PHYSICS TODAY

June 2021 • volume 74, number 6

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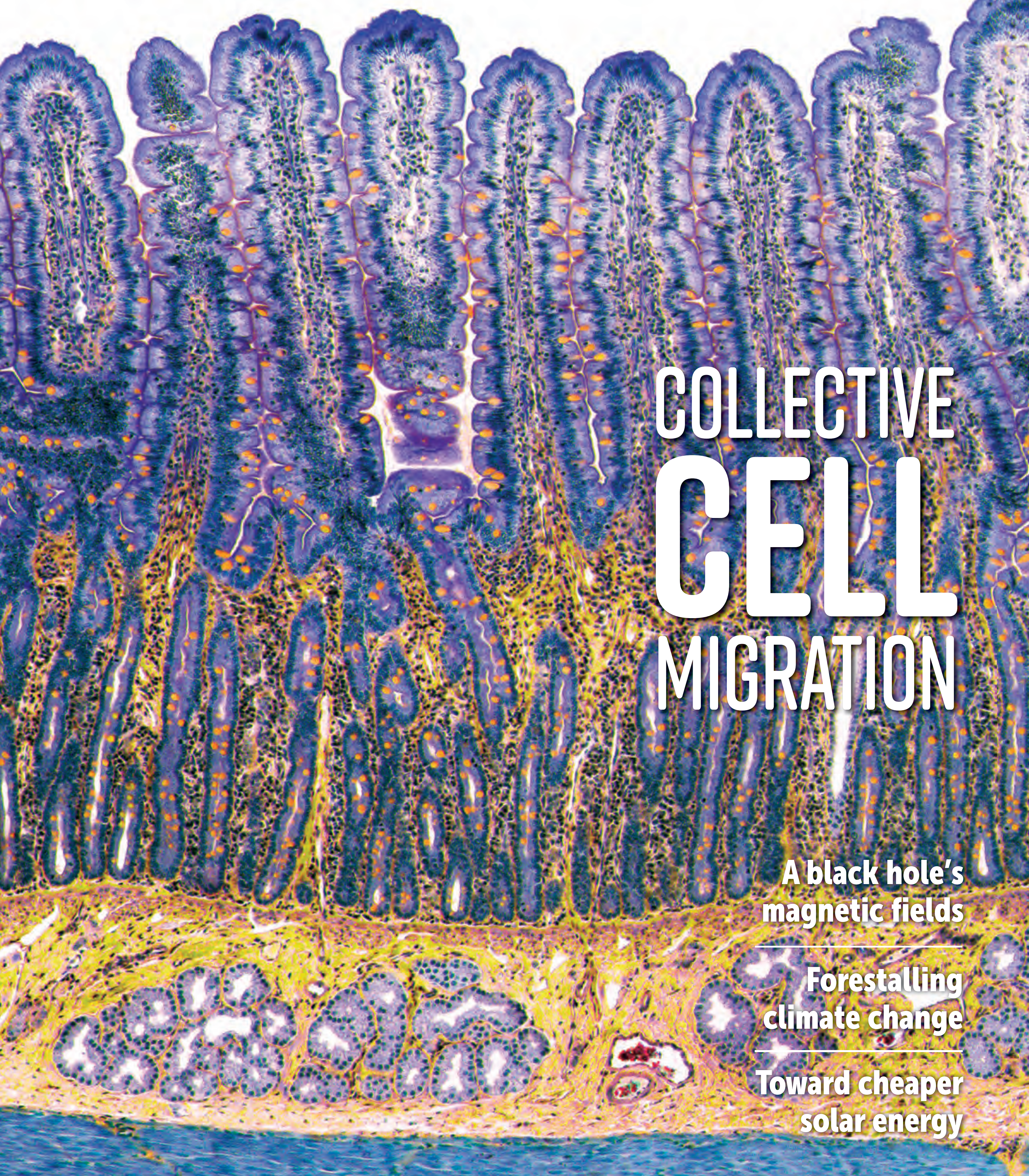

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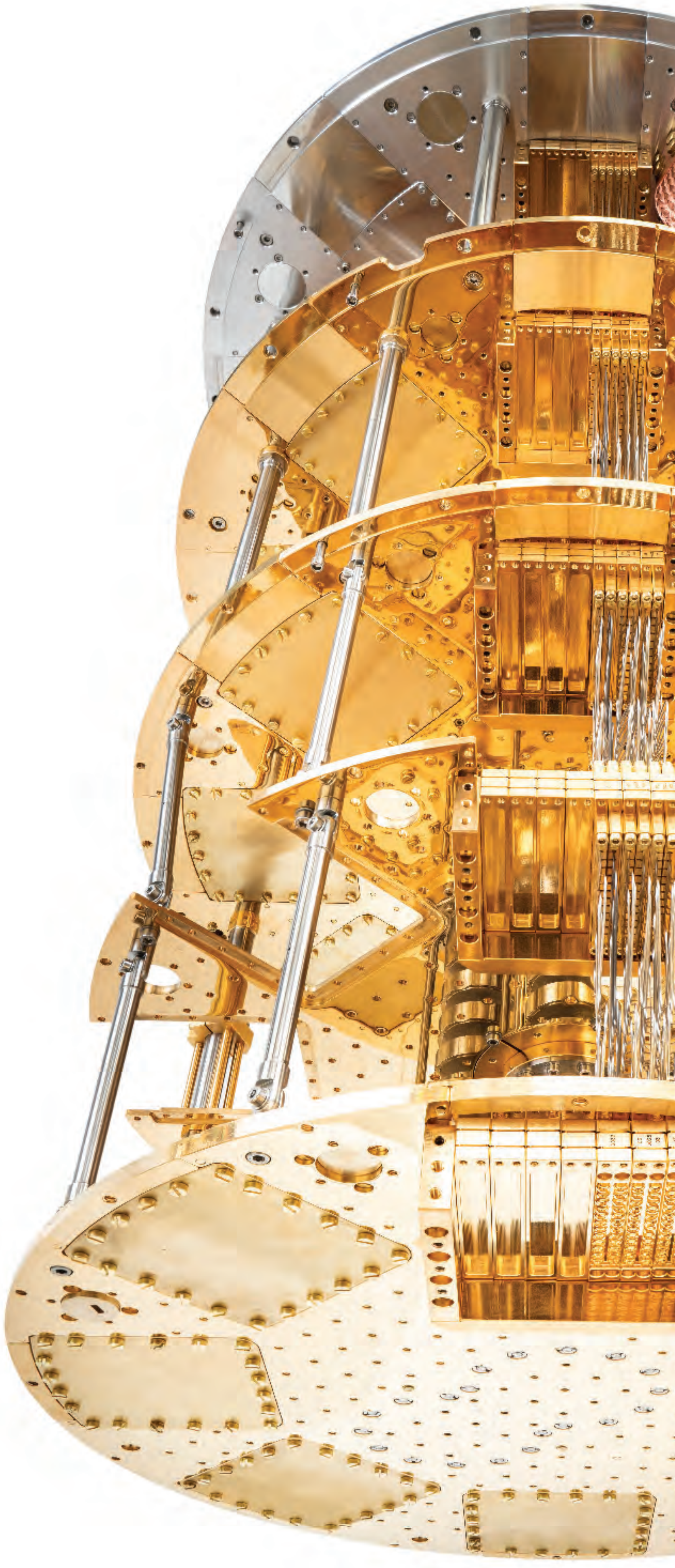

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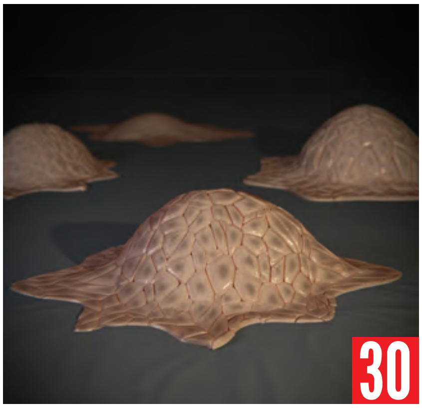

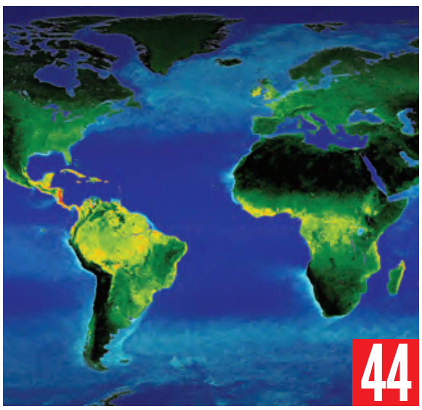

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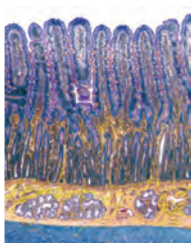
FEATURES

SPECIAL FOCUS ON BIOPHYSICS



ON THE COVER: This optical micrograph shows a cross section of finger-like projections, known as villi, from the uppermost part of a mammalian intestine. The inner surface of the intestine renews itself every three to five days as epithelial cells migrate from the bottom to the top of the villi, where they are shed into the intestine and discarded. For more on collective cell migration in living tissue, turn to the article by Ricard Alert and Xavier Trepat on **page 30**. (Image by Steve Gschmeissner/Science Photo Library.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org

BROOKHAVEN NATIONAL LABORATORY

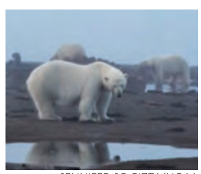
Moving for muons

The much-anticipated result from the Muon $g-2$ experiment (see page 14) was made possible by transporting a massive superconducting magnet from New York to suburban Chicago in 2013. Physics Today chronicles the voyage and the subsequent work that enabled the recent muon measurement.
physicstoday.org/Jun2021a

LANELL WILLIAMS

Equity in science

Women of color often face discouragement and hostile environments in STEM. Bryné Hadnott reports on how such experiences inspired Harvard University graduate student LaNell Williams to found the Women+ of Color Project, which is devoted to increasing representation in STEM PhD programs.
physicstoday.org/Jun2021b



JENNIFER JO PIZZA/NOAA

Arctic research

David Kennedy was recently appointed chair of the US Arctic Research Commission, a body that advises the White House and Congress. He talks to Physics Today's Toni Feder about his decades spent in the Arctic and the challenges faced by its ecosystem and the Indigenous people who live there.
physicstoday.org/Jun2021c

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FROM THE EDITOR

Narrow specialization and other forms of sin

Charles Day

I recently had cause to look up occurrences of the phrase "statistical significance" in the PHYSICS TODAY archive. Among the earliest appeared in the May 1958 issue in a review of the seventh volume of *Annual Review of Nuclear Science*. It caught my eye because the reviewer, Sidney Warshaw of Argonne National Laboratory, was unusually waspish.

Warshaw took issue with the unevenness of the volume's articles, which include "Hyperons and heavy mesons (systematics and decay)" by Murray Gell-Mann and Arthur Rosenfeld and "Vertebrate radiobiology (lethal actions and associated effects)" by Victor Bond and James Robertson. Whereas Warshaw praised the volume's physics articles, he dismissed the others as containing "much less information per word" and as becoming "a series of rather disconnected sentences, or short paragraphs with not much more information."

The range of topics exasperated Warshaw. "Your reviewer is as opposed to narrow specialization as he is to other forms of sin," he wrote. "Still it would seem that even a modern da Vinci would have trouble maintaining a continuously high level of interest in all of the disparate titles in this volume."

Critical acuity aside, Warshaw was an apt choice for reviewer. His research encompassed nuclear physics, particle physics, the effects of radiation on matter, and radiobiology. When confronted with the disparity of the articles in *Annual Review of Nuclear Science*, he speculated that they all dealt "somehow with problems that arose, historically, from the discovery of ionizing radiation."

The volume's disparity had a more proximate cause. The journal arose not as the result of the publisher of Annual Reviews identifying a promising new field to enter and profit by. Rather, in the early 1950s, the National Research Council's (NRC's) committee on nuclear science approached Annual Reviews with a partnership offer: We'll edit a journal devoted to nuclear science if you'll publish it. Annual Reviews took full editorial control from the NRC in 1953.

The volume that Warshaw reviewed was the last under the journal's first editor, James Beckerley, who served as the Atomic Energy Commission's director of classification in 1949–54. In that capacity, he was present at the 1953 AEC inquiry that deprived J. Robert Oppenheimer of his top security clearance in 1954. "If Oppenheimer or his witnesses had given anything away, they'd have been had up for it," Beckerley recalled in 1987, "but they knew better than the prosecutors what ought not to be said."[1]

Beckerley's successor as editor-in-chief of *Annual Review of Nuclear Science* was Emilio Segrè. By the mid 1960s, the number of radiobiology articles had dwindled to about one per volume. At first glance, that shift might seem, in Warshaw's words, to constitute a sinful narrowing of specialization. But in fact, under Segrè, who remained editor until 1977, the journal expanded its coverage to include astrophysics and geophysics. In 1978 it changed its name to the one it retains to this day, *Annual Review of Nuclear and Particle Science*.

A search for the most highly cited articles in the journal, before and after its name change, reveals a remarkable consistency of impact. Among them is Robert Hofstadter's "Nuclear and nucleon scattering of high-energy electrons," which appeared in the very volume that Warshaw reviewed for PHYSICS TODAY in 1958. More recent hits include Hans-Thomas Janka's "Explosion mechanisms of core-collapse supernovae" (2012) and Ulrich Heinz and Raimond Snellings's "Collective flow and viscosity in relativistic heavy-ion collisions" (2013).

What lessons does the history of *Annual Review of Nuclear and Particle Science* hold for us today? Although the NRC committee that launched the journal might have cast too wide an editorial net, the journal's editors, from Segrè to his successors, simultaneously narrowed the scope to nuclear physics while broadening it beyond investigations into the atomic nucleus. As nuclear and particle physics evolve, so does the content of the journal. Recent articles have covered the application of deep learning to data from the Large Hadron Collider, the search for axions, and primordial black holes as candidates for dark matter.

By contrast, it's hard to feel confident in the longevity of new journals whose focus is on a currently fashionable field. The number of physicists is hardly exploding. Their output can be comfortably accommodated in existing journals whose scope, like that of *Annual Review of Nuclear and Particle Science*, evolves with time.

Reference

1. M. R. Lehman, "Nuisance to nemesis: Nuclear fallout and intelligence as secrets, problems, and limitations on the arms race, 1940–1964," PhD dissertation, U. Illinois at Urbana-Champaign (2016), p. 236.

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The future of meeting exhibitions

In his column titled "The future of meetings" (PHYSICS TODAY, February 2021, page 8), Charles Day expresses doubts that exhibitors will return to scientific meetings once the COVID pandemic eases. As someone who has attended every American Physical Society (APS) March Meeting as an exhibitor for the past 20 years, I would like to offer a different perspective.

It is easy to forget that the scientific enterprise is a very human endeavor. Behind each publication, each new result, each grant proposal are people with wants and needs, aspirations and worries. The same is true for the manufacturers of scientific equipment, authors of software packages, and publishers of journals. COVID-19 has forced us apart for public safety, but we should not mistake that necessity as a step toward ever-increasing efficiency.

Yes, it can be tedious packing up our portable booths and product samples and sending them with our team to different convention centers. It would be easier to stay home and to tell ourselves a story about how virtual webinars can replace seeing and talking to researchers face to face. But there is a trap in seeking to rationalize every expenditure of time and money with a narrowly defined return on investment. Exhibiting at the APS March Meeting and other conferences is about more than generating a list of leads.

The human face we present to each other on the exhibit floor brings the technical and commercial down to the personal. Sometimes I spend 20 or 30 minutes talking with a graduate student about how they might improve a measurement using equipment they already have in their lab. I greatly enjoy seeing the same people year after year during our brief time to catch up, seeing careers progress, and occasionally being able to connect people who have a shared problem or interest. The return on such investments is measured over decades, not quarters.

Matt Kowitt (left) speaks to three 2015 March Meeting attendees about new Stanford Research Systems instruments. (Courtesy of M. Kowitt.)

And they humanize what we all do: They're reminders that on both sides of each purchase order or technical support call there are real people—people that we get to know and care about, whose judgments we learn to trust, and who ultimately drive our collective effort forward.

So long as APS invites exhibitors to join the March Meeting, Stanford Research Systems and I will be there to meet old friends and make new ones, show our new instruments, and have some fun in the process.

Matt Kowitt
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Leaving politics aside

David Kramer's story "The undermining of science is Trump's legacy" (PHYSICS TODAY, March 2021, page 24) was much too political for a magazine like PHYSICS TODAY. In a nutshell, the article said that climate science was de-emphasized, while artificial intelligence, quantum information science, and biotechnology were enhanced. Every administration emphasizes some areas of science and de-emphasizes others. The article admitted that R&D funding was increased to $165 billion from $118 billion over Donald Trump's presidency. That does not sound like "searing pain" to me. Kramer's report also made gratuitous insults to William Happer and Steven Koonin, scientists with at least the credentials of the others mentioned.

The development of the COVID-19 vaccines in one year instead of the normal 5–10 was an enormous scientific and industrial achievement spearheaded by Trump. There is still the problem of distribution, of course, but if the country is largely vaccinated by summer, it will be a great accomplishment, with credit to be shared by both the Trump and Biden administrations.

Better PHYSICS TODAY should stick to physics and leave the condemnation or praise of politicians to other media outlets.

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In his March 2021 report "The undermining of science is Trump's legacy" (page 24), David Kramer conflates science itself with his personal preference for the government planning of scientific research. They are two different things.

Throughout the piece, Kramer smuggles in his own value judgments about what governments should do regarding science. For combating climate change, for example, he ranks the 2015 Paris Agreement highly. Another person with the same understanding of and appreciation for climate science might prefer, for whatever reason, that governments do the opposite of what Kramer wants. (Murray Rothbard's essay "Law, property rights, and air pollution" provides insight into environmentalism without interventionism.[1])

Similar implied value judgments hold for Kramer's comments on federal budgets and workforce: It is not interfering with scientific research to cut federal funding. Tax-funded research funnels resources into what Kramer ostensibly deems important. But all goods are scarce, so what is the opportunity cost—that is, what scientific research is not performed in other areas? No one can say. Kramer is suggesting that governments should determine the amount and direction of societal spending on scientific research, and others may simply have different opinions.

Kramer's report is not about undermining objective science itself. Rather, it is a description of the high subjective value he places on government-directed scientific research.

Reference

1. M. N. Rothbard, *Cato J.* **2**, 55 (1982).

Christopher Barsi
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If I have learned anything about scientific writing in my 35-year career, it is that scientists should be careful when writing on matters of politics and public policy. We tend to be too cocksure of our own thinly vetted opinions and present them poorly to boot. David Kramer's report "The undermining of science is Trump's legacy" (March 2021, page 24) is an unfortunate example.

For starters, facts presented in the piece do not support the title. About a full page in, Kramer admits that funding for science increased 10–20% under Donald Trump. That does not undermine science.

The story quotes representative Bill Foster (D-IL), who has a PhD in physics, on the "searing pain" of the Trump years. A check of Foster's record shows that in the 2019–20 Congress he voted with Speaker Nancy Pelosi (D-CA) 100% of the time. His credentials as a physicist notwithstanding, his opinion is better understood politically, not scientifically.

The story makes several egregious assertions without any backing. For example, Kramer writes that "Trump sidelined Anthony Fauci . . . and Deborah Birx . . . . In their place, he installed Scott Atlas, a radiologist who argued that the virus should be allowed to spread largely unimpeded." That is a bizarre take on the facts! Fauci, not Atlas, was, and is, the governmental face of the pandemic response. And has there ever been a more aggressive effort to impede the spread of a virus? Most any unbiased individual would applaud Trump for seeking a variety of opinions. The ideas of Atlas—who is much more than "a radiologist"[1]—were neither flippant nor influential.

Kramer states that "an indisputable legacy of the Trump administration was an unparalleled level of political interference with science—data disappeared, scientists were silenced, ..." Those are serious charges, but the lack of examples to back them up suggests to the thoughtful reader that there are no indisputable examples to give. Kramer's "most far-reaching example of attempted interference" apparently centers on the Harvard Six Cities study on pollution and health and its reliance on confidential raw data. That controversy started in 2009 and extended through the Obama years;[2] it is hardly a Trump-era issue.

In fairness to Kramer, the Six Cities study was reviewed by an independent panel that agreed with its results. In

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fairness to Trump, the principle of transparency should be praised and the data used in formulating public policy should be made public, even if it requires redaction. That is especially true for medical science, where evidence shows that a significant number of classic studies cannot be reproduced.[3]

Most people act in good faith. Those whom you dislike are rarely as evil as you might want them to be. Give credit where it is due. And back up criticism with your own transparency. That is the way of science.

References

1. See R. E. Heller III, "Op-Ed: Atlas shrugged? The legacy of Scott Atlas, MD," MedPage Today (20 December 2020).
2. See E. A. Grant, *Harvard Public Health* (fall 2012), p. 30.
3. See M. Baker, *Nature* **533**, 452 (2016).

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Origins of the asteroid-impact hypothesis

The April 2021 Back Scatter, "Iridium marks the spot" (page 64), should have given credit to Luis Alvarez, Walter Alvarez, and their team, who proposed the hypothesis that an asteroid impact caused the mass extinction event 66 million years ago, and cited their publication.[1]

I was present at conferences where the Alvarez team was ridiculed and insulted because a physicist (Luis Alvarez) dared to intrude on geologists' turf. The team did meticulous research and global checking of the iridium anomaly at the Cretaceous–Paleogene (K–Pg) boundary (or Cretaceous–Tertiary boundary, as it was known in the 1980s). I am glad that that careful work has been independently verified many times over. But the work mentioned in the Back Scatter is not new news, just further confirmation. Please give credit where it is due.

Reference

1. L. W. Alvarez et al., *Science* **208**, 1095 (1980).

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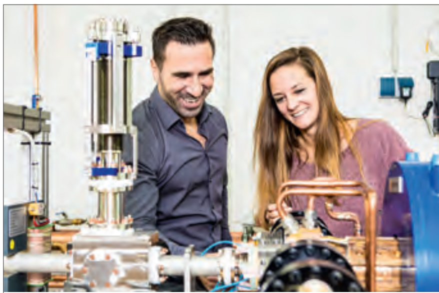


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Muon measurements embolden the search for new physics

Evidence is mounting that the value of the particle's anomalous magnetic moment cannot be predicted by the best-available theory.

FIGURE 1. THE MAGNET RING for Fermilab's Muon $g-2$ experiment measures an unwieldy 14.2 meters across. It traveled by barge and on special trucks during its relocation to Illinois from Brookhaven National Laboratory in New York. (Courtesy of Reidar Hahn/Fermilab.)

Since its inception in the 1970s, the standard model of particle physics has been remarkably successful at describing the building blocks that make up the universe. Despite its triumphs, the model is known to be incomplete; it fails to explain gravity, dark matter, and matter–antimatter asymmetries, to name just a few phenomena. But it does a good job characterizing its 17 constituent particles, and so far there's no consensus around anything more complete.

