last year, an arbitrator ruled in the faculty's favor: Student evaluations at Ryerson can no longer be used to assess teaching effectiveness for high-stakes decisions such as tenure and promotion.

The case could prove to be a harbinger. Traditional SETs will become illegal, predicts Carl Wieman, a physics Nobel laureate at Stanford University and a leader in science, technology, engineering, and math (STEM) education studies. "It will be hard for an institution to say they are still collecting SETs but not using them in tenure and promotion decisions," he says. University of California, Berkeley, statistics professor Philip Stark, who was an expert witness in the Ryerson case, says class-action suits are in the works. "SETs don't measure teaching effectiveness; you can't make a course better with the information that comes in. They are biased. There are all sorts of problems."

STUDENT EXPERIENCE SURVEY, SAMPLE QUESTIONS

(provided by the University of Oregon Office of the Provost)

The inclusiveness of this course is:

- ☐ Beneficial to my learning
- ☐ Neutral
- ☐ Needs improvement to help my learning

The opportunities for student interaction in this class are:

- ☐ Beneficial to my learning
- ☐ Neutral
- ☐ Needs improvement to help my learning

The clarity of assignment instructions and grading is:

- ☐ Beneficial to my learning
- ☐ Neutral
- ☐ Needs improvement to help my learning

The degree to which the course includes active learning is:

- ☐ Beneficial to my learning
- ☐ Neutral
- ☐ Needs improvement to help my learning

"Garbage in, garbage out"

Study after study has shown that SET responses are biased. In physics, female instructors are often rated 7–13% lower than males, notes physicist Noah Finkelstein, codirector of the Center for STEM learning at the University of Colorado Boulder (CU). Similar patterns are observed in other STEM fields. The degree of disparity varies by discipline, course, level, institution, and other factors, but across the board SETs penalize women, underrepresented minorities, nonnative English speakers, and older and physically less attractive instructors of both sexes. SET ratings are affected by the condition of the classroom, the time of day a course takes place, and other things that are outside the instructor's control, says Stark. The strongest correlation with high ratings is expectations, he adds. "If students go in thinking they will get a good grade, they give higher evaluations."

Most traditional SETs include broad questions like, "How would you rate the quality of the course overall?" and "How would you rate the quality of the instructor overall?" Such questions are coming under increasing criticism because the responses are frequently biased and unactionable—instructors don't glean ideas about how to improve their teaching. Some responses are even abusive. "That type of question offers up a vacuum to fill," says Richard Taylor, physics chair at the University of Oregon, "and encourages whatever biases students have, implicit or explicit."

Students have written, for example, "the teacher is a crybaby," and "I would rather watch my mother's head be cut off and her hair used to mop up the blood than take another class with [instructor's name]." Such comments take an emotional toll, the instructors who received them say. They also note that instructors can feel pressured to inflate grades in a bid for better ratings. (These two examples are from large STEM classes at a research-intensive university; the instructors requested anonymity because of concern about renewing their contracts.) Some departments remove incendiary comments before the instructor sees them.

Even specific questions are often misguided, argues Stark. Students are not the right people to ask about the effectiveness of a course or whether an instructor fostered an atmosphere that is consistent with campus goals for inclusion, he says. "They can't judge that. I've seen questions on whether the instructor has mastery of the material. How on Earth would a student know that?" Finkelstein agrees: "We are asking students the wrong questions and using the data badly."

Most institutions employ a numerical rating system, and it's common to evaluate teaching based only on the broad questions; some research-intensive universities ignore teaching altogether in evaluating faculty. The numerical rating approach itself is flawed. For starters, notes Wieman, students have a tendency to go down the list and check off the same score for every question. And, says Stark, "averages of categorical material are meaningless and misleading. Reporting distributions would be preferable."

Arguments about the numbers were a big part of the Ryerson grievance case. "Things went downhill when the surveys went online," says Sophie Quigley, the computer science professor who filed the case on behalf of the faculty union. The university began dicing the numbers in new ways, she says. "The math was bad." For example, in some cases the averages were not even calculated properly. What's more, she notes, the student response rate took a dive, and those students who chose to respond are self selected, and may be motivated by disgruntlement with the course or instructor. Says Quigley, "It was garbage in, garbage out."

Ideally teacher evaluations could be used both for students to give voice to their opinions and for teachers to improve their teaching. "But the data don't correlate with anything you care about," says Wieman, "not learning, teaching, or good teaching methods." And, he adds, the SETs make faculty afraid to switch to more innovative teaching methods because the evidence shows that student ratings initially drop when instructors try new approaches. "Everybody knows SETs don't have validity, but they are the only evaluation people have."

Fairer approaches

Concerns about measuring teaching effectiveness, improving teaching, and mitigating bias are prompting institutions to rethink their approach to evaluating instructors. Academia has more robust ways to evaluate faculty members' research activities, including grants obtained, papers published, PhD students graduated, invited talks, and the like, says Gabriela Weaver, a chemistry professor and special assistant to the provost for educational initiatives at the University of Massachusetts Amherst. "If we want to measure how people teach, the measure should correlate with student learning," she says.

With three principal investigators at other institutions, including CU's Finkelstein, Weaver is conducting a cross-disciplinary project to test different approaches to measuring teaching effectiveness. In the NSF-funded project, called "Transforming Higher Education—Multidimensional Evaluation of Teaching," three US university campuses are implementing and studying variations on three-part teacher evaluations—the student voice, peer evaluation, and self-reflection by instructors. "We want to create a more holistic system," Weaver says.

STUDENTS ENGAGE IN ACTIVE LEARNING in an introductory physics class taught by Eric Cornell at the University of Colorado Boulder.

Meanwhile, a handful of universities have begun introducing similar approaches on their own. The University of Southern California revamped its student evaluation procedures in 2018 as part of an initiative on teaching excellence. The macro changes at USC include introducing a university-level definition of teaching excellence and new infrastructure to develop and reward it "in serious and tangible ways," says Ginger Clark, associate vice provost for faculty and academic affairs and the director of the university's Center for Excellence in Teaching. Individual departments customize their approach to the best teaching practices in their own disciplines, she adds. The university uses peer review as its primary tool for evaluating teaching, but it incorporates self-evaluations and student surveys. And the surveys, instead of focusing on the course and instructor, now hone in on the student's own experience. "Students are not trained in pedagogy, but we had been using them as our experts," says Clark. "If we are honest about teaching, we need to know what we are measuring."

Called "student learning experience evaluations," USC's new student surveys do away with global questions. Instead, they pose such questions as whether course concepts were well explained, whether the instructor encouraged discussion, whether the instructor was receptive to diverse viewpoints, and whether the criteria for the class were clear. Students are also asked how much time they spent on homework, how often they interacted with the instructor outside class, and how they participated in learning for the course. Other questions on similar surveys around the country ask whether the instructor's handwriting

GLENN ASAKAWA/UNIVERSITY OF COLORADO

is legible, whether the student could hear the instructor, and whether the student understood the textbook.

"We were concerned about bias, and also about random nastiness that didn't seem warranted," says Michael Dennin, a physicist who serves as vice provost for teaching and learning at the University of California, Irvine (UCI). The university put into practice a long-ignored policy to require additional evidence about teaching, and has revamped the surveys. "We are consistent with the national focus," Dennin says, "which is to move toward language that asks the students to assess experience in the classroom rather than to directly assess the professor." It's still early, he adds, but the shift seems to reduce bias. The UCI student experience surveys have replaced numerical ratings with categories from "strongly agree" through "strongly disagree" because psychology studies suggest that people give more thought to questions when so formulated.

The University of Oregon introduced a campus-wide overhaul to teacher evaluations this past fall. It replaced traditional SETs with self-reflection, peer review, and student feedback. As is the case at other universities at the vanguard of tuning their teacher evaluations, the questions are now designed to reflect student experience, and students fill out surveys a few weeks into a term and again at the end. The midterm feedback is seen only by instructors, says physics chair Taylor, and it can be helpful for adjusting one's teaching. The survey responses are no longer numerical ratings, and students are asked to single out something that was especially helpful and something that they would like to see changed. "We've made a complete mental model shift," says Sierra Dawson, the university's associate vice provost for academic affairs.

Burdens, rewards, and support

Using peer review to evaluate instructors is controversial. Proponents assert that with minimal training, faculty members can learn to evaluate their peers fairly and usefully, and that doing so can be a rotating service duty. And, they say, observing other instructors can be helpful for improving one's own teaching. But critics point out that no consensus exists on what makes up good teaching and that evaluators need to know the course material and be familiar with the student population to gauge level and pace. A further complication is that course preparation, office hours, mentoring, and other aspects of teaching occur outside the classroom and so far have been left out of teacher evaluations, which consider mainly lecturing.

Physics education researchers have identified practices that lead to better student outcomes in physics and "seem to be similarly effective" across fields in STEM and even the social sciences, says Wieman. Based on that research, he advocates collecting data on the practices instructors use in the classroom. He developed a rubric, which, he says, "is informative, and gives a proxy for measuring teaching effectiveness." Doing so, he says, works for large and small classes and avoids bias. In a spinoff of Wieman's approach, some departments keep track of activities in a classroom. "We send trained undergraduates into a class to note what's happening every two minutes," says CU's Finkelstein. This is not peer review, he notes, but is meant to complement other sources as a measure of what is going on in class.

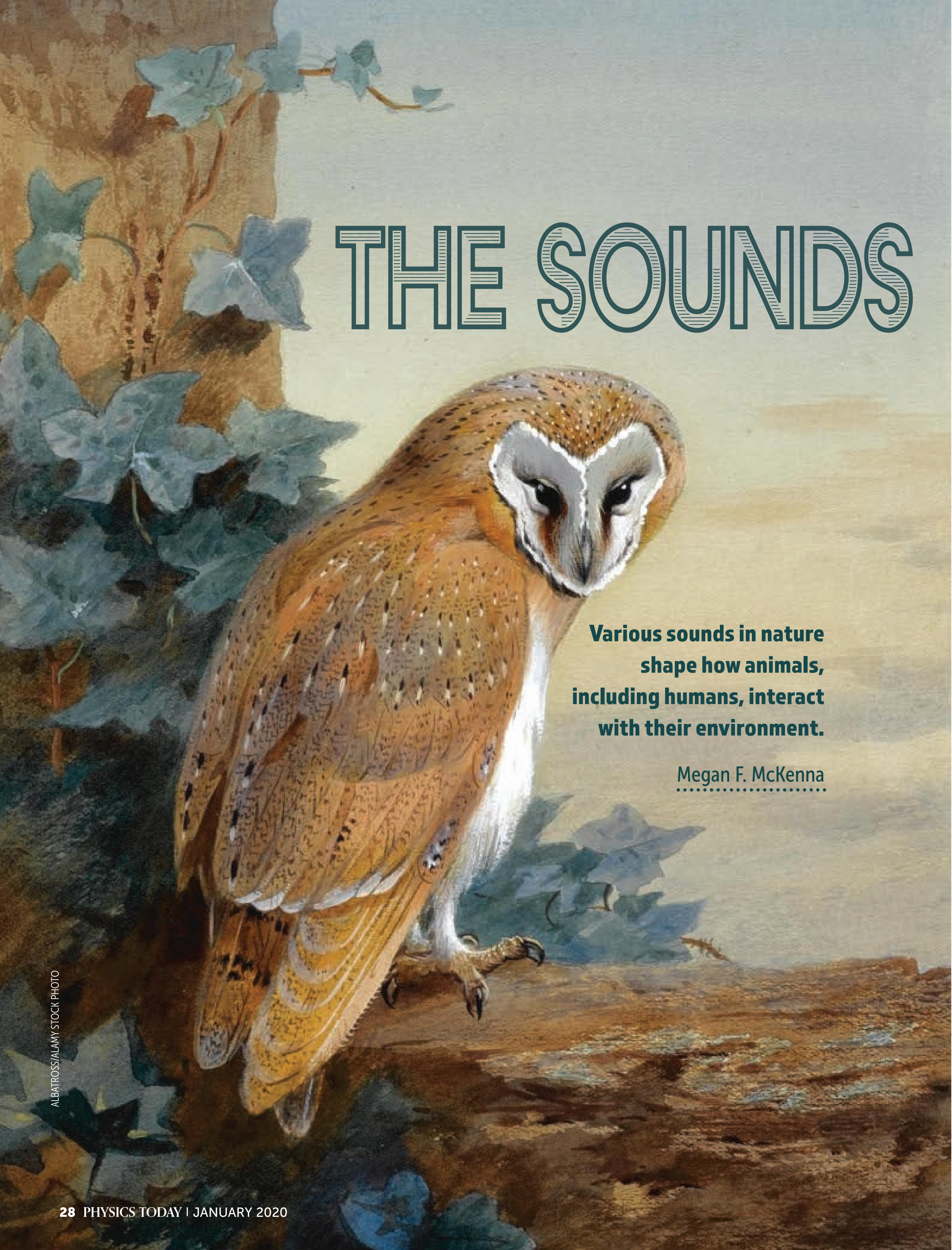
University administrators recognize that any change can be difficult to implement and that, for example, expanding peer review of teaching may be seen by faculty members as a chore. "Our job is to improve teaching without taking away from research," says UCI's Dennin. In the past, he adds, negative teacher ratings have been "very relevant, but if you made the bar you were fine. And being great didn't give you a boost." Emily Miller, associate vice president for policy at the Association of American Universities, says that placing increased attention on teaching does not hurt research productivity. Researchers who are working to improve teaching are "as effective at getting grants and research dollars as they were before," she says. "And they may become more competitive for getting top graduate students."

Still, it's not just reward and punishment; the other piece for getting buy-in is offering support. To that end, UCI and other campuses offer assistance to departments and instructors with self-evaluations, definitions of excellent teaching, and more.

In 2018 the National Academies of Sciences, Engineering, and Medicine launched an ongoing roundtable on systemic change in undergraduate STEM education. "Radical things are happening on the landscape of higher education, with new technologies, changing student demographics, new models of certification for jobs," says Heidi Schweingruber, director of the National Academies board on science education. The roundtable is looking at how to catalyze improvements in instruction. "There will be implications for tenure and promotion, but we haven't gone deeply into it yet." One thing that has become clear from the roundtable, she adds, is that evaluations of teaching are a "potential lever for change."

Change is always stressful, says Taylor, but pilot studies in a few University of Oregon departments suggest that the new approach will be beneficial to instructors. "There is angst because people are unsettled." Within a couple of years, he says, the new three-pronged evaluation system "will become the norm, and it will be a better norm."

Toni Feder PT



THE SOUNDS

Various sounds in nature shape how animals, including humans, interact with their environment.

Megan F. McKenna

ALBATROSS/ALAMY STOCK PHOTO

Megan McKenna is an acoustic biologist at the natural sounds and night skies division of the National Park Service in Fort Collins, Colorado.

AROUND US

The world is full of sounds that carry information. A rushing stream, like the one shown in figure 1, can improve your mood and lowers stress.[1] A clap of thunder alerts you to take cover. Unique sounds can remind you of home. Understanding how sounds influence behaviors and interactions with the environment is paramount to the field of acoustic ecology. It originated in the 1970s when researchers began exploring people's awareness of sound as a response to the deteriorating listening environment from noise pollution.[2] Now the field also has important applications in urban planning, musical composition, landscape architecture, animal behavior, and wildlife conservation.

Almost all animals possess an auditory sensory system that can detect and respond to sounds in nature. Such information provides them with an assessment of the environment and alerts them to the presence of threats, potential mates, and food.[3] In some animals, the auditory sensory system has spectacular specialization. For example, a fox can hear the footsteps of a mouse—a potential meal—under three feet of snow (see figure 2), and a deer can detect the nearby rustle of leaf litter and run from a possible predator.

But sensitive hearing in a noisy environment can have weighty consequences. In modern times, human activities have introduced various novel acoustic stimuli. Temporary and permanent hearing damage can result from prolonged exposure to especially loud sounds. Even without damage, chronic exposure to low levels of noise pollution can degrade hearing abilities for people and wildlife. Sounds that otherwise would be heard are not.

Diverse voices

Acoustic ecology is part of sensory ecology—a field that examines how animals, including humans, use information obtained from the environment in different aspects of their lives. Over the past few decades, acousticians, psychologists, neuroscientists, ecologists, and conservation biologists have expanded the understanding of how natural sounds mediate behavior, modify ecological interactions, and drive evolutionary patterns. Much of the acoustic-ecology literature continues to focus on human experiences: This article focuses more broadly on how animals interact with sound in their environment and the vital role that sound plays in ecosystems.

Like many fields that involve a diversity of disciplines and applications, acoustic ecology has terminology that can have ambiguous meaning when applied across specialties. Although the terms and definitions are valuable in the context in which they were developed, collectively they present challenges. For example, sound and noise are often used interchangeably to describe an acoustic source. A common definition of noise is unwanted sounds that interfere with a signal of interest. Noise, however, is not a purely subjective designation. Any sound that serves no function is noise. Most sounds produced by human transportation and other machinery are unintended, serve no function, and are therefore noise regardless of the listener's attitude. Unintended sounds do exist in nature, like the footfalls of an animal, but such sounds provide vital cues for some animals and are considered sounds to the receiver and noise to the producer.

Numerous terms have been used to categorize different sources of sound. Importantly, the unique characteristics of each acoustic source can influence how it is perceived and what responses it receives. I prefer common ecological terminology to distinguish the types of acoustic sources. Abiotic sounds refer to those generated from the physical environment; biotic sounds, to ones made either intentionally or unintentionally from living organisms; and anthropogenic noise, to the unintended and functionless sounds from humans. All the sounds of a given place and time, and the factors that influence their transmission, make up an acoustic environment. How animals filter or perceive the sounds creates a soundscape.

The four broad categories of acoustic-ecology research and their important links are illustrated in figure 3. The first, sensory systems, investigates how acoustic cues are obtained by anatomical structures, processed by neurological pathways, and ultimately perceived by the listener. The second, acoustic environments, quantifies the condition and characteristics of sounds in an environment and the acoustic cues available to a listener. Understanding why and how sounds are advantageous to an animal falls into the third category, functions of sound. The fourth, the effects of noise, aims to understand how noise from human activities affects individual- and population-level responses and the inherent consequences to the ecosystem.

NPS/DAVID RESTIVO

FIGURE 1. LISTENING TO NATURAL SOUNDS, such as the running water of McDonald Creek, pictured here in Glacier National Park, has restorative properties. In a recent study, participants who listened briefly to natural sounds after watching an unsettling video showed greater mood recovery than those who heard natural sounds intermingled with human voices and motorized vehicles.[1]

Specialized sensory systems

The sensory structures and neurological pathways associated with hearing are vast. The examples that follow serve as a simple primer to the rich literature that explores diverse and fascinating sensory systems. Many invertebrates and all classes of vertebrates can detect and process acoustic stimuli in their environments. The ability to hear typically refers to the detection of pressure waves, or the oscillating compressions and rarefactions of the medium, usually air or water. For example, humans, other vertebrates, and many invertebrates—including the most conspicuously acoustic crickets, katydids, grasshoppers, and cicadas—identify such waves with tympanal ears, thin membranes coupled to mechanosensory cells that transduce the membrane vibration into electrical impulses. Hearing systems in animals perform auditory tasks such as frequency analysis, sound-source localization, and auditory-scene analysis. Those capabilities, some acoustic ecologists argue, evolved early in vertebrates and have been modified by selection in different species.[4]

Given the wide range of frequency sensitivities across taxa, significant morphological variation exists in the mechanosensory machinery of vertebrates.[3] For example, geckos have the most sensitive and frequency-selective hearing of all lizards.[5] They are the only nocturnal lizards to produce sounds for communication. Unlike in other lizards, geckos have a papillae structure—the membrane of mechanosensory cells—with unique modifications that maximize the number of oscillating frequencies or potential channels of information.[6]

The barn owl has one of the best-studied source-localization capabilities. To hone in on the exact location of a sound—think a scurrying mouse in forest leaf litter at night—a barn owl processes the horizontal location by using the difference in the sound's arrival to each ear and the vertical location by using the difference in sound levels between its asymmetrically placed ears.[3] The horizontal and vertical locations are invaluable information to a nocturnal, aerial predator. For most other birds and mammals, the elevation of the sound source is nearly impossible to determine because the difference in arrival time and intensity is confounded. The multifaceted auditory capabilities of the barn owl are possible because of the morphology of its ears and neurological features, including auditory nerve encoding, similar to other avian species.

Many invertebrates can detect the particle-velocity component of a sound wave. They use flagellar mechanosensory structures, such as hairs or antennae, that project into the oscillatory flow. Such an acoustic sensory capability is lacking in humans. Because the oscillatory motion attenuates close to the source, some species of insects, including certain mosquitoes (*Toxorhynchites brevipalpis*), actively use the mechanosensory cells to increase detection of more distant sounds.[6]

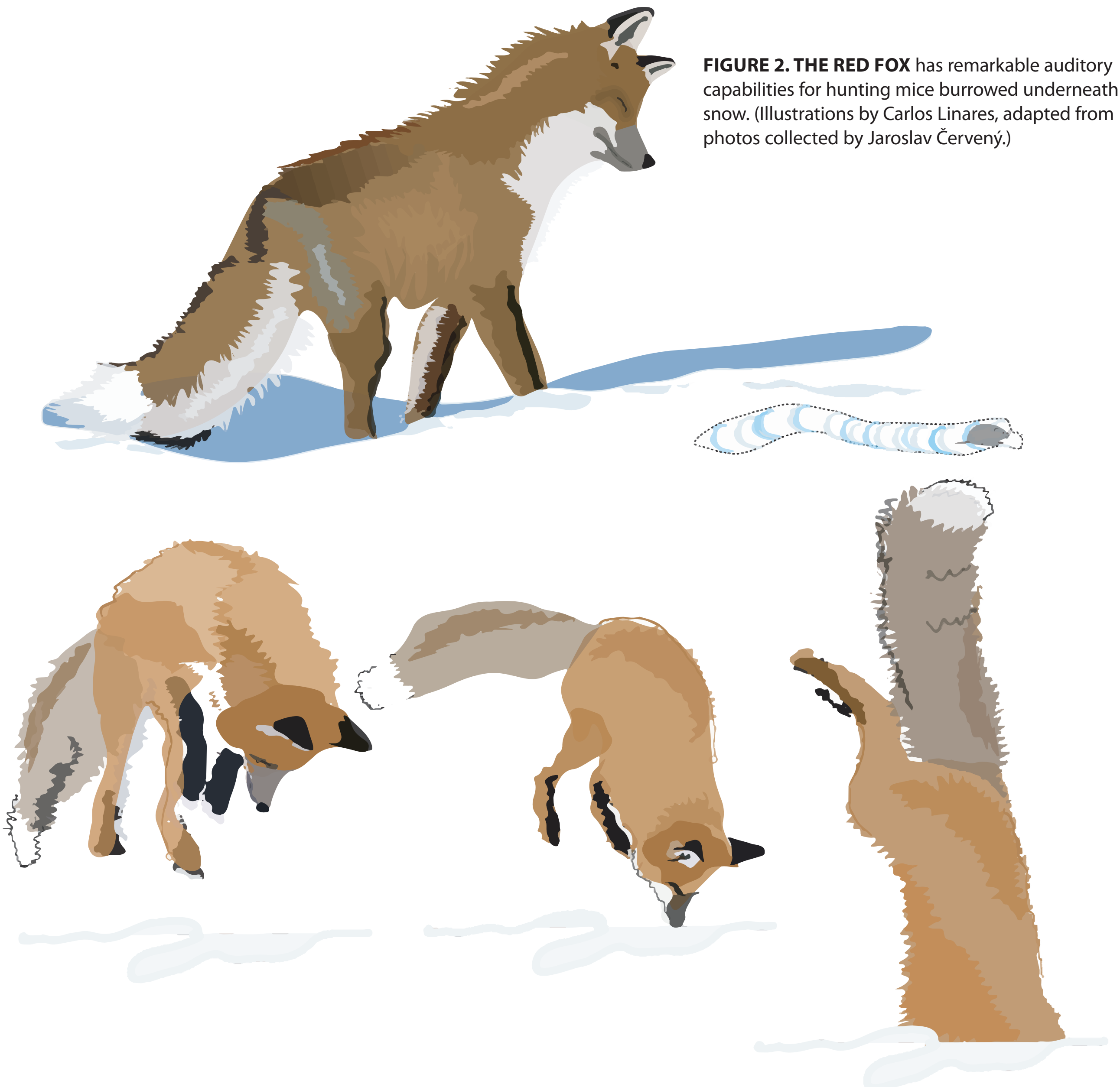


FIGURE 2. THE RED FOX has remarkable auditory capabilities for hunting mice burrowed underneath snow. (Illustrations by Carlos Linares, adapted from photos collected by Jaroslav Červený.)

Complex acoustic environments

The diversity of acoustic sensory systems is not surprising given the complexity and variety of acoustic stimuli in the environment. Those sounds shape how animals interact with their surroundings. Behavioral modifications driven by the acoustic environment can operate from short time scales, such as the few seconds it takes for a predator to capture its prey, to evolutionary time scales, in which deviations in behavior lead to speciation. Scientists characterize the acoustic environment, and the related soundscape, by capturing various acoustic features and the ambient conditions to understand how they may be interpreted by a receiver. Researchers addressing human hearing are developing standard analyses based on the psychoacoustic parameters of sound—loudness, roughness, sharpness, and tonality—to advance the field toward measuring and assessing the acoustic environment in relation to human perception.

Despite that progress, researchers lack a universal method or metric for quantifying acoustic environments.[7] Accurately characterizing them is vital for interpreting acoustic cues available to people and animals and deciding acceptable sound levels for conservation efforts, urban planning, and product safety. The most common way to characterize sound is to measure the variation in pressure in a defined time period and frequency range and convert the values to the decibel scale. How the pressure in the given time period and frequency range is described depends on the specific metrics used, and there are many. That diversity of metrics has led to some confusion when comparing multiple studies. Furthermore, although the decibel, the most common unit for sound level, is useful for quantities that span several orders of magnitude, a value is not always directly comparable to another because it is a ratio of a measured pressure quantity to a reference. Because sound levels may include both the signal and the ambient conditions, scientists have more difficulty interpreting the meaning of sound-level measurements to a listener.

Understanding sensory systems can inform how best to characterize the acoustic environment. Most animals, including humans, have varying sensitivity to sounds at different frequencies. To quantify those differences and discriminate what sound is heard, researchers apply a frequency-weighting function to a measured sound. If the hearing thresholds for a species are known, the function adjusts sound levels based on specific hearing sensitivities. To assess the effects of anthropogenic noise, scientists have worked extensively on marine-mammal hearing in the field and in the lab to develop frequency-weighting functions and threshold levels.[8]

To determine when an acoustic sensory environment becomes degraded, researchers quantify the change to it from optimal acoustic conditions. Under natural, ambient acoustic conditions, an individual is in a listening area—a circular region whose radius is the distance at which an individual first detects a sound. Researchers can, therefore, use deviations from natural sound levels to estimate reductions in a listening area and quantify the loss of hearing opportunities in humans and wildlife. According to one study,[9] which assumed that the detection range is limited primarily by spreading loss, the listening area can be reduced by 50% for each 3 db increase in noise above ambient conditions. Although the results provide a useful estimate of how the sensory environment is changing for organisms, signal detection by animals in complex acoustic environments is still an active area of research, and investigations continue into how noise degrades auditory capabilities.

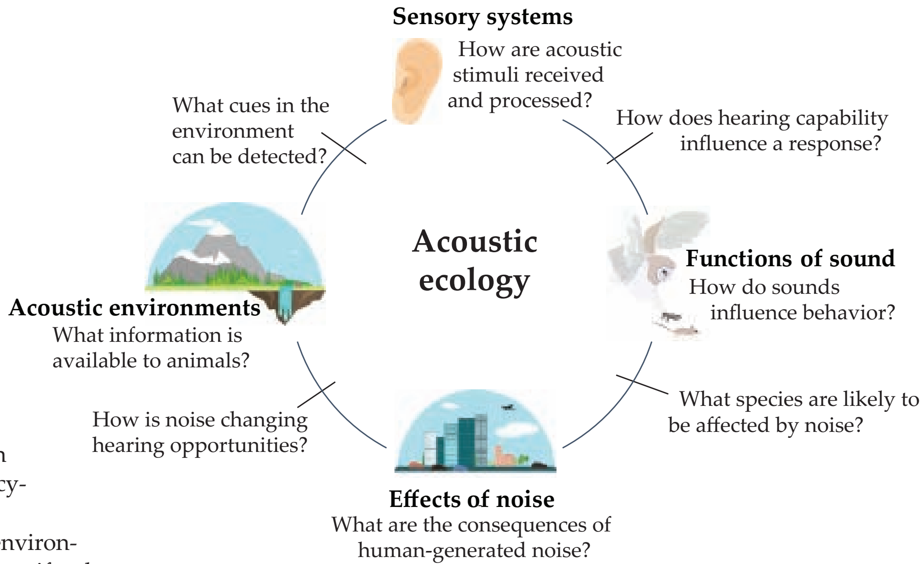


FIGURE 3. ACOUSTIC ECOLOGY is a diverse research field that incorporates various questions related to sound in the environment. Those questions fall into four broad categories with important links between research objectives. (Illustrations by Carlos Linares; owl image adapted from a photograph by Warren Photographic.)

Biotic and abiotic sounds

Biotic sounds are typically thought of as vocalizations specifically produced to attract mates, find food, alert others to nearby predators, and defend territory. One example is the calls male amphibians emit to attract mates. The intended listener is nearby, and a chorus of calls from multiple individuals provides a cue about habitat quality. In fact, in some amphibian species, an individual may prefer to move to a new mating habitat if others are already present. Those powerful choruses of biotic sound offer a potential method for amphibian-habitat restoration.

Like the amphibian chorus, biotic sounds may unintentionally provide cues for other species. One well-studied example is the coral reef, in which the biotic sounds emitted from fish, urchins, shrimps, and other animals are important settlement cues for planktonic larvae of fish and invertebrates (see figure 4a). The sounds indicate that the area is a suitable place to live.[10] Larval fishes likely perceive acoustic cues through particle motion.[11] To fully understand the function of a reef's complex biotic sounds, researchers will need to improve measurements of such particle motion.

Abiotic sources of sound elevate background levels and create spatial and temporal variations that make it difficult for listeners to perceive acoustic signals. In terrestrial environments, wind, bodies of water, and rain are the dominant abiotic sounds; in marine environments, wind and associated surface agitation and rain dominate. The evolution of hearing sensitivities and communication-signal characteristics is likely driven by slow-varying abiotic sources such as flowing water rather than by more episodic sources like thunder claps. For example, fish species with enhanced auditory sensitivity across broad frequency ranges can adapt to quieter environments such as lakes; fish species with less-specialized hearing are found more commonly in fast-flowing aquatic habitats.

Animals can detect and perceive sound signals better if they are produced at a frequency range with less abiotic noise, a band that acoustic ecologists call the silent window.[12] When a quiet frequency band isn't available, animals can briefly modify an acoustic signal. In windy conditions, king penguins increase the number of calls they emit and the number of syllables per call to presumably increase the probability of detection. Another signal modification—known as the Lombard effect, first observed in humans and subsequently documented in various bird and mammal species—increases amplitudes in noisier conditions.[13]

In response to increased abiotic sounds, animals sometimes switch to or add another sensory modality to communicate. In conditions with high wind and waves, humpback whales breach the water's surface and slap their pectoral fins rather than vocalize. The switch to primarily surface-generated visual and audio signals potentially improves their perception of important social cues in those noisier conditions. Over evolutionary time scales, frog populations inhabiting areas near fast-flowing streams and waterfalls performed more foot flagging—a visual mating behavior—than populations in naturally quieter habitats that mainly use vocalizations to attract mates, as illustrated in figure 4b. Those short- and long-term communication modifications provide important insights on how more recent human-induced noises likely affect different animals.

Noise alters animal behavior

The increasing human population has dramatically raised ambient sound levels.[14] Noise from human activity is a recent evolutionary pressure that is becoming widespread, and it continually changes as people develop technology, for example. Wildlife responses to noise are well documented across various species, and our understanding of the consequences continues to grow.[15]

One way to isolate noise from the visual, chemical, and structural changes induced by human activity is to conduct playback experiments. In them, the noise is turned on and off to determine if it alone alters animal behaviors or ecological interactions. In one study, traffic noise hindered the hunting success of a bat species that relies on the incidental sounds from large, ground-running arthropods, as depicted in figure 4c. In response, an individual bat's health may suffer, or the bat may abandon its prime habitat; less-successful hunting could reduce the population's survival rate or force it to find a new habitat.

Furthermore, such individual- and population-level changes cascade through other biological communities. Birds pollinate plants and disperse seeds, but when noise disrupts their behavior, the plant community can shift across a landscape, and the consequences last long after the source of noise goes away.[16]

Acoustic ecology in conservation

The condition of acoustic environments is critical to ecological systems and shapes the quality of peoples' visits to natural areas.[9] A bird song alerts a visitor to a rare species. Footsteps of a bear signal to hikers to take precaution. Preserving opportunities to hear natural sounds is an important component of protecting wildlife, ecosystem functioning, and visitor experiences.

Developing effective acoustic conservation strategies requires an understanding of when and where particular sounds are most vital to wildlife and visitors. Additionally, knowing what species are predicted to be most vulnerable to noise and therefore will benefit most from preserving certain sounds may

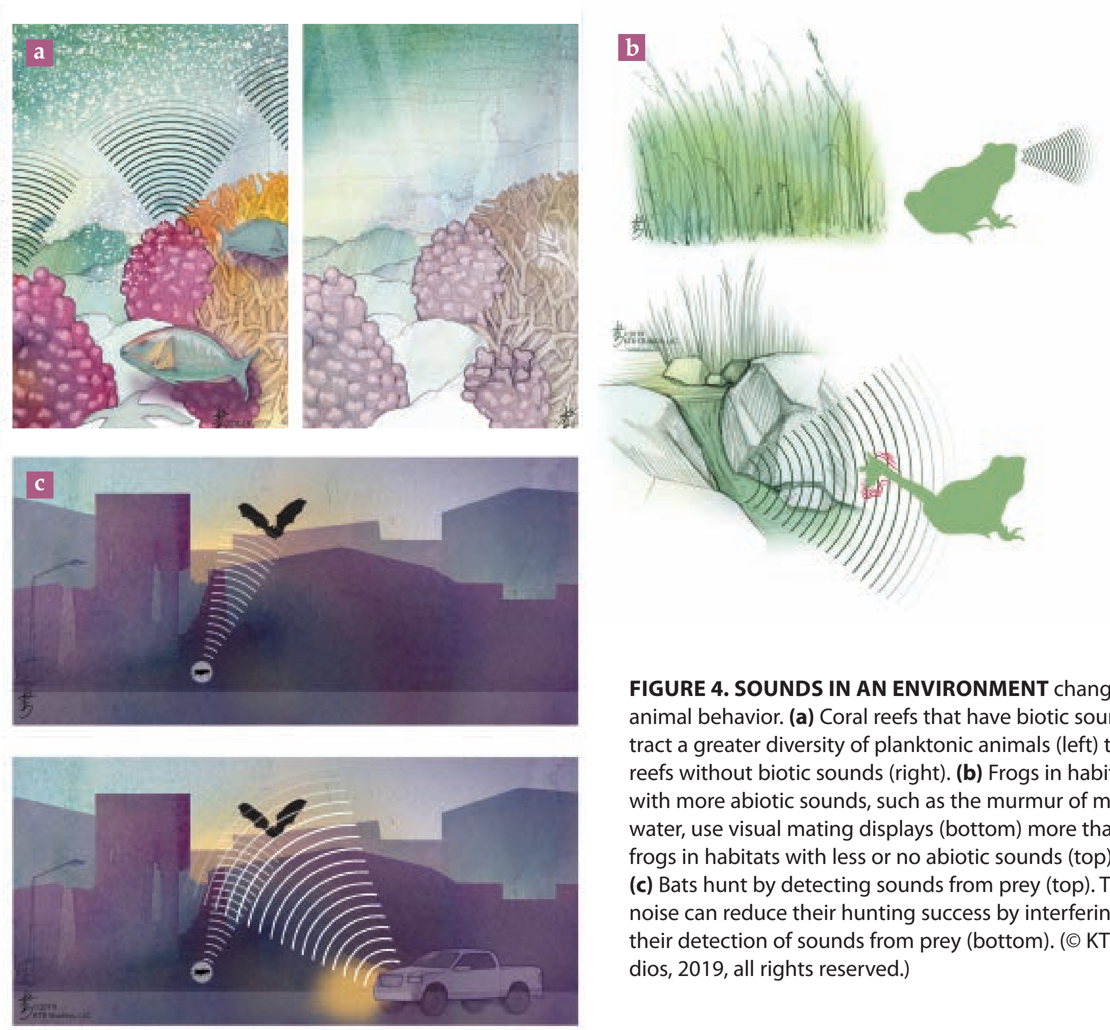


FIGURE 4. SOUNDS IN AN ENVIRONMENT change animal behavior. **(a)** Coral reefs that have biotic sounds attract a greater diversity of planktonic animals (left) than do reefs without biotic sounds (right). **(b)** Frogs in habitats with more abiotic sounds, such as the murmur of moving water, use visual mating displays (bottom) more than do frogs in habitats with less or no abiotic sounds (top). **(c)** Bats hunt by detecting sounds from prey (top). Traffic noise can reduce their hunting success by interfering with their detection of sounds from prey (bottom). (© KTB Studios, 2019, all rights reserved.)

be key to developing sound-mitigation strategies. For example, weekend road closures in Rock Creek Park in Washington, DC, benefit both visitors who want to escape the buzz of the city and breeding songbirds that are producing calls to attract mates.[17] Installing noise barriers around oil- and gas-extraction sites returns rural landscapes to nearly natural acoustic conditions, and, unsurprisingly, the biological community benefits.[18]

Another aspect of acoustic ecology is worthy of mention: our cultural heritage. Many human sounds are intrinsic to a given place and are thus protected for their historical and cultural value. Such sounds, including the clang of mission bells, Native American drumming, and the crack of musket fire, can immerse the listener in a cultural experience and connect them to a time or place they otherwise would never encounter. Preserving those unique sounds and enhancing and creating opportunities to hear cultural sounds, without modern-day noise intrusions, is invaluable to our rapidly changing society.