Violations of the standard model can serve as clues about what might be missing, but they're extremely hard to come by. So it was big news when, in 2001, researchers at Brookhaven National Laboratory announced such a disagreement: Their measurement of the muon's magnetic moment anomaly, a_μ (described in the box on page 16), was 2.6 standard deviations above the value predicted by the standard model (see PHYSICS TODAY, April 2001, page 18). The level of certainty was too low to claim a discovery—particle-physics experiments generally require a discrepancy of 5 standard deviations, which corresponds to a chance of a false positive of less than 0.000056%.

Now, 20 years after that initial result, the Muon $g-2$ collaboration at Fermilab has a stronger claim of a standard-model discrepancy. Its measurement of a_μ agrees with the Brookhaven result and has an uncertainty of 3.3 standard deviations.[1] Together, the Brookhaven and Fermilab data give a value for a_μ that differs from the standard-model value by 4.2 standard deviations—tantalizingly close to the 5 needed to claim a discovery.

Decay detection

In a sense, the Muon $g-2$ experiment at Fermilab is an upgrade of the earlier Brookhaven one. Both used the same experimental technique to measure a_μ, and they even shared equipment. The 14.2-meter-diameter magnet ring at the heart of the earlier experiment was shipped from New York to Illinois for the new measurements (see figure 1). The move was driven by the need for better statistics,[2] and the researchers chose Fermilab because of its higher-intensity proton source.

As was the case at Brookhaven, the experiment begins when protons are smashed into a fixed target. The collisions produce pions that decay into muons. Protons generate more positively charged pions and muons than negatively charged ones, so the apparatus siphons off the positive muons and injects them into the magnet ring. After about 64 μs and a few hundred trips around the ring, each muon decays into two neutrinos that fly away and a positron that gets detected by one of the 24 calorimeters situated around the ring (see figure 2).

During their short lifetimes, the muons are directed in a circular orbit around the ring by a near-perfectly uniform 1.45 T vertical magnetic field. They move in the horizontal plane, so their momentum vectors orbit around the magnetic field direction at the cyclotron frequency ω_c.

Muons have spin, which means they also have magnetic dipole moments. The dipole moments rotate in the magnetic field at a frequency ω_s. If muons were completely described by relativistic quantum mechanics, their dipole moments and momenta would rotate at the same rate around the magnetic field direction. But real muons are more complicated, and interactions with the electromagnetic vacuum cause their magnetic moments to rotate slightly faster than their momenta. The difference between those frequencies, $\omega_a = \omega_s - \omega_c$, reflects contributions from quantum electrodynamics and quantum chromodynamics (QCD).

The Muon $g-2$ experiment doesn't directly probe the muons. Instead, ω_a can be

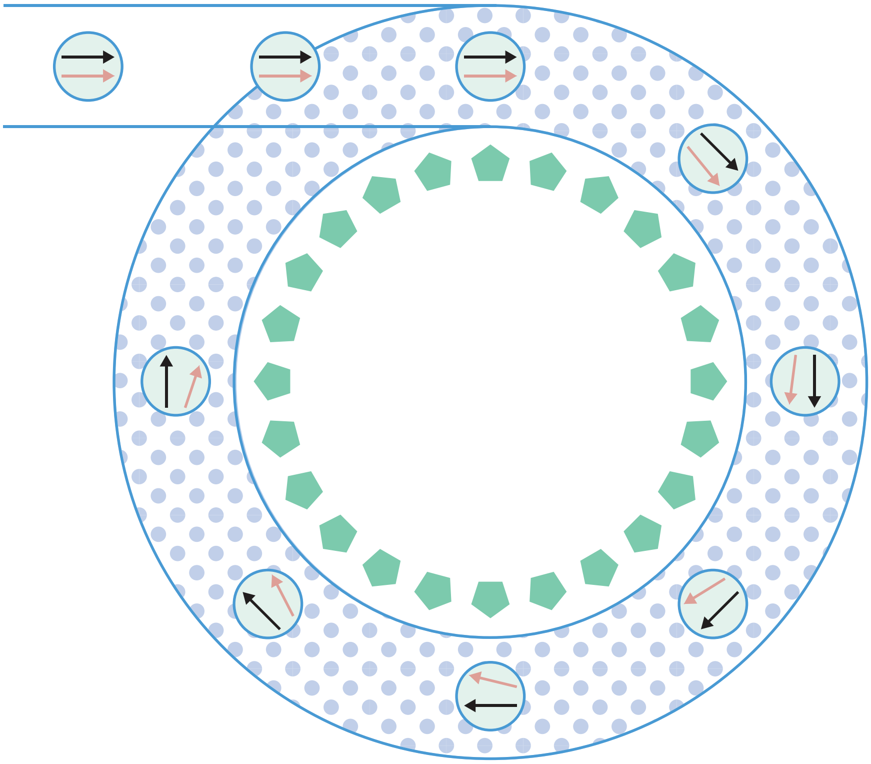

FIGURE 2. MUON SPINS (orange arrows) rotate slightly faster than their momenta (black arrows) as the particles travel in a vertical magnetic field (blue dots). When the muons decay, the level of spin–momentum alignment affects the energies of the emitted positrons. Detectors (green pentagons) around the inside of the magnet ring track the inward-spiraling positrons. (Image by Freddie Pagani.)

inferred from the positrons they emit. The level of alignment between the muons' momenta and magnetic moments affects the energy distribution of the positrons produced when the muons decay—specifically, close alignment produces more high-energy positrons. To find ω_a, the researchers track the time dependence of the energy distribution's shape changes.

Measuring ω_a alone is not enough to confront the standard model. Theoretical calculations predict a value for a_μ, a parameter that connects the muon's spin to its magnetic moment. (See the box for details.) The two quantities are related by $\omega_a = a_\mu|q|B/m$, where q is the muon's charge, m is its mass, and B is the magnetic field strength. To derive ω_a, the researchers also need to measure B with high accuracy and precision.

Upcycling

Although the magnet ring in the Fermilab experiments came from Brookhaven, its magnetic field is now better characterized and controlled. The researchers used adjustable wedges, shims, and coils to fine-tune the field locally and a series of NMR magnetometers to monitor it. Additionally, they suppressed ambient temperature fluctuations that cause the steel in the magnets to expand and contract. Those adjustments reduced the amplitude of fluctuations in the field strength, averaged around the ring, by a factor of 2.5.

The new measurements also benefited from improved positron detection. Upgraded detectors have increased spatial and temporal resolution for separating individual events, and the researchers employed a new laser calibration system that monitored how each calorimeter's response to an event varied over time. The technology didn't exist during the Brookhaven experiment.

Advances in computing underpin the new result. For one, the Fermilab researchers store all their data—nearly 1 petabyte per month—which wasn't possible at Brookhaven. Now they have much more complete information to search for potentially overlooked systematics, and so far they haven't uncovered any such issues.

Simulations have also improved significantly. They were used alongside the Brookhaven experiments to look for unanticipated problems, but at the time they were rather crude. Now simulations can accurately capture the details of the muon-beam dynamics in the storage ring, the evolution of the muon spin, and the predicted detector response. Reassuringly, the researchers still haven't seen any unexpected behavior.

The technical improvements tackled every known source of experimental uncertainty from the Brookhaven experiments and reduced the overall systematic error by about a factor of 2, thereby increasing confidence in both the approach and the result. But the largest source of uncertainty, then and now, is an insufficient number of events.

The amount of data presented in the collaboration's new papers is comparable to that from Brookhaven, but it comes from only the first of at least five runs and represents just 6% of the data that are expected to be generated at Fermilab. The second and third runs, which incorporated additional improvements informed by the first run, are already complete; their results are expected to be published by next summer. According to Chris Polly, a spokesperson for the collaboration and a physicist at Fermilab, there's about a 50-50 chance that those results will push the muon anomaly beyond 5 standard deviations.

A deeper dive

But before they can confidently claim evidence of physics beyond the standard model, particle physicists will have to grapple with the following question: Is it possible that either the experimental or the theoretical value is wrong?

When the Muon $g - 2$ experiment moved to Fermilab, researchers were divided about whether additional data would support or refute the intriguing, but far from definitive, evidence of a muon anomaly. Now that the experiment has been scrutinized and fine-tuned, the researchers are confident in their result and in their control over sources of systematic errors. Proving the experiment wrong, Polly says, would mean uncovering a serious misunderstanding of its underlying physics.

If the discrepancy between experiment and theory does reach discovery-level certainty, that would be a sign of new physics. But it wouldn't be a map for figuring out what or where that physics is. When the

What's in a name?

The name of the Muon $g-2$ collaboration stems from the fact that the experiment measures the muon anomaly $a_\mu = (g-2)/2$, where g is a dimensionless magnetic moment that relates a particle's spin $\mathbf{S}$ to its magnetic moment $\boldsymbol{\mu}$, charge q, and mass m: $\boldsymbol{\mu} = g(q/2m)\mathbf{S}$.

The Dirac equation predicts that for a spin-½ particle, $g = 2$ and $a_\mu = 0$. But because of interactions with the electromagnetic vacuum, the muon has a g slightly larger than 2. The most precise experimental value of the anomaly to date is $a_\mu = 0.001\,165\,920\,61(41)$; the standard-model value is 0.001 165 918 10(43).

muon anomaly was first discovered, researchers were hopeful that it would point to supersymmetry, the idea that each fundamental particle has a yet-unseen superpartner. Data collected by the ATLAS and CMS experiments during the Large Hadron Collider's first two runs have since ruled out the simplest supersymmetric models, though, so support for that explanation has weakened.

Ideally, another experiment will provide a second sign to narrow down the theoretical options. Fermilab's Mu2e experiment, which observes muon-to-electron conversions, and B factories, which study the decay of B mesons, are prime candidates for such a signal.

Calculations and conjectures

Corrections to the theoretical value of a_μ are also still being refined. They come from quantum electrodynamics calculations that account for muons interacting with the electromagnetic vacuum through the creation and annihilation of virtual particles. The first and largest correction, uncovered by Julian Schwinger in 1948, accounts for a muon emitting and reabsorbing a virtual photon.

Since then, the effects of more than 10 000 electromagnetic, electroweak, and strong-interaction corrections have been calculated and are included in the standard-model prediction for a_μ. By far the largest source of uncertainty comes from the strong-interaction, or hadronic, corrections, which are notoriously hard to calculate. Indeed, they can't be calculated directly, and the contributions from processes involving virtual quarks are estimated using a model informed by experimental data.

In 2017 dozens of researchers from around the world united to form the Muon $g-2$ Theory Initiative. Their goal was to improve the theoretical value of a_μ so it could be compared with experiments—particularly the then-upcoming Fermilab results—and their focus was on lowering uncertainty in the hadronic contributions. The group's result,[3] published in 2020, was used for comparison with the Fermilab measurement. It represents a significant improvement and incorporates multiple independent calculations of the hadronic corrections, complete with quantified uncertainties.

Theoretical and experimental values of a_μ currently have comparable uncertainty, but the experimental value's uncertainty is expected to drop by about a factor of 4 with ongoing and planned experiments, and theory needs to keep up. One attractive approach is to use a first-principles calculation of the hadronic corrections to a_μ based on lattice QCD, which approximates the physics of quarks and gluons on a grid of points. In fact, a lattice QCD calculation of a_μ was published the same day as the Fermilab results and garnered significant attention for agreeing with experiments, thereby challenging the notion that new physics might lie behind the muon's magnetic moment.[4]

Although the lattice result is intriguing, Polly cautions against putting it on equal footing with the Theory Initiative's value. Multiple groups are still working to figure out the right way to use lattice QCD to calculate hadronic corrections for a_μ and cross-check their results, whereas decades of work by hundreds of physicists underpins the data-reinforced approach. If mounting evidence continues to support a difference between the two techniques, understanding that difference will be essential to determining if the muon is actually exhibiting physics beyond the standard model.

Christine Middleton

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Polarized light shows hot gas swirling around a galactic core

The images of galaxy Messier 87 provide evidence of magnetic field lines in its innermost region. Those lines likely trace the event horizon of a supermassive black hole.

The picture that the Event Horizon Telescope (EHT) collaboration released to the public in 2019 rocketed to fame under headlines lauding the first-ever photograph of a black hole. That image showed the bending of radio waves into a ring around the central region of an elliptical galaxy, Messier 87 (M87). The ring's dimensions matched general relativity's predictions of synchrotron emission from hot plasma swirling near the black hole's event horizon.[1]

The EHT collaboration has now reported an analysis of the polarization of the radiation emitted by that plasma. The results provide the first evidence of a dynamic magnetic field near a galaxy's core, seen in figure 1, and support the long-held conviction that a galactic core hosts a spinning, supermassive black hole.[2] With those observations in hand, astrophysicists can test theories about the forces that determine how fast a black hole accumulates material and how plasma gets ejected from the galactic center out into space.

A curious ray

In 1918 US astronomer Heber Curtis peered at M87 from the Lick Observatory in California and reported "a curious straight ray … apparently connected with the nucleus by a thin line of matter." Curtis was looking at a jet of plasma launched at relativistic speed from the galaxy's center, although the theory to explain it came 30 years later. Radio observatories later linked the upstream end of the jet to a prominent radio source at M87's center 55 million light-years from Earth in the Virgo galaxy cluster.

By the 1970s many theorists were convinced that such compact radio sources provided evidence that supermassive black holes occupy the centers of galaxies, including M87 and our own Milky Way, just as general relativity predicted. More specifically, Einstein's field equations describe the geometry of empty spacetime around a so-called Kerr black hole, one that spins about a central axis and is characterized entirely by its mass and angular momentum.

Inspired by Roger Penrose's theory of black hole formation, Roger Blandford and Roman Znajek suggested that jets emerge from galaxies as the outflow from an accretion disk—the region in which magnetized gas swirls around the event horizon.[3] (See PHYSICS TODAY, December 2020, page 14.) The spinning black hole acts like a magnetized conductor whose rotational energy is extracted and expelled in the form of jets.

Tracing the dynamics of those accretion and outflow processes, however, requires directly observing the immediate surroundings of a black hole. But the small-scale structure of a black hole's event horizon, tens of millions of light-years away, has the same angular size as would an apple on the Moon as seen from Earth. "To a radio astronomer in the 1960s and 1970s, the idea that you could resolve at this scale was complete fantasy. Only the most visionary would dream about it," says Blandford. But the development of very long baseline interferometry (VLBI), which combines observations from multiple radio antennas to create images of regions in space that are difficult to observe with a single antenna, led others to declare imaging a black hole as merely "a very hard thing to do," he says.

VLBI depends on a network of radio antennas. For the EHT, those antennas are spread across four continents to form a virtual telescope with an Earth-sized aperture. Each antenna records signals emitted by the target source, and the signals' arrival times are later cross-correlated for each pair of antennas. From those correlated signals, an image of the emission source can later be reconstructed.

The angular resolution of an array increases not only with the distance, or baseline, between antennas but also with the frequency of the observed radiation. At frequencies of 230 GHz, corresponding to a wavelength of 1.3 mm, Earth-sized baselines achieve the highest angular resolution in ground-based astronomy—sufficient to observe supermassive black holes in M87 and the Milky Way at the scale of the event horizon.

The EHT project, started in 2009, comprises a VLBI network of millimeter-wavelength radio telescopes, shown in figure 2. Those telescopes comprise arrays of individual radio dishes with baselines ranging from hundreds to thousands of kilometers.

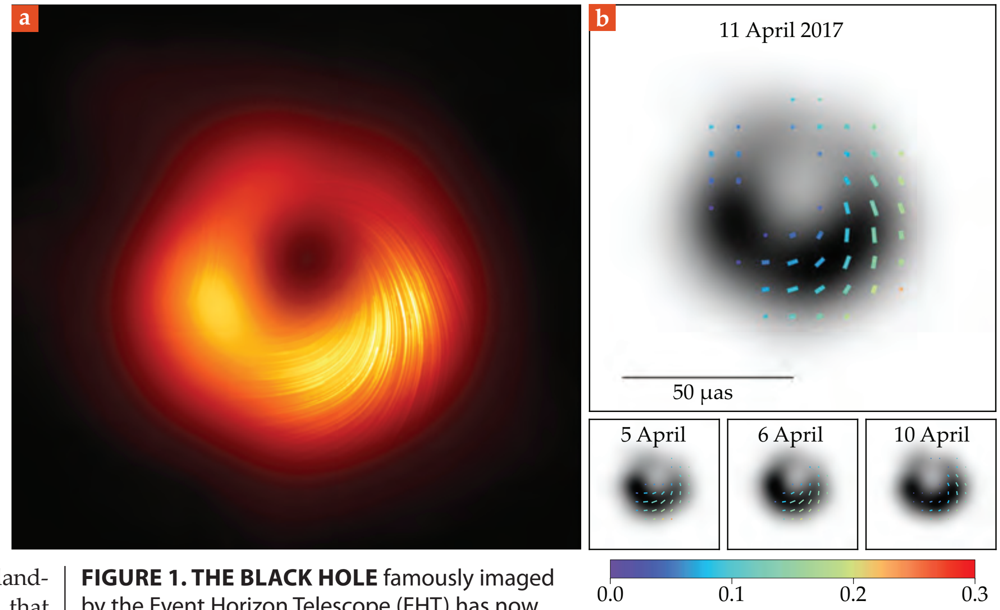

FIGURE 1. THE BLACK HOLE famously imaged by the Event Horizon Telescope (EHT) has now been analyzed in polarized light. **(a)** The lines in this image mark the polarization's orientation in the accretion flow close to the edge of the black hole at the center of galaxy Messier 87. **(b)** Data collected over four days in April 2017 show maps of polarized radiation in the accretion flow. The swirling pattern reveals the gas flowing in the same direction as the black hole. The gray scale shows the emission intensity, and the colored ticks indicate the polarization direction and fraction. (Courtesy of the EHT collaboration; adapted from ref. 2.)

MAD spirals

Over five nights in April 2017, the EHT monitored radio emission from the accretion disk around M87. There, spacetime curvature causes electromagnetic radiation to bend and twist. Electrons tightly orbit the magnetic field lines; as a result, the emitted radio waves are polarized by the orientation of the original fields.[4] Revisiting the 2017 data to establish measurements of the light's polarization, the collaboration has now published images that show the pattern of magnetic fields near M87's core, plotted in figure 1b. "It's like looking at a medical x ray. All of a sudden you can see the underlying skeleton that supports everything," says Harvard University's Sheperd Doeleman, a collaborator on the EHT.

In one find, the total level of polarization measured was far below that expected given the fundamental processes involved. Although the radiation emitted by thermal electrons as they gyrate around magnetic field lines should be polarized, not all the light that travels to Earth is fully polarized. That's because as the radiation makes its way through the plasma along the observer's line of sight, another electromagnetic process—Faraday rotation—comes into play.

If all the magnetic field lines around M87 were neatly aligned, the radiation's polarization would be strong and rotated by the same amount. But if the field lines were instead tangled together, whatever polarization the radiation originally had would be reduced. The EHT's observation of up to 20% polarization in the brightest regions, then, is consistent with fields being tangled on small scales.

Another clue about the magnetic field's structure came from the polarization's orientation. Rather than a radial

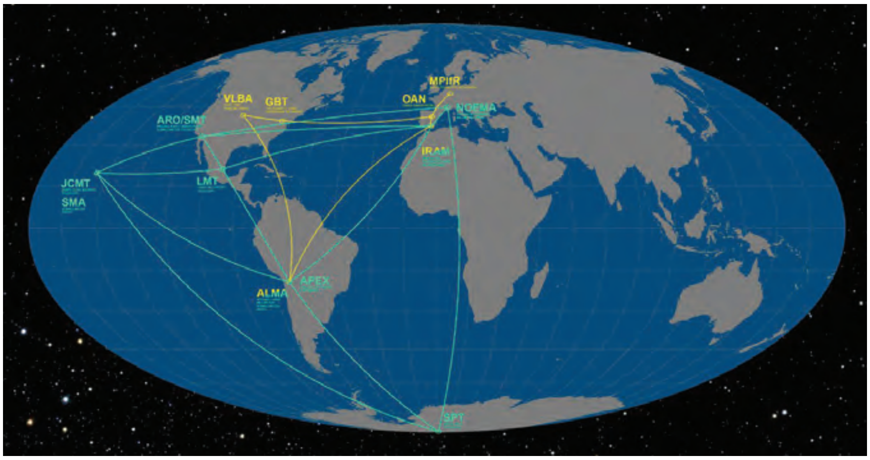

FIGURE 2. RADIO TELESCOPES spanning half the globe make up the Event Horizon Telescope (turquoise) and the global Very Long Baseline Array (VLBA; yellow). The networks combine observations at 1.3 mm and 3 mm wavelengths, respectively, to provide high-angular-resolution images of radio sources. (Courtesy of ESO/O. Furtak.)

pattern, which would imply a field that followed the plasma and encircled the black hole, the polarization appeared with an azimuthal twist, seen in figure 1a. That distribution implies that electric fields are distributed in a spiral around the center and the magnetic field topology is poloidal—that is, along the direction of the jet.

With those observations, the EHT researchers could piece together the processes by which the black hole funnels material to its center. EHT team member Monika Moscibrodzka of Radboud University and her colleagues have simulated a library of templates that represent 120 models of accretion flows and jets, especially their emissivity properties. From the emissivity, the researchers calculated millions of light trajectories that originate at points on the accretion disk and travel through curved spacetime until arriving at telescopes on Earth.

Comparing a gallery of 72 000 simulated images to the new observations showed that the data were compatible with the magnetically arrested disk (MAD) model.[4] In that model, magnetic flux accumulates and intensifies in the accreting gas. The field generates a pressure that's large enough to reduce the accretion rate and create a bottleneck in the disk that pushes back against the inflow.[5]

Future horizons

From the MAD models, the EHT researchers estimated that M87's 6-billion-solar-mass black hole swallows the surrounding gas at a rate of 1/1000th the mass of our sun per year. Still, that's powerful enough to launch relativistic jets of charged particles that stretch for thousands of light-years, according to energy conservation mechanisms first proposed in the 1970s.

Observations by the Atacama Large Millimeter/Submillimeter Array (ALMA) in Chile, whose 66 antennas dominate the overall signal collection of the EHT, captured images of the jet in polarized light, shown in figure 3. Those observations allowed the researchers to infer polarization and magnetic field properties along the jet on scales of up to 6000 light-years.[6] "Based on standard models, we expect the jet to be confined by very strong magnetic fields at its base, close to its launching point," says Ciriaco Goddi, who works at Radboud University and with the EHT collaboration. The combined information from ALMA and the EHT establishes that link.

The next-generation EHT will produce movies of the jet launch region and the magnetic field structures that propel matter outwards from M87. Showing dynamically how magnetic fields launch jets will answer the next big question: How exactly do magnetic fields extract energy from a spinning black hole?

More telescopes are already being added to the EHT. The collaboration will observe at more wavelengths and will target other galaxies and black holes. Says Blandford, "This is the start of the story, not the end."