Area protection provides an opportunity to implement acoustic conservation strategies, but urban planners are applying acoustic-ecology concepts to create natural listening experiences. Perhaps the greatest benefit will be achieved through human connection and awareness of sounds in our own backyards. Typically, city planners and policymakers do not engage with residents about their acoustic sensory experiences, but the perception of urban landscapes is shifting from that of barren ecological settings to places of wonder.

The hoot of an owl, the howl of a coyote, and the song of a bird connect people to the natural world and are signals of a thriving ecosystem. Multidisciplinary approaches, including understanding the interactions between many sensory systems, and cross-disciplinary collaborations are needed to fully recognize and mitigate the damaging effects of dramatically changing acoustic experiences. By integrating landscape architecture, ecology, acoustics, psychology, and innovative design, future city planners will design more sustainable cities for healthier citizens—both people and wildlife.

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PT

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JOHANNES KEPLER'S PURSUIT *of* HARMONY

Aviva Rothman

The great astronomer linked the speed of planetary orbits to musical scales—and to the harmonious interaction of humans on Earth during a time of religious warfare.

Most people who have heard of Johannes Kepler, pictured here at age 39, remember him primarily as an astronomer who changed our understanding of planetary motion. He is most famous for his discovery that planets move in elliptical orbits rather than in the pure circles theorized by those who came before him. He deemed Earth a planet like any other, one that revolved annually around the Sun. That belief made him one of the first to accept Copernicus's heliocentric cosmos.

Portrait of Johannes Kepler (1571–1630), painted in 1610. (Unknown artist, via Wikimedia Commons, PD-US.)

But Kepler did not view astronomy as his highest calling. In a letter from 1605, written only a few weeks after he formulated his theory of elliptical orbits—following a careful study of the orbit of Mars—he wrote the following to a friend in London: "If only God would set me free from astronomy so that I might turn to the care of my work on the harmony of the world."[1] Kepler was referring not only to the work that would become his 1619 masterpiece *The Harmony of the World* (see figure 1), containing what we now call the third law of planetary motion, but also to a larger project that linked the harmonic motions of the cosmos to the possible future harmony of humans on Earth.

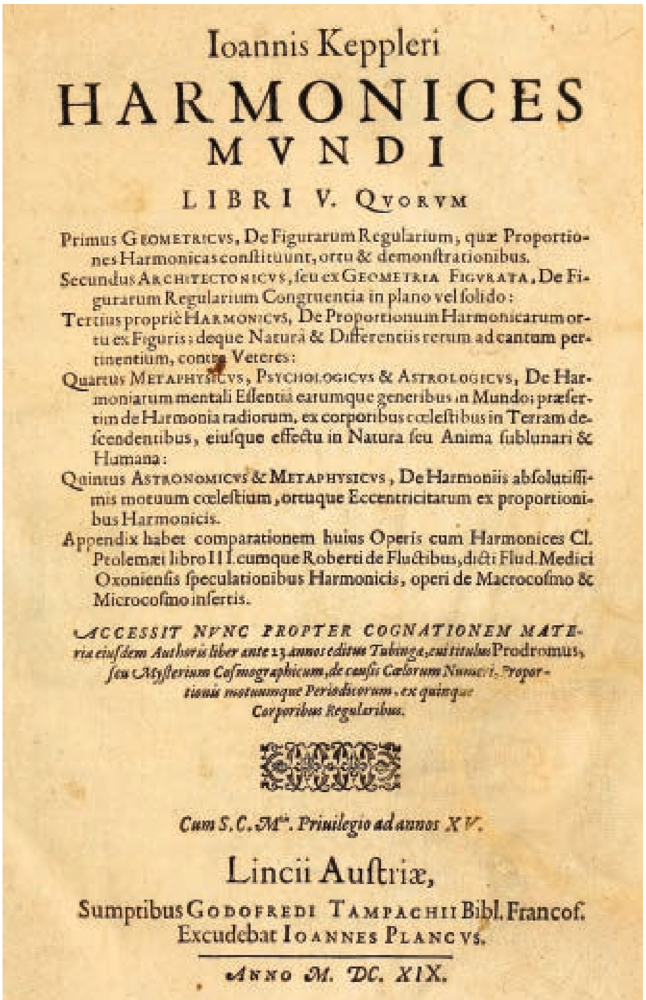
Ioannis Keppleri
HARMONICES MVNDI
LIBRI V. QVORVM
Primus GEOMETRICVS, De Figurarum Regularium, quæ Proportiones Harmonicas conſtituunt, ortu & demonſtrationibus.
Secundus ARCHITECTONICVS, ſeu ex GEOMETRIA FIGVRATA, De Figurarum Regularium Congruentia in plano vel ſolido:
Tertius propriè HARMONICVS, De Proportionum Harmonicarum ortu ex Figuris; deque Naturâ & Differentiis rerum ad cantum pertinentium, contra Veteres:
Quartus METAPHYSICVS, PSYCHOLOGICVS & ASTROLOGICVS, De Harmoniarum mentali Eſſentiâ earumque generibus in Mundo; præſertim de Harmonia radiorum, ex corporibus cœleſtibus in Terram deſcendentibus, eiuſque effectu in Natura ſeu Anima ſublunari & Humana:
Quintus ASTRONOMICVS & METAPHYSICVS, De Harmoniis abſolutiſſimis motuum cœleſtium, ortuque Eccentricitatum ex proportionibus Harmonicis.
Appendix habet comparationem huius Operis cum Harmonices Cl. Ptolemæi libro III. cumque Roberti de Fluctibus, dicti Flud. Medici Oxonienſis ſpeculationibus Harmonicis, operi de Macrocoſmo & Microcoſmo inſertis.
ACCESSIT NVNC PROPTER COGNATIONEM MATERIæ eiuſdem Authoris liber ante 23 annos editus Tubingæ, cui titulus Prodromus, ſeu Myſterium Coſmographicum, de cauſis Cœlorum Numeri, Proportionis motuumque Periodicorum, ex quinque Corporibus Regularibus.
Cum S. C. Mtis. Priuilegio ad annos XV.
Lincii Auſtriæ,
Sumptibus GODOFREDI TAMPACHII Bibl. Francof.
Excudebat IOANNES PLANCVS.
ANNO M. DC. XIX.

FIGURE 1. THE OPENING PAGE of *Harmonices Mundi* (*The Harmony of the World*) by Johannes Kepler, from the original 1619 printing. (From the Posner Family Collection, Carnegie Mellon University Libraries, PD-US.)

Kepler devoted his life to the cause of harmony; it was both the intellectual bedrock for and the crucial goal of his seemingly disparate endeavors. To Kepler, the quest was not merely academic or theoretical. The world in which he lived was beset by overwhelming discord as the Holy Roman Empire moved ever closer to a devastating religious and civil war. The spark that finally ignited the conflict was the famous 1618 defenestration of Prague, in which aggrieved Protestants threw two Catholic bureaucrats and their unfortunate secretary from a third-story window. That incident took place a mere four days before Kepler completed his *Harmony of the World*, and the war the incident began would ultimately wipe out one-third of Germany's population.

Yet Kepler persisted in pursuing his goal of harmony through the discordant havoc of war, exile, his excommunication from the Lutheran Church, and a great deal of personal loss and hardship. His ultimate goal was both to reveal the harmony in nature and to work toward a worldly harmony that might follow from it. Although Kepler's ideas about what might constitute earthly harmony changed over time, he ultimately came to believe that following God's harmonic model in the heavens meant accepting the peaceful coexistence of diverse religious views on Earth.

Kepler the astronomer-priest

The fact that Kepler doesn't seem to have wanted to spend the majority of his time on the things that made him famous is representative of the trouble we moderns have had both in understanding him and in understanding premodern science more generally. Kepler had varied interests, from astrology and music to politics and chronology, and he wrote a great deal on many subjects, from short works on snowflakes and trips to the Moon to long pamphlets on theology. Even though he spent so much time developing precise astronomical calculations based on observation—the kind of thing people today want to see as representative of the scientific enterprise—his eclectic interests have made it difficult to fit him into traditional stories of the history of science, which describe a progressive move away from ungrounded and inaccurate speculation toward objectivity and precision.

Then comes Kepler's strange relationship with the churches of his day. Kepler was raised as a Lutheran, studied theology in the seminary at Tübingen, and hoped to become a priest. That plan did not happen. Instead, he was sent to serve as a teacher of mathematics at the Lutheran high school in Graz. When he was expelled from the Catholic city along with its other Lutheran residents, he moved to Prague to work under Tycho Brahe, famed astronomer and imperial mathematician to the Holy Roman Emperor. Ultimately, Kepler rose to become imperial mathematician upon Tycho's death. Despite his move away from the priesthood, he continued to care about theological questions, write about theological issues, and frame his pursuits theologically. He was, in his own words, an "astronomer–priest" who unveiled the book of nature for its readers.[2]

Kepler also continued to identify as a Lutheran even though he was excommunicated from the church in 1619. His excommunication was the result of a disagreement about the Lutheran approach to communion, the ritual in which the presence of Christ's body and blood is celebrated by consuming sacramental bread and wine. Historians have largely ignored the reasons for Kepler's excommunication, perhaps because Galileo Galilei's famous trial over heliocentrism has made it easy to assume that Kepler's excommunication was rooted in similar causes. In the famous *A History of the Warfare of Science with Theology in Christendom*, Andrew Dickson White positioned Kepler alongside Galileo as a warrior in the battle of science against religion.[3]

That story is utterly wrong, and not just because Kepler's excommunication happened for reasons unrelated to his heliocentrism. It's wrong because it doesn't take seriously what Kepler understood himself to be doing or how his work fits into the bigger religious, cultural, and intellectual landscape of 16th- and 17th-century Europe. More recent histories of science and religion have emphasized the ways that religious thought was integral to the scientific work of many luminaries of the scientific revolution.[4]

Kepler himself has yet to be fully placed into that revised picture.[5] That is unfortunate, because he provides us with an important lens onto the intersections of science, religion, and politics at the moment when modern science is said to have been born. That perspective helps us understand his world in new and important ways. So let us take seriously what Kepler says and think about what *he* thought he was doing and why he placed such value on his work on harmony.

The harmonic tradition

To understand what harmony meant to Kepler, we need to review a longer history of the concept.[6] That intellectual tradition can be traced back to the Greek mathematician Pythagoras, who supposedly passed a blacksmith's shop one day and discovered that hammers of different weights produced different sounds, some consonant in combination and some dissonant. As he later determined by experimenting with strings and their pitches, the reason for those differences lay in the numerical relationship between the various weights or lengths of string. Musical harmony could thus be linked directly to ordered numerical relationships.

Although the Pythagoras of legend discovered the theory of harmony empirically, ancient theorists insisted that the mathematical relationships governing harmony could be determined *a priori*. Plato linked that vision of harmony to the cosmos. In his *Timaeus*, he described a cosmos whose interplanetary distances could be represented on a musical scale and whose planetary motions produced beautiful harmonies that were orchestrated by their creator much as a musician played his instrument.

The medieval theory of music, drawing from the work of the sixth-century Roman philosopher Boethius, underscored the idea of a mathematical link between music and the heavens. Medieval theory divided seven liberal arts into the trivium—grammar, logic, and rhetoric—and the quadrivium—arithmetic, geometry, astronomy, and music. That division established music as a science rather than an aesthetic taste or skill. Boethius also famously identified three types of music: *musica instrumentalis*, which encompassed singing and instrumental performance; *musica humana*, the music of the body and soul; and *musica mundana*, the music of the spheres.

Harmony was both mathematical and moral; it linked music not only to the ordering of the cosmos but also to the ordering of human society. Plato made that linkage clear by ending his *Republic*, a vision of the ideal state, with the Myth of Er, a vision of the musical cosmos. Though harmony might embrace differences, only certain combinations of an otherwise discordant jumble of conflicting elements could be allowed. In the *Republic*, Plato forbade all innovation in music because it would inevitably alter the foundations of political society. The Roman statesman Cicero also linked the well-ordered state with the notion of harmony. He suggested that the beauty of the state, like the beauty of music, lay in a clear, hierarchical division of the individual elements that composed it and could brook no modifications that would upset that order.

Similar ideas of harmony and hierarchy were extended later to the Catholic Church. In the 13th century, Thomas Aquinas wrote that the pope, like the king in a polity, sat on the highest rung of the churchly hierarchy. All steps of the hierarchy, from the priesthood down to the laity, were necessary in order to preserve its harmonious status.

The Eucharist, the sacrament of communion, represented communal harmony. Taking communion was not only a way to experience the miracle of God's presence; it was also a ritual of social unity, a way to signal one's membership in the community. Refusing to partake in the communion implied communal discord. Thus some parishioners refused to take the

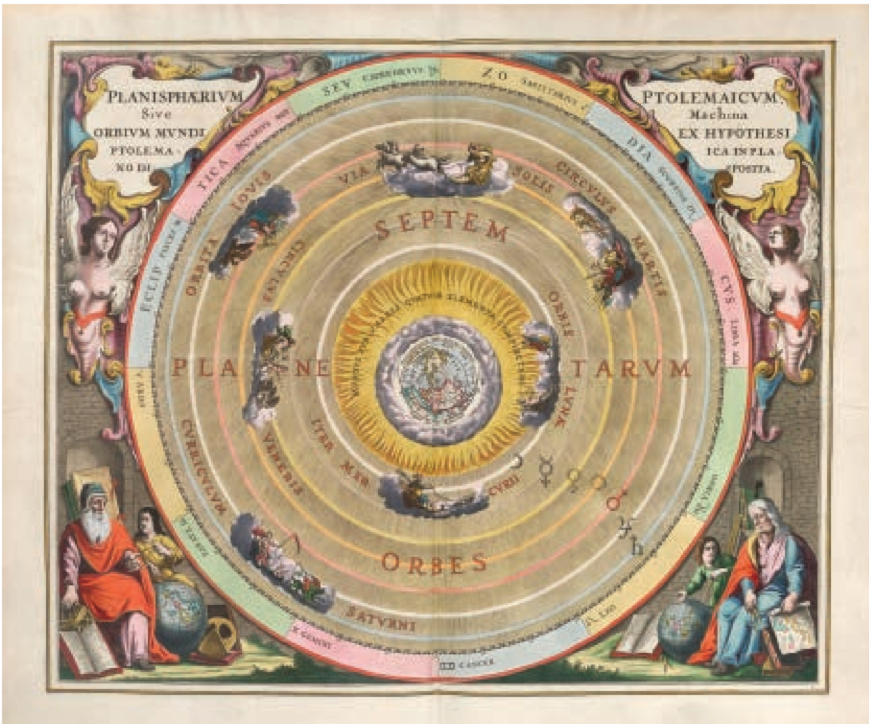

FIGURE 2. A 17TH-CENTURY DRAWING OF THE PTOLEMAIC COSMOS. Earth lies at the center of the system; the Sun and the planets, represented here as their namesake Roman gods, orbit Earth; the stars sit in the outermost sphere. (From *Harmonia macrocosmica*, 1661, Andreas Cellarius, PD-US.)

communion if they were in the midst of a dispute with a fellow community member. When a member deliberately broke ties with the rest of the community and engaged in sin, they were excommunicated—literally, denied the ability to partake of the communion and thus cast out of the larger community.

After the Reformation, notions of what constituted proper hierarchy and proper communal harmony differed from confession to confession. Communion continued to signify communal harmony and belonging, but it also became a primary sign of *proper* belonging. In an era of religious warfare, it was imperative not to partake of the communion alongside heretics. To do so would be to signal approval of their blasphemous beliefs and to threaten the harmony that united the community of true believers.

Changes in the harmonic ideal

The move to a heliocentric cosmos shook the foundations of the harmonic tradition, which was anchored firmly to the geocentric Ptolemaic cosmos. That cosmos was organized in a clear hierarchical chain, shown in figure 2, in which one could descend from the fixed stars to the planetary spheres to Earth and the realm of man at the center. The harmony linking those realms—*musica mundana* and *musica humana*—depended for many on that hierarchical chain and on the centrality of man in it. In his 1611 poem "An Anatomy of the World," John Donne famously bemoaned the loss of the harmonious cosmos caused by the Copernican vision. He wrote, "The sun is lost." He also noted the social implications of the cosmic shift: "'Tis all in pieces, all coherence gone, / All just supply, and all relation; / Prince, subject, father, son, are things forgot, / For every man alone thinks he hath got / To be a phoenix."[7]

Although the move to a Sun-centered cosmos seemed to some to threaten the idea of cosmic harmony, Copernicus relied on the language of harmony to argue for the superiority of heliocentrism. As he explained in the introduction to his *De revolutionibus*, the profusion of eccentrics, epicycles, and equants in the Ptolemaic system "was just like someone taking from various places hands, feet, a head, and other pieces. . . . Since these fragments would not belong to one another at all, a monster rather than a man would be put together from them." Copernicus argued that his system, in contrast, was harmonious because in it "heaven itself is so linked together that in no portion of it can anything be shifted without disrupting the remaining parts and the universe as a whole."[8]

Similarly, 16th-century astronomer Rheticus insisted that the Copernican cosmos was more harmonious than the older world system. Rheticus argued that earlier astronomers would have had better luck had they more closely "imitate[d] the musicians who, when one string has either tightened or loosened, with great care and skill regulate and adjust the tones of all the other strings, until all together produce the desired harmony, and no dissonance is heard in any."[9]

Copernicus and Rheticus appealed to harmony in abstract and largely rhetorical ways. Kepler, however, regarded rescuing the theory of harmony in a post-Copernican cosmos as a central task of *The Harmony of the World*. He sought to describe new planetary intervals that would yield harmonious proportions when the Sun, rather than Earth, lay at the center. To do that, Kepler relied on two factors that he believed distinguished modern harmonies from ancient ones: polyphony, or music with independent melodies or voices that harmonize together, and just intonation, in which thirds and sixths are consonant.

Kepler was fluent in the musical theory of his day; he had read the works of 16th-century composer and theorist Gioseffo Zarlino and music theorist Sethus Calvisius, whom he cited as an authority in *The Harmony of the World*.[10] Pythagorean theories of harmony insisted that all harmonious intervals had to be formed from ratios of the tetrad, the numbers one through four; that excluded thirds and sixths, whose ratios relied on the number five. But Kepler believed that a theory of music that excluded thirds and sixths was untenable. The problem with earlier approaches to music, he argued in *The Harmony of the World*, was that the Pythagoreans had trusted philosophy and abstract numbers over the judgment of their ears.

Kepler, by contrast, followed those who hoped to establish a theory of harmony that, while rooted in mathematics, would also sound good to the listener by including thirds and sixths. That was especially important for Kepler because without a system of intonation that allowed for thirds and sixths, true polyphony was impossible. And in Kepler's view it was polyphony, above all, that distinguished the superiority of modern music. He argued that only in polyphonic music can man finally imitate true cosmic harmonies.

Kepler ultimately developed a new geometrical system—in contrast to the arithmetical system of the Pythagoreans—for grounding the harmonies. He linked that geometrical system not to the distances between planets, which is how planetary harmony had been understood up until that point, but to their speeds—in particular, their angular velocities with reference to the Sun at the moments of perihelion and aphelion. Those speeds determined the scale of each planet by demarcating their highest and lowest notes (see figure 3). Together, the convergent and divergent angular velocities of the planets produced polyphonic harmonies. Kepler thus created a system in which *both* monody and polyphony were present, the first in the motions of the individual planets and the second in their combined movements. Although polyphony was superior because it represented the cosmos as a whole, Kepler insisted that monody, too, had a place in God's ultimate vision and contributed to the beauty of the whole.

One implication of that approach to cosmic harmony was that the actual sounds produced by the planetary motions were, on the whole, dissonant. But the musical theory of Kepler's day had increasingly embraced dissonance as an essential contribution to the beauty of the overall harmony. Kepler compared the use of dissonance in musical harmony to the use of yeast, salt, or vinegar in cooking; although complete dishes aren't made from those ingredients, they are still used to great effect. Furthermore, given the specific intervals produced by each planet, moments of harmonic consonance between the majority of them would be incredibly rare. According to Kepler, the planets all played a perfect harmony at the very moment of Creation, and they might play one again at the end of days. Before then, large-scale dissonance and smaller harmonies were all that could be expected.

Social harmonies

Kepler's understanding of harmony had components that were either absent or undervalued in most theories of harmony before the 16th and 17th centuries—namely polyphony and dissonance. He emphasized in the opening of *The Harmony of the World* that his new vision might yield important insights for those who hoped to achieve harmony of church and state. What kind of social insights, then, followed from Kepler's vision of harmony?

In contrast to earlier thinkers who linked social harmony with hierarchy and conformity, Kepler extended his ideas to society by embracing a vision that valued diversity over homogeneous unity. When it came to music, he argued that "the harmonious singing of parts . . . without any variety in them, ceases to be pleasing altogether."[11] He invoked that notion of harmony when articulating an ecumenical vision of a religious community that embraced diversity and disagreement in its midst. Just as music was only harmonious if it contained many different notes, earthly communities, Kepler believed, needed to create a kind of cohesiveness that embraced difference.

The reunified Christendom that Kepler hoped to help create was not, in his view, to be identified with any one confession, not even his own. Rather, Kepler's harmonious social order would embrace all confessions. It would offer some common ground on which everyone could agree and yet also allow for the fact that nobody would be able to agree on everything, particularly when it came to questions of theology.

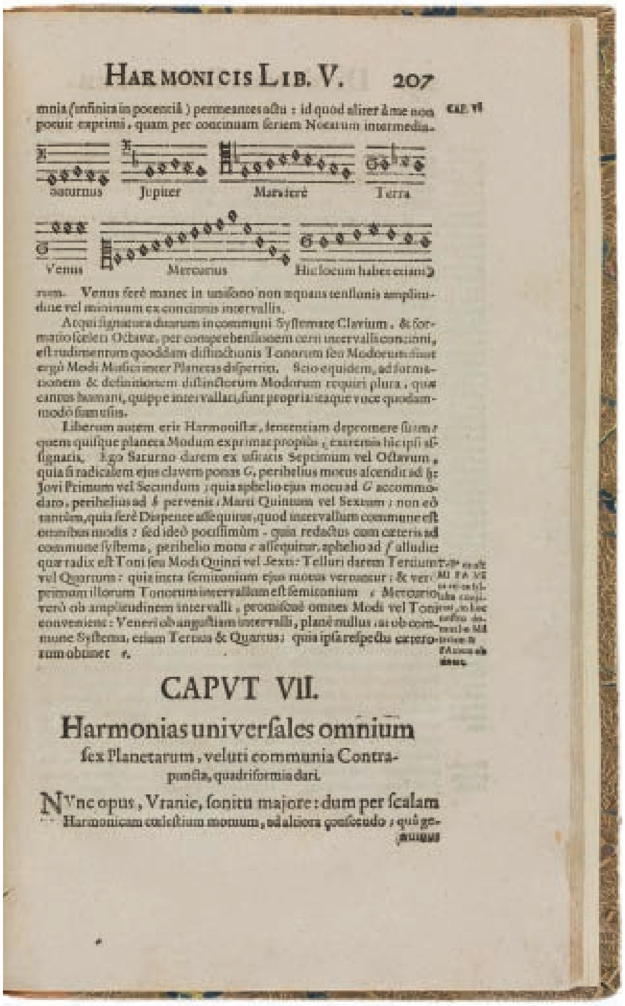

FIGURE 3. KEPLER'S MUSICAL SCALES FOR THE SIX KNOWN PLANETS: Saturn, Jupiter, Mars, Earth, Venus, and Mercury. The final scale represents the Moon; *hic locum habet etiam* translates to "here the moon also has a place." The highest and lowest notes of each planetary scale are determined by the planet's angular velocity with reference to the Sun at the moments of perihelion and aphelion. (From Johannes Kepler, *Harmonices Mundi*, 1619, Posner Family Collection, Carnegie Mellon University Libraries, PD-US.)

As an example of harmonious social order that embraced multiple religious views, Kepler argued that as a believing Lutheran he should be allowed to partake of the Catholic communion. He felt that members of different denominations could take communion together so long as they agreed on the general intention of the ritual, if not its specific theological meaning. Communion would become not a sign of agreement to a particular type of community—as it had been before—but a sign of agreement for a new, more expansive vision of Christian community that embraced all denominations equally and allowed for dissent and plurality of opinion.

Significantly, his excommunication from the Lutheran Church was linked to his unorthodox position on the sacrament of communion. Catholics and Lutherans believed that the presence of Christ in the Mass was both real *and* physical; Calvinists believed that that presence was real but spiritual. Kepler, who disagreed with the physical implications of the Lutheran conception, felt that the Calvinists had come closest to the truth.

Kepler believed that allowing for dissent was important because God's community included all of Christendom, Catholics and Protestants alike. No one religious community could have a monopoly on the truth, and partisan exclusivity was a destructive force. "I am pleased either by all three parties, or at least by two of them against the third, in the hopes of agreement," he wrote in his 1623 *Confession of Faith*, a small published pamphlet in which he described his religious views. "But my opponents are only pleased by one party, imagining eternal irreconcilable division and quarrel. My hope, so help me God, is a Christian one; theirs, I do not know what."[12]

Kepler extended the idea of accepting dissent to other instances as well, like the battles between Catholics and Protestants over Pope Gregory XIII's calendar reforms of 1582. There, too, his goal was to find points of commonality on which Catholics and Protestants might unite harmoniously even though they were still committed to their particular doctrines, practices, and even calendars. After all, as Kepler argued, "Christ the Lord neither was nor is Lutheran, nor Calvinist, nor Papist."[13]

Kepler's attitude toward scientific truth differed from his attitude toward religious truth. The history of astronomy, he believed, revealed clear progress over time and showed that mathematics and cosmology were realms in which certainty, and hence unanimity, were theoretically possible. The history of the church, however, revealed the opposite—dissension only increased over time. In arguing for churchly unity, he therefore emphasized peace and harmony rather than complete agreement, and he pointed to the harmony of the cosmos as a model.

In his scientific work, he portrayed himself as an astronomer–priest, aligning himself with a theology independent of religious strife. Astronomy was a way to reveal God's hand in the world, one that had some hope of offering universal truths on which anyone could agree.

An unrealized vision

Kepler hoped that in his lifetime he might see a world that followed the model of cosmic harmony. Instead, he saw the opposite—Europe torn apart by the most brutal war it had ever seen. Yet Kepler's vision is worth embracing—in its hopefulness, its inclusiveness, and its recognition that a community can both disagree and remain united. Kepler himself drew hope from his conception of the origins of harmony. He believed harmony was buried deep within every one of us; eventually, it would work its way out.

In *The Harmony of the World*, Kepler reminded his readers that although the cosmos itself had once produced a perfect and complete harmony, it would not do so again until the end of days—and maybe not even then. God, it seemed, had meant for humans to be satisfied with the beauty of the smaller harmonies produced by individual groups of planets and to accommodate themselves to the dissonance of the whole. Even in that dissonance, they might find beauty.

Kepler ultimately agreed with the poet Alexander Pope, who a century after him thought harmony pointed a way to a world that might be improved by difference. In Pope's words, such a world would be "Not Chaos-like together crush'd and bruis'd, / But, as the world, harmoniously confus'd: / Where order in variety we see, / And where, tho' all things differ, all agree."[14]

This article was adapted from my book The Pursuit of Harmony: Kepler on Cosmos, Confession, and Community *(University of Chicago Press, 2017).*

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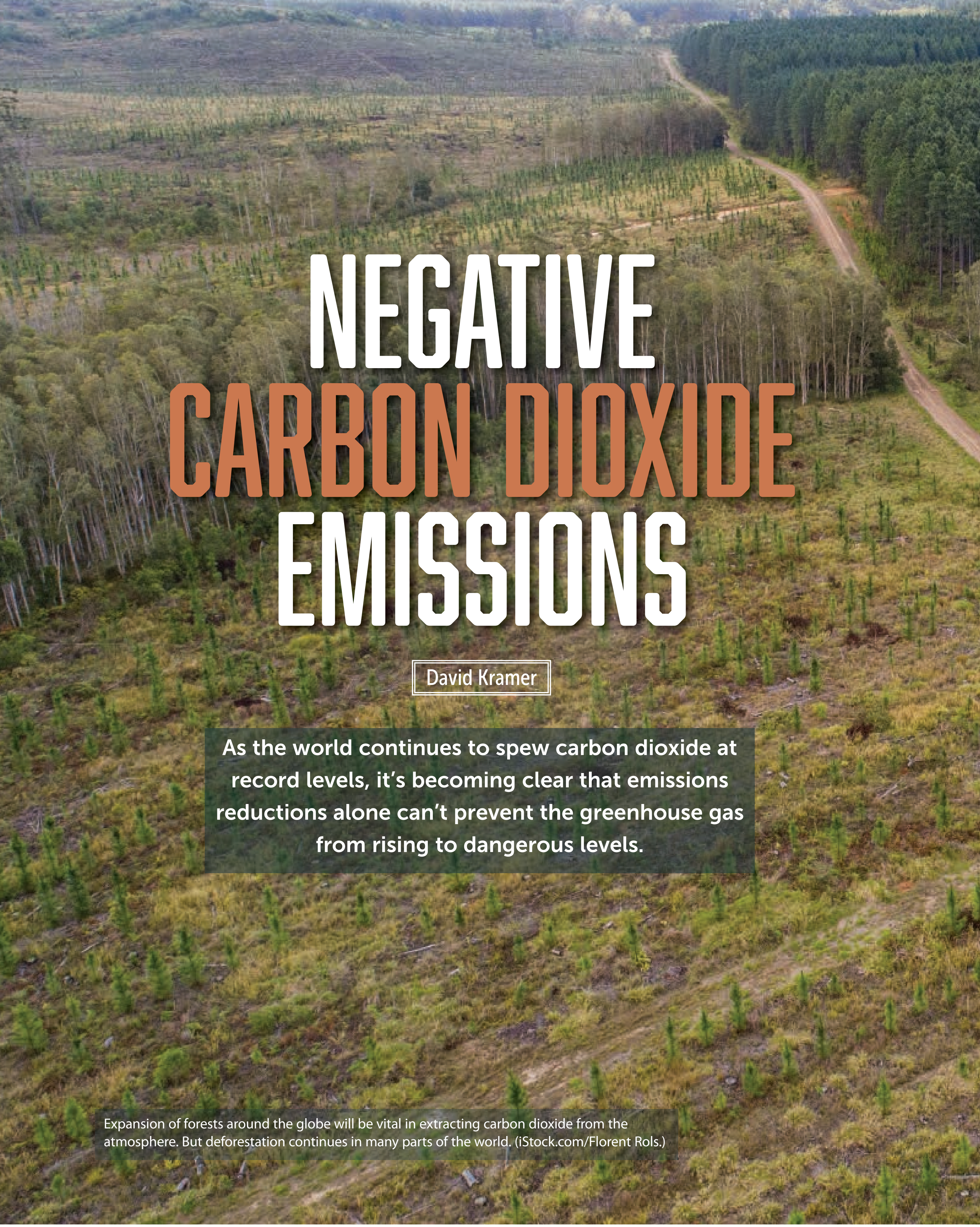
NEGATIVE CARBON DIOXIDE EMISSIONS

David Kramer

As the world continues to spew carbon dioxide at record levels, it's becoming clear that emissions reductions alone can't prevent the greenhouse gas from rising to dangerous levels.



Expansion of forests around the globe will be vital in extracting carbon dioxide from the atmosphere. But deforestation continues in many parts of the world. (iStock.com/Florent Rols.)

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In December 2015 in Paris, 186 nations pledged their best efforts to keep the average global temperature "well below" 2 °C from its preindustrial average, with a goal to not exceed a 1.5° increase. But with carbon dioxide emissions increasing year after year and President Trump rescinding the Paris treaty, many climate scientists say it's likely inevitable that the world will overshoot the atmospheric CO_2 level that could keep temperatures in check.

Annual global CO_2 emissions, currently about 37 gigatons, climbed 0.9% from 2018 to 2019, according to projections by the Global Carbon Project. That follows a 2.7% jump in 2018. China, which produces more than one-quarter of the world's total emissions, has committed to leveling off its CO_2 output, but not until 2030. Demand for electricity in India, now the third largest emitter, is expected to double over the next 20 years, and coal is expected to remain the major contributor, according to BP's 2019 *Energy Outlook*. The need to reduce CO_2 emissions is made more urgent by the difficulty of reducing agricultural sources of nitrous oxide and methane, greenhouse gases that contribute the equivalent of 10–20 Gt of CO_2 per year.

From its preindustrial level of 280 parts per million, atmospheric CO_2 has risen to roughly 410 ppm and is increasing at a rate of 2.5 ppm annually. It's uncertain what the CO_2 concentration will be if and when a 1.5° or 2° increase occurs, because warming will continue even if emissions were immediately brought to zero. About half of anthropogenic CO_2 is removed from the atmosphere by oceans and terrestrial sinks within 30 years, but the other half will endure for centuries or more, according to the United Nations' Intergovernmental Panel on Climate Change (IPCC). Positive feedback loops from the warming that has already occurred include the effects of shrunken ice cover in the Arctic and methane emissions from melting permafrost.

Estimates of when the world will top safe CO_2 levels have varied over time. A 2013 IPCC forecast said the 1.5° threshold could be breached as soon as 2021. In a 2018 report, the panel estimated that Paris commitments, even if followed by more stringent emissions reductions in 2030, won't be sufficient to limit warming to 1.5°. Some studies suggest that existing emissions have already committed the world to a greater than 33% chance of 1.5° warming or more, whereas others suggest the world may have 20 more years at current emissions rates before blowing past the mark.[1]

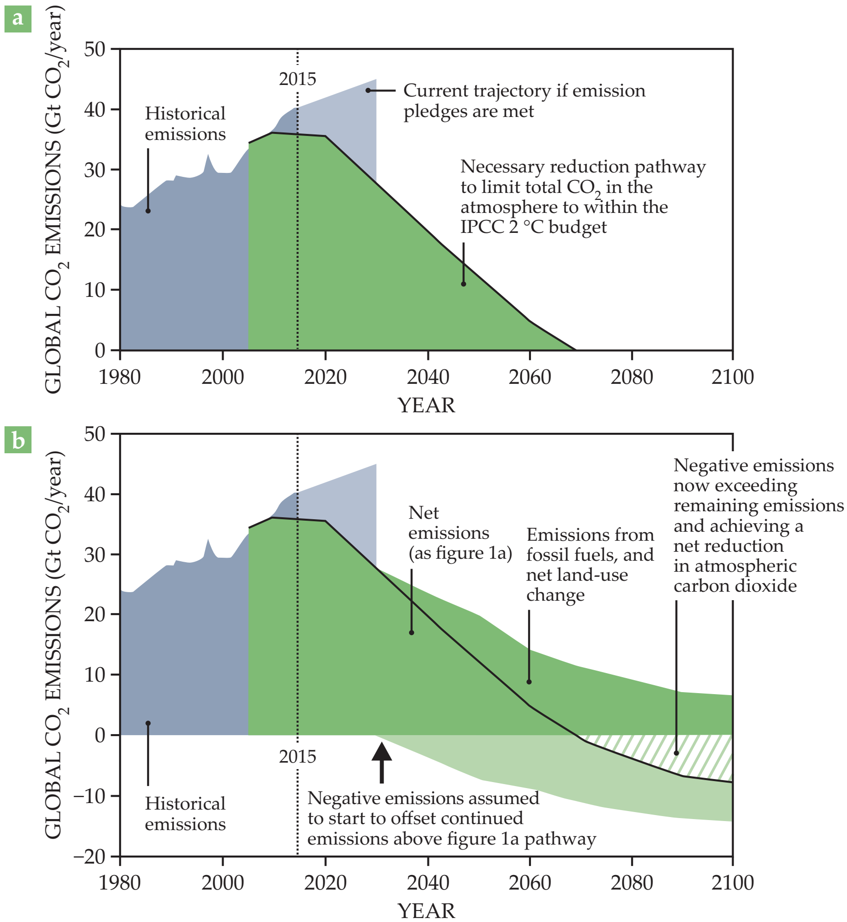
Bringing CO_2 concentrations back to safe levels, many scientists believe, will require the extraction of a significant amount of CO_2 from the atmosphere. There are two ways to mitigate CO_2-caused warming: geoengineering to curb the amount of solar radiation reaching Earth's surface, and removing excess CO_2 from the atmosphere. Known as negative emissions technologies (NETs), the various methods that take the second approach form the subject of this article.

The role of NETs

The February 2019 National Academies of Sciences, Engineering, and Medicine committee report *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* concluded that achieving Paris goals without retarding economic growth will likely require that 10 Gt of CO_2 be extracted from the atmosphere annually by 2050, and that figure will need to increase to 20 Gt annually by 2100. The committee said that a combination of currently available NETs could be ramped up to the 10 Gt level by 2050, but constraints—chiefly the availability of land—might limit their potential to just half that amount.

Those NETs, which could be implemented for $100 or less per ton of CO_2, are reforestation, afforestation (establishing forests on land not previously forested), improved forest management, agricultural and coastal management practices that add carbon to soils and sediments, and bioenergy with carbon capture and storage (BECCS). "We have the technology today. It's not crazy expensive and it adds up to gigatons," says National Academies committee member Jennifer Wilcox of Worcester Polytechnic Institute.

Capturing and storing CO_2 in such quantities will be a massive undertaking. Julio Friedmann, senior research scholar at Columbia University's Center for Global Energy Policy, regards the 10 Gt target as comparable to the mass of annual global oil and gas production. "We have to create an industry the size of the oil and gas industry that runs in reverse. And we're on the clock. If we could do that over 200 years, I'd be a lot more relaxed. But we've actually got 30 years to do that."



ESTIMATED GLOBAL REDUCTION (a) in CO_2 emissions required to limit temperature increases to 2 °C above preindustrial levels. The gray shaded area at the top shows projected emissions through 2030 if all current emission reduction pledges from the 2015 Paris agreement were to be met. In fact, emissions have continued to grow and are projected to reach record levels in 2019. **(b)** Gradual reduction in CO_2 emissions that could be possible with a significant and growing contribution of negative emissions technologies, beginning around 2030. Note that immediate large reductions to emissions are also required. (Source: European Academies Science Advisory Council policy report 35, 2018, adapted from K. Anderson, G. Peters, *Science* **354,** 182, 2016.)