Rachel Berkowitz

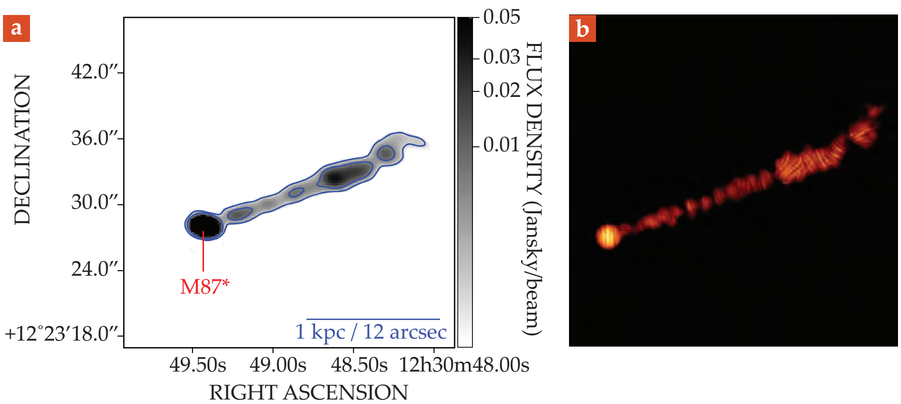

FIGURE 3. PLASMA JETS launch from the Messier 87 galaxy at nearly the speed of light. **(a)** The intensity of the light captured by the Atacama Large Millimeter/Submillimeter Array in Chile on 6 April 2017 shows the structure of the kiloparsec-scale jet composed of a bright core at the galactic nucleus (M87*) and knots along the jet (blue contours). The image is shown in equatorial coordinates based on Earth's relative position on 1 January 2000. (Courtesy of ALMA/ESO/NAOJ/NRAO.) **(b)** Shown here in polarized light, the jet extends 6000 light-years from the center of M87. The lines mark the orientation of polarization and the structure of the magnetic field. (Adapted from ref. 6.)

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A European snowstorm is linked to climate change

Precipitation that fell across the continent came from part of the Arctic Ocean that's only recently been free of ice.

FIGURE 1. SNOW FELL in Rome, for only the second time in 35 years, during a 2018 event that brought extreme winter weather to much of Europe. A new analysis attributes that snowfall to the winter retreat of Arctic sea ice. (Image from iStock.com/ROMAOSLO.)

The warming of Earth's climate doesn't mean that the whole planet is warm all year round. Much of the world continues to experience cold, snowy winters. And there's even some reason to think that climate change will lead to an overall increase, not decrease, in severe winter weather across the Northern Hemisphere's temperate latitudes.

The extent of that effect, however, is somewhat controversial. Weather varies from year to year, cold snaps and blizzards are nothing new, and the decades-long trends in their frequency are noisy. It's challenging to establish a correlation between severe winter weather and climate change, let alone a causal relationship.

A new study by Hannah Bailey of the University of Oulu in Finland and her colleagues takes a different tack.[1] In addition to examining trends and correlations, the researchers focused on a specific snowfall event that hit Europe in February and March of 2018. The snow blanketed Germany and the UK, among other countries, and even reached as far south as Rome, as seen in figure 1. By analyzing the isotopic makeup of the snow, the researchers traced its provenance to the Barents Sea, part of the Arctic Ocean whose location northeast of the Scandinavian Peninsula is shown in figure 2.

In decades past, the Barents Sea reliably froze over in the winter, and it wouldn't have been able to supply the atmosphere with such moisture. But in 2018, 60% of its surface was free of ice. The researchers conclude that in the absence of Arctic warming, the snowfall would not have happened—at least not in the same way.

Summer Sun

The northern polar region is bearing the brunt of climate change. For every degree that Earth's average surface temperature rises, the Arctic's rises by two. The warming is enhanced by a feedback loop: In the past, the Arctic was covered year-round with ice, which reflected light and kept out the warmth of the summer Sun. But once some of the summer ice cover is lost, sunlight penetrates the open water, and the ocean warms further. (See the article by Martin Jeffries, James Overland, and Don Perovich, PHYSICS TODAY, October 2013, page 35.)

The Arctic remains colder than the temperate latitudes, but the temperature difference is smaller now than it was just a few decades ago. And the flattening temperature gradient could plausibly lead to more extreme midlatitude winter weather. (See the article by James Overland, PHYSICS TODAY, March 2016, page 38.)

The temperature gradient is accompanied by a pressure gradient, which is usually strong enough to keep the coldest air confined to a powerful vortex that encircles the North Pole. But Arctic warming, the theory goes, destabilizes the confinement, and the cold air can creep southward. The polar vortex, for example, can temporarily break up into smaller vortices that carry frigid weather to regions that are unaccustomed to it.

The existence of wayward polar vortices is beyond doubt. Just this February, one of them beset the central US with bitter cold and snow—and knocked out Texas's electrical grid. Europe was likewise afflicted this winter. But the causal connection to Arctic warming has been trickier to conclusively establish, and the literature is full of arguments both for[2] and against[3] the link.

Winter wind

The decline of the Arctic's summer ice cover is a dramatic manifestation of the changing of Earth's overall climate. But the winter ice is shrinking too, with the loss so far concentrated in the Barents Sea.[4]

The Barents Sea is fed by the Norwegian Atlantic Current, a poleward extension of the Gulf Stream, which makes the sea more vulnerable to melting than other parts of the Arctic Ocean. In 1979, the beginning of the era of satellite data, most of the Barents Sea was known to be frozen over in the winter. But by 2018 most of that ice cover had been lost.

An open body of water in an otherwise cold climate is potentially consequential because it can supply the atmosphere with large amounts of moisture that can later fall as snow. The same so-called lake effect explains the snowfall patterns around the Great Lakes in the US: Buffalo, New York, which is downwind of the lakes, gets more than twice the average annual snowfall as Milwaukee, Wisconsin, which is upwind.

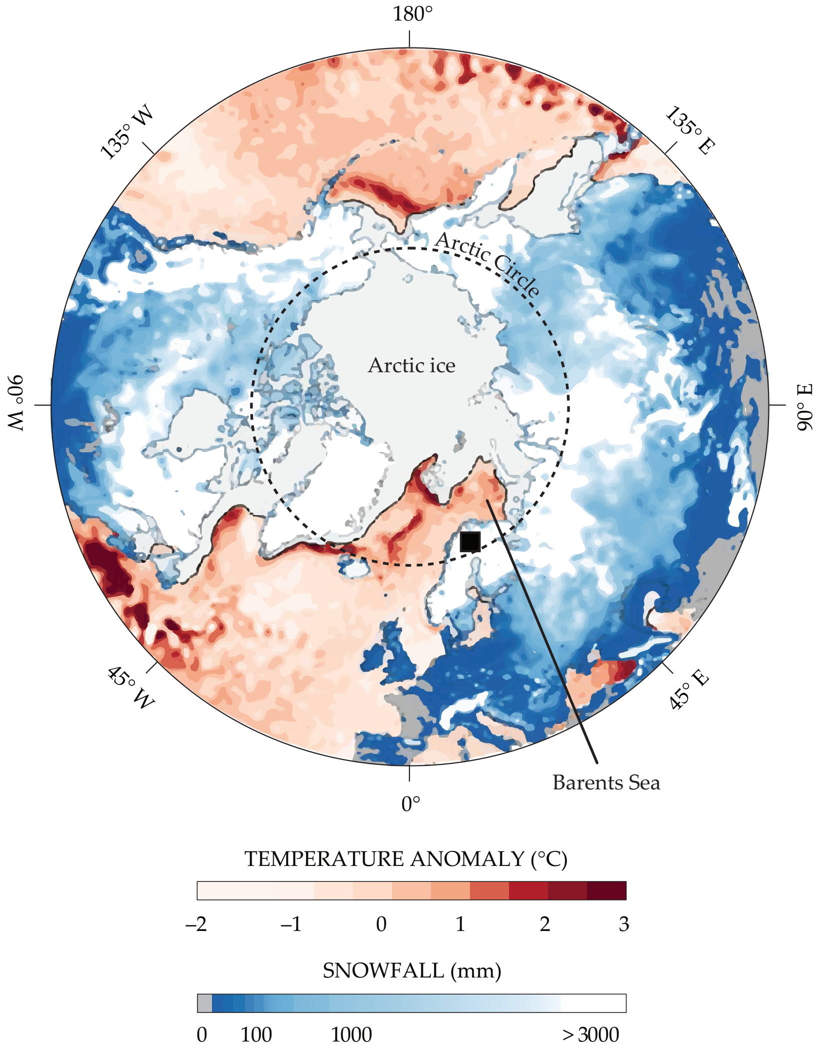

FIGURE 2. THE ARCTIC OCEAN is predominantly covered by ice (light gray) in the winter. But an increasingly frequent exception is the Barents Sea, one of the only swaths of water north of the Arctic Circle to have been free of ice in March 2018. The open water supplied the atmospheric moisture that fell as snow in Europe in that year between 19 February and 28 March. The black square marks the site of the weather station in northern Finland where isotopic analysis pinpointed the source of the snow. (Adapted from ref. 1.)

In February and March 2018, the winds were blowing in the right direction to convert Barents Sea moisture into European snow. But is that what happened? To find out, Bailey and colleagues turned to isotopic analysis.

Out of equilibrium

Almost all naturally occurring water molecules are isotopically identical: two atoms of hydrogen-1 bound to one atom of oxygen-16. But a fraction of a percent of molecules incorporate a heavier atom, such as deuterium (^{2}H) or ^{18}O. (Molecules with more than one heavy atom are vanishingly rare.)

The heavier isotopic variants behave differently in the water cycle. Compared with the most abundant variant, they're slightly slower to evaporate, among other things, and slightly quicker to condense. Heavy-isotope concentrations therefore vary among different samples of water, depending on the water's history. For example, heavy isotopes are more abundant in seawater, where they can accumulate for millions of years, than they are in fresh water, which is dominated by recent precipitation.[5]

Most isotope-fractionating processes have the same dependence on mass, so ^{2}H and ^{18}O concentrations tend to vary in tandem. But that pattern can be broken by nonequilibrium processes such as fast evaporation, in which $H_2{}^{18}O$'s two extra neutrons cause more of the heavy molecules to be left behind than would be under equilibrium conditions. The evaporated water thus has a deuterium excess—an anomalously high concentration of ^{2}H relative to ^{18}O.

And fast evaporation is exactly what happens over an ice-free Barents Sea. When cold, dry Arctic air sweeps over the much warmer open water, it quickly takes up moisture before blowing away from the sea. Water sourced from the Barents Sea under those conditions therefore should—and does—have a large deuterium excess.

At a weather station in northern Finland, marked by the black square in figure 2, Bailey and colleagues continuously collected samples of atmospheric water vapor. Though small in volume, the samples are sufficient to measure isotopic concentrations, and the samples collected during the winter of 2018 showed large increases in deuterium excess during exactly the periods of heavy snowfall. Atmospheric trajectory modeling and analysis of the snow itself both confirmed it: The vast majority of the moisture that supplied the snowfall came from the Barents Sea.

More to come

The result represents a direct connection between a specific instance of extreme winter weather and the retreat of Arctic sea ice, which, in turn, is linked to the warming of Earth's climate. The snow, in other words, was caused by climate change.

The analysis of just one event is limited in its predictive power. But there's little reason to believe that events like 2018's are going to go away. Climate models project that well before the end of the century, the Barents Sea will be completely free of ice year-round.[4] Evaporation from the sea will continue pumping moisture into the atmosphere, and that moisture has to go somewhere. When the winds blow in the right direction, it could supply Europe with more heavy snow—or, as the climate warms further, winter rain.

Johanna Miller

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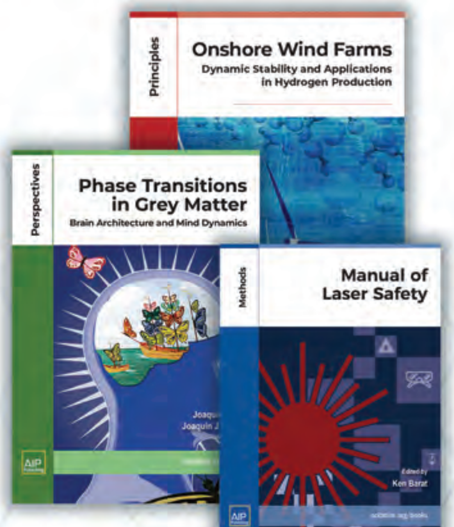

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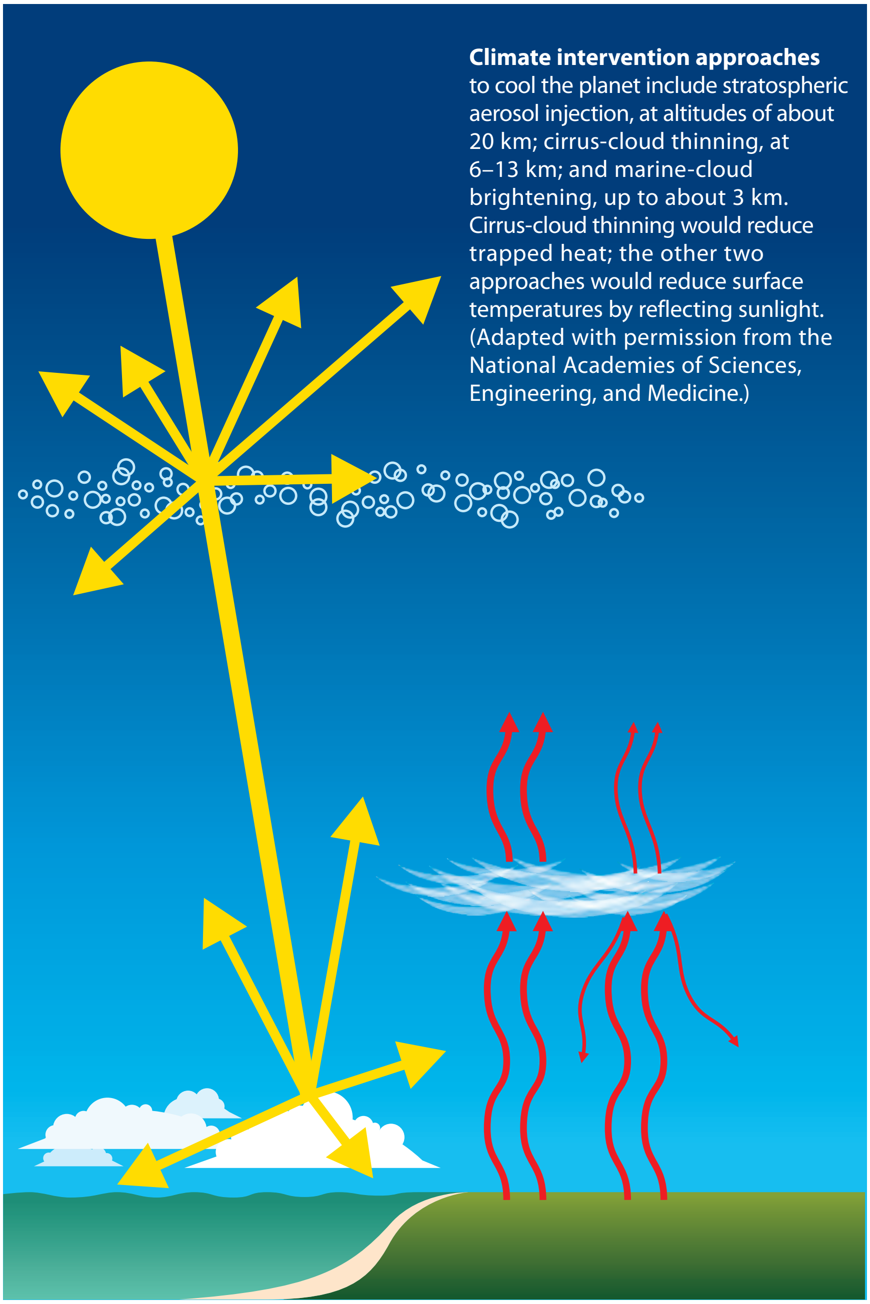

Climate intervention approaches to cool the planet include stratospheric aerosol injection, at altitudes of about 20 km; cirrus-cloud thinning, at 6–13 km; and marine-cloud brightening, up to about 3 km. Cirrus-cloud thinning would reduce trapped heat; the other two approaches would reduce surface temperatures by reflecting sunlight. (Adapted with permission from the National Academies of Sciences, Engineering, and Medicine.)

Solar geoengineering research should be cautiously ramped up, says the US National Academies of Sciences, Engineering, and Medicine (NASEM) in a report released on 25 March. Tools to cool the planet cannot undo global warming, but they may avert some of its worst impacts.

Today's average global temperature is 1.2 °C higher than preindustrial levels, and last year was among the three hottest on record, according to the World Meteorological Organization. The 2015 Paris Agreement's long-term goal is to keep the rise well below 2 °C and to try to limit it to 1.5 °C. But models predict that unless extraordinary measures are taken, the increase could reach or even exceed 4 °C by the end of the century.

"We are in a critical time for tackling climate change," says Chris Field, an environmental scientist at Stanford University who chaired the NASEM committee. "We know it's difficult to make societal changes to get to zero greenhouse gas emissions. That difficulty provides a compelling motivation to understand the full portfolio of options." Solar geoengineering may be a useful addition to the existing options of reducing emissions, removing carbon from the atmosphere, and adapting to warming. (See, for example, the article "Negative carbon dioxide emissions," by David Kramer, PHYSICS TODAY, January 2020, page 44.)

The report, *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*, urges that research be pursued in the intertwined areas of science, technical feasibility, impacts, risks, and benefits. Ethics, public perceptions, and governance of climate interventions also need to be considered. It recommends that the US government invest $100 million–$200 million over five years. Such a funding level would represent a multifold increase over current global spending on climate intervention but would be a small fraction of the overall funding for climate studies.

The report emphasizes inclusivity; the whole world should be involved in decisions that have universal impact. And while it endorses research, it also stresses that neither NASEM nor the report's authors advocate the deployment of solar radiation modification. Research into solar geoengineering "is a threat-reduction study," says Paul Wennberg, an atmospheric chemist at Caltech and a member of the NASEM committee. "It's shocking that we are thinking about doing this kind of stuff. It shows we are globally in a pickle. It highlights how critical it is to quickly reduce our greenhouse gas emissions."

Stratospheric aerosol injection

The NASEM report examines three approaches to climate intervention. (Climate researchers use various terms for climate modification, including solar geoengineering, solar radiation management, and solar radiation modification.) The best-understood approach is stratospheric aerosol injection: Particles or gaseous precursors such as sulfur dioxide are added to the stratosphere at altitudes of about 20 km, leading to an increase in reflected sunlight and reduced surface temperatures. The effect has been observed with volcanic eruptions. For example, the 1991 eruption of Mount Pinatubo spewed 15 megatons of SO_2 into the stratosphere, which cooled the planet by about 0.4 °C. Because the stratosphere is stable, such effects persist for a few years.

Suppose the world does its best to cut greenhouse gas emissions but still winds up heading for 2.5–3 °C warming, says Douglas MacMartin, a climate researcher at Cornell University. "If you reflect about 1% of sunlight, you would keep temperatures below 1.5 °C warming." That could be done, he says, by annually injecting about 10 megatons of SO_2 into the stratosphere. "It might be enough to avoid catastrophic sea-level rise, and limit the risk of forest fires and hurricanes." For comparison, he notes that industrial pollution includes about 100 megatons of SO_2 a year.

Stratospheric aerosol injection would undoubtedly cool the planet. But many questions remain: What types of aerosols should be used? At what latitudes should they be injected? What's the best time of year to inject them? What would the regional effects be? What are the risks? What are the unknown unknowns?

Helene Muri is a research professor of physics at the Norwegian University of Science and Technology in Trondheim. To date, she says, "there are no monsters in the models. We haven't seen anything that says we should remove climate intervention from the toolbox." But, she says, the risks are not yet clear. "We know some things about natural climate responses to stratospheric aerosol enhancement, like temperatures and precipitation, but when it comes to health-related impacts, changes in air quality, vector-borne diseases, we have many questions."

Research in stratospheric aerosol injection so far rests on modeling; measurements to date are from volcanic eruptions and rocket plumes. A group at Harvard University plans the Stratospheric Controlled Perturbation Experiment, or SCoPEx. It involves sending a balloon to the stratosphere, releasing small amounts of aerosol, and then using instruments on the balloon to monitor the plume evolution, small-scale turbulence, atmospheric chemistry, light scattering, and other parameters.

"One of the issues that keeps me up at night concerns using sulfate aerosols," says SCoPEx leader Frank Keutsch. Sulfate not only destroys the stratospheric ozone layer, it also heats the stratosphere. That heating changes atmospheric dynamics and circulation. "We understand the chemistry of ozone fairly well," he says, "but more studies about how stratospheric aerosol injection would affect dynamics and circulation are needed."

The first step for the experiment is to test balloon navigation, communication, and instrumentation in the cold, low-pressure stratospheric environment. A June balloon launch from near Kiruna in northern Sweden was canceled in response to opposition by the Indigenous Sami and other local groups; now that test flight plus a later one in which 2 kg of calcium carbonate would be released are on hold.

Daniel Bodansky, a law professor at Arizona State University who focuses on international climate law, says that small experiments such as SCoPEx that do not have global implications shouldn't require global consensus. "Things should be done safely at a national level, modeling good behavior," he says. "It's premature to have international governance."

Cloudy approaches

Another approach to climate intervention is marine-cloud brightening, which entails adding particles to clouds to make them optically thicker and more reflective. The effect lasts a day or two. It occurs when vessels spew pollution and form so-called ship tracks (see the image on page 24; see also PHYSICS TODAY,

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November 2017, page 80). The optimal clouds for marine-cloud brightening are typically no higher than 3 km and are found off the west coasts of California, South America, and South Africa. Lynn Russell, an atmospheric chemist at the Scripps Institution of Oceanography and a member of the NASEM committee, notes that the effect is dampened when the particle density gets too high. "A lot of the processes involved in marine-cloud brightening we know about only theoretically."