Steven Koonin, a New York University physicist and noted skeptic of the climate science consensus, agrees that "anyone who aspires to stabilize emissions in the next 50 years has got to be thinking about negative emissions technologies." He also puts the required scale at tens of gigatons per year of CO_2 by 2050.

The National Academies panel warned that afforestation, reforestation, and BECCS would compete with each other and with food production for finite arable land. BECCS, which the committee found had the potential to remove up to 3.5 Gt/year, likely will also be held back by the inability to gather all the necessary biomass economically.

Additionally, meeting the full capture potential from improved agricultural practices would require either a revolutionary breakthrough in agricultural productivity or wholesale changes in diets, including greatly reduced meat consumption and reduced food waste, the National Academies report said. Demand for wood will constrain improvements to forest management. Further limitations will come from resistance to adopting improved farming practices and from continued coastal development that reduces wetlands and marshes; both of those constraints will hold back the potential for increasing carbon uptake in soils and sediments.

In marked contrast to the National Academies findings, the European Academies Science Advisory Council said in a February 2018 report that NETs are unlikely to remove even several gigatons of CO_2 per year after 2050. "Negative emission technologies may have a useful role to play but, on the basis of current information, not at the levels required to compensate for inadequate mitigation measures," the report stated. Low technological readiness, high costs, and negative effects on terrestrial and marine ecosystems are factors weighing against NETs, it said. The world should instead focus efforts on halting the loss of forests and the degradation of lands that are adding to the greenhouse gas burden, and on deploying carbon capture and storage at power plants and other point sources of CO_2 emissions.[2]

Natural solutions

Research published in October 2017 by the Nature Conservancy and other institutions indicated that a combination of natural measures could provide more than one-third of all climate mitigation measures—including emissions reductions—necessary from now to 2030 to keep warming below the 2° mark, and it would cost \$100/ton or less. Most of that potential is from reforestation, avoided deforestation, and improved forest management. Lesser contributions would come from improving agricultural management practices, restoring wetlands and coastal areas, and other practices.

Those measures collectively would remove 11 Gt of CO_2 annually and could be implemented without affecting food production, according to the study. Up to one-third of the natural measures could be accomplished for \$10/ton or less. The researchers assumed that CO_2 emissions are held level for the next decade and then plunge to just 7% of current levels by 2050.[3]

More controversial but well-publicized findings were published by researchers led by Thomas Crowther of ETH Zürich in July. Increasing the world's forest cover by nearly 900 million hectares—an area equivalent to the entire US—could increase storage by 205 Gt, about one-quarter of the total atmospheric CO_2 pool, the authors asserted. Enough suitable land is available to accommodate as many as the one trillion new trees without impinging on global food supply or urban areas, they said.[4]

Others dispute those findings. "My biggest objection to the [ETH] paper is the notion that a billion hectares is just sitting there doing nothing," says Rob Jackson, a Stanford University professor who chairs the academic collaboration Global Carbon Project. "There is no discussion of land disturbances, water requirements, or of how you would incentivize land ownership" to achieve the reforestation. For example, although it might be possible to carry out large-scale tree planting in the western US, where so much of the land is publicly owned, government would have to provide costly incentives to landowners in the eastern half of the country to reforest their property.

Friedmann also questions the ETH results. "From an energy perspective, from a land perspective, from a nutrient perspective, from what we understand about tree physiology, it doesn't make sense. I don't understand the basis on which they would make the claim," he says. "Second, we haven't figured out how to stop chopping down trees yet."

No one argues that planting more trees won't be part of the solution, though. Nearly all the modeled pathways to achieve the Paris goals that were assessed by an IPCC special report on lands released in August 2019 require land-based mitigation and land-use changes consisting of different combinations of reforestation, afforestation, reduced deforestation, and bioenergy. The IPCC report also noted that options for storing more CO_2 in soils and vegetation don't lock up carbon indefinitely. When vegetation matures or when soil carbon reaches saturation, CO_2 removal declines toward zero. The accumulated carbon in vegetation and soils is at risk from future loss triggered by flood, drought, fire, pest outbreaks, and poor management.[5]

New forests and their improved management could soak up 2.5 Gt/year, the National Academies report said. Worldwide adoption of improved agricultural practices could increase CO_2 capture in soils by 3.5 Gt/year, the report said. Those measures include reduced- and no-tillage farming, planting seasonal cover crops, converting marginal croplands to perennial grasses and legumes, adding manure and compost to soils, and improving the management of grazing lands.

SILICON KINGDOM HOLDINGS

ARTIST'S CONCEPT OF AN "ARTIFICIAL TREE," a direct air capture system in development by Arizona State University and investors. The translucent spiral structure contains an ion exchange resin that when dry has an affinity for CO_2. Once saturated, the spiral structure is lowered into the cylinder, where moist air causes the CO_2 to be released and captured.

Bioenergy with carbon capture and storage

BECCS is a hybrid of natural and technological approaches. The first step involves growing biomass to remove CO_2 from the atmosphere. Rather than the biomass staying in place as in the case of planting trees, it is harvested and subjected to one of several processes—combustion, fermentation, thermochemical conversion such as pyrolysis or gasification, or microbial conversion—that release the original carbon as CO_2, which is then captured and stored. Energy thus generated could produce either electricity or, through electrolysis, hydrogen. Cost estimates for the processes range from \$80 to \$150 per ton of CO_2 captured and stored. "I think \$100 is a totally fair number to

CARBON ENGINEERING

CARBON ENGINEERING has demonstrated its direct air capture technology at its Squamish, British Columbia, pilot plant. The company has a partnership with Occidental Petroleum to design a plant capable of scrubbing 1 million tons of CO_2 per year.

throw around," says Daniel Sanchez, an engineer at the University of California, Berkeley, who studies CO_2 removal methods.

As with other NETs requiring land conversion, BECCS will be constrained by agriculture, land degradation, water scarcity, and ecological concerns. Competition with food production and other sustainability concerns are likely to limit BECCS to 0.5–5.0 Gt/year, according to the IPCC. "If this is a technology the world wants to pursue seriously, we can get to one billion tons of CO_2 put underground each year," says Sanchez. "Beyond that you get into tremendous uncertainties about how we use and manage our lands." In their modeling, Sanchez and his colleagues developed a global inventory of marginal agricultural land—areas that come into production only part of the time. They narrowed that further to include only lands located above known geological storage reservoirs.[6]

A 2016 DOE report found the US could produce at least 1 Gt of dry biomass from agricultural, forestry, waste, and algal materials each year without adversely affecting the environment or food production. That biomass could produce enough biofuel or biopower to displace a little less than a third of US petroleum output.

The economics of unsubsidized electricity generation from biomass aren't favorable. The process is only about 25% thermally efficient, compared with the 42% efficiency of natural gas power generation. (The efficiency of both can be increased in combined cycle plants, where waste heat is harnessed.) Natural gas is cheaper than biomass, and capital costs for BECCS are more than four times those for a gas plant, the report said.

While relatively straightforward in concept, BECCS has been demonstrated on an industrial scale in only a handful of places. The largest such demonstration is the US Department of Energy–funded Illinois Industrial Carbon Capture and Storage Project, in which 1 million tons of CO_2 per year is being captured from corn fermentation at an Archer Daniels Midland ethanol plant and injected into a sandstone formation more than 2100 meters underground. But Niall Mac Dowell, who leads the clean fossil and bioenergy research group at Imperial College London, says BECCS is ready for prime time. "Pretend you are the US government. If you give me a long-term contract for removing CO_2 from the atmosphere for \$100 per ton, I guarantee that I can finance a BECCS project on that basis."

The BECCS technology has an inherent advantage over solely land-based approaches to CO_2 capture, says Mac Dowell. "When you put a ton of CO_2 into geology, it is permanently removed. Locking it up in a tree is inherently leaky. You could have a forest fire, a lightning strike, and someone could decide in 100 years to not do it anymore." Managing forests incurs additional perpetual costs, he adds.

If BECCS is used to produce biofuels by pyrolysis, the co-product biochar can be added to soils for long-term carbon storage. For dedicated biochar production, the pyrolysis liquids and volatiles can be burned to generate electricity or process heat.

Biochar has the benefit of improving soils for growing crops or biomass. But its potential is limited, says Jackson: "I don't believe [biochar] is feasible at the gigaton scale. As a tool to improve degraded soils, it has a lot of advantages. But as a tool to be applied across millions of hectares, I don't see how we would do it. Spread it by helicopter? Plow it into lands on national forestlands?"

Direct air capture

Extracting CO_2 directly from the atmosphere using giant fans and chemical processes has been attracting a lot of attention in the past year. At least four fledgling companies are developing variations of the technology, known as direct air capture (DAC). (See PHYSICS TODAY, September 2018, page 26.) In May, Carbon Engineering, based in British Columbia, Canada, announced a joint venture with Occidental Petroleum to develop an engineering design for a plant capable of scrubbing 1 million tons of CO_2 from the atmosphere each year. Construction is expected to commence in 2021. Occidental and Chevron Corp were among investors providing a total of $68 million in new equity financing last year. In June, New York–based Global Thermostat announced that ExxonMobil had invested an undisclosed amount to scale up Global's DAC technology.

Oil companies and DAC may seem to be odd bedfellows, but the relationship is symbiotic. In addition to providing direct financing, the petroleum industry creates a ready-made market for the captured CO_2, which is needed for enhanced oil recovery. Also known as tertiary recovery, EOR forces pressurized CO_2 into depleted reservoirs to extract otherwise unrecoverable oil. Since it is miscible in petroleum, CO_2 also lowers the viscosity of the oil, which improves its flow to extraction wells.

Susan Hovorka, a geologist with the University of Texas at Austin, says oil and DAC should mix. "It's a perfectly reasonable step toward getting the NETs portfolio commercialized."

"If we want to do something like DAC on a gigaton scale, we can't do it without the help of the energy companies," agrees Wilcox. "It will take an immense workforce and will transition the jobs workers now have to doing this. The workers will require the same exact skill sets."

Wilcox is skeptical of DAC's feasibility, however. "It's really fundamental chemical engineering, and a really hard separations process," she says. "Most of those pushing the field are physicists. That's fine, but I feel like they are missing a big piece, like the process engineering. You can do a techno-economic analysis and say something costs x dollars per ton, but until you actually build it and prove it and show it, it's, like, not real."

Global Thermostat officials say its process can extract CO_2 for $100/ton, though it has yet to demonstrate it at scale. Wilcox says paper studies indicate costs of $100 to $150 a ton are feasible in the long run, but the Swiss company Climeworks is the only DAC pioneer to have sold commercial systems. The largest produces 900 tons of CO_2 per year for a greenhouse in Hinwal, Switzerland, at a cost of $600/ton. That was the exact cost estimated by the American Physical Society in a 2011 report on DAC.[7]

Climeworks hopes to lower that cost to $200/ton in the next three years, says spokesperson Louise Charles, and ultimately to $100. Steve Oldham, CEO of Carbon Engineering, told a Washington, DC, conference in October that the company's cost is "way, way, way less than $600 per ton." Howard Herzog, senior research engineer at the MIT Energy Initiative, notes the distinction between gross and net costs of DAC. If all the energy used to drive the Climeworks process is carbon-free, for example, gross and net costs would be the same. But if natural gas fuels Climeworks' power, then its net CO_2 removal cost would be well over $1000 a ton, he says.

Wilcox believes DAC may be more relevant in a post-2050 world, when forest fires, droughts, sea-level rise and the other negative impacts of climate change have reached the point where $300/ton for CO_2 extraction may not look so expensive.

Friedmann, a DAC enthusiast, thinks the technology will provide half of CO_2 capture needs. He says high cost is the only hurdle DAC faces. "That's okay. We know how to drop the cost of things," he says, citing the dramatic reduction in the cost of photovoltaics over the past several decades.

Large-scale deployment of DAC, however, will require enormous amounts of energy. One study published in July found DAC could constitute as much as a quarter of the world's total energy demand[8] by 2100. Energy is required not only to power the fans that continuously force air to flow past contactors that contain adsorbing chemical compounds, but also to provide heat to extract the CO_2 from the saturated compounds. Compressing and transporting the purified CO_2 to storage sites adds to energy requirements. Depending on the adsorbing compound used—currently either amines or hydroxide solutions—waste heat from industrial processes might supply a portion of the need.

Klaus Lackner, director of Arizona State University's Center for Negative Carbon Emissions, aims to reduce energy consumption with an "artificial tree" that uses wind to move air past chemical contactors. The trees' "leaves" contain an ion exchange resin that has a high affinity for CO_2 when dry. Once saturated with CO_2, they are moved to an enclosed wet environment, where the gas is released and concentrated.

In April 2019, Arizona State announced an agreement with a group of investors including Lackner to build and deploy 12-column clusters of the devices that will remove 1 ton of CO_2 per day. At full scale, such farms will be capable of capturing 3.8 million tons of CO_2 annually, at the familiar cost of $100 a ton, according to the university. All DAC approaches feature far smaller geographic footprints and water requirements relative to land-based NETs. For example, a forest of artificial trees capable of capturing as much CO_2 as the Amazon rain forest would be 500 times smaller than the natural version, says Wilcox.[9]

Storage

Although not a NET itself, CO_2 storage is intrinsic to both DAC and BECCS. Experts say the pore space in sedimentary rocks around the globe is more than enough to sequester all the CO_2 that humanity could ever want to remove from the air. DOE has estimated that the total storage capacity in the US alone ranges between 2.6 trillion and 22 trillion tons of CO_2.[10] China has enough storage to hold 600 years' worth of its current emissions.[11] Globally, the number is easily 20 trillion to 30 trillion tons, says Friedmann.

SOLIDIA TECHNOLOGIES

SAMPLES OF NOVEL CONCRETE in cylinders are tested by Solidia Technologies employees prior to curing with CO_2. Building materials present a route to permanently remove CO_2 from the atmosphere.

As of last year, just five dedicated geological CO_2 storage locations were operational worldwide, according to the Global CCS Institute. The longest-running is in the North Sea's Sleipner gas field, where since 1996, 1 million tons of CO_2 from Norwegian natural gas processing has been injected beneath the seabed every year, with no leakage. The sole dedicated geological storage site in the US is at the DOE-funded Illinois ethanol plant demonstration. The world's largest dedicated geological storage site, at Chevron's liquefied natural gas project in Western Australia, began operating in August. The company says it will sequester up to 4 million tons of CO_2 each year.

Compressing and injecting CO_2 makes up a small fraction of the total cost of BECCS or DAC. Sanchez says it will cost between $1 million and $33 million to drill a well capable of injecting 1 megaton of CO_2 annually. Assuming a 20-year lifetime for the well, that's less than $1 per ton of CO_2. He estimates the total cost of storage, including operation, maintenance, monitoring, and verification, at around $5/ton.

A report by the Congressional Research Service says that long-term average cost of CO_2 transport and storage should stay below the level of approximately $12–$15/ton in North America, due largely to the abundant capacity offered by deep saline formations.[11] Herzog's estimate is much higher: up to $50/ton.

Incorporating CO_2 into building materials is another way to store captured CO_2. Solidia Technologies in New Jersey has developed a process it says could reduce the carbon footprint of cement and concrete production by 60%. Solidia's cement is cured with CO_2 instead of water, and that process forms calcium carbonate and silica to harden the concrete. About 0.5 Gt of CO_2 could be captured per year if the company's technologies were adopted by the entire precast concrete industry, says Solidia chief technology officer Nicholas DeCristofaro. Concrete made with the company's proprietary cement locks up about 300 kg of CO_2 per ton as it cures in a CO_2-rich environment. The manufacture of Solidia's cement itself also produces 30% less CO_2 than conventional Portland cement. (Cement production contributes about 8% of global CO_2 emissions.) Solidia's concrete curing process wouldn't work for the larger ready-mix concrete market.

CO_2 mineralization

Solidia concrete is an artificial version of CO_2 mineralization, a naturally occurring capture process also known as rock weathering. "It is technically mineralization to make concrete block with CO_2," says Phil Renforth, associate professor at Heriot-Watt University in the UK. The same chemical reactions occur on certain rocks, and they can be accelerated either by exposing a greater surface area of the rock to the atmosphere or by bringing CO_2-bearing liquid into contact with the rock at depth. Compared with storing CO_2 in geological formations, rock weathering chemically transforms the CO_2 into carbonates such as calcite, magnesite, dolomite, and quartz. If performed subsurface, mineralization can induce seismicity of the sort that has occurred with wastewater injection from oil and gas hydrofracturing.

Mineral carbonation requires rocks rich in calcium, magnesium, or iron cations, such as peridotite, basaltic lava, and ultramafic and mafic rocks containing olivine. Peter Kelemen, a Columbia University geochemist, says enough mantle rock is located within a few kilometers of Earth's surface to permanently capture hundreds of trillions of tons of CO_2.

When finely ground, olivine-rich rock can absorb up to its weight in CO_2. For more common basalt and volcanic material, the ratio is about 20%. Renforth says as much as 10 Gt of rock mining and grinding per year is feasible by 2100. For comparison, about 50 Gt of rock is extracted globally each year by the aggregate industry.

Mineralization may be cost-competitive with direct air capture systems, the National Academies committee said. But it warned that mining and spreading the rock would create enormous volumes of waste that could contaminate water, air, or both.

Renforth says the required particle fineness will depend on the reactivity of the rock. Negative emissions would, of course, be reduced by the CO_2 generated to extract and crush the rock, transport it to the application site, and distribute it. Cost estimates vary widely from a low of $20 to hundreds of dollars per ton of CO_2 extracted, he says.

Kelemen says he and coinventors have filed a patent application on a process for weathering magnesium-rich rocks that involves heating up the carbonated rock to drive off the CO_2 for capture, and then recycling the rock. Once again, the cost is projected at $100 per ton of CO_2 captured.

In a marine environment, mineralization might raise the alkalinity of the ocean surface and thereby increase its CO_2 capture capacity. The process would offer an added benefit of countering the CO_2-caused ocean acidification that is damaging coral reefs and other sensitive marine ecosystems.

One 2017 study suggested that dissolving huge quantities of finely ground olivine particles (10 μm) in ice-free coastal areas—roughly 9% of the entire ocean surface—could extract 800 Gt of carbon (3000 Gt of CO_2) by 2100. Olivine mining would have to be increased by two orders of magnitude to achieve that level, the researchers said, and CO_2 emissions from crushing operations could offset as much as 20% of the gas captured. Pollution from impurities such as silica, iron, and heavy metals also is possible.[12]

Taking action

Implementing NETs at the necessary scale will require increased R&D to improve the understanding of mineralization, to mature DAC, and to better determine the effects of land-based approaches on food production and ecosystems, among other needs. The National Academies report suggested a detailed portfolio of NETs R&D totaling as much as $1 billion annually. In September the think tank Energy Futures Initiative offered a 10-year, $10.7 billion R&D and demonstration program to bring CO_2 removal to commercial readiness.[13]

But it will take more than R&D alone to bring some NETs, including DAC, to fruition, says Friedmann. "We know the recipe; we've done it over and over again. We have sustained, long-lived R&D programs that drop the price enough that we start making policy. And we expand policies to align with markets. That is exactly what we did for solar, wind, and nuclear, and batteries."

To nurture wind and solar, states enacted renewable portfolio standards, while the federal government offered investment tax credits and production tax credits. Adoption was then spurred on by stimulus money during the last recession, loan programs, and feed-in tariffs (long-term purchase contracts to renewable energy producers that are based on the cost of the technology).

"It's not necessarily what is technically achievable; it's about the political will, and the extent to which governments, especially the US, are willing to provide economic incentives to leave CO_2 in the earth or to put it back in the earth," says Wilcox. "It's not all going to happen by advancing technology and getting costs down."

Notably, in the US a measure known as 45Q, first enacted in 2008 to incentivize the capture of CO_2 for EOR, was expanded last year to make eligible both CO_2 captured and stored and CO_2 captured for other uses. The tax credit will increase to $50/ton for stored and $35/ton for CO_2 that's put to use. The tax credit could exceed the cost of capture for industries producing ethanol, ammonia, and hydrogen, according to the report by the Energy Futures Initiative. It estimated that 45Q could stimulate storage or utilization totaling 50–100 Mt of CO_2 per year, depending on public acceptance, the availability of pipelines and storage sites, and other factors.

Bipartisan, bicameral legislation known as the Utilizing Significant Emissions through Innovative Technologies Act and introduced in February 2019 would authorize increased R&D on CO_2 capture and utilization, ease regulatory hurdles on construction of CO_2 pipelines, and further extend 45Q. The Senate bill was reported out of committee and awaits floor action. But as of press time, none of five subcommittees with jurisdiction in the House have considered the measure.

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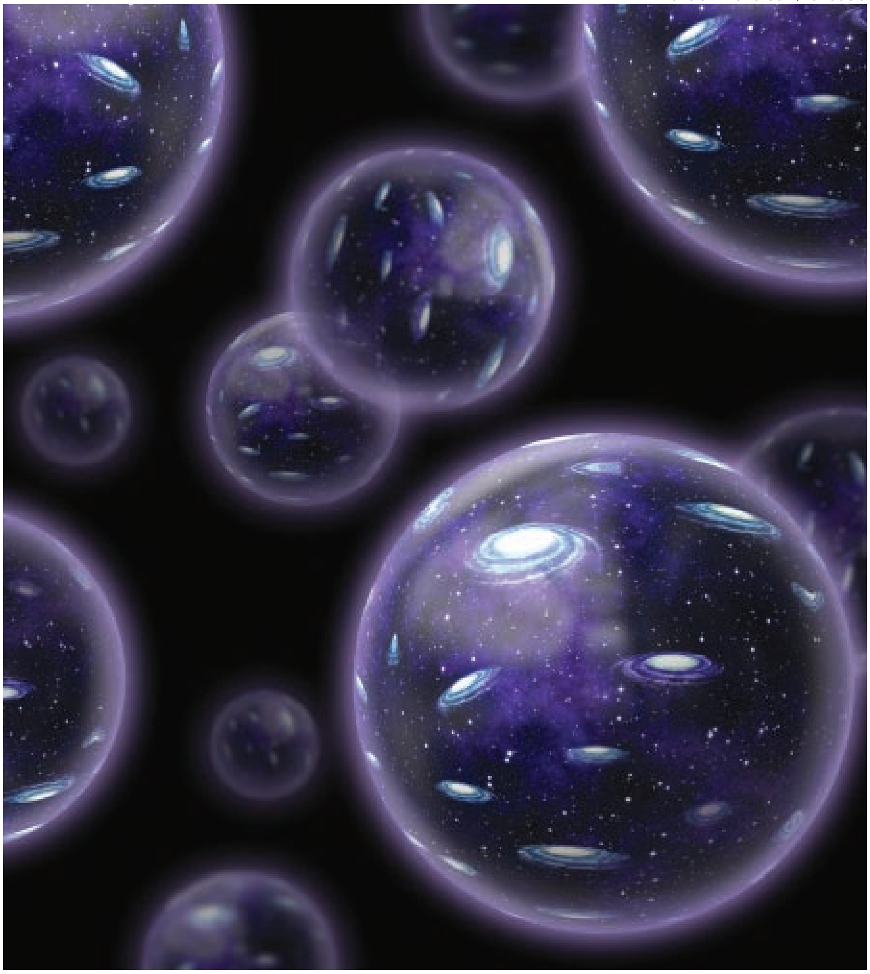
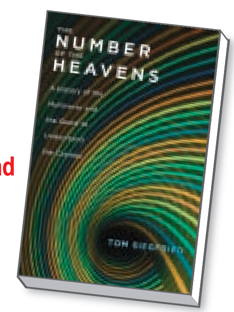


Making the modern multiverse

One of the liveliest scientific debates is whether our universe is unique. Unlike some controversies, the multiverse debate is highly interdisciplinary. Philosophers, theologians, and of course physicists all cling to entrenched positions about the multiverse's reality. Perhaps no other topic than the multiverse has so clearly and passionately raised the question of what constitutes science.

Into this debate comes *The Number of the Heavens: A History of the Multiverse and the Quest to Understand the Cosmos* by Tom Siegfried, the former editor-in-chief of *Science News* and author of three books including *Strange Matters: Undiscovered Ideas at the Frontiers of Space and Time* (2002). Despite his journalistic credentials, Siegfried is not a dispassionate observer or tour guide. He boldly asserts his opinions as he enumerates the many ways humanity has understood the multiverse from antiquity to today.

The Number of the Heavens
A History of the Multiverse and the Quest to Understand the Cosmos
Tom Siegfried
Harvard U. Press, 2019. $29.95



Combining interviews of modern physicists and philosophers with a detailed historical narrative of ancient, medieval, and Renaissance interpretations of the word "world," Siegfried's text fills an important gap in the expanding body of multiverse literature. His approach to the multiverse is liberal: Possible multiverses have, at times, included other planets in our solar system, other stars in our galaxy, planets around other stars in our galaxy, other galaxies in our universe, and parallel universes in both space and time. Siegfried thus gives the interpretation of the multiverse a wide berth. However, only the parallel-universes interpretation is relevant to modern physicists.

The Number of the Heavens is intended for a general audience. The book's first two-thirds is replete with ancient conceptions of the multiverse—though clearly the ancient thinkers were usually considering other possibly habitable planets rather than multiple universes. Nowadays, no scientist or philosopher doubts the existence of such worlds, even Earth-like ones, whereas the evidence for multiple universes is as yet nonexistent.

Siegfried sees the modern interpretation of the multiverse as an inevitable logical evolution of Copernican thought. Why would our universe be singular? Seven other planets aside from Earth populate our solar system alone, 100 billion or more suns are in the Milky Way, and a similar number of galaxies exist in the observable universe.

Siegfried writes about many historical scientists, Copernicus included, who entertained the notion that some version of a multiverse may exist. The historical prologue, though interesting, takes up most of the book. That leaves only a few chapters for Siegfried's juiciest prose on the modern meaning of the multiverse: brane worlds, Everett's many-worlds theory, and the inflationary multiverse.

The imbalance between ancient and modern multiverse conceptions isn't the book's only shortcoming. Most notably, the perspectives of multiverse opponents are only minimally covered. As an experimental cosmologist working to constrain models of inflation, I was disappointed not to find a description of the most promising approach to discovering evidence for inflation and potentially the multiverse as well: B-mode polarization of the cosmic microwave background.

Siegfried rejects science philosopher Karl Popper's idea that the demarcation between scientific and unscientific theories lies in the ability to be proven false. But Siegfried proposes no alternative. Instead, he cites the opinions of Steven

Weinberg, Leonard Susskind, Sean Carroll, Lisa Randall, and other multiverse proponents, or asserts his own opinions. His referring to opponents of the multiverse with the pejorative "deniers" links them with deniers of evolution, climate change, or worse. A less partisan presentation would have improved the book's balance. Finding multiverse opponents is not exactly difficult; an informative, if heated, debate recently took place between multiverse proponents and opponents in reaction to the article by Anna Ijjas, Paul Steinhardt, and Abraham Loeb in the February 2017 issue of *Scientific American*. Healthy debate is a welcome feature of the multiverse landscape.

Other books on the multiverse include Brian Greene's *The Hidden Reality: Parallel Universes and the Deep Laws of the Cosmos* (2011) and Max Tegmark's *Our Mathematical Universe: My Quest for the Ultimate Nature of Reality* (2014). Those texts largely eschew the history of the multiverse and cover the pertinent, if esoteric, physics more thoroughly.

The Number of the Heavens shines when Siegfried adopts a journalistic neutrality about the arguments for and against the multiverse. His wry wit is evident throughout, but nowhere more so than when relating past episodes of confusing and even contradictory interpretations of metaphysical ideas.

At the outset, Siegfried stresses that "there is no greater story in science than the human quest to comprehend the cosmos." Our understanding of the universe is rapidly expanding. But physicists still debate the definition of the words we use to describe the cosmos's capaciousness. Even the term multiverse constantly evolves. At least with *The Number of the Heavens*, we finally know where it began.

Brian Keating
University of California, San Diego
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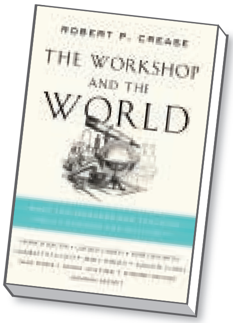
ISTOCKPHOTO.COM/TRIFONOV_EVGENIY

Why do people mistrust science?



The Workshop and the World
What Ten Thinkers Can Teach Us About Science and Authority
Robert P. Crease
W. W. Norton, 2019. $26.95

The Workshop and the World: What Ten Thinkers Can Teach Us About Science and Authority attempts to uncover the origins of science skepticism and contribute to the highly politicized US debates about climate change. Robert Crease addresses the problem of science and authority through 10 historical characters—thinkers, as he calls them—Francis Bacon, Galileo Galilei, René Descartes, Giambattista Vico, Mary Shelley, Auguste Comte, Max Weber, Kemal Atatürk, Edmund Husserl, and Hannah Arendt. That mix is a clever choice, especially because some of those chosen are not the usual suspects in Anglo-American histories of science. The diversity helps broaden the scope and complexities of Crease's discussion, and that alone may be an interesting reason to read the book.

Each chapter of *The Workshop and the World* covers moments when the authority of "this thing we call science," to paraphrase Alan Chalmers, was under threat. And therein lies the strength and weakness of Crease's book. The strength is acknowledging that science has often had to both earn its authority and negotiate with those in authority. The weakness is thinking of science as a necessary, well-defined category with a natural authority that should be recognized at all times and in all places.

Much of Crease's argument rests on the label "science denier," which I think needs a less politically biased clarification. Crease says, "Ensuring the authority of science requires carefully considering the social and historical context" in which a particular scientific community evolves. Here in Europe, where the word "science" is not quite so politicized, I may be missing important US-local points of the discussion. But targeting so-called science deniers as a uniform, antiscientific group seems excessively simple. Moreover, by comparing them to ISIS terrorists, for example, I am not sure the author does what he claims when he writes, "To confront science denial we have to understand what stories are unfolding in his [the denier's] head and where they come from."

As a historian of science, I welcome attempts to understand the present through history. One should, however, be careful with the use of universal categories that might easily be challenged, such as the word science (yes, singular) as we find it in the book. Crease's narrative seems to unravel as follows: Bacon invented how to institutionalize modern science, and people such as Galileo and Descartes had to fight against those who opposed an otherwise obvious need for such methods and institutions. After that, some thinkers—including Vico, Shelley, Husserl, and Arendt—helped shape the social authority of science with their valid criticisms of it.

Meanwhile, members of the Inquisition, dictators, contemporary Trump supporters, and others have stubbornly or irrationally attacked the authority of science. I believe that the Manichean story is far too simple. I wonder, for example, if Crease would regard President Dwight Eisenhower's 1961 farewell address warning about the dangers of technocracy as antiscience.

Crease proposes as solutions a list of short-term and long-term policies, the most surprising being to demand that any person wanting to participate in the public sphere take a pledge for science. That sounds to me like a totalitarian attempt to expel criticism. Who would write and police that pledge? And how far could it go without becoming ideological rather than scientifically neutral? A diverse group of philosophers of science would probably never agree on a common text for the pledge. Perhaps we should leave the work of granting scientific citizenship to Comte and his positivist church in chapter 6 of Crease's text or to a new Atatürk in chapter 8.

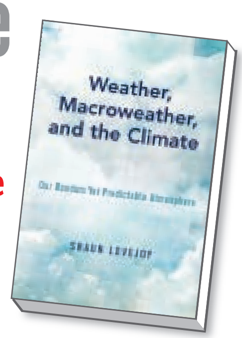
Some long-term strategies that Crease suggests, including the emphasis on science education and nuanced historical accounts of how we got here, may indeed be helpful. And if done honestly, those strategies will prevent science from being used as a simplistic ideological catchword, which, at the end of the day, is what science deniers—and some self-appointed science promoters—do.

Jaume Navarro
University of the Basque Country
Bilbao, Spain

ISTOCKPHOTO.COM/POBYTOV

An introduction to our chaotic atmosphere and climate

The geophysical community recognizes that the observational data they collect are incredibly complex. As temporal and spatial scales get larger, the fluctuations in the atmospheric and other Earth fields systematically increase or decrease. Such behavior occurs not only in climate dynamics but in seemingly unrelated fields such as geomorphology. A closer look reveals that complex signals are governed by statistical relationships that connect billions of structures over a wide range of time and length scales. The resulting quantifiable scaling laws capture the power law growth or decay of fluctuations. Lewis Fry Richardson first proposed the idea in the Richardson $4/3$ law of turbulent diffusion.



Weather, Macroweather, and the Climate
Our Random Yet Predictable Atmosphere
Shaun Lovejoy
Oxford U. Press, 2019. $34.95

The ubiquitous nature of scaling laws is masterfully analyzed in *Weather, Macroweather, and the Climate: Our Random Yet Predictable Atmosphere* by Shaun Lovejoy. Recipient of the 2019 Lewis Fry Richardson Medal, Lovejoy has devoted his career to understanding scaling laws empirically and theoretically. In his book, he shows readers from all backgrounds the atmosphere from a new perspective. Although he places the discussion in a broader context, the main focus is on his research: In the late 1970s, he broke new ground on the statistical analysis of precipitation using monofractals. Lovejoy then covers the extension of those ideas to other turbulence-dominated domains in the 1980s and 1990s using multifractals. Subsequently, multifractals have proven to be important for phenomenological descriptions and models of highly turbulent processes in the physical sciences and marine biology.

Lovejoy explains that generations of scientists who studied turbulence suspected that many vortices, cells, and structures could be explained by high-level statistical laws. Chaos theory characterizes the universal behavior underlying seemingly random dynamical systems. But the underlying mathematics proved difficult, largely because most of the activity is in tiny, violently active areas that are buried in a hierarchy of structures. Lovejoy emphasizes that scale-dependent stratification caused by gravity poses an additional obstacle to the application of turbulence theory to the atmosphere.

Weather, Macroweather, and the Climate explains in simple terms the concept of atmospheric variability, from millimeter to planetary scales and from milliseconds to billions of years. Five years ago, researchers found that classical approaches had underestimated the variability by a quadrillion (a million billion).

In the most important chapter, Lovejoy explains his empirical observation of low-frequency "macroweather" at intermediate time scales of about 0.1 to 100 years, in between the fast time scales of conventional weather and the slow time scales of climate. He clearly describes how the familiar weather–climate dichotomy becomes the weather-macroweather-climate trichotomy, and he details how scientists can exploit the long-term memory of the atmosphere–ocean system to make accurate monthly to decadal forecasts. Lovejoy illustrates that applying the scaling approach to the Anthropocene—the current geological period of man—can reduce the large uncertainties in current climate projections out to 2050 and 2100.

The author asks and answers the fundamental question, What is climate? He also addresses Richardson's basic questions, Does the wind have a velocity? and How big is a cloud? Through his answers, Lovejoy explains why the fractal dimension of atmospheric motion is $D = 23/9 = 2.555\ldots$, which is larger than the $D = 2$ flat value that theoreticians have predicted but smaller than the usual $D = 3$ volume-filling value. He also shows that Mars is our statistical twin and why that shouldn't surprise us, and he explains how the multifractal butterfly effect causes extreme events.

The book has more than a dozen boxed sidebars that provide even more information. Undergraduate and postgraduate students looking for an introduction to atmospheric modeling will not easily find one more readable than *Weather, Macroweather, and the Climate*.

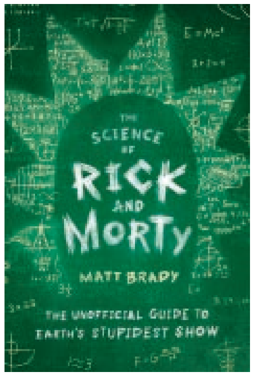
Costas Varotsos
National and Kapodistrian University of Athens
Athens, Greece

NEW BOOKS & MEDIA

The Science of Rick and Morty

The Unofficial Guide to Earth's Stupidest Show

Matt Brady
Atria Paperback, 2019. $17.00 (paper)

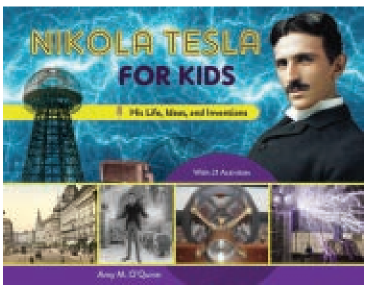


The adult animated sitcom *Rick and Morty*, which chronicles the misadventures of an antihero scientist and his grandson, has entertained audiences since 2013. Now teacher and writer Matt Brady gives fans a closer look at the science depicted in the show. For example, Rick and Morty travel to many planets. In his explanation of the transit method, one technique astronomers use to detect faraway worlds, Brady compares the blip of an exoplanet in front of its host star to a shadow flitting across an ominous horror-movie hallway. One episode of the show, "M. Night Shaym-Aliens!" has Rick concentrating dark matter to travel across space. Brady separates that fiction from what physicists know about dark matter and how they know it. Even with the references to *Rick and Morty*, science-prone readers who are not fans of the show will probably find something they like in the book. —AL

Nikola Tesla for Kids

His Life, Ideas, and Inventions, with 21 Activities

Amy M. O'Quinn
Chicago Review Press, 2019. $16.99 (paper)

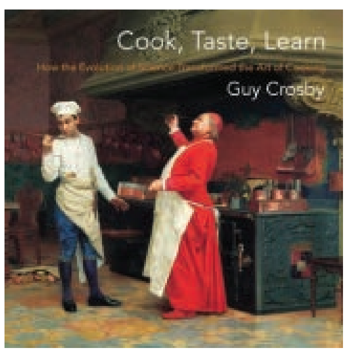


A gifted physicist, engineer, and inventor, Nikola Tesla emigrated to the US in 1884, when he was 27 years old. Although he would go on to develop many technologies that we take for granted, such as AC electrical power and radio, Tesla never earned the renown of some of his more famous contemporaries, such as fellow inventor Thomas Edison. In *Nikola Tesla for Kids*, teacher and educational writer Amy O'Quinn presents an easily accessible introduction to the life and remarkable ideas of this eccentric genius. Aimed at readers 9–12 years of age, the book includes 21 hands-on activities and more than 70 black-and-white photos and illustrations. —CC

Cook, Taste, Learn

How the Evolution of Science Transformed the Art of Cooking

Guy Crosby
Columbia U. Press, 2019. $26.95

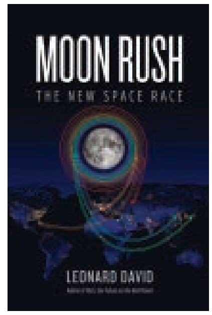


In *Cook, Taste, Learn*, food scientist Guy Crosby discusses the science involved in food preparation, from improving flavor to increasing energy and nutrients. He starts with a history of human development, beginning with the ability to control fire and the emergence of agriculture. He then discusses how the cooking of food has given us an advantage over all other species by influencing the human brain's development and increasing our life spans. He explains how early theories in the classical sciences evolved and were applied to cooking and explores the chemistry and physics involved in various cooking techniques. Each chapter features one of the author's favorite recipes to help illustrate the science involved. —CC

Moon Rush

The New Space Race

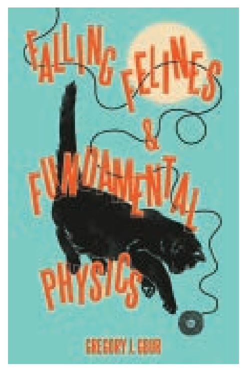
Leonard David
National Geographic Partners, 2019. $26.00



Amid the plethora of books marking the 50th anniversary of the first Moon landing, *Moon Rush* aims to guide the reader through the past, present, and future of Earth's satellite, with an emphasis on its future. Veteran space journalist Leonard David begins with a discussion of the Moon's origins and moves on to the mid-20th-century space race before launching into the current resurgence of interest in lunar exploration, from Moon outposts and mining operations to orbiters acting as interplanetary way stations. Rather than serving as a mere stepping-stone to other destinations, however, the Moon is itself a valuable resource, says David, and is becoming the focus of attention in a new space race among scientists, governments, and private companies. —CC

Falling Felines and Fundamental Physics

Gregory J. Gbur
Yale U. Press, 2019. $26.00



A falling cat's innate ability to land on its feet has intrigued scientists "for almost as long as science itself has existed," writes physics professor Gregory Gbur in *Falling Felines and Fundamental Physics*. One reason is that until the 19th century, the study of animal motion was limited by the speed of the human eye. The development of photography over the past two centuries has allowed researchers to better study animal movement, which in turn has led to advances in various scientific disciplines, including physics, neuroscience, physiology, mathematics, and robotics. With numerous anecdotes about eccentric scientists and crucial insights into long-standing scientific puzzles, *Falling Felines* is both entertaining and educational. —CC

Gastropod

Cynthia Graber and Nicola Twilley

2014–

The 45-minute podcast, which covers the science and history of food, reached its fifth anniversary in September 2019. Science journalist hosts Cynthia Graber and Nicola Twilley recently reported on the use of CRISPR to improve yogurt making and on the history of genetically modified crops. Another recent episode dug into the science of omega fatty acids and the diseases that supplement makers claim they can cure. New episodes are served every two weeks.