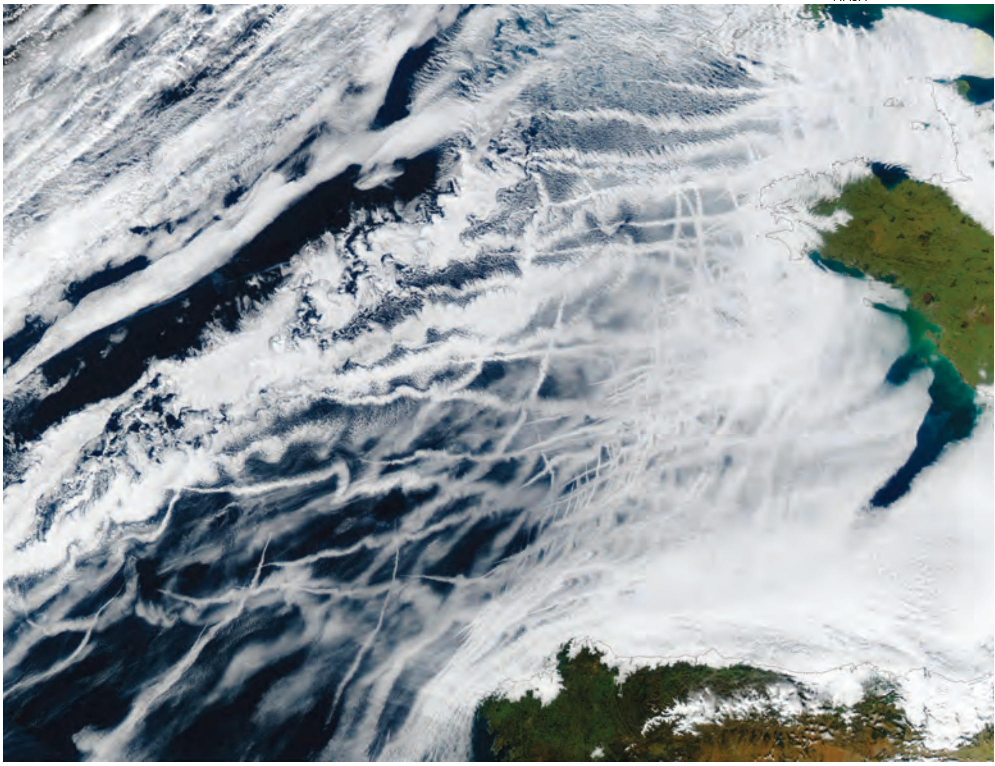
The marine-cloud brightening project at the University of Washington runs simulations varying, for example, the size and concentration of the particles. The project team hopes to collect supporting data by spraying salts from a ship into the air and measuring the clouds and resulting change in reflection. Such experiments would be small scale, says project leader Sarah Doherty. "At most, it might change the distribution of drizzle from the clouds within about 10 km downstream but would have no measurable impact on climate or ecosystems."

Both approaches would have global effects, although marine-cloud brightening might also be able to target extreme weather events through regional cooling. In Australia, scientists are using marine-cloud brightening to try to cool the area near the Great Barrier Reef to protect its corals.

The third approach to climate intervention that the NASEM report tapped for further study is cirrus-cloud thinning. Unlike stratospheric aerosol injection and marine-cloud brightening, which would cool Earth by reflecting sunlight, cirrus-cloud thinning would work by removing IR-absorbing clouds from the atmosphere and thus reducing trapped heat. Compared with the other intervention approaches, it's a more direct analogue to removing greenhouse gases—although no greenhouse gases are removed in the process. "If you got rid of all cirrus clouds, you could negate the warming from doubling CO_2," says Ulrike Lohmann, an environmental scientist at ETH Zürich in Switzerland.

But how to rid the atmosphere of cirrus clouds is "a tricky question" and has so far been studied only with computer models, Lohmann says. Cirrus clouds occur naturally at altitudes of about 6–13 km in midlatitudes. Seeding the atmosphere with mineral dust, such as from the Sahara desert, could form them at warmer temperatures and lower altitudes. Consequently, they would contain fewer, larger ice crystals that would sediment faster, leading to shorter-lived cirrus clouds and reduced warming.

NASA



SHIP TRACKS are clouds that form from the exhaust that ships spew. Marine-cloud brightening would be a purposeful analogue with the intention of reflecting sunlight to help cool the planet.

Cirrus-cloud thinning is the only climate intervention that targets IR radiation. It would change precipitation patterns less than the solar radiation modification methods, Lohmann says. One danger "would be if you put the material in the wrong place, you would form cirrus clouds where you don't want them, and that could lead to warming." But clouds are just around for hours to days, so you can easily stop the process, she says. Greenhouse gases, by contrast, remain for decades.

Still, like the other climate intervention approaches, cirrus-cloud thinning is a Band-Aid, not a solution. "Anything we do, short of removing CO_2 from the atmosphere, just addresses symptoms. That is doable for a limited time, but if greenhouse gases continue to rise and we need to offset to a larger and larger extent, that would be problematic," says Lohmann. "I see climate intervention coming into effect for a limited time until we get rid of CO_2 from the atmosphere and stop emitting greenhouse gases."

The scientists researching climate intervention mostly do it on the side or with a primary goal—and funding—related to broader climate studies. "Understanding cloud feedback is important for climate change models," Russell says. "There haven't been enough observations to constrain models, and the effects of clouds on climate are still a big gap." Addressing the many scientific and technical questions about climate intervention requires a combination of modeling, lab experiments, and field tests, notes Caltech's Wennberg. "We don't advocate for outdoor experiments unless lab tests are not possible."

Most important to limiting the global temperature rise is tackling its causes, says Keutsch of SCoPEx. "I hope that stratospheric engineering will never be used. At the same time, I worry that humanity is cutting emissions and reacting too slowly to prevent severe climate impacts. If the impacts are severe, albedo modification is an action you can take quickly." Climate intervention could become attractive to decision makers, he adds. "They may have no choice, to save lives and the planet. I hope we never reach that point.

But in case we do, we need to do research now so we are prepared."

Global impact, global input

The sense that any deliberate tinkering with the environment that would have global implications should also have global consultation has inspired investment in climate intervention expertise. DECIMALS is a fund distributed by the UK-based Solar Radiation Management Governance Initiative. In 2018 DECIMALS supported eight research groups in low- and middle-income countries with a total of $450 000 to model how solar radiation management could affect their respective regions. The groups are paired with collaborators in high-income countries, and they share information with each other. They access data from mainstream climate models to home in on local issues. A longer-term goal is for the researchers to become trusted experts who could advise policymakers in their own countries.

Izidine Pinto is part of a climate research team in South Africa that is studying how stratospheric aerosol injection will affect mean and extreme temperatures and rainfall throughout Africa. So far, he says, the models show a reduction in temperature but more complicated results for precipitation. "There are only winners when it comes to temperature. But there are both winners and losers when it comes to rainfall." A future direction, he says, is to compare the effects on agriculture and animal species with increasing climate change and solar geoengineering.

Dust storms and storm tracks in the Middle East and North Africa are the focus of DECIMALS-funded research by Khalil Karami, an atmospheric scientist who splits his time between Leipzig University in Germany and the Institute for Advanced Studies in Basic Sciences in Iran. Dust storms result from interactions between precipitation, wind, temperature, humidity, and soil moisture, and dust is transported around the globe. Storm tracks, the paths along which storms are driven by winds, transfer moisture and heat over large distances. Both phenomena have implications for climate and human health, Karami says, "so it's crucial to assess how stratospheric solar engineering affect them."

In Argentina, atmospheric scientist Inés Camilloni leads a group that is looking at possible impacts of stratospheric aerosol injection on water availability in the La Plata basin, among South America's most populated regions. "We are looking at what we can expect in terms of river flow and expected impacts in the production of hydroelectric energy, floods, and droughts," she says. "We found that the mean flow would increase by 15–30%." More water is good, she says, but the maximum flow would also increase, so a possible negative consequence from solar radiation management compared with ongoing global warming would be more floods.

Youth are also involved in climate intervention. Gideon Futerman first learned about reflecting sunlight to cool the planet in 2016 when he was 13 years old. "I had a geography teacher who was convinced that the only way to combat warming was through giant mirrors," he says. Futerman rejected the space mirror idea but became interested in solar radiation management. "I'm not saying I'm in favor of deploying it," he says, "but we need to be well informed to make that decision. If we get to a 3 or 4 °C increase, solar radiation management may look attractive."

Now finishing his last year of secondary school near London, Futerman notes that "it will be my generation and the next generation who are burdened with the consequences of climate change. It's a matter of intergenerational justice that young people be consulted in the decision-making process."

Masahiro Sugiyama of the University of Tokyo's Institute for Future Initiatives conducted surveys in six Asian Pacific countries about attitudes toward climate intervention. He found that people from low- and middle-income countries were more willing than those from high-income countries to entertain the idea. They were also more concerned about the effects of climate change, he notes, and their countries are generally more climate vulnerable.

"It's essential in thinking about these technologies that we understand public perception," says NASEM committee member Peter Frumhoff, chief climate scientist and director of science and policy at the Union of Concerned Scientists. "Social feasibility is as important as

GIDEON FUTERMAN AND BENJAMIN GOLDSTEIN

GIDEON FUTERMAN (right) and Benjamin Goldstein at a Global Youth Climate Strike in London in 2019.

technical feasibility." Use of technologies cannot be decided by Bill Gates, Harvard University, or the US, he says.

Objections and controversy

A main objection to solar radiation modification is the unknown risks. It might, for example, disrupt precipitation on the planet. Those concerns can be explored at least partially through research. (See PHYSICS TODAY, November 2013, page 22, and August 2014, page 20.)

Another objection is the slippery slope—that having invested in research, people and governments would inevitably implement the fruits of those efforts. The NASEM report recommends building in exit ramps, criteria for terminating research programs or areas, if a research activity "is deemed to pose unacceptable physical, social, geopolitical, or environmental risks or if research indicates clearly that a particular [solar geoengineering] technique is not likely to work."

Perhaps the most widespread concern is the so-called moral hazard: the notion that if people—and fossil-fuel interests—feel they can get by with, say, injecting aerosol into the stratosphere to cool the planet, they would get lazy about addressing the root causes of global warming. None of the climate intervention approaches address ocean acidification, atmospheric greenhouse gas concentrations, or the underlying causes of climate change. Michael Mann and Ray Pierrehumbert, scientists who have long been vocal about their global warming concerns, detail their criticisms of solar geoengineering in a 22 April commentary in the *Guardian*.

And climate interventions would likely require a long-term commitment; once begun, they should continue until the greenhouse gas forcing they palliate has abated, says Caltech's Wennberg. A premature, abrupt termination would lead to rapid warming, he explains, "which could expose the world to even higher risks than never having deployed solar radiation modification schemes in the first place."

National security is another concern: Consider a scenario in which some country or rogue actor deploys climate intervention on its own. If some other country then suffers a catastrophic weather event and blames the deployment, it could lead to political conflicts, or in the worst case, war, notes Cornell's MacMartin. "That's why everyone needs a seat at the table."

Laying the groundwork so that decisions about climate intervention can be truly global may be at least as daunting as figuring out whether it is a safe and smart way to go. Janos Pasztor is executive director of the Carnegie Climate Governance Initiative (C2G). "Many fear the potential negative impacts of solar radiation modification," he says. "How do we weigh the risks? Who should make decisions about where and when to use solar radiation modification?"

The Intergovernmental Panel on Climate Change's sixth assessment report, slated to be available in late 2022, is expected to include new information on solar radiation modification, says Pasztor. He and his colleagues at C2G are working to get the topic taken up by the United Nations General Assembly in 2023. Says Pasztor: "Based on my personal intergovernmental work experience, it will take a minimum of 10 years to start developing a governance framework for solar radiation modification."

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The cost of solar energy production has plunged, but it needs to fall further

The Department of Energy has lowered its 2030 targets for the price of energy from photovoltaics and concentrated solar power. But the low-hanging fruits have been picked.

A 2.8 MW SOLAR ARRAY located in Wareham, Massachusetts. In a carbon-free scenario, solar energy is likely to make up 30–50% of the US's electricity generation by 2050.

Although solar energy usage has grown dramatically in the US over the past decade, far more dramatic growth will be needed if the nation is to meet President Biden's ambitious plan to decarbonize the US electricity system by 2035. Solar provided just 2.3% of US electricity production last year, according to the US Energy Information Administration. The Department of Energy says solar will need to supply 30–50% of total US power needs in a zero-carbon electricity system.

Solar installations of photovoltaics (PVs) in the US had a capacity of 19.2 GW of direct current (GWdc) last year, according to the Solar Energy Industries Association. That was a 43% increase from 2019 installations, and it brings the total installed US capacity to 97.2 GWdc. Capacity values reported in DC typically are 10–30% higher than those reported in AC capacity, according to the Energy Information Administration. That is because the output of a PV system depends on the availability of sunlight, and the output of panels may reach their peak capacity only a few hours out of the year.

Solar energy ranked first among new electricity-generating sources in the US during the past two years and accounted for 43% of all new electricity capacity in 2020. According to the consulting firm Wood Mackenzie, the US solar industry is expected to quadruple in capacity in the next decade, to more than 400 GWdc.

In March, DOE announced a new goal to cut the cost of utility-scale PV energy 60% by 2030. The new levelized cost of energy (LCOE) for grid-scale solar, 2 cents per kilowatt hour, represents a cut to less than half the current average of 4.6¢/kWh. LCOE is an estimate for the revenue required to build and operate an electricity source over a specified period. The agency moved up its previous 2030 target of 3¢/kWh to 2025.

The proposed cost-target cuts for PV systems come atop the steep reductions that have been achieved in the past decade. (See the figure on page 28.) Today PVs are the cheapest electricity source in parts of the Sun Belt when the Sun is shining. BloombergNEF, a research consultancy, projects that the capital cost for a typical 10 MW utility-scale PV plant in the US will drop by more than 50% by 2030, to $400 million, from $840 million today.

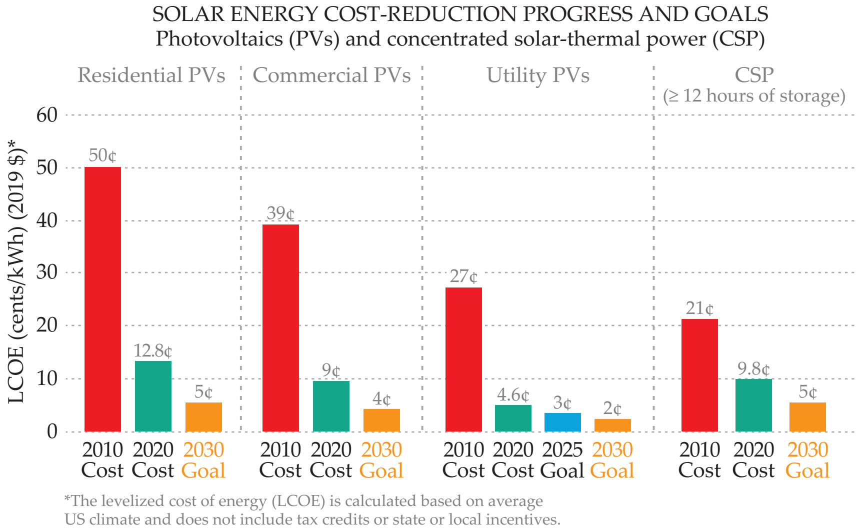
But as PV systems start meeting a more significant fraction of total demand, PVs' intermittency becomes a serious impediment to further deployment, a DOE official says. That variability will be addressed with batteries and other types of energy storage, which add significantly to the total cost of solar. The new DOE goals reflect the need to offset the storage costs to allow solar power to compete with other nonintermittent electricity-generating sources. Natural gas is the lowest-cost and largest source of nonintermittent power.

Hundreds of gigawatts

In 2012, at the outset of the SunShot Initiative, the Obama administration's cost-reduction effort, LCOE targets for utility-scale PVs in 2020 were set at 6¢/kWh. That goal was met four years early, and the 3¢ target was instituted for 2030. To set benchmark LCOE values as an average value for the nation, DOE calculates them for one location that has moderate solar resources, such as Kansas City.

Becca Jones-Albertus, director of the solar energy technologies office in DOE's Office of Energy Efficiency and Renewable Energy, says Biden's zero-carbon plan will require hundreds of gigawatts of new solar capacity through 2035. "We need to increase annual deployments by a factor of two to five. One of the most effective ways to increase deployments is to drive down costs."

But costs for utility-scale systems have already plunged by as much as 80% in the past 10 years, driven by myriad technology



COSTS OF UTILITY-SCALE, commercial, and residential photovoltaics have all fallen sharply over the past decade. Future reductions are likely to be less dramatic. (Courtesy of DOE EERE.)

developments. Crystalline silicon wafers have increased in size from 156 mm^2 to as much as 210 mm^2. The larger size means fewer connections and reduced efficiency losses from spacing and contacts, says Arnulf Jäger-Waldau, senior scientist at the energy efficiency and renewables unit of the European Commission. Wafers, the slices of silicon from which solar cells are fabricated, have also gotten thinner, which has lowered their manufacturing costs. More-efficient monocrystalline PV cell technology has overtaken multicrystalline cells in market share over the past five years, notes David Feldman of the National Renewable Energy Laboratory (NREL).

As a result, solar panels, which package dozens of cells, have more than doubled in efficiency from around 10% in the early 2000s. John Rogers, a senior energy analyst at the Union of Concerned Scientists, notes that his rooftop panels in northern Massachusetts are 22% efficient. “The panels I put on my roof five years ago are 360 watt, and you can get 400-, 450-watt ones and larger.”

The scope of utility-scale projects also has increased and has resulted in a lower cost per unit of energy. “We’re now seeing projects in the hundreds of megawatts,” says Rogers. “I remember 20 years ago, when someone said we’re going to do a one-megawatt project, I thought, ‘Yeah, sure you are.’”

Cost reductions and demand growth to date have resulted from a “virtuous cycle,” Rogers says. “You had the tax policy in the 2009 [American Recovery and Reinvestment Act] stimulus that increased demand, which drove supply, which brought down costs, which increased demand. That cycle has kept costs going down a whole lot further and faster than I would have imagined.”

DOE left unchanged the cost targets it set for commercial- and residential-scale PV installations in 2016, as it did for concentrated solar-thermal power (CSP). In that technology, sunlight from hundreds of mirrors is reflected onto a central tower and produces heat that is absorbed by a medium such as molten salt. The thermal energy is used to drive electricity-generating turbines.

The LCOE targets for residential- and commercial-scale installations are set at 5¢/kWh and 4¢/kWh, respectively. Their current values are 12.8¢/kWh and 9¢/kWh, respectively. Meeting them by 2030 will be a challenge, says a DOE official.

Most of the higher costs for residential and commercial installations are attributable to nonhardware, so-called soft costs. (See the figure on page 29.) Those include overhead and administration, sales and marketing, permitting, inspection, interconnection, labor, and supply chain costs. Collectively, those can add up to a large fraction of the total cost for all types of solar installations, but they are much higher—half or more of the total—for residential and commercial PV systems.

Focus on materials

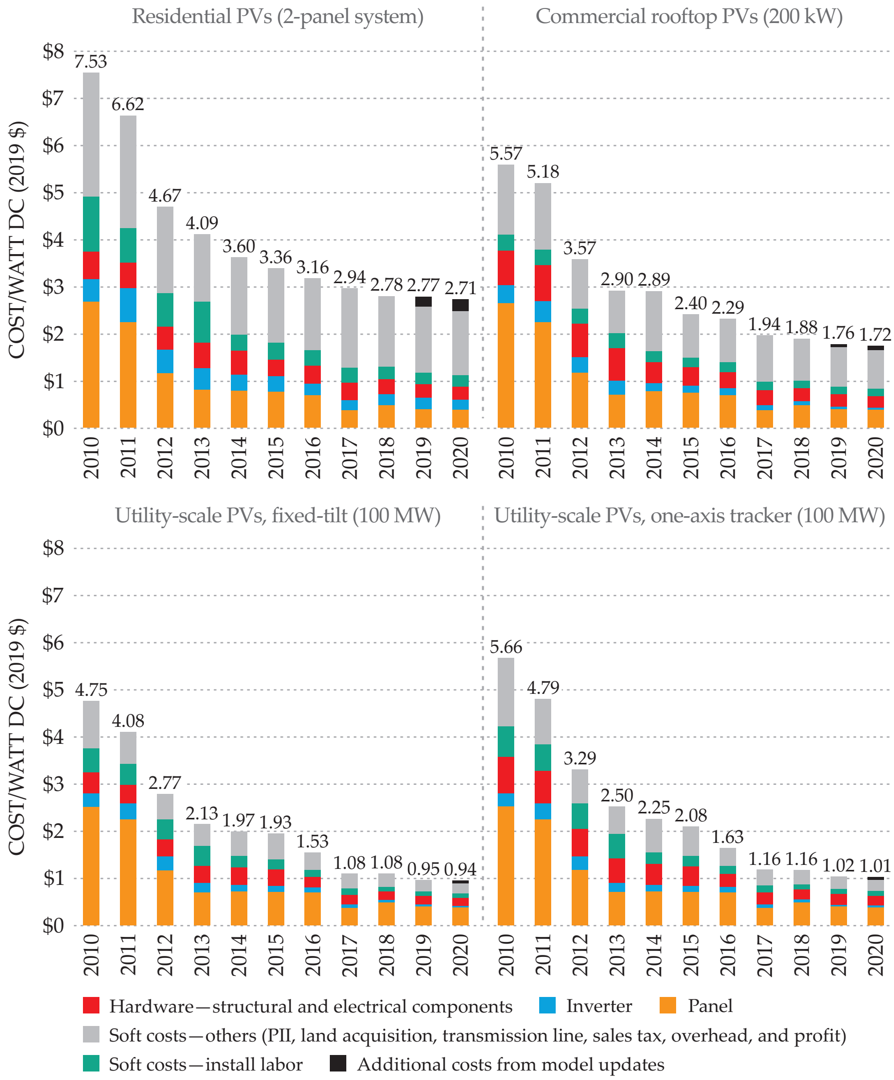
Wringing additional costs out of solar energy has become more difficult. The pace of annual cost reductions has slowed significantly in the past two years, compared with the steepness of the early 2010s, NREL statistics show. “The easy wins are over,” says Jones-Albertus, and further reductions will need to come from “all of the cost buckets.” That includes driving efficiency improvements in today’s two commercial technologies, crystalline silicon and cadmium telluride, to near their theoretical limits. Industry adoption of multijunction cells, consisting of two or more stacked semiconductor layers with different bandgaps, will improve efficiencies by making use of a larger portion of the solar spectrum. And bifacial modules, which capture photons that are reflected off the ground to the back side of panels, might increase efficiencies by 5–10%, Feldman says.

Crystalline silicon currently accounts for 80% of the US PV market, and that technology will continue to dominate the PV landscape for the next decade, say market analysts. The remaining 20% is CdTe, which is the exclusive global realm of one US company, First Solar. DOE in March awarded $20 million to the NREL to set up a consortium that aims to increase domestic CdTe PV material and panel production, achieve cell efficiencies above 26%, and decrease panel costs.

The barriers to entering the CdTe market are high, says Jäger-Waldau. First Solar’s technology is proprietary, so unlike silicon, off-the-shelf manufacturing equipment isn’t available. “You need knowledge of the production process, and you need a fundamental understanding of the material properties. That requires a substantial research department, and it’s difficult for newcomers without [sales revenue] to finance that.”

What’s more, cadmium is toxic. Its use is limited by the European Union’s Restriction of Hazardous Substances Directive. However, CdTe’s melting point is three times that of cadmium, says a First Solar spokesperson, adding that the compound’s high stability and its insolubility in water limit its bioavailability in the event of an accident.

Although tellurium, produced as a byproduct of copper mining, is about as rare as platinum, the First Solar spokesperson points to an NREL analysis that found that the supply of tellurium should be sufficient to support



SOFT COSTS have declined significantly for all types of solar energy systems, but they remain proportionally greater for residential- and commercial-scale installations. The cost of solar panels has fallen steeply since 2010. Utility-scale panels can be fixed (lower left) or can track the Sun throughout the day (lower right). PII: permitting, interconnection, and inspection. (Courtesy of National Renewable Energy Laboratory.)

annual production of 100 GW's worth of CdTe thin films. The company's current annual manufacturing capacity is just over 6 GW.

Perovskites, such as a hybrid organic–inorganic lead or tin halide–based compounds, have the potential to make highly efficient thin-film solar cells with very low production costs. (See PHYSICS TODAY, May 2014, page 13.) But they have yet to be commercialized. In March, DOE awarded $40 million to 22 university and industry projects to advance perovskite PV device and manufacturing R&D. Another $14 million was awarded to the NREL and Sandia National Laboratories to create an independent perovskite validation and testing center. DOE set aside $3 million more for a prize competition to encourage perovskite commercialization.

"There's a danger that perovskites are the shiny new object, but we have seen incredible gains in efficiencies in the last few years, particularly when paired [in tandem cells] with silicon," says Rogers. Whereas a conventional monocrystalline silicon cell has achieved 26% efficiency in the lab, pairings with perovskites have reached 29%, he says. Challenges include lifetime stability and manufacturing perovskites at scale. "The technologies today last on the order of months; we need them to last for years and decades," says Jones-Albertus.

In addition to cheaper cells and panels, achieving the DOE cost target will require lowering the price of other hardware, including inverters, wiring, and systems to reposition and orient the panels as the Sun moves, says Jones-Albertus.

Concentrated solar thermal

DOE is supporting research on solar thermal energy principally as a way to store heat for electricity generation when the Sun doesn't shine. Storage capability increases the value of CSP relative to cheaper PVs, says Jones-Albertus. The department's cost target for CSP is 5¢/kWh by 2030—half its current cost.

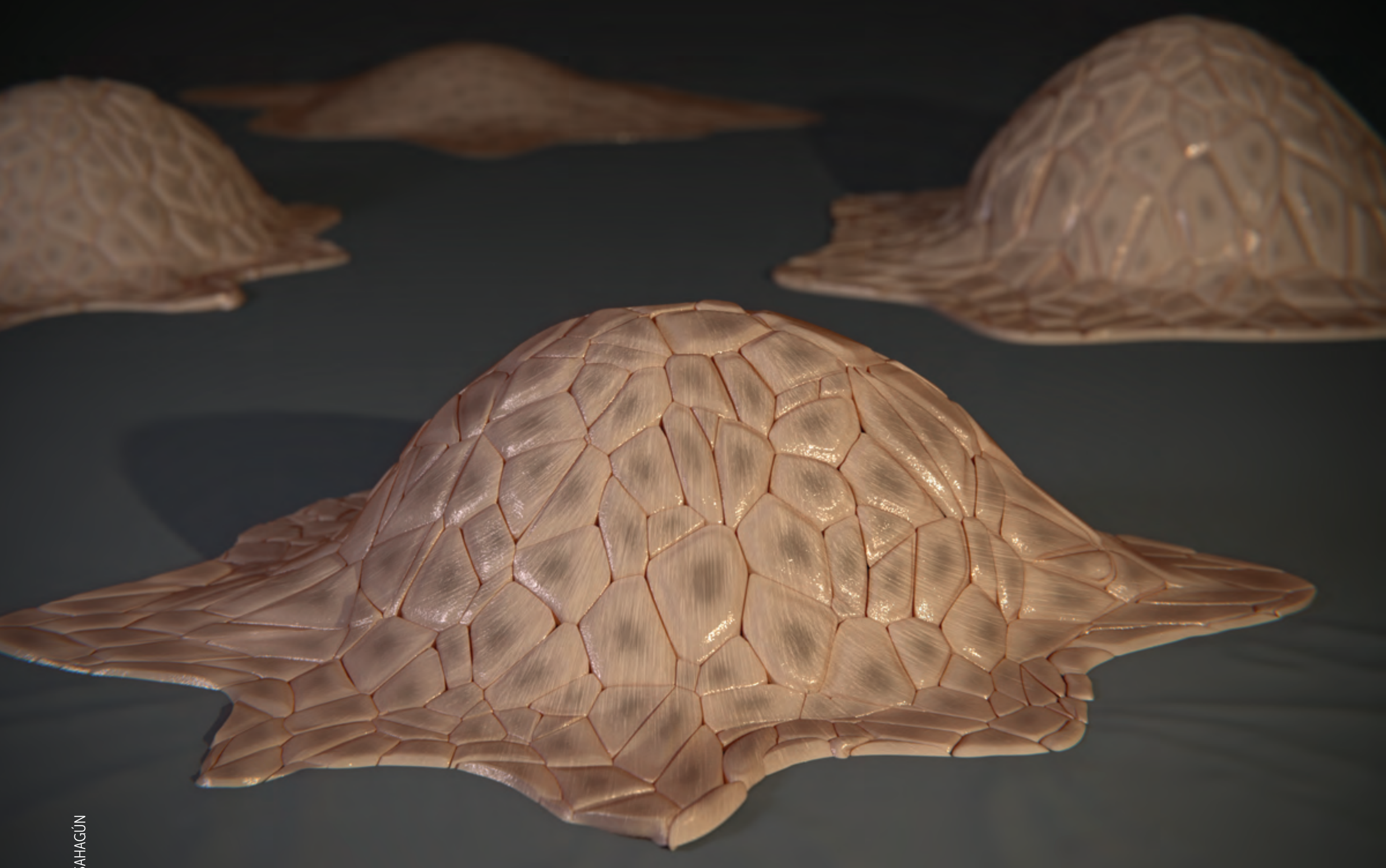
Utility-scale energy storage with long duration—six hours or more—grows in importance as wind and solar generation grow. According to Mark Mehos, the NREL group manager for thermal systems R&D, various analyses have shown that if the 5¢ target is achieved, CSP with thermal storage for long durations will be less expensive than the combination of PVs and batteries, since CSP scales more efficiently. "To hit Biden's 2035 target, you will need long-duration storage," he says.

A number of ways are available to improve the efficiency of heliostats, the thousands of mirrors that are arrayed in a CSP plant to reflect sunlight to the central concentrator. Heliostat costs, which have been halved in the past decade to $\$100/m^2$, could again be halved, says Mehos. Increasing reflectivity from 93% to 97% would reduce the number of mirrors required at a plant. It might be accomplished either by reducing the thickness of the glass covering the silver reflective material or by replacing the glass with a polymer substrate.

DOE is supporting the development of silica particles that could replace molten salt as the heat-transfer medium. Those particles, which Mehos says are "dirt cheap," can be heated to around 800 °C, compared with the 565 °C maximum for salt. The higher temperature could allow supercritical carbon dioxide to replace steam for driving electricity-generating turbines. The improvement in thermodynamic efficiency from that cycle could reduce the size of power stations to as little as one-tenth that of a modern coal power plant. That could help ease the financing of CSP plants, which are large capital projects.

David Kramer PT

Living cells ON THE MOVE



ENRIQUE SAHAGÚN

Ricard Alert and Xavier Trepat

Spectacular collective phenomena, such as jamming, turbulence, wetting, and waves, emerge when living cells migrate in groups.

Ricard Alert is a postdoctoral research fellow at Princeton University in New Jersey. **Xavier Trepat** is an ICREA Research Professor at the Institute for Bioengineering of Catalonia in Barcelona, Spain.

Much like birds fly in flocks and fish swim in schools, cells in our body move in groups. Collective cell migration enables embryos to develop, wounds to heal, and cancer cells to invade healthy tissue. Such phenomena involve complex biochemical regulation, but their dynamics can be predicted by the emerging physical principles of living matter. (For more about biochemical regulation in cells, see the article by Christoph Zechner and Christoph Weber on page 38 of this issue.)

At the microscale, our body is a busy maze filled with moving cells. Their movements are slow, rarely exceeding 10 μm/min, but they are crucial to immune response and tissue self-renewal. Through the same mechanisms that sustain these and other physiological functions, cell movements drive devastating diseases such as acute inflammation and cancer. Indeed, they can be considered diseases of cell movement because arresting the right cells in a controlled manner would be sufficient to prevent their spread. Take cancer as an example. Whereas its origin is well known to be genetic, we could prevent tumor cells from metastasizing in distant organs if we could halt their movement. Understanding cell migration is therefore crucial to improving current strategies for fighting disease.

Cell migration comes in different flavors. Some cell types move as isolated self-propelled particles. For example, to chase and destroy pathogens, immune cells move individually through tissue pores. Similarly, in some types of cancer, single cells dissociate from tumors and travel through surrounding tissue, eventually reaching blood vessels and metastasizing at distant organs. By contrast, in embryo development, cells move in groups to enable the precise positioning of tissues and organ progenitors. Well after birth, those movements continue to shape organs and drive wound healing. In tissues such as the skin, a continuous sheet of tightly adhered cells moves cohesively over any damaged area to heal it.

Likewise, cancer cells migrate in the form of cell sheets, strands, and clusters, as shown in figure 1a. Within those groups, cells organize themselves to behave like an aberrant organ. This added functionality is thought to provide malignant tumors with distinct strategies to improve their chances of spreading into surrounding tissues.

Collective migration is also involved in maintaining the inner surface of the gut—the fastest self-renewing tissue in mammals. It renews entirely every three to five days, which implies a daily loss of several grams of cells. Tissue renewal proceeds because of the division of stem cells that reside at the bottom of tissue invaginations called crypts. The progeny of those stem cells then migrates from the crypt to the top of fingerlike protrusions called villi, where they are shed into the fluid-filled interior of the intestine (see figure 1b) and discarded.

A myriad of molecular processes, from genetic programs to sensing and signaling pathways, regulate collective cell migration. Yet, they act on a limited number of physical quantities to determine cell movement. Therefore, coarse-grained approaches may provide crucial insight into biological questions. Furthermore, collective cell behaviors have inspired new physical theories of living systems. In this article we highlight progress on that front.

Cell assemblies as living matter

What physical principles underlie collective cell motion? In traditional condensed matter, interactions between electrons or atomic nuclei give rise to fascinating collective phenomena such as magnetism and superconductivity. In an analogous way, cell–cell interactions can also lead to emergent collective phenomena in migrating cell groups. When treating cell colonies as materials, however, we must take into account some key features of living matter.

First, the primary constituents of living tissues are cells and extracellular networks of protein fibers, such as collagen. The interactions between these mesoscale constituents are orders of magnitude weaker than interatomic interactions in conventional solids. With notable exceptions, such as bone, most biological tissues are soft materials, which can easily deform and flow.

Second, cells are machines with internal engines. Specialized proteins known as molecular motors harness the energy of chemical reactions to generate forces and produce mechanical work. These energy-transducing molecular processes ultimately power cell migration and allow cells to move autonomously without externally applied forces. The continuous supply of energy drives living tissues out of thermodynamic equilibrium. Importantly, the driving is local; it occurs at the level of single cells. In other words, cells are active constituents, and living tissues are a paradigmatic example of active matter—an exploding new field in nonequilibrium statistical physics.

Cells are not only mechanically active; they also sense their environment, process information, and respond by adapting their behavior. For example, stem cells plated on substrates of different stiffness differentiate into distinct cell types—from

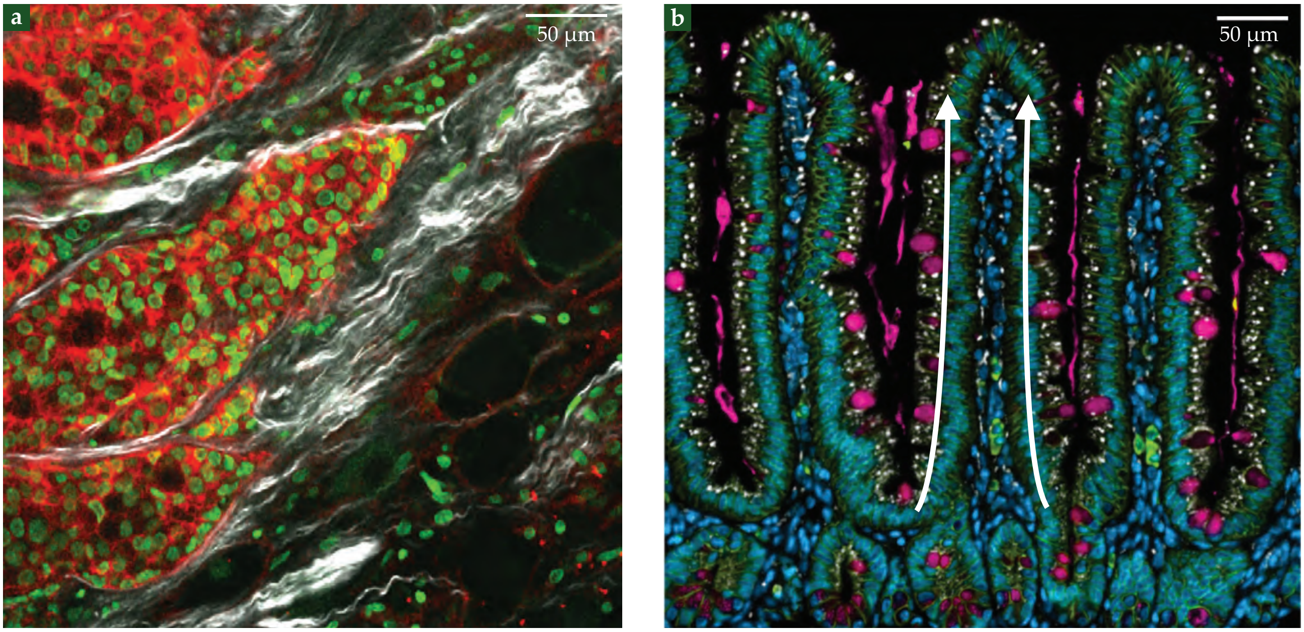


FIGURE 1. COLLECTIVE CELL MIGRATION in the human body. **(a)** Breast cancer cells from a patient sample migrate into the surrounding extracellular matrix. Cell nuclei are green, the cell–cell adhesion protein E-cadherin is red, and collagen fibers are white. (Adapted from O. Ilina et al., *Dis. Model. Mech.* **11**, dmm034330, 2018.) **(b)** Intestinal cells migrate, as indicated by the white arrows, to renew the inner surface of the gut. (See D. Krndija et al., *Science* **365**, 705, 2019.) Cell nuclei are blue, mucus-secreting goblet cells are pink, the cell–cell adhesion protein p120 is green, and lysosomes are white. (Image courtesy of Kristen A. Engevik.)

brain cells to bone cells. Living tissues are adaptive; they respond in programmed ways to environmental cues, such as external forces, mechanical properties of the extracellular matrix, and concentrations of nutrients and signaling molecules.

Consequently, cell–cell and cell–environment interactions are often quite complex. Unlike atoms and electrons in conventional condensed matter, cellular interactions cannot in general be fully described via an interaction potential with a fixed functional form. Thus, a key challenge in the physics of living matter is to find effective ways to capture complex cell behaviors in terms of simple interactions.[1]

To flow or not to flow

One way to think about interactions between deformable epithelial cells comes from the physics of foams. In foams, gas bubbles arrange in polygonal packings, with the liquid phase filling the interstitial spaces and providing surface tension at bubble interfaces, shown in figure 2a. Cells in epithelial monolayers (see figure 2b) also acquire polygonal shapes, with roughly straight edges subject to active tension generated inside cells. This description of tissues as cell packings goes back to work by Hisao Honda and collaborators in 1980, and it was later popularized in work by Frank Jülicher and colleagues.[2]

Because cells are deformable, edge lengths vary dynamically. These variations change the energy—or more formally, the Hamiltonian—of the cellular network, which one can write in terms of areas A_i and perimeters P_i of N cells, as

$$H = \sum_{i=1}^{N} \left[\frac{\kappa}{2}(A_i - A_0)^2 + \frac{\Gamma}{2}(P_i - P_0)^2 \right].$$

This expression assumes that cells resist changes in their area and perimeter around the preferred values of A_0 and P_0, with elastic moduli κ and Γ respectively. The preferred perimeter P_0 depends on cell–cell interactions and cellular activity, with cell–cell adhesion promoting longer edges and cellular tension favoring shorter edges. The preferred perimeter and preferred area define a dimensionless parameter $p_0 = P_0/\sqrt{A_0}$, which contains information about the preferred cell shape. Higher p_0 corresponds to more elongated cells, whereas smaller p_0 corresponds to more isotropic shapes—with less perimeter for the same area.

For a given p_0, edge lengths vary until the system reaches its ground state and minimizes the energy in the equation. In that process, an edge can shrink until it eventually disappears and a new cell–cell interface forms (see figure 2c). Known as T1 transitions, those events allow cells to change neighbors and drive topological rearrangements of the cellular network.

The ability to reorganize its constituents determines whether a material is solid or fluid. If cell rearrangements are difficult, the cellular network resists shear deformations; the tissue is solid. In contrast, if cells can rearrange easily, the network yields to shear; the tissue is fluid. At small p_0 (that is, for rounder cells), the equation implies that an energy barrier prevents T1 rearrangements. However, as p_0 increases and cells become more elongated, the energy barrier decreases (see figure 2c). At a critical value of p_0 around 3.81, the barrier vanishes (see figure 2d) and cells can rearrange freely.[3]

That simple model thus predicts a solid–fluid transition in tissues that is driven by changes in cell shape (see figure 2e). It's a striking prediction that showcases the bizarre mechanical properties of materials with deformable constituents. In conventional condensed matter, solids can melt by increasing temperature, or they can melt by either reducing the packing fraction or, equivalently, decreasing pressure. Tissues, however, can melt at a fixed temperature and at the maximum packing fraction, without gaps between cells.[3] They can become fluid by increasing the cell perimeter-to-area ratio in one of two

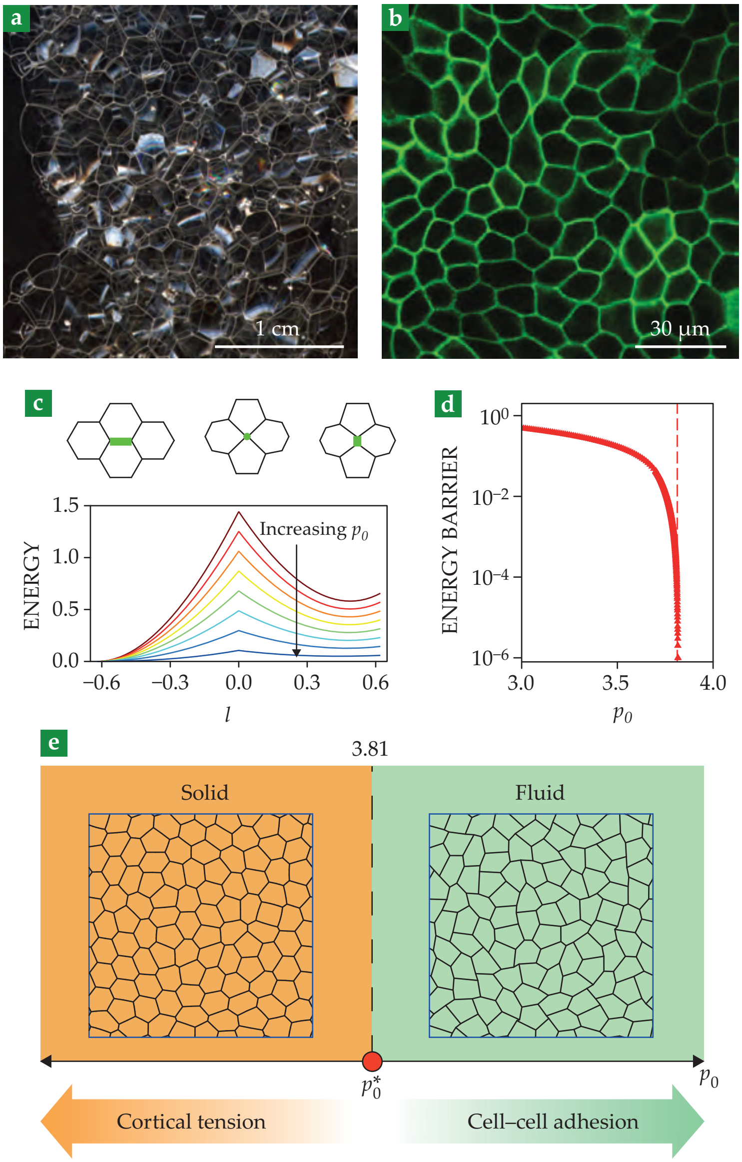


FIGURE 2. BIOLOGICAL TISSUES as foam. **(a)** Seen is a picture of soap foam. (Image by André Karwath aka Aka, CC BY-SA 2.5.) **(b)** A monolayer of epithelial cells is labeled with membrane-targeted green fluorescent protein. (Adapted from X. Trepat, E. Sahai, *Nat. Phys.* **14**, 671, 2018.) **(c)** For a group of four cells undergoing a T1 cell rearrangement, the energy increases as the length l of one of its edges (green) contracts ($l < 0$), and energy decreases as the edge expands perpendicularly ($l > 0$). Each curve has a different value of the cell-shape parameter p_0, from 1.8 to 3.5 top to bottom. **(d)** The energy barrier for a T1 rearrangement decreases with p_0, eventually vanishing at $p_0^* \sim 3.81$. **(e)** Tissues can undergo a fluid–solid transition when the cell shape changes because of changes in either cell–cell adhesion or cell-generated cortical tension. (Panels c–e adapted from ref. 3.)

ways: either decreasing intracellular tension or, counterintuitively, increasing the cell–cell adhesion. The more that cells adhere to one another, the more they elongate and the easier it is for them to rearrange.

Shortly after its prediction,[3] such a solid–fluid transition was experimentally verified in layers of human bronchial epithelial cells.[4] The same study showed that cells from healthy individuals tended to be caged by their neighbors and form a solid tissue, whereas cells from asthmatic individuals tended to remain unjammed and form a fluid tissue. Therefore, the experiments suggested, fluid–solid transitions in tissues are involved in disease—a finding that opens the door to new treatments based on preventing those phase transitions.

Fluid–solid transitions also occur during development, which enables tissues first to turn fluidic so they can remodel and acquire their shapes and then to solidify and mature. The emerging picture is that in different biological contexts cells can tune their shape and use the physical principles governing phase transitions in foams to decide whether to flow or not to flow.

Aligning with neighbors

The action starts once tissues become fluid and cells can move. Cells then start to flow collectively in ways that depend on how they align with their neighbors. These cell–cell interactions depend strongly on cell shape.

Cells come in many different shapes, such as roughly spherical and rodlike. Some develop a head–tail asymmetry and migrate persistently in one direction, which can be represented by a vector known as cell polarity. And in groups, cells can align their individual polarities to form phases of matter with orientational order.

The alignment interactions and the resulting oriented phases can be described using concepts from magnetism and liquid crystals. For example, cells in a group can spontaneously break symmetry and align in a common direction. To capture the emergence of this kind of alignment, known as polar order, one can introduce ferromagnetic-like interactions between individual cell polarities. At a coarse-grained level, collective cell polarity can be thought to result from an effective free energy, with a sombrero shape that is familiar from the Landau theory of phase transitions.

In other situations, cells align along one axis but have no preferred direction of motion. Known as nematic order, this type of alignment takes its name from nematic liquid crystals, which are used in LCD screens. Some of the most prominent features of liquid crystals are singular points known as topological defects, in which alignment is locally lost. You can find such defects on your own hands: Shown in figures 3a and 3b, they are the points at which your fingerprint ridges meet.

Recently, researchers have discovered topological defects in several cell assemblies, from bacterial colonies to epithelial tissues, which confirms that they can be described as liquid crystals (see figure 3c). Interestingly, topological defects can play important biological roles. For example, in epithelial monolayers, they promote cell death and extrusion[5] (see PHYSICS TODAY, June 2017, page 19). In colonies of the motile soil bacterium *Myxococcus xanthus*, such defects promote the formation of multicellular aggregates known as fruiting bodies, which allow the bacterial population to survive starvation.[6]

Flowing on their own

Capturing orientational order is not enough to account for collective cell flows. To understand how cell alignment translates

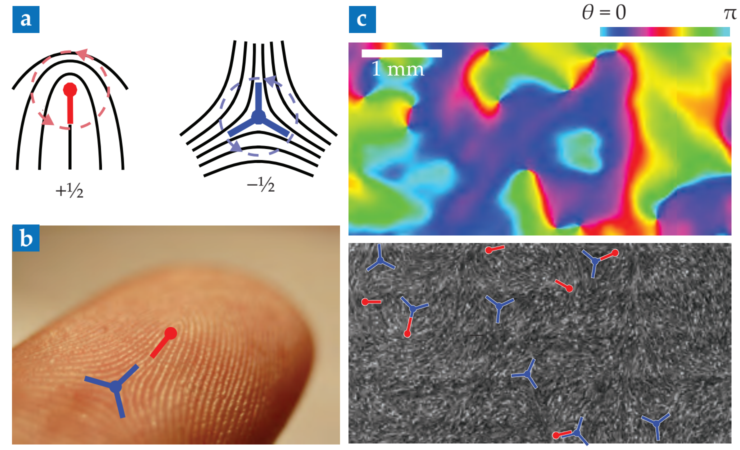


FIGURE 3. TOPOLOGICAL DEFECTS in cell monolayers. **(a)** Seen here are schematics of nematic topological defects. The local alignment axis (black) is undefined at the defect core (central point). Defects are characterized by their topological charge, defined as the winding number of the alignment direction around the defect core. **(b)** Topological defects are seen in a fingerprint. (Adapted from Frettie/Wikimedia Commons/CC BY 3.0.) **(c)** The color map at the top shows the angle of cell alignment in a cell monolayer. Defects are the points where all colors meet. In the bottom image, defects are highlighted in a phase-contrast microscope image of the monolayer. (Panels a and c adapted from K. Kawaguchi, R. Kageyama, M. Sano, *Nature* **545**, 327, 2017.)

into collective motion, physicists describe cell assemblies as active matter.[1,7] For example, when cells align with polar order, they can start migrating in the direction of alignment.[8] Such collective motion is known as flocking. The active-matter theory of the phenomenon, inspired by the mesmerizing flights of bird flocks, was developed more than 25 years ago.[9] Today, the principles of flocking are applied to many other systems—from synthetic active colloids to bacterial swarms.

To describe nematic cell colonies, researchers use the theory of active liquid crystals, which generalizes the hydrodynamics of liquid crystals to include active (cell-generated) stresses. The theory explains, among many other phenomena, the cell flows observed around topological defects. It also successfully describes many other active systems—from biopolymer gels to shaken granular materials. Employing general theories of active matter to characterize cell migration is particularly useful because it reveals connections to apparently unrelated systems. This approach is allowing the community to classify active systems based on their symmetries, in the spirit of universality classes in statistical mechanics.

For example, the theory of active liquid crystals was originally inspired by the complex autonomous flows found in bacterial suspensions and in the cell cytoskeleton. Soon after formulating the theory, researchers predicted that internal active stresses would generate an instability whereby the fluids start flowing spontaneously, without any external forces applied.[10] To drive flows, active stresses have to overcome alignment forces in the liquid crystal, which happens only at sufficiently large spatial scales. Consequently, the theory predicted that a strip of active fluid would flow only if it was wide enough.[10]

More than a decade later, those predictions were tested in cell monolayers.[11] Whereas cells confined in narrow stripes did not flow, cells confined in stripes wider than a critical width developed a collective shear flow, as predicted by the theory. In large tissues, cell flows become chaotic and create disordered patterns of swirls known as active turbulence.[12] Confinement can therefore organize these chaotic cell flows, either taming them into simple shear flow or preventing them altogether.

The regulatory role of confinement may be relevant in embryonic development and tumor invasion, in which cell groups often migrate in tracks defined by surrounding tissue (see figure 1a). Overall, recent work reveals how cells can leverage the physics of active fluids to produce collective flow patterns, and how confinement controls whether and how cell groups flow on their own.

To spread or not to spread

What happens if the confinement is released and a cell monolayer is exposed to free space? Cells at the edge of the monolayer can sense that they have neighboring cells on one side but not the other. In ways that are not yet clear, edge cells respond to this asymmetric environment by polarizing toward free space, as shown in figure 4a. Specifically, the cells extend protrusions known as lamellipodia, with which they exert directed and persistent traction forces on the underlying substrate to migrate toward open ground.

Because cells in the monolayer adhere to each other, the migrating edge cells pull on those in the second row, which then also polarize, migrate, and pull on inner cells (see figure 4b), thus setting the monolayer under tension.[13] At the molecular level, this supracellular coordination is mediated by a protein known as merlin, which transduces intercellular forces into cell polarization. In such a mechanically coordinated way, the entire cell monolayer spreads on the substrate and becomes progressively thinner.[14] Combined with other mechanisms, such collective cell migration helps, as in wound healing, to close the gaps in epithelial tissues.

But tissues are not always spread on substrates. Under certain conditions, a cell monolayer may instead retract from the substrate and eventually collapse into a droplet-like cell aggregate,[15] as illustrated in the opening image on page 30. Tissue spreading and retraction are reminiscent of the wetting and dewetting of liquid droplets. The degree of wetting depends on the balance between cohesive forces in the liquid and adhesive forces with the substrate.

By analogy, early models proposed that tissue wetting was dictated by a competition between cell–cell (W_{cc}) and cell–substrate (W_{cs}) adhesion energies,[16,17] encoded in a spreading parameter $S = W_{cs} - W_{cc}$. When $S < 0$, cell–cell adhesion dominates and the cell aggregate retracts from, or dewets, the substrate, whereas when $S > 0$, cell–substrate adhesion dominates and the aggregate spreads over, or wets, the surface (see figure 4c). This simple conceptual framework is sufficient to interpret the behavior of cell aggregates when the levels of cell–cell and cell–substrate adhesion are varied.[16,17] Even so, the analogy to passive liquids does not explicitly account for the active nature of cells.

Recent work addressed that limitation by treating the cell monolayer as a droplet of an active liquid.[15] Using this approach, one obtains the spreading parameter directly in terms of active cellular forces. Supported by experiments, the model predicts that the tissue wetting transition results from the com-

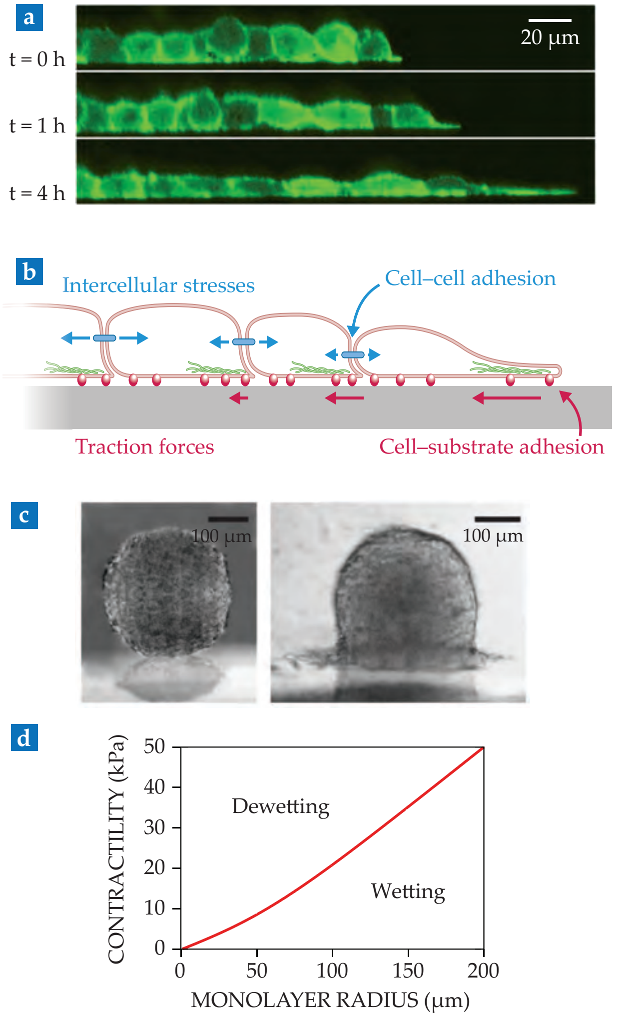


FIGURE 4. TISSUE WETTING. (a) Shown is a side view of a cell monolayer as it starts spreading. (Adapted from ref. 14.) **(b)** This schematic presents cell–substrate forces and cell–cell stresses involved in tissue spreading. (Adapted from S. R. K. Vedula et al., *Physiology* **28**, 370, 2013.) **(c)** Cell aggregates may either remain as droplet-like spheroids (left) or wet the underlying substrate (right). (Adapted from ref. 16.) **(d)** This phase diagram of active tissue wetting shows that for a given tissue contractility, which represents cell–cell pulling forces, only sufficiently large monolayers wet the substrate. (Adapted from ref. 15.)

petition between two types of active forces: Whereas cell–substrate traction forces promote spreading, cell–cell pulling forces, or tissue contractility, promote retraction.

That active wetting framework makes another key prediction: The spreading parameter depends on the droplet radius. Cell monolayers larger than a critical radius wet the substrate, whereas smaller monolayers dewet from it (see figure 4d). The prediction is striking because it has no counterpart in the classic wetting picture, in which the spreading parameter depends solely on surface tensions. For ordinary liquid droplets, size does not matter. Tissue wetting, by contrast, is size dependent. This prediction has been verified in experiments, which provide evidence for the active nature of tissue wetting.[15]

Besides its relevance to physics, the existence of a critical size for tissue wetting might explain drastic changes in tissue morphology during embryonic development and cancer progression. A disturbing possibility, for example, is that a growing tumor might become able to spread onto surrounding tissue once it reaches a critical size.

Overall, the work described above exemplifies how the quest to understand collective cell migration motivates the development of new physics, as in the example of active wetting. This physics approach offers clues on how cell aggregates can tune active forces to control whether to spread or not to spread.

Mechanical waves without inertia

Tissue spreading exhibits yet another striking collective phenomenon: Mechanical waves start spontaneously at the leading edge of a cell monolayer and propagate across it,[14] as shown in figure 5. The waves are slow, with speeds between 10 μm/h and 100 μm/h and wavelengths that span several cell diameters. Like longitudinal sound waves, waves in tissues stretch and compress the cells as they travel. More strikingly, the waves are self-sustained; they can travel distances as long as 1 mm unattenuated.

The observation is surprising because cell motion is so slow that inertia is negligible. Thus, tissue waves cannot be sustained by the common back-and-forth between kinetic and potential energies, familiar from the harmonic oscillator. Moreover, many sources of dissipation, including cell–cell and cell–substrate friction, exist in tissues and could potentially damp the waves. Thus, the very existence of mechanical waves in tissues implies an active driving mechanism that compensates damping and generates an effective inertia.

The quest to understand such waves has led to a plethora of physical models and revealed several possible

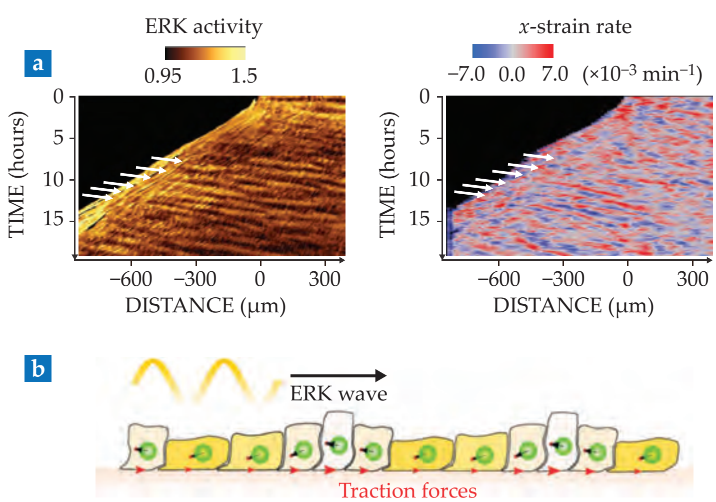


FIGURE 5. WAVES during tissue spreading. **(a)** These space–time plots show the activity of the signaling molecule ERK (left) and the strain rate (right). Waves (white arrows) appear as oblique lines, whose slope gives the wave speed. (Adapted from N. Hino et al., *Dev. Cell* **53**, 646, 2020.) **(b)** Cells polarize and migrate against the wave. In spreading tissues, the wave travels inward from the leading edge (left to right here) and directs cell migration (black) toward free space (left), as traction forces (red) point to the right. (Adapted from ref. 18.)

mechanisms.[1] Recently, experiments have shown (see figure 5a) that mechanical waves are accompanied by waves of ERK, an extracellular signaling molecule that affects cellular activity. Following those observations, researchers developed a theory based on the feedback between the molecule and cell mechanics, which produces coupled chemical and mechanical waves. Assuming that cells polarize in response to stress gradients in the monolayer, the theory also explains propagation away from the leading edge in spreading tissues,[18] as sketched in figure 5b.

The results show that cells can exploit mechanochemical feedbacks to transmit local information over long distances. Such tissue-scale communication is relevant for wound healing, as it enables distant cells to coordinate their migration toward the wound. Similar principles operate in morphogenesis, in that mechanochemical feedbacks enable coordinated cell deformations to precisely shape tissues without requiring local genetic control of cellular forces. The research shows that the cells' ability to generate, sense, and respond to signals—both chemical and mechanical—can give rise to emergent phenomena as counterintuitive as mechanical waves without inertia.

The physics of active living matter is increasingly successful at explaining the dynamics of collective cell migration. This core biological process is being understood through concepts such as orientational order, flow, turbulence, jamming, wetting, and wave propagation. The mechanistic origin and physical properties of these phenomena in cells, however, differ fundamentally from those in nonliving matter. Whereas new active-matter theories manage to explain the broad phenomenology of collective cell migration in terms of a small number of physical variables, how cells tune these variables through thousands of genes and biochemical reactions remains a major open question.

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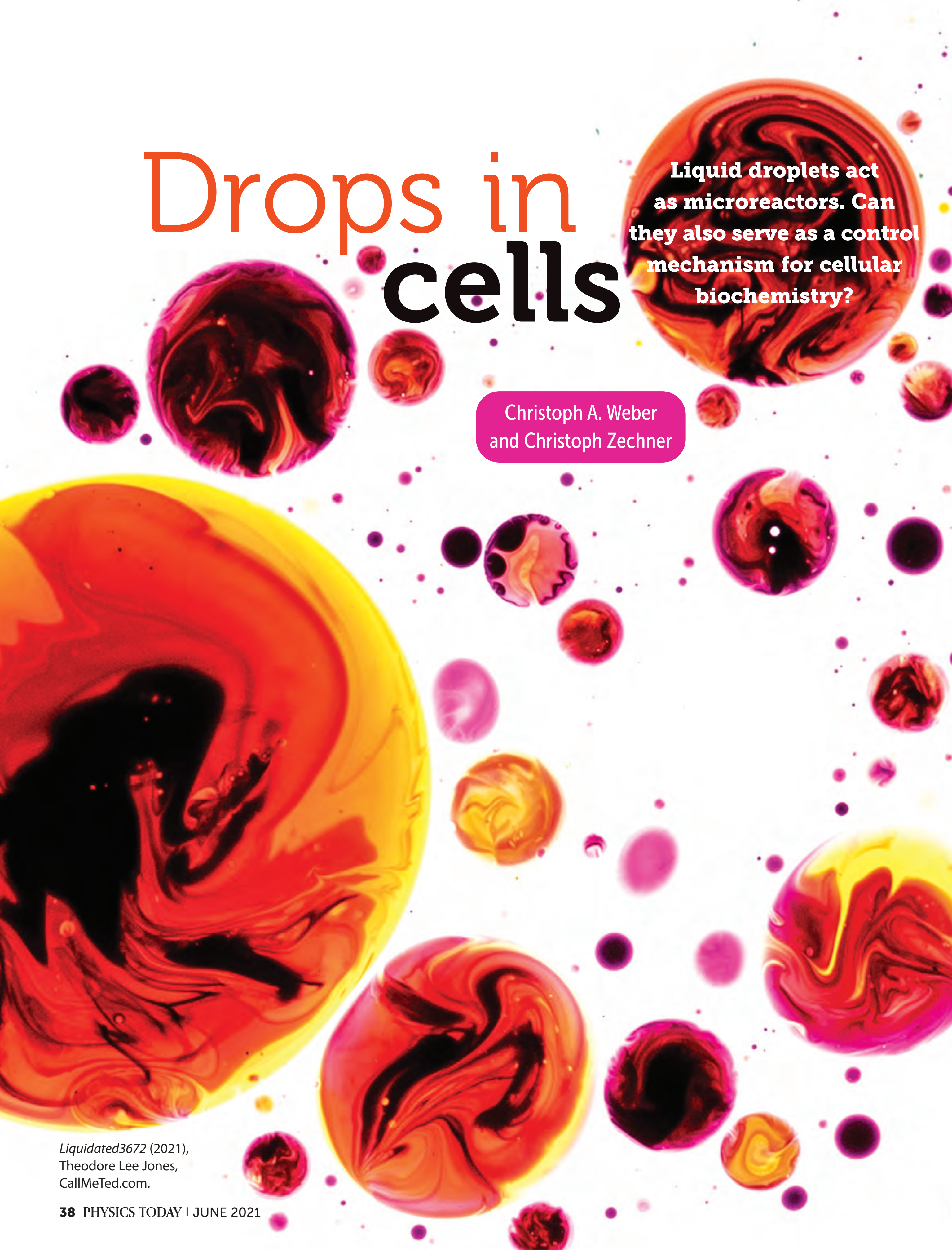
Drops in cells

Liquid droplets act as microreactors. Can they also serve as a control mechanism for cellular biochemistry?

Christoph A. Weber and Christoph Zechner



Liquidated3672 (2021), Theodore Lee Jones, CallMeTed.com.

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A major challenge in cell biology remains unraveling how cells control their biochemical reaction cycles. For instance, how do they regulate gene expression in response to stress? How does their metabolism change when resources are scarce? Control theory has proven useful in understanding how networks of chemical reactions can robustly tackle those and other tasks.[1] The essential ingredients in such approaches are chemical feedback loops that create control mechanisms similar to the circuits that regulate, for example, the temperature of a heating system, the humidity of an archive, or the pH of a fermentation tank.

Theories for the control of biochemical reactions have largely focused on homogeneous, well-stirred environments. However, macromolecules inside cells are often highly organized in space by specialized subunits called organelles. Some organelles, such as the cell nucleus, are bound by a membrane. By contrast, another class of organelles—biomolecular condensates—show the hallmark physical properties of liquid-like droplets, and they provide chemically distinct environments for biochemical reactions.[2–4]

Such droplets can act as microreactors for biochemical reactions in a living cell (see figure 1). Their liquid nature sustains the fast diffusion of reactants while their specific composition gives rise to the partitioning of reactants in or out of the droplets. In general, the concentrations of reactants inside condensates differ from the concentrations outside. Those differences modify reaction fluxes, which, in turn, can dramatically affect reaction yield and other properties of chemical reactions. Just how such modified fluxes govern the biochemistry inside cells remains poorly understood.

In this article, we use the physics of phase separation and control theory to speculate on how liquid condensates could realize feedback control strategies in living cells.

Controlling well-mixed systems

Biochemical reactions serve as biology's basic building blocks for processing and controlling cellular information. They regulate cellular metabolism and the sensing of environmental cues through signal transduction. They also regulate the expression of genes, whose information, stored in DNA, is transcribed and translated into functional proteins.

Networks of chemical reactions provide a useful mathematical description of such processes. In that formalism, molecules are described as particles, which diffuse randomly inside a reaction volume. When two (or more) molecules of the right type encounter one another, they can undergo a chemical reaction. Once the reaction occurs, the original reactant molecules are converted into a set of product molecules. In the bimolecular reaction, $A + B \rightleftharpoons C + D$, molecule types A and B are converted into C and D. Intracellular processes typically comprise a multitude of reaction cycles, in which the products of one reaction serve as the reactants of another reaction and so forth. That interdependence results in intricate networks of chemical reactions, which can exhibit rich and complex dynamical behaviors, such as oscillations or multistability.

The dynamics of chemical reaction networks can be described using the theory of chemical kinetics, which captures how the concentrations of different chemically interacting molecules change with time. In its conventional form, chemical kinetics applies to well-mixed systems—that is, to reactions that run much more slowly than the molecules diffuse inside the reaction volume. In other words, the size of the reaction volume is much smaller than the corresponding reaction–diffusion length scale. Local changes in concentration that arise from a reaction will therefore be instantaneously homogenized by fast diffusion. In such a well-mixed system, the rate at which a reaction takes place depends only on the number of molecules present in the system; the exact spatial positions of those molecules become irrelevant. Well-mixed chemical systems can be fully characterized in terms of the temporal dynamics of the reactants' concentration levels.

A hallmark of biochemical networks inside cells is their remarkable robustness against random fluctuations in their molecular constituents, changes in their surroundings, or other potential disturbances. Previous studies have demonstrated that negative feedback mechanisms play a pivotal role in stabilizing various cellular processes against such disturbances.[5] Autoregulatory gene networks, in which a protein inhibits its own expression, are archetypical examples. If the protein level falls below a certain set point, the protein's inhibitory effect on transcription weakens and the protein level begins to rise. As the set point is approached (or exceeded), the negative feedback becomes more pronounced, which in turn reduces production of more of the protein. In that way, protein levels can be maintained within narrow ranges, despite potential disturbances that may affect the system.

Although that simple example illustrates the core idea behind negative feedback regulation, biological systems are often substantially more complex, involving many reaction cycles, concurrent feedback loops, and strong nonlinearities. Extracting simple principles that shed light on the functioning of such systems becomes challenging.

Control theory provides a rich framework for abstracting and analyzing dynamical systems subject to feedback. Beyond its traditional applications in engineering, control theory has proven a powerful way to study and reverse-engineer biological systems. In fact, by casting a given biological system within the formalism of control theory, a large repertoire of mathematical tools and concepts becomes applicable. Those tools and concepts make it possible to assess the essential properties of the system under consideration, even when some of its details are unknown.

Control theory basics

In a classical control problem, one considers an arbitrary physical process with input x and output y. For example, y could correspond to the temperature of a room, whereas x could be the power of a heating device in that room. The goal is to control the output y with respect to a certain reference value u, such as a desired ambient temperature, through a negative feedback loop. That loop contains a controller, which measures the mismatch between y and u and calculates an appropriate control input x to reduce the mismatch.

The function that maps y and u to x is referred to as a control law. In engineering applications, it is chosen based on performance and available resources. One of the simplest control laws is called proportional control. Here, the controller adjusts x purely based on the instantaneous mismatch between y and u. More precisely, $x = G(u - y) = eG$, where G is the feedback gain, which determines how strongly the controller reacts to a mismatch e. When G is sufficiently high, the closed-loop dynamics will be predominantly governed by $G(u - y)$, which in turn will effectively reduce the mismatch between u and y. Control is exerted even in the presence of a potential disturbance d; that disturbance could be a physical perturbation to the system or additional and possibly unknown fluxes and fluctuations.

More effective controllers can be achieved by extending the control law and adding terms that are proportional to the integral of the mismatch e, its derivative, or both. So-called proportional-integral-derivative controllers exhibit improved dynamical properties compared with pure proportional ones, such as zero steady-state error or improved convergence toward the desired reference value u.

To demonstrate more concretely how biochemical feedback systems can be studied using control theory, let's consider a simple toy model of protein expression.[6] In that system, proteins are produced and degraded with rate constants x and γ (see figure 2a). Dynamics are affected by a perturbation d, which for simplicity we consider constant. In a steady state, the protein level is given by $y = (x + d)/\gamma$. That is, protein level y is sensitive to the perturbation d and scales linearly with it.

Now consider a modification to the network: The protein negatively regulates the expression of additional protein by binding to its own promoter (figure 2b). In that case, the protein production rate can be described using a Hill-type function such that $x(y) = \lambda K^n/(K^n + y^n)$; n, K, and λ are positive parameters. For small y, the production rate will be close to λ, whereas for large y, it approaches zero. Linearizing the function around the steady-state value of y reveals a simple controller structure, in which the protein production rate is approximately given by the mismatch between some reference u and the protein level y, multiplied by a constant gain G (see figure 2b). Both u and G are functions of the kinetic parameters K, n, and λ; explicit dependences are omitted here for compactness.

That simple analysis shows that our genetic feedback circuit acts, to first order, like a proportional-feedback controller in that it tries to maintain the protein level y at some target value u. Thus if G is sufficiently large, y attains values close to u, even in the presence of the perturbation d. That can be seen when comparing the protein levels in time subject to a constant perturbation for the open-loop and closed-loop genetic circuits (figure 2c). Although the open-loop circuit is sensitive to perturbations, they are largely suppressed in the corresponding closed-loop system. References 6–8 provide further information on how control theory can elucidate biological and other physical systems.

Phase separation and chemical reactions

Liquid condensates can form in a multicomponent mixture via phase separation and stably coexist within an environment of lower concentration.[9] The thermodynamic behavior of such a mixture is governed by the minimization of the free energy, which accounts for the competition between the interaction energy and entropy. For phase separation to occur, molecules in a solvent need to attract each other or repel the solvent molecules such that the gain in interaction energy of a coexistence state outcompetes the corresponding disadvantage of forming an interface.

That phase coexistence is affected by various physicochemical control parameters such as concentrations of molecules and salt, pH, and temperature. The parameters define the phase diagram, which depicts the equilibrium parameters of the coexisting phases—that is, the condensate and its environment. Minimization of the free energy at a fixed average concentration of molecules implies that coexisting phases have the same chemical potential at thermodynamic equilibrium. The chemical potential corresponds to the slope of the free-energy density. Most importantly, the coexisting phases might differ not only in their respective concentrations but also in salt concentrations, pH, and other control parameters.

A spatially heterogeneous chemical potential leads to molecular fluxes, whose existence indicates that the system is not at thermodynamic equilibrium. An emulsion composed of many droplets provides one example. To see why an emulsion is not at equilibrium, we need to consider the droplet interfaces. The

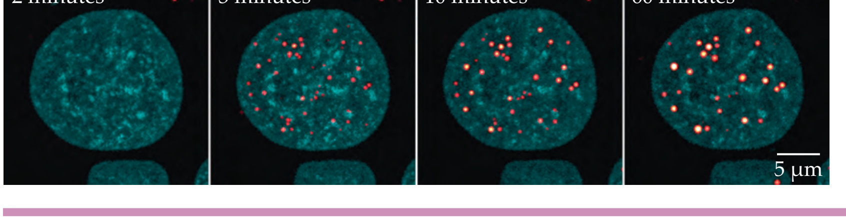

FIGURE 1. LIQUID DROPLETS could conceivably act as feedback controllers to regulate biochemical processes in cells. In this microscope image, fluorescently labeled proteins form liquid droplets inside the nucleus of a HeLa cell after the ambient temperature is lowered. (Image © Adam Klosin.)

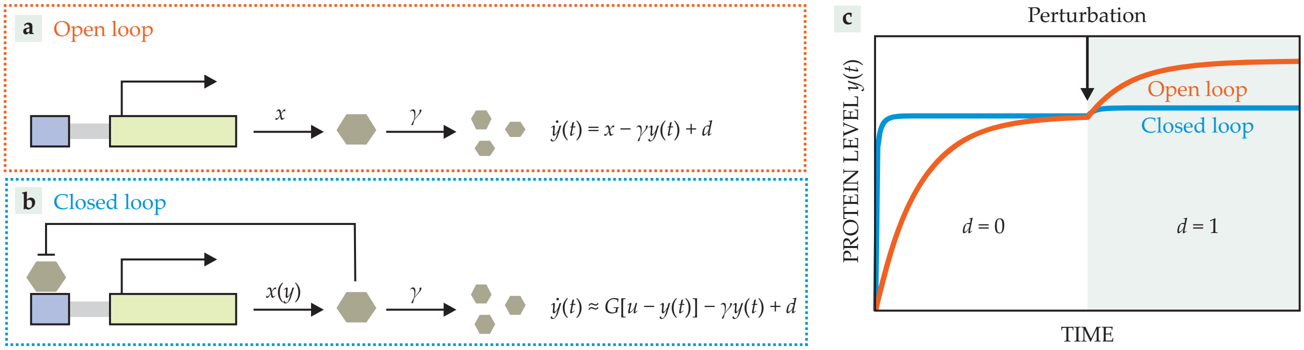

FIGURE 2. THE EXPRESSION OF A GENE (bent arrow on green rectangle) is initiated in this toy model by the activation of a promoter (blue rectangle) to yield the corresponding protein (gray hexagons) at a concentration that changes at the rate $y(t)$. **(a)** In the absence of feedback (open loop), protein molecules are produced and degraded with the rate constants x and γ, respectively. **(b)** In the presence of negative feedback (closed loop), the protein inhibits its own expression rate, which depends on the protein concentration y. **(c)** Open-loop expression is less robust against a constant perturbation d than closed-loop expression.

total interfacial area is lowest—and therefore the free energy is minimized—in the case of a single droplet. An emulsion of many droplets thus evolves with time toward a single drop corresponding to thermodynamic equilibrium.

Chemical reactions can affect the coexistence of phases. At thermodynamic equilibrium, a chemical reaction imposes a further constraint on the system: The sum of reactants' chemical potentials on each side of the reaction scheme (weighted by the stochiometric factors) must balance.

In general, in a mixture with M independent components and s chemical reactions at thermodynamic equilibrium, there are only $(M - s)$ independent concentrations.[10] The remaining concentrations are typically associated with the conserved quantities of the reactions, such as the total mass or the total molecular volumes of the reactants. For example, an incompressible ternary mixture ($M = 2$) with a reversible chemical reaction $A \leftrightharpoons B$ ($s = 1$) gives one independent concentration that is equal to the conserved quantity of the chemical reaction. In general, the phase diagram exhibits a lowered dimension compared with the same system without chemical reactions, and the axes of the corresponding phase diagram of the reaction—the maximal number of coexisting phases—reduce by one for each chemical constraint. Thus, according to the Gibbs phase rule, chemical reactions at thermodynamic equilibrium suppress the coexistence of multiple phases. That reduction to a smaller set of conserved variables and the suppression of multiphase coexistence do not necessarily prevail away from thermodynamic equilibrium.

An interesting case is a chemical reaction maintained away from equilibrium through the supply of fuel molecules. Those molecules get irreversibly degraded in a reaction step that breaks the reaction rates' detailed balance and leads to phenomena that are impossible at thermodynamic equilibrium.[9] A paradigm of such reactions is the division of liquid condensates, which represents the inverse kinetics of thermodynamic systems becoming more heterogeneous via fusion.

Coexisting phases also affect chemical reactions. To see why, consider a simple mixture of two types of molecules: scaffolds and clients. Scaffold molecules make up the condensates, whereas clients undergo chemical reactions.[11] If the clients are dilute, their impact on the scaffold-rich condensates can be neglected. However, because of the presence of condensates, the reacting clients experience a spatially heterogeneous environment. Such an environment has essentially two key effects on chemical reactions. First, the reacting clients are partitioned in or out of the condensates, where partitioning arises from the interactions between clients and scaffold molecules. Second, inside each phase, clients follow a reaction–diffusion type of kinetics with reaction rates specific to each phase. The rates emerge because each phase differs in its concentration and in its reaction rate constants. The two effects are instrumental in liquid condensates' regulation of chemical reaction, and they embody the condensates' potential as control strategies for biochemical reactions.

Control of chemical reactions in demixed systems

To gain a better understanding of how phase-separating systems could control reactions, it is useful to analyze their dynamical properties from a control theory perspective. To that end, we consider a simple phase-separating system that demixes into two phases: one rich in scaffold molecules; the other, poor (figure 3a). Kinetic equations for the scaffold concentrations can be derived from thermodynamic considerations in the limit where diffusion through the droplet is fast compared with the first-order reaction rate constant.[12] In that limit, concentrations in each phase are approximately homogeneous, which means the change in the dilute-phase scaffold concentration $c^{\mathrm{II}}(t)$ can be described by an ordinary differential equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\, c^{\mathrm{II}}(t) = \frac{kV}{V - V^{\mathrm{I}}(t)}\,[c^{\mathrm{II}}_{\mathrm{eq}} - c^{\mathrm{II}}(t)] + s[c^{\mathrm{II}}(t),\, V^{\mathrm{I}}(t)], \qquad (1)$$

where k is a relaxation rate toward equilibrium that depends on diffusivity, for instance. The term $c^{\mathrm{II}}_{\mathrm{eq}}$ is the equilibrium dilute-phase concentration, and V and $V^{\mathrm{I}}(t)$ are the total and droplet volume, respectively. The equation captures the partitioning of scaffold molecules between the dilute and dense phases. The kinetics of $c^{\mathrm{II}}(t)$ are affected by the reaction flux s, possibly through the production and turnover of scaffold molecules. That reaction flux drives the system away from equilibrium.

We can now recast this phase-separating system using the notion of feedback control. In particular, if we consider the dilute-phase scaffold concentration as the system's output $y(t)$, then the sum of the two exchange fluxes on the right-hand side implement what can be thought of as an error calculation between the current concentration—that is, the output $y(t) = c^{\mathrm{II}}(t)$—and the corresponding equilibrium concentration, or the reference value $u = c^{\mathrm{II}}_{\mathrm{eq}}$. The resulting error is multiplied by a time-dependent gain $G = kV/[V - V^{\mathrm{I}}(t)]$.

The droplet therefore acts like a proportional controller to maintain dilute-phase scaffold concentrations at a certain set point, despite additional fluxes and perturbations (see figure 3b). The effectiveness of the controller depends on the feedback gain G, which emerges from the physical properties of the mixture, such as interaction strengths among scaffold molecules and their diffusivity.

A similar feedback control structure can also be identified for dilute molecules that partition into liquid condensates. However, in contrast to the scaffold molecules, the controller no longer regulates absolute concentrations, but instead adjusts the ratio between inside and outside concentrations. We call that ratio the effective partition coefficient $p(t) = c^{\mathrm{I}}(t)/c^{\mathrm{II}}(t)$. How $p(t)$ changes can be expressed by the equation

$$\frac{\mathrm{d}}{\mathrm{d}t}\,p(t) = kV\left(\frac{1}{V^{\mathrm{I}}} + \frac{p(t)}{V^{\mathrm{II}}}\right)[p_{\mathrm{eq}} - p(t)] + s[c^{\mathrm{I}}(t), c^{\mathrm{II}}(t)]. \qquad (2)$$

Here, p_{eq} (defined as $c_{\mathrm{eq}}^{\mathrm{I}}/c_{\mathrm{eq}}^{\mathrm{II}}$) is the partition coefficient at equilibrium, and V^{I} and V^{II} are the volumes, respectively, of the dilute and dense phases. The expression suggests that for client molecules, the droplet resembles a proportional controller with output $y(t) = p(t)$, reference $u = p_{\mathrm{eq}}$, and feedback gain (see figure 4a). Thus, whereas client concentrations in each phase are sensitive to additional fluxes and perturbations, the partition coefficient can be robustly maintained through the feedback control loop (see figure 4b). The feedback, in turn, provides interesting ways to control the concentrations of downstream chemical processes such as enzymatic reactions.

How plausible is the idea that biomolecular condensates serve as feedback controllers inside cells? Although the field is still young, several recent studies point toward biological systems in which droplet-mediated feedback control may indeed be relevant. One example is the suppression of concentration fluctuations.[12–14] Because the concentration of scaffold molecules inside and outside the condensate is thermodynamically constrained, the condensate is expected to respond to fluctuating concentrations by changing its size. The concentrations within each phase are much less affected. In line with the scaffold control scheme shown in figures 3b and 3c, the condensate can thus be understood as a feedback controller, which tries to minimize the mismatch between the concentrations in each phase and their reference equilibrium value. The effectiveness of the controller (as reflected by the feedback gain G) depends on the underlying physical parameters and interactions. Earlier studies have used control-theoretical concepts to identify hard lower bounds on the suppression of noise in homogeneous biochemical feedback circuits.[15] Understanding how spatial compartmentalization affects those results is an important open problem.

A related and more complex negative feedback circuit has been recently proposed in the context of transcriptional condensates.[16] They are thought to enhance the transcription of messenger RNA (mRNA) by concentrating the required transcriptional machinery, such as transcription factors, cofactors, and polymerases. Interestingly, the study found that as soon as the newly transcribed mRNA exceeds a certain set point, it can promote the dissolution of the condensate and thereby arrest transcription. This gives rise to a negative feedback circuit, which could reliably control the duration and output of transcription despite potential disturbances.

Evidence is growing that condensates can control aggregation processes, including formation of physiological filaments such as actins and microtubules, and of disease-related fibrils such as amyloids. Although the biological roles of aggregates are diverse, their formation shares some common physical principles. Initial aggregates form via primary nucleation and grow mostly at their ends, and secondary nucleation allows small aggregates to form near the surface of existing aggregates.[17]

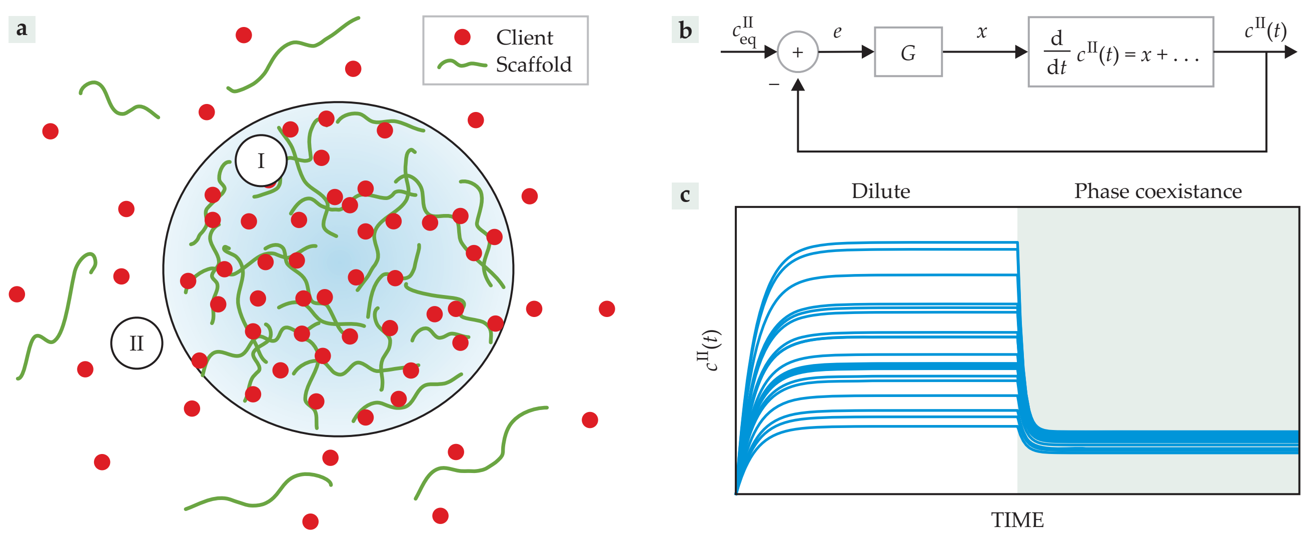

FIGURE 3. FEEDBACK CONTROL in a phase-separating system. This schematic illustration of the system **(a)** features scaffold (green) and client (red) molecules both inside (I) and outside (II) a phase-separated droplet. **(b)** Feedback control maintains the concentration of scaffold molecules outside the droplet, $c^{\mathrm{II}}(t)$, at its equilibrium value $c_{\mathrm{eq}}^{\mathrm{II}}$ through a proportional controller whose gain G depends on various quantities. Among them are the droplet volume and relaxation rate toward equilibrium. **(c)** Example trajectories demonstrating scaffold-based control for the case when the production rate of scaffold molecules varies randomly. As soon as phase separation is activated and droplets form (gray shaded area), dilute-phase concentrations are tightly regulated through feedback control.

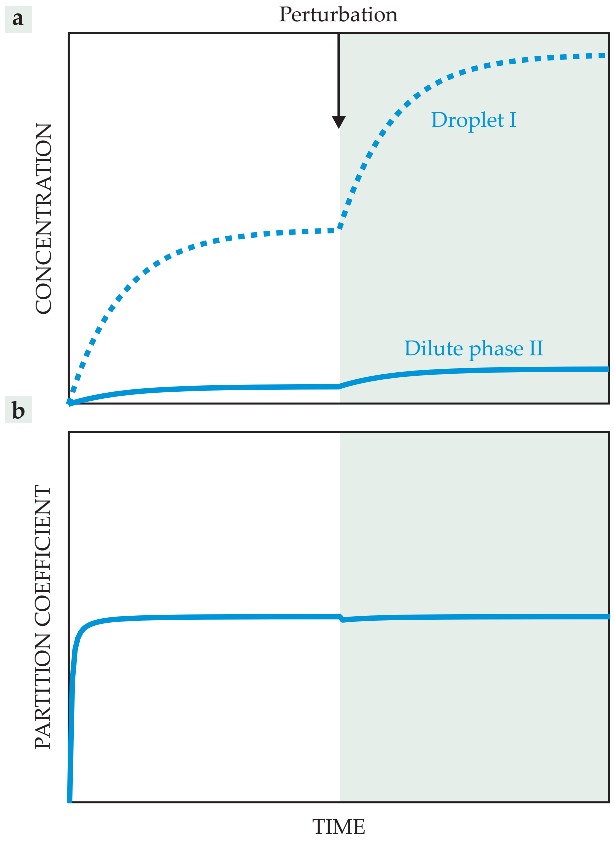

FIGURE 4. FEEDBACK CONTROL of clients. The concentration of a client **(a)** is sensitive to the onset of a perturbation (gray area), but the partition coefficient **(b)**—that is, the ratio of concentrations in the droplet and dilute phase—is robustly maintained by the droplet-mediated proportional controller.

Interestingly, condensates can mediate a feedback mechanism for aggregates already forming solely via primary nucleation. As monomers partition into the condensate and aggregate within it, their concentration inside the condensate should decrease. However, a fraction of the aggregated monomers is replenished by the partitioning flux, which tries to maintain the partitioning of monomers inside and outside the condensates. As a result, the growth of aggregates inside the condensates is favored, whereas aggregation outside is suppressed. For this simple aggregation process, condensates provide a mechanism that is reminiscent of a control circuit. The scaffold-rich condensate serves as a controller that adjusts the partitioning of aggregation-prone monomers and thus regulates the nucleation kinetics. That feedback is similar to the client example depicted in figure 4 and equation 2.

Researchers have recently found a similar but slightly more intricate feedback mechanism that is mediated by condensates. It occurs in systems of fibrils that undergo secondary nucleation and grow at their ends.[18] Interestingly, the mechanism controls the number and size of aggregates by changing the condensate's characteristic physical parameters, such as the monomer partitioning and condensate size. The findings support the potential relevance of condensates in regulating physiological assemblies or disease-related amyloid fibrils.

Final thoughts

The ideas outlined in this article illustrate how condensates in living cells could act as biomolecular controllers, akin to a thermostat regulating the temperature of a room. The similarities rely on the ability of condensates to mediate negative feedback and stabilize the properties of chemical reactions in dynamically changing conditions. The feedback in phase-separating systems originates from condensates coexisting with an outer phase of different concentration. That situation can give rise to molecule fluxes through the condensate interface that maintain specific concentration levels inside and outside or maintain functions of the concentrations.

We limited our biomolecular examples to proportional control, which is one of the simplest feedback control architectures. However, more robust and effective control strategies, such as integral feedback control,[1,8] could be realized when phase separation is coupled to additional reaction cycles. That possibility suggests a fruitful avenue for further research.

But why is the view that condensates can mediate feedback control helpful in the first place? First, consider a different question: Is it useful to describe a modern computer by modeling the physics of electron transport in each individual transistor? For many physicists, the answer to this question is no—because such an approach would be exceedingly complex and could fail to capture the system's emergent properties.

Cells host an extremely and analogously complex network of biochemical processes, many of which we are only beginning to understand. Analyzing such systems through control theory provides a universal strategy to extract the relevant structural and dynamical features of biological processes—without requiring a detailed physical description of the system. Understanding the interplay between spatial compartmentalization and biochemical reactions through control theory may open up new avenues to comprehending and even controlling functionality in living cells.

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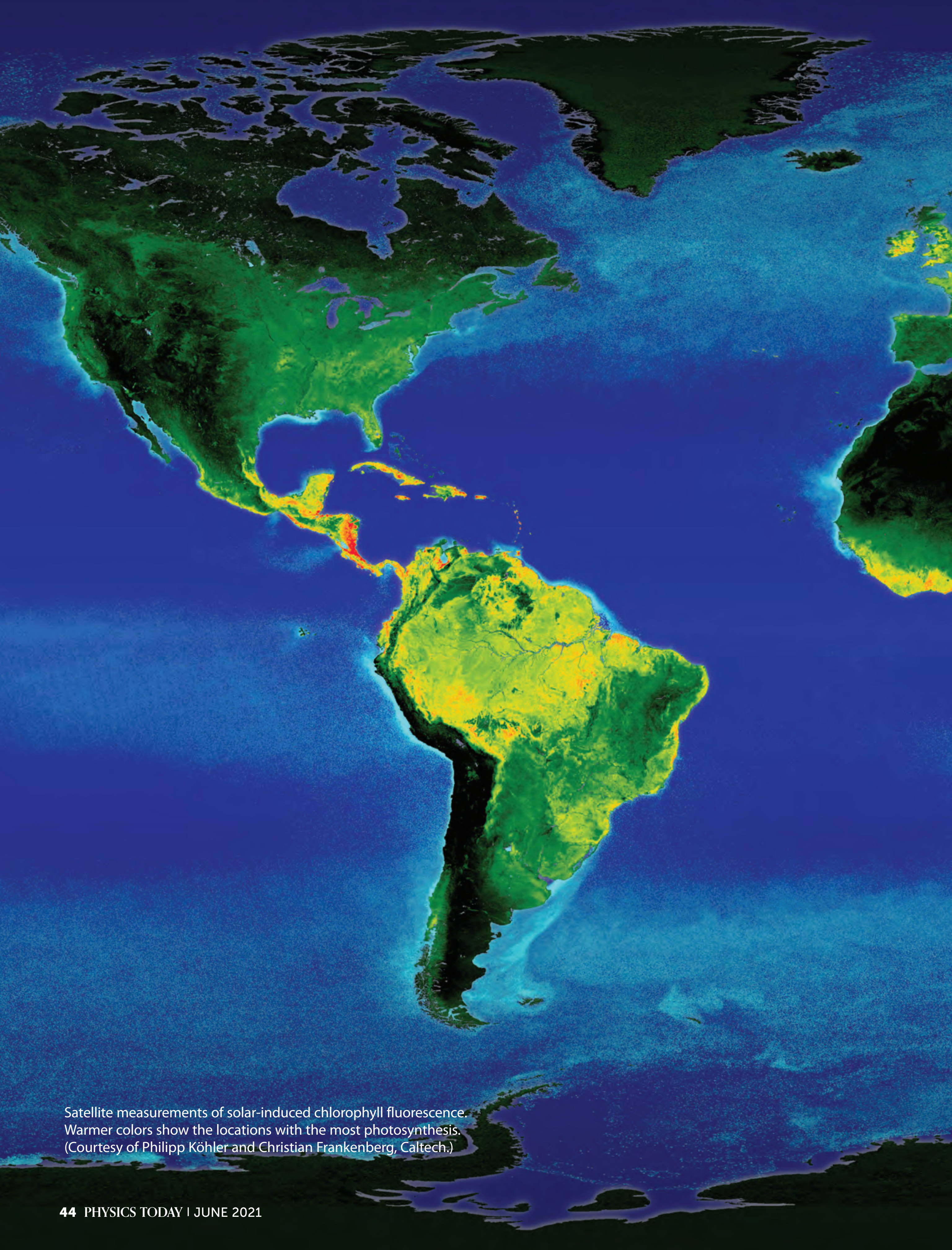

Satellite measurements of solar-induced chlorophyll fluorescence. Warmer colors show the locations with the most photosynthesis. (Courtesy of Philipp Köhler and Christian Frankenberg, Caltech.)

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Accelerating progress in CLIMATE SCIENCE

Tapio Schneider, Nadir Jeevanjee, and Robert Socolow

Interdisciplinary teams that integrate theory, data, and computing can now produce urgently needed, action-oriented climate science.

Over the past 50 years, anthropogenic climate change has shifted from an abstract possibility predicted by a few scientists to a reality everyone can see and feel. Global-mean surface temperatures have risen 1 °C, and the Arctic has warmed a staggering 3 °C.

The principal cause is rising atmospheric carbon dioxide from the burning of fossil fuels. Transitioning to a low-carbon economy in the next several decades will be necessary to avoid catastrophic climate change that could, for example, push outdoor temperature and humidity in the Persian Gulf region beyond what humans can endure.[1] But even if societies succeed in bending carbon emissions downward, they will still need to adapt to climate changes that are already underway, including more severe heat waves, heavier rainstorms, and less summer irrigation water resulting from reductions in snowpack.

Adapting to that future requires accurate and actionable science. Although older and current climate models have predicted that Earth would warm and will continue to warm, projections vary greatly. For example, in scenarios in which CO_2 emissions are promptly curtailed and ramp down to zero over the next 50 years, current models project that globally averaged surface temperature may still increase anywhere from 0.5 °C to 1.5 °C by 2050.

The large spread arises because of various uncertainties—such as how clouds respond to warming and how much heat oceans absorb—which are further compounded by the chaotic multidecadal variability of the climate system. Regional predictions are even more uncertain. And pinning down the shifting probabilities of extreme events, such as landfalling hurricanes or droughts, is still further out of reach.

A problem of scales

Together the atmosphere, land, oceans, cryosphere, and biosphere form a complex and highly coupled system. The fundamental laws governing the physics of the system are known, but the interactions of its many degrees of freedom exhibit emergent behavior that is not easily computable from the underlying laws.

The core challenge is to capture the Earth system's great range of scales in space and time. Take cloud cover, a crucial regulator of Earth's energy balance. The scales of its processes are micrometers for droplet and ice-crystal formation, meters for turbulent flows and convective updrafts, and thousands of kilometers for weather systems. Global climate models cannot resolve horizontal scales finer than about 50 km. Phenomena with smaller scales are represented by coarse-grained models, or "parameterizations," which are systems of algebraic or differential equations that contain empirical closure parameters or functions to relate unresolvable processes to what is resolved. Biological processes, similarly, require coarse-grained models to connect what is known about the microscale biophysics of cells and plants to the emergent macroscale effects of heat stress or water limitation on tundra, tropical rain forests, and other biomes.

The traditional approaches to such multiscale problems are unlikely to yield breakthroughs when employed in isolation. Researchers have made deductive inferences from fundamental laws with some success. But deducing, say, a coarse-grained description of clouds from the underlying fundamental physical laws has remained elusive. Similarly, brute-force computing will not resolve all relevant spatial scales anytime soon. Resolving just the meter-scale turbulence in low clouds globally would require about a factor of 10^{11} increase in computer performance.[2] Such a performance boost is implausible in the coming decades and would still not suffice to handle droplet and ice-crystal formation.

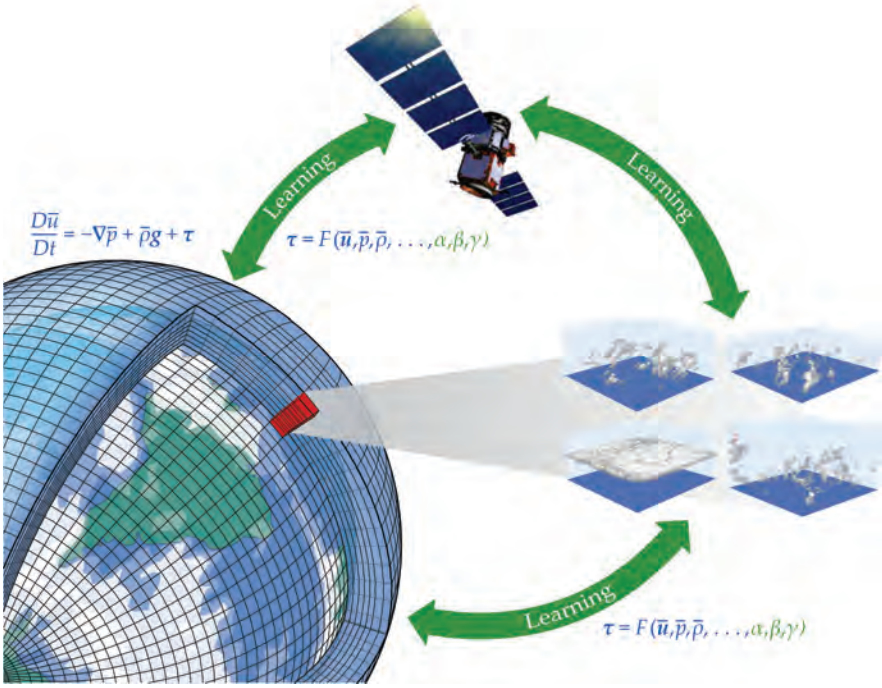

FIGURE 1. A LOOP connecting theory, data, and computing provides a framework to accelerate climate science. Theory yields the structures of coarse-grained models; in this case, it is the fluid-flow equations with an unknown closure function *F*. Learning from observations and local high-resolution simulations constrains unknown closure parameters and functions. Observations and local simulations target model weaknesses, and the cycle repeats. (Adapted from ref. 9; cloud simulations courtesy of Clare Singer.)

Machine learning (ML) has undeniable potential for harnessing the exponentially growing volume of Earth observations that is available. But purely data-driven approaches cannot fully constrain the vast number of coupled degrees of freedom in climate models. Moreover, the future changed climate we want to predict has no observed analogue, which creates challenges for ML methods because they do not easily generalize beyond training data.

Dramatic progress may lie ahead by judiciously combining theory, data, and computing. Since the scientific revolution of the 17th century, the path to scientific success has been to develop theories and models, probe them through experiment and observation, revise them by learning from the data, and iterate. We believe that progress in climate science lies in a program that builds on that loop and accelerates and automates it with ML tools and high-performance computing, as illustrated in figure 1.

Advance theory

Parametric sparsity is a hallmark of scientific theories and is essential for generalizability and interpretability of models. For example, Newton's law of universal gravitation has only one parameter, the gravitational constant. It replaced Ptolemy's epicycles and equants, the deep-learning approach of its time. Ptolemy's overparameterized model gave a good fit to the then-known planetary motions but did not generalize beyond them. The law of universal gravitation, by contrast, generalizes from planets orbiting stars to apples falling from trees. Because of its parametric sparsity, Newton's theory produces trusted out-of-sample predictions, uncertainty estimates, and causal explanations.

Climate science needs to predict a climate that hasn't been observed, on which no model can be trained, and that will only emerge slowly. Generalizability beyond the observed sample is essential for climate predictions, and interpretability is necessary to have trust in models. Additionally, uncertainties need to be quantified for proactive and cost-effective climate adaptation. Fortunately, the fundamental laws governing the microscale physical aspects of the climate system, including the quantum mechanics of radiation and molecules, the laws of thermodynamics, and Newton's laws governing fluid dynamics, are well understood.

The task for physical theory is to coarse-grain the known microscale laws into macroscale models: By averaging over microscales, coarse-graining obtains models for the macroscale matched to the resolution of climate models. Processes that need to be coarse-grained for droplet-scale microphysics are illustrated in figure 2; those for the land biosphere are shown in figure 3.

Researchers are pursuing new approaches, guided by systematic averaging and homogenization strategies, to model turbulence, convection, clouds, and sea ice, for example.[3] Empirical closure parameters and functions, which may be stochastic to reflect variability and uncertainty,[4] represent how smaller-scale phenomena affect the macroscale. Theory provides the structure of the coarse-grained models and closure functions and ensures, for example, the preservation of symmetries and conservation laws. But theory taken too far results in misspecified models that lead predictions and understand-

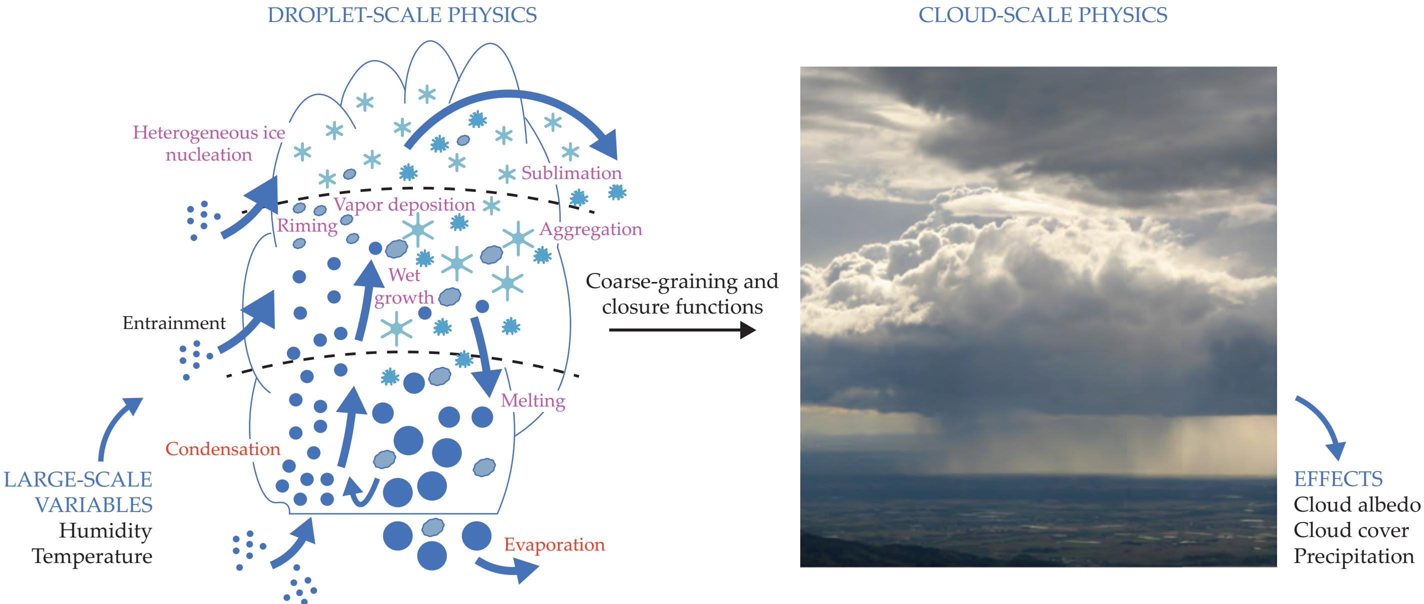

FIGURE 2. CLOUD MICROPHYSICS PARAMETERIZATIONS take in resolved values of temperature and humidity and then model the many unresolved interactions between suspended and precipitating cloud water and ice. The process produces as outputs precipitation and size distributions of cloud condensate, which determine cloud optical properties. (Left-hand image adapted from H. Morrison et al., *J. Adv. Model. Earth Syst.* **12**, e2019MS001689, 2020; right-hand photo by jopelka/Shutterstock.com.)

ing astray. Where theory can go no further, closure parameters and functions must be inferred from data. The box on page 49 illustrates one example.

Harness data

Where theory reaches its limits, data-driven approaches can harness the detailed Earth observations now available. Often the data do not provide direct information about small-scale processes, such as in-cloud turbulence, that need to be represented in models. But the data do provide indirect information. For example, the observable distribution of liquid water and ice contains indirect information about in-cloud turbulence. Additional small-scale information can be generated computationally in high-resolution simulations for processes with known microscale governing laws, such as sea-ice fracture mechanics and convection and turbulence in the atmosphere and oceans.

Earth observations such as the energy fluxes at the top of the atmosphere are commonly used to calibrate models. What remains largely untapped, however, is the potential to discover and calibrate coarse-grained models by systematically harnessing all Earth observations jointly with data generated in high-resolution simulations.

Data-assimilation tools, used in weather forecasting for decades, and newer ML methods can be exploited for the task. For example, Bayesian approaches can be used to learn about closure parameters or functions, uncertainties, and errors in model structure.[5] ML emulators can greatly accelerate Bayesian learning, making it amenable to use with computationally expensive climate models.[6]

Where model structures are unknown *a priori*, researchers may exploit data-hungry deep-learning approaches with proven scalability to high dimensions, or they may use sparsity-promoting discovery of coarse-grained models from dictionaries of differential-equation terms.[7] Whichever approach is pursued, preserving symmetries and conservation laws is essential, either bottom-up through the model structure or top-down through constraints on loss functions. Generalizability, interpretability, and uncertainty quantification remain crucial as well.[8] The field is ripe for experimentation and progress.

Leverage computing power

High-performance computing hardware is transitioning from architectures with central processing units to ones with graphics processing units (GPUs), tensor processing units, and other accelerators. To leverage the emerging architectures, climate models are being rewritten to an extent not seen in decades, to allow them to continue their march toward kilometer-scale resolution. As a result, the simulations of various phenomena, including monsoons and hurricanes, will improve. Simulations of rainfall will get more detailed, but they won't necessarily become more accurate until Earth's energy balance is captured correctly. That milestone will require more accurate simulations of low clouds and ocean turbulence. Those processes are out of reach in global models even at kilometer resolution.

Local simulations, however, can resolve smaller-scale processes whose governing equations are known. By capturing aspects of the present climate and climates for which there are no observed analogues, local high-resolution simulations can help prevent overfitting to the observed data. For example, clouds and the turbulence that sustains them can be simulated with meter-scale resolution in domains comparable to climate-model grid columns that are tens of kilometers wide. That approach suffices to resolve the most energetic turbulence, but smaller-scale phenomena, such as cloud microphysics, must still be represented by more uncertain coarse-grained models.

Isolated high-resolution simulations in a few locations have been used previously to calibrate cloud models, for example.

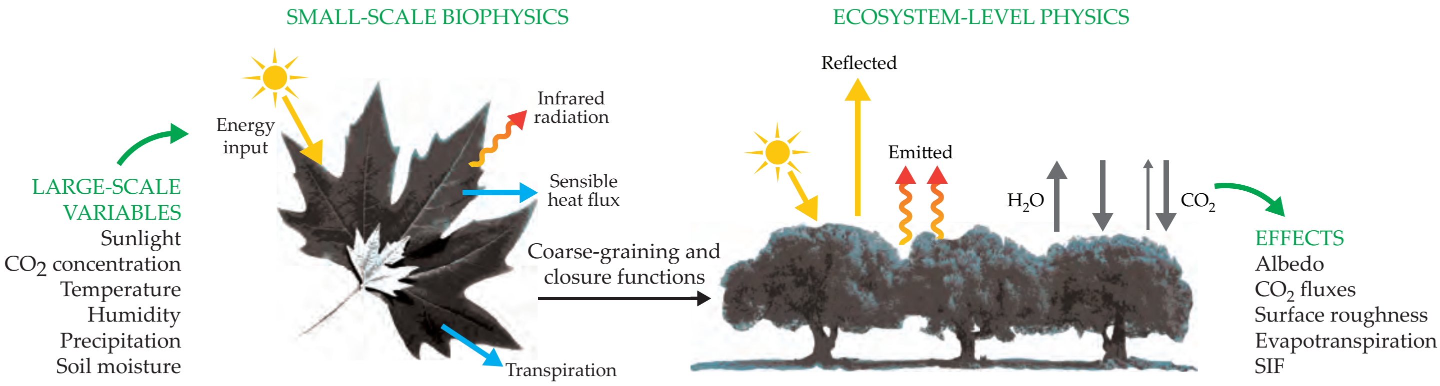

FIGURE 3. LAND BIOSPHERE PARAMETERIZATIONS take in resolved variables such as temperature and sunlight and then coarse-grain processes such as plant hydraulics, transpiration, and photosynthesis. As outputs, they produce evapotranspiration, energy fluxes, and albedo, in addition to observables, such as solar-induced fluorescence (SIF), that are critical for closing the loop between models and observations. (Left-hand image adapted from Mostafameraji, CC BY-SA 4.0; right-hand image adapted from George Tekmenidis, CC BY-SA 3.0.)

Now massive cloud-computing resources (the other kind of cloud) make it possible to run thousands of high-resolution simulations concurrently. Automatically targeting the simulations to regions and seasons where they maximize information gain about a coarse-grained model is one way to close and accelerate the theory-data-computing loop.[9] The approach is similar to the ML paradigms of active and reinforcement learning, which have seen spectacular successes recently.

The theory-data-computing loop capitalizes on the successful methods of natural science. Theory directs data exploitation to areas where the science is most uncertain and provides model structures that are parametrically sparse, interpretable, and generalizable. ML tools and extensive computing accelerate the loop, potentially by orders of magnitude. This balanced approach to ML-accelerated science avoids the dual pitfalls of overreliance on reductionist theories for complex systems and overparameterization in purely data-driven, deep-learning approaches. The theory-data-computing loop requires a substantial initial investment in human and computational resources but results in climate models that, once calibrated with data, are computationally efficient and interpretable tools for prediction and scientific investigation.

To illustrate how ML-accelerated climate science may break new ground, consider three representative problems: How do atmospheric and oceanic turbulence, polar climates, and net carbon uptake by the land biosphere respond to climate change? Each of them responds strongly to the most familiar climate variation of all: the seasonal cycle. Seasonal variations in climate statistics—for example, temperature, sea-ice extent, and net carbon uptake—far exceed the climate changes expected over the coming decades. Some evidence suggests that seasonal variations are indicative of how the climate system may respond to the much slower greenhouse warming, apparently because similar mechanisms govern the response to seasonal insolation changes and longer-term changes in the concentration of greenhouse gases. Climate predictions may thus be improved by calibrating process-based models with the seasonal cycle.

Turbulence, convection, and clouds

The principal sticking points in predicting climate are the subgrid-scale turbulent and convective motions in the oceans and atmosphere. In the oceans, the turbulent motions are the conduit through which momentum, heat, and tracers such as CO_2 are transferred between the surface and the deeper ocean; they regulate the rate at which oceans take up heat and carbon. In the atmosphere, they transfer momentum, heat, and water vapor to and from Earth's surface. They are critical for the formation of clouds, nourishing them with water vapor through convective updrafts. Figure 4 illustrates some of the turbulent processes.

Clouds are the most visible outward manifestation of the turbulent and convective motions. They cool and warm Earth by reflecting sunlight and by reemitting some of the thermal IR radiation they absorb back to the surface, respectively. The net effect is that clouds cool Earth by 5 °C.

Simulated cloud cover often diverges widely from what is observed because the turbulent and convective motions that produce it are not well represented in models. For example, most models simulate fewer low clouds over subtropical oceans than are observed, and the seasonal cycle of cloud cover is likewise poorly captured, as figure 5a shows. The inability of climate models to adequately simulate clouds has long been recognized as the dominant source of uncertainty in climate projections. (See the article by Jeffrey Kiehl, PHYSICS TODAY, November 1994, page 36.)

The problem of simulating and understanding turbulence, convection, and clouds is well matched to the theory-data-computing approach. Recent theories have systematically coarse-grained the equations of fluid motion, be it by developing either separate equations for smaller-scale isotropic turbulence and convective