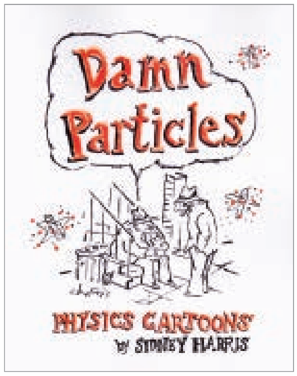
—AL

Damn Particles

Physics Cartoons

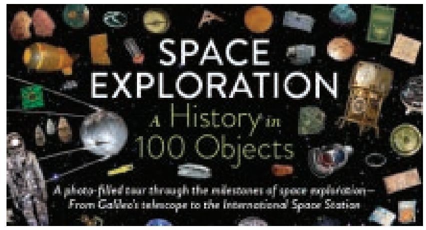
Sidney Harris

Kindle Direct Publishing, 2019. $14.95 (paper)



Veteran cartoonist Sidney Harris has published a new collection, titled *Damn Particles*. Harris summarizes complex physics concepts "with an economy of inked lines that flow from his pen," writes Arthur W. Wiggins, a professor emeritus at Oakland Community College, in the foreword to the book. One cartoon shows Isaac Newton's father reading equations to him before going to bed. Another illustrates how garbage near the event horizon of a black hole in a trash can gets pulled in. The captions are pithy, insightful, and funny.

—AL



Space Exploration

A History in 100 Objects

Sten Odenwald

The Experiment, 2019. $25.00

From the 70 000-year-old Blombos ochre drawing to the first-ever image of a black hole, *Space Exploration: A History in 100 Objects* presents an eclectic selection of the tools and technologies humans have developed over the millennia to depict, study, and interpret the cosmos. Author Sten Odenwald, a NASA astrophysicist, says he made a point of choosing not only iconic images but also lesser-known ones that probably "you've never even heard of before." Arranged chronologically, the entries feature stunning photography paired with several paragraphs of explanatory text.

—CC PT

NEW PRODUCTS

Focus on photonics, spectrometry, and spectroscopy

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

Versatile ultrafast fiber laser

Originally developed for ophthalmic applications, Toptica's FemtoFiber vario 1030 microjoule fiber laser—with a center wavelength of 1030 nm—can be used in many other areas, ranging from micromachining and materials processing to the life sciences. The robust, compact, passively cooled design and detachable laser head make it suitable for OEM integration and industrial use. The FemtoFiber vario 1030 provides 2 W of output power at an adjustable repetition rate of up to 1 MHz and down to pulse on demand. It features a variable pulse duration that is less than 300 fs and is controlled by group-delay dispersion. According to the company, the FemtoFiber vario 1030 offers superior temporal and spatial beam quality. ***Toptica Photonics Inc***, *5847 County Rd 41, Farmington, NY 14425, www.toptica.com*

Spectroelectrochemistry instruments

Following its acquisition of DropSens, Metrohm has announced the first fully integrated range of instruments for research in spectroelectrochemistry. The system combines electrochemistry and spectroscopy in the study of spectral changes as a function of applied potential or current. Optical monitoring complements the limited structural information available from the electrochemical response. Metrohm's SPELEC platform combines a light source, spectrometer, and potentiostat/galvanostat. It uses one software with dedicated functions to synchronize and easily treat and analyze data. The SPELEC instrument is available in several wavelength ranges: UV–visible (200–900 nm), visible–near-IR (350–1050 nm), Raman (785–1010 nm), Raman shift (0–2850 cm^{-1}), and near-IR (900–2200 nm). ***Metrohm AG***, *9250 Camden Field Pkwy, Riverview, FL 33578, www.metrohm.com*

Ultrafast laser for multiphoton imaging

Coherent's Chameleon Discovery NX laser delivers deep multiphoton microscope images suitable for live-tissue imaging in neuroscience and other intravital applications. It can also be used for ultrafast spectroscopy and other time-resolved studies. The laser offers power levels up to 3 W. A group-dispersion-delay precompensator with enhanced dynamic range enables the short-pulse durations that are essential for high-brightness and high-contrast imaging. The Chameleon Discovery NX provides tuning from 660 nm to 1320 nm while simultaneously producing a high-power fixed wavelength output at 1040 nm. Optional total power control can help optimize laser power for each image plane's depth. The technology provides fast rise time and analog and digital control of laser power, which may be synchronized with the microscope scanning optics. ***Coherent Inc***, *5100 Patrick Henry Dr, Santa Clara, CA 95054, www.coherent.com*

Deep-UV spectroscopy workstations

McPherson now offers two deep-UV spectroscopy workstations—one is diagnostic, the other is analytical—to facilitate teaching and experimentation in vacuum and UV physics. The diagnostic system, which equips the spectrometer with a sensitive CCD detector, can be used to study spectral emission of laser interaction, high harmonic generation, plasma formation, luminescence, and other processes. The analytical system has a tunable deep-UV light source instead of the CCD detector. Its users can measure transmission, photocathode response, and reflection; explore photoelectric effects; and perform basic physics experiments to study quantum behaviors useful for technologies such as quantum cryptography. Complex systems can be constructed by blending diagnostic and analytical system components or by adding user-designed parts. ***McPherson Inc***, *7A Stuart Rd, Chelmsford, MA 01824-4107, https://mcphersoninc.com*

Broadband multinuclear benchtop NMR spectrometer

According to Oxford Instruments, its X-Pulse is the first benchtop NMR system with true multinuclear capability. The high-resolution 60 MHz system can be tuned to any nucleus from silicon-29 to phosphorus-31 without having to change NMR probes, so users can select whichever nucleus they want on a single instrument. A unique flow cell and a variable temperature probe allow dynamic chemical reactions to be continuously monitored, with variable temperature capability from 20 °C to 70 °C. New shimming technology delivers narrow line shapes of less than (0.35 Hz)/(10 Hz) as standard and makes it easier to separate overlapping peaks and identify smaller concentrations of compounds. A traditional magnet design with high thermal mass makes X-Pulse insensitive to sample temperature variations, whether static or flowing, and eliminates sample temperature artifacts. ***Oxford Instruments plc**, Tubney Woods, Abingdon OX13 5QX, UK, https://nmr.oxinst.com*

Peak-picking software

In collaboration with Fujitsu, Shimadzu has developed Peakintelligence software for triple quadrupole liquid chromatography–mass spectrometry (LC–MS/MS). It is designed to reduce analysis time and dependency on operator expertise and to increase research efficiency. Equipped with algorithms developed with artificial intelligence, the software automatically detects peaks that appear frequently. The product works with LC–MS/MS systems that use method packages for primary metabolites and cell-culture profiling. According to the company, even when processing chromatograms that previous algorithms couldn't handle, Peakintelligence can reliably detect peaks without parameter adjustment. ***Shimadzu Scientific Instruments Inc**, 7102 Riverwood Dr, Columbia, MD 21046, www.ssi.shimadzu.com*

Tunable femtosecond laser

KMLabs claims that its Y-Fi VUV is the first tunable femtosecond source to deliver vacuum UV light. That capability lets users probe material and molecular properties on ultrafast time scales. The Y-Fi VUV offers discrete wavelength tunability from 6.0 eV to 10.8 eV, which was previously only available at a synchrotron. In angle-resolved photoemission experiments, that tunability allows surface effects to be distinguished from bulk effects. For time-of-flight studies of molecules, the Y-Fi VUV can differentiate among otherwise identical isomers. It can be focused down to below 10 μm, which allows examination of new types of samples, including polycrystalline, spatially inhomogeneous, and faceted materials. The source produces pulses with durations below 250 fs, so users can probe ultrafast dynamics of molecules and materials. It has a 1 MHz repetition rate for rapid data collection. ***KMLabs Inc***, *4775 Walnut St, Ste 102, Boulder, CO 80301, www.kmlabs.com*

System for UV to near-IR spectroscopy

The PoliSpectra M116 MultiTrack spectrometer from Horiba Scientific can simultaneously measure up to 32 channels. The multiwavelength system has a concentric optical design with a UV-extended spectral range—below 185 nm with optional N2 purge—and a customized fiber bundle that, according to the company, provides high throughput and imaging quality with minimal cross talk. When the high-speed, low-noise, 2D back-illuminated scientific CMOS sensor is running at 94–188 frames/s, it can be configured with 8, 16, or 32 fiber input channels for simultaneous acquisition of UV to near-IR spectra (2048 pixels/spectrum). The PoliSpectra M116 provides 1 nm spectral resolution and high sensitivity. It is suitable for such applications as reflectometry, plasma- and light-source calibration monitoring, and blood and DNA analyses. ***Horiba Scientific Division of Horiba Instruments Inc***, *20 Knightsbridge Rd, Piscataway, NJ 08854, www.horiba.com/scientific*

Tandem quadrupole mass spectrometers

Waters Corp has upgraded its Xevo TQ-S micro mass spectrometer to better quantify highly polar, ionic compounds in food. It also introduced its Xevo TQ-S cronos tandem quadrupole mass spectrometer for routine quantification of large numbers of small-molecule organic compounds over a wide concentration range. Xevo products include the StepWave ion guide for long-lasting sensitivity and performance; tool-free probe maintenance and ionization source cleaning; and a choice of ionization sources, including UniSpray, for analyzing a broad range of compounds. To simplify method development and transfer, the Xevo TQ-S uses the Quanpedia extensible and searchable database for quantitative liquid chromatography–mass spectrometry (LC–MS) and LC with tandem MS. TargetLynx XS software streamlines data review and processing. ***Waters Corporation***, *34 Maple Street, Milford, MA 01757, www.waters.com*

Enhanced triple quadrupole tandem mass spectrometry

Sciex's Triple Quad 5500+ System–QTRAP Ready couples triple quadrupole liquid chromatography–tandem mass spectrometry and the company's QTRAP functionality in a single system. According to Sciex, the QTRAP functionality, which can be implemented by activating a field-upgradable license, has a linear ion trap that adds depth to data quality. A switching time of 5 ms in multiple reaction monitoring and Scheduled MRM mode makes the system more efficient because it can perform positive and negative ion analysis in the same acquisition, without compromising sensitivity. With a dynamic range of up to six orders of magnitude, the Triple Quad 5500+ System–QTRAP Ready delivers a scan speed of 12 000 Da/s. It is suitable for applications in such fields as food science, the environment, forensics, pharmaceuticals, and the life sciences. ***AB Sciex LLC***, *500 Old Connecticut Path, Framingham, MA 01701, https://sciex.com*

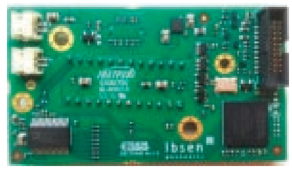
Spectrometers integrated with lasers

Wasatch Photonics' new Raman spectrometer series features a multimode laser with 350 mW of power mounted in a slightly raised lid above the spectrometer. The instruments have direct powering and software control of the laser via the spectrometer's USB and power supply. The streamlined design economizes on space and hardware cost. Users can connect both legs of a Raman probe or sampling accessory directly to a single unit. The upper FC/PC connector provides laser light for excitation, while an SMA connector acts as spectrometer input to detect the Raman signal. The WP Raman spectrometer series is available in multiple wavelengths with configuration options for resolution, range, optical coupling, and detector cooling. ***Wasatch Photonics**, 808 Aviation Pkwy, Ste 1400, Morrisville, NC 27560, https://wasatchphotonics.com*

Laser wavelength and power meter

The LambdaMeter wavelength and power meter from Gamma Scientific performs wavelength and power measurements of traditional laser sources, vertical-cavity surface-emitting laser devices, and light-emitting diodes. According to the company, it does so at lower cost than traditional spectrometers. The meter also allows for real-time monochromator wavelength monitoring. The LambdaMeter is compatible with CW and pulsed sources from 365 nm to 1100 nm, and short-wave IR options are available. Using proprietary optical filtering techniques and onboard calibration data, the LambdaMeter can resolve wavelength with accuracies to ±0.25 nm and ±0.01 nm repeatability. Irradiance absolute accuracy is ±1%. A transimpedance amplifier with five gain ranges achieves high dynamic range, and temperature-stabilized detectors and optical filters deliver high stability. ***Gamma Scientific**, 9925 Carroll Canyon Rd, San Diego, CA 92131, www.gamma-sci.com*

Spectrometer electronics for CMOS sensors



Ibsen Photonics has upgraded the OEM electronics for its spectrometers and unveiled a fast, compact digital image sensor board (DISB) with a USB bridge board. The DISB-101T electronics comes with a serial peripheral interface that makes it easy to integrate into instruments. It offers fast readout—up to 4800 Hz for 256 pixels—and a configurable external trigger input with ±10 ns jitter delay. A new lamp control function has also been added. The DISB-101T supports various CMOS detector arrays from Hamamatsu and works with Ibsen's Freedom 101/109 spectrometers and ultracompact Pebble VIS 105. The DISB–USB bridge has a form factor similar to that of the DISB-101T and can be stacked on top of the DISB. That enables a fast USB interface with a frame rate of up to 2000 Hz for 256 pixels. ***Ibsen Photonics A/S**, Ryttermarken 17, DK-3520 Farum, Denmark, https://ibsen.com* PT

OBITUARIES

John Robert Schrieffer

A towering figure in theoretical condensed-matter physics, John Robert Schrieffer died on 27 July 2019 in Tallahassee, Florida. He is best known for his crucial contributions to the theory of superconductivity, a problem that since its discovery in 1911 had vexed physicists searching for a microscopic explanation of the phenomenon.

Born in Oak Park, Illinois, on 31 May 1931, Schrieffer moved with his family to Eustis, Florida. At his small high school, he was encouraged to pursue self-study in mathematics and sciences. His interest in building radios was kindled in 1944 when, while babysitting, he began reading a copy of *The Radio Amateur's Handbook*. Schrieffer set his sights on studying electrical engineering at MIT, where he instead became captivated by physics. He completed his bachelor's thesis under John Slater.

Schrieffer had intended to do graduate studies in nuclear physics, and he received a Fulbright scholarship to the UK to work with Léon Rosenfeld and Patrick Blackett. But fate intervened; because of the Korean War and his father's failing health, he remained in the US. Schrieffer knew of John Bardeen and the transistor, so he was delighted to be offered the opportunity to study under him at the University of Illinois at Urbana-Champaign. Initially, Schrieffer worked on surface electron transport in semiconductors, even performing experiments in Bardeen's laboratory. In spring 1955, sensing that Bardeen was gearing up for another attack on superconductivity, Schrieffer selected it as a thesis topic. Postdoctoral researcher Leon Cooper arrived in Urbana that fall.

In the early 1950s, work by Herbert Fröhlich and Bardeen independently derived an isotope effect for the critical temperature, but the main phenomenon remained unexplained, largely because no techniques were available to address the many-body problem. By the time Bardeen, Cooper, and Schrieffer began their assault, Bardeen was convinced of two important aspects: that the electronic spectrum must exhibit an energy gap, and that the many-electron wavefunction must reflect a condensation in momentum space, with long-range phase coherence. A major advance was made when Cooper solved the problem of two electrons above a quiescent Fermi sea. He took into account the effective attractive interaction mediated by phonons, which resulted in a bound state of electrons. Schrieffer's focus crystallized on finding a many-electron theory that could incorporate Cooper's bound pairs, which, though not quite bosons, somehow needed to be condensed.

The crucial inspiration came several months later, while Schrieffer was in New York City for an American Physical Society (APS) meeting; during a subway ride, he first scrawled the iconic BCS wavefunction on paper. The publication in 1957 of their revolutionary approach, known as BCS theory, was swiftly recognized as a definitive work and indeed proved seminal. A torrent of results soon followed, which explained or were validated by numerous experiments. The microscopic theory of superconductivity had been solved. (Subsequent work by Philip Anderson and Yoichiro Nambu would resolve the subtle issue of gauge invariance.) The significance of BCS theory was recognized in 1972 with the Nobel Prize in Physics. Schrieffer's oral history interviews with the American Institute of Physics (https://tinyurl.com/tklwrlx) provide a wonderful account of the early days of BCS.

As an NSF postdoc in fall 1957, Schrieffer went first to the University of Birmingham and then to the Niels Bohr Institute in Copenhagen, where he met Anne Grete Thomsen, his future wife. After a year teaching at the University of Chicago, Schrieffer joined the University of Illinois faculty in 1959. He was at the University of Pennsylvania from 1962 to 1980, when he went to the University of California, Santa Barbara, and was the second director of its Institute for Theoretical Physics. His presence at the institute and on the physics faculty contributed greatly to the university's stature and to its rise to prominence in the sciences and engineering. His final academic appointment, starting in 1992, was as a Florida State University professor and chief scientist of the National High Magnetic Field Laboratory, where, once again, he helped establish the credentials of a major new endeavor.

For more than four decades, Schrieffer worked at the forefront of condensed-matter physics. In 1979 Schrieffer, Wu-Pei Su, and Alan Heeger developed their celebrated model of polyacetylene. They found a mechanism for spin–charge separation—that is, excitations with charge but no spin or spin but no charge, as if the electron, which is a fundamental particle, had split into two pieces. Further work by Schrieffer and others explored the phenomenon of fractionalization. That reified earlier field theoretical models and identified for the first time materials, such as polyacetylene and fractional quantum Hall systems, where fractional charge, spin, and statistics are manifested by their low-energy excitations.

John Robert Schrieffer

AIP EMILIO SEGRÈ VISUAL ARCHIVES

In 1983 Schrieffer was awarded the National Medal of Science, and he served as APS president in 1996. Sadly, due to illness, the last 20 years of his life were extremely difficult and indeed tragic. Throughout his struggles, Anne stood by him until her death in 2013. In addition to his brilliance—and the light in his eye when he discussed physics—Bob's kindness and avuncular nature were treasured by his many students, colleagues, and friends.

Daniel Arovas
University of California, San Diego
La Jolla
Greg Boebinger
Nick Bonesteel
National High Magnetic Field Laboratory
Florida State University
Tallahassee

Gaurang Bhaskar Yodh

Experimental particle physicist Gaurang Bhaskar Yodh, known for his work at accelerators and with cosmic rays, died peacefully in Irvine, California, on 3 June 2019. Thoughtful and caring, he enjoyed life and was infectiously optimistic.

Gaurang was born in Ahmedabad, India, on 24 November 1928 and was raised in Bombay (Mumbai). He graduated from the University of Bombay in 1948 and then traveled to the University of Chicago, where he was recruited to join the group of Enrico Fermi and Herbert Anderson. At the time, Gaurang was unique as an Indian in the US aspiring to be a particle experimentalist. His PhD research, done in the early days of strong-interaction physics, probed interactions of pions with protons and neutrons and tested theories about mesons and isotopic spin conservation. Gaurang was profoundly inspired by Fermi, who died in 1954, and he finished his PhD with his other great mentor, Anderson, in 1955. Shortly thereafter, Gaurang did a postdoc with Wolfgang Panofsky at Stanford University, where he again worked on pion physics, but with electrons in the incident beams.

Physics was not Gaurang's only important pursuit. He was an accomplished sitarist, whose teacher hailed from the same musical family and esteemed tradition as the celebrated Ustad Vilayat Khan. In 1949, in Chicago's Mandel Hall, Gaurang gave the first of many sitar concerts; he gave another at the San Francisco Museum of Modern Art in 1955. In 1956, on the Westminster recording label, with Dinesh Patel playing the tabla, he recorded the two-volume *Music of India*, among the earliest albums of sitar music in the US.

After his postdoc, Gaurang returned to Mumbai because, as he said, he wanted to "make a difference" for India. In joining the physics department at the Tata Institute of Fundamental Research, he hoped to start an experimental accelerator-based particle-physics program. Unfortunately, the timing was not right for major Indian investments he sought, and

JORDAN GOODMAN

Gaurang Bhaskar Yodh

two years later Gaurang and his wife, Kanwal, returned to the US. Gaurang's first physics faculty job was at the Carnegie Institute of Technology in 1958. After three years he joined the physics and astronomy department at the University of Maryland in College Park. He worked there until 1988; he then moved to the University of California, Irvine, where he stayed for the rest of his career.

Initially, Gaurang carried out experiments at accelerators. That research involved meson scattering, reactions, resonances, and decays. In 1963, $SU(3)$ flavor symmetry was in its infancy. Gaurang, together with George Snow and one of us (Meshkov), established the validity of $SU(3)$ in particle reactions and followed with a series of papers on $SU(6)$ and symmetry breaking.

In the late 1960s, Gaurang's interests shifted to cosmic rays. In 1972, with Yash Pal and James Trefil, he published what was a startling observation at the time about the energy dependence of proton scattering cross sections. The phenomenon, sometimes referred to as the YPT effect, showed that the strength of proton interactions increases with energy rather than remaining constant or asymptotically decaying to zero, as was commonly assumed. The finding, later confirmed at CERN, helped explain many observations of cosmic rays and had consequences for physics at accelerators. Gaurang then started follow-up collaborations, first atop Mount Chacaltaya in Bolivia, then in New Mexico at the Sunspot Solar Observatory, and then in College Park. The resulting calorimetry and analysis work provided the first evidence that cosmic-ray composition became increasingly dominated by heavy particles near the spectrum knee at roughly 1 PeV.

Gaurang also began developing transition radiation detectors to identify relativistic charged particles and thus facilitate exploration of cosmic-ray composition. His 1975 paper "Practical theory of the multilayered transition radiation detector," written with Xavier Artru and Gérard Mennessier, is still a standard reference in the field. By the mid 1980s, Gaurang's interests shifted to high-energy gamma rays from space, which he studied as part of the Cygnus experiment at Los Alamos National Laboratory. That work led to the development of ground-based water Cherenkov gamma-ray telescopes for studying gamma rays and searching for sources of cosmic rays. In the 1990s and 2000s, Gaurang and colleagues pursued those detection techniques and their high-altitude offspring in two major collaborations, Milagro and HAWC. At Irvine, Gaurang also conducted neutrino research. He was a contributor to the AMANDA and IceCube Neutrino Observatory collaborations based in Antarctica, and he was a champion for the ARIANNA project, which is developing radio techniques to look for astrophysical neutrinos.

Beyond searching for new physics, Gaurang was an NSF grant monitor who advocated for the scientific community in fiscally difficult times. He and Kanwal also sponsored the Yodh Prize, presented at the biennial International Cosmic Ray Conference, and other awards. He received accolades for distinguished teaching of physics to undergraduates and even taught sitar courses in the music department. He took great pleasure in mentoring young people, especially PhD students, postdocs, and junior faculty, many of whom have had distinguished careers. To them and to us, Gaurang has been a generous, inspirational mentor and friend.

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Jianshi Zhou is a research professor in the department of mechanical engineering at the University of Texas at Austin, and **Greg Fiete** is a physics professor at Northeastern University in Boston, Massachusetts.

Rare earths in a nutshell

Jianshi Zhou and Gregory A. Fiete

The elements' electronic configurations help explain why the rare earths are key ingredients in dozens of technological products—cell phones, computer hard drives, and lasers among them.

As a class, the rare-earth elements comprise the 15 silvery-white metals, from lanthanum to lutetium, in the sixth row of the periodic table and the transition metals scandium and yttrium. Despite their name, most rare earths are not actually rare; nearly as many neodymium atoms reside in Earth's crust as nickel atoms, for example. But neither do rare earths congregate in rich metal veins. They are instead widely distributed at low concentrations in mineral and coal deposits, which have made mining efforts difficult (see PHYSICS TODAY, October 2018, page 22).

The heterogeneous distribution notwithstanding, rare earths exert an outsize influence on our daily lives in the common products made with them, including motors, speakers, hard drives, and lasers. Materials that are exploited for their electrical, magnetic, or optical properties often consist of a few distinct types of atoms. Because of that compositional simplicity, their properties can be surmised, at least partially, from the location of their constituent atoms in the periodic table. This Quick Study explores the influence of the rare earths' electronic structure on their properties and applications.

Lanthanide contraction

The filling and spatial extent of the outer electron (5*d* and 6*s*) shells, which are most important in chemical bonding, are essentially unchanged across the entire rare-earth series. What varies from element to element is the number of electrons in the inner *f* shell. Because the atoms' electronegativities are nearly identical, a compound that incorporates a given rare earth can easily incorporate one of the others as a substitute. Indeed, the rare earths exhibit a linear dependence, known as the lanthanide contraction (see figure 1a), of their atomic radii on atomic number *Z*.

The ability to substitute one rare earth for another produces what's known as chemical pressure on surrounding elements in a material. That pressure is either positive or negative, depending on whether the radius of the substituted element is smaller or larger than the native one. And it allows researchers to finely tune the properties of even a complex compound. A case in point: The magnetic phase of titanium oxide compounds ($RTiO_3$) can be tuned from antiferromagnetic, with *R* ranging from lanthanum to gadolinium, to ferromagnetic, with *R* either yttrium or any element between holmium and lutetium.

Electrons in a rare earth occupy shells of either [Xe]$4f^{n}5d^{1}6s^{2}$ or [Xe]$4f^{(n+1)}5d^{0}6s^{2}$. The electrons in the 4*f* energy shell are more localized spatially—by virtue of being held closer to the nucleus—than are the 5*d* or 6*s* electrons. As a result, the orbital angular momentum *L* of the 4*f* electrons mimics that of a free atom. Such an *L* is unusual in materials where the crystalline environment is often strongly felt by the outer electrons.

By contrast, the *d* orbitals actually experience that crystalline environment, and their *L* averages to zero due to its precession in the crystal field. Moreover, the greater spatial extent of outer *d* orbitals in the transition metal ions gives rise to greater variability in their atomic radii and therefore less material control under substitution as compared to the rare earths.

The magnitude of *L* has important implications for how the spin, or intrinsic angular momentum *S*, of an electron combines with its orbital motion. Einstein's special theory of relativity transforms the electric field of the nucleus into a magnetic field in the reference frame of the electron, which thus couples the electron's orbital motion to its spin. The strength of that spin–orbit coupling is proportional to Z^4, so it is especially large in the heavy ($Z>56$) rare-earth elements.

When the spin–orbit coupling is large, *S* and *L* are no longer independent, and the total angular momentum $J = L + S$ be-

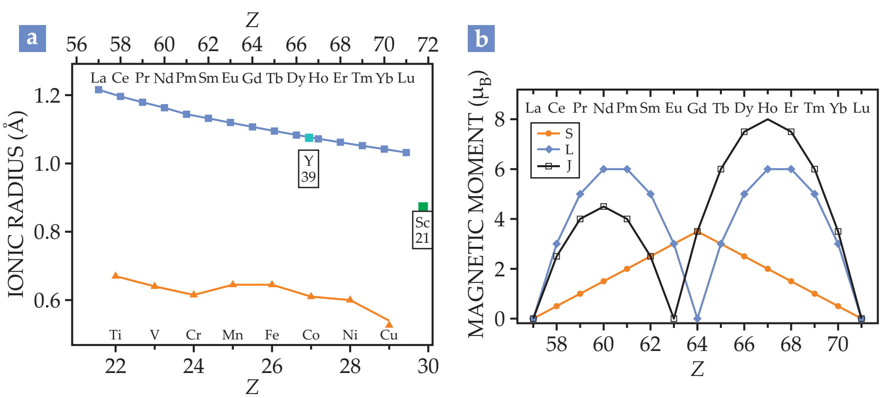

FIGURE 1. LANTHANIDE CONTRACTION AND SPIN CYCLES. (a) The ionic radii of rare-earth R^{3+} ions and transition-metal M^{3+} ions are plotted as a function of atomic number *Z*. Compared with the transition metals' *d* orbitals, the rare earths' *f* orbitals have only a weak, indirect effect on bonding. **(b)** The effects of spin *S*, orbital angular momentum *L*, and total moment *J* on the magnetic moment of rare-earth ions are plotted as a function of *Z*. The double-peak structure is a consequence of Hund's rules for atomic-shell filling.

comes a good quantum number. Figure 1b plots the value of *J*, *L*, and *S* as a function of *Z*.

The multiplets of energy levels for electronic states on each rare-earth ion create a rich spectrum of light emission, most of it in the visible range of the electromagnetic spectrum. Moreover, the large magnetic moments of some rare earths and their anisotropy—the moment's preferred direction in the crystal field—make the materials strongly magnetic.

Lasers and magnets

The lanthanide contraction, the identical nature of the outer electronic structure, and the spin–orbit coupling in the rare earths are exploited in a variety of applications. This Quick Study focuses on just two. Yttrium aluminum garnet (YAG) is a hard, durable, and transparent crystal widely used in lasers because of its high gain. The material's lasing transition occurs between two energy levels of an Nd^{3+} ion in a Nd:YAG laser. In a YAG crystal co-doped with Er^{3+} and Ho^{3+}, even more efficient lasing occurs because of the more favorable energy transfer between those ions.

Yittrium lithium fluoride is another popular host crystal for lasers. Because of their identical outer electronic structure and similar ionic size, Eu, Tm, and Yb make ready substitutes for Y^{3+} in the material. Other rare earths serve important functions in yet other laser systems. For example, carbon dioxide lasers produce IR light from transitions between molecular vibration levels. During high-power operation, some of the CO_2 converts into CO, which often causes the laser to fail. Lanthanum strontium cobalt oxide is a rare-earth oxide that, when used as an electrode in the laser, catalyzes the conversion of CO back to CO_2 and significantly extends the laser's life span. Without La, the catalyst is unstable.

Magnetic applications benefit from the rare earths' strong spin–orbit coupling. The interactions between the magnetic moments of electrons in partially filled 3*d* and 4*f* orbitals produce especially strong ferromagnetism. The magnets' most impressive feature is their extremely large coercive field ($\mathbf{H}_c$), a measure of their ability to resist demagnetization. That field in rare-earth ferromagnets is an order of magnitude higher than it is in traditional permanent magnets such as iron, and results from the spin-orbit-coupling-induced magnetic anisotropies in the rare earths.

Popular rare-earth and transition-metal permanent magnets include samarium cobalt, neodymium iron boron, terbium iron, and gadolinium cobalt. Nd, Sm, Tb, and Gd have some of the largest moments of any rare earths (see figure 1b). And their alloys offer such advantages as a high Curie temperature and coercive field. They commonly replace traditional permanent magnets and are often found in wind generators, electric car motors, data recorders, and voice-coil actuators. (Figure 2 lists some of the dozens of applications that use rare-earth elements.)

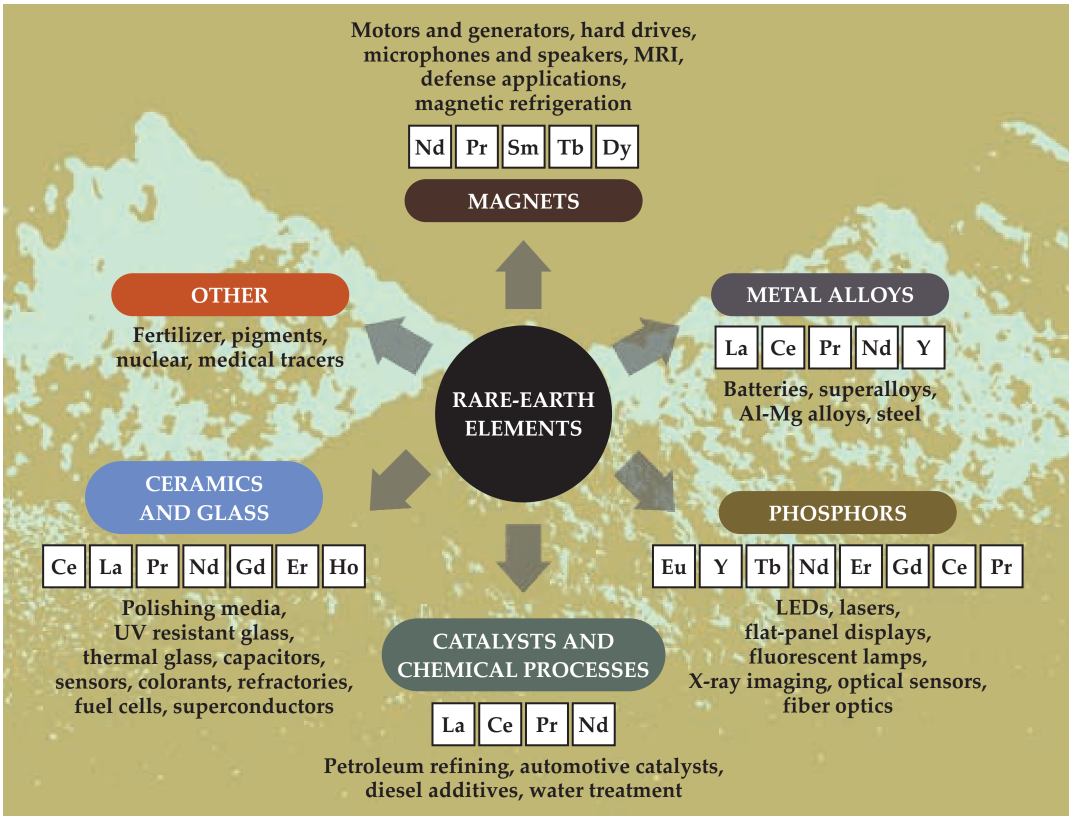

FIGURE 2. DOZENS OF APPLICATIONS use rare-earth elements as key ingredients.

The bonding mismatch in a complex compound can cause a structural distortion. One can systematically tune that distortion or correct for it through rare-earth substitutions. In the orthorhombic RMO_3 perovskites, for instance, the electron kinetic energy is proportional to the deviation of the bond angle *M*-O-*M* from 180°, where *M* represents a transition metal. A rare earth in the series from Lu^{3+} to La^{3+} widens the deviation from 145° to 165° in $RNiO_3$. As a result, the perovskite changes from a metal to an insulator; and during that phase transition the strength of electronic correlations can be tuned over a broad range. Indeed, $RNiO_3$ is a classic system for studying electronic correlations in solids.

Near the crossover from strong to weak correlations, exotic properties such as colossal magnetoresistance in the manganese oxides and high-temperature superconductivity in the copper oxides can be observed. And in those oxides, the lanthanide contraction is a key knob for tuning their electronic states.

Additional resources

▶ J. M. D. Coey, *Magnetism and Magnetic Materials*, Cambridge U. Press (2009).
▶ *Handbook on the Physics and Chemistry of Rare Earths*, vols. 1–43, Elsevier (1978–2013).
▶ J. H. L. Voncken, *The Rare Earth Elements: An Introduction*, Springer (2016).
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Artificial pattern mimics nature

As people age, they may find their wrinkled skin neither pleasing nor useful. But biological systems take advantage of such patterns. For example, wrinkles on the inner surface of the human intestine and on the surface of the brain have evolved to improve digestion and intelligence, respectively. To make wrinkle patterns, inhomogeneous stress fields in the intestine, brain, and other biological tissues induce mechanical instabilities that buckle and deform the tissues as they grow in volume. Although theoretical studies sometimes assume that tissues start with stress-free configurations, that's not the case for many living ones.

Yangkun Du and Michel Destrade of the National University of Ireland Galway and their colleagues have now quantified the effects of initial stress fields on soft materials. They grew a pattern on a two-dimensional hydrogel. By then forming it into a tube and shrink-fitting it inside a ring of rubber, the researchers created a compressive stress in the hydrogel and a tensile stress in the rubber. The initially smooth hydrogel became unstable within an hour; this image shows the pattern that formed on the inner surface of the hydrogel after 24 hours. In comparison, a stress-free tube the researchers made never achieved the same degree of pattern complexity. The initial stress turned out to be controllable, which could help scientists who are trying to make artificial tissues. (Y. Du et al., *Soft Matter* **15**, 8468, 2019. Image courtesy of Congshan Liu, Zhejiang University.)

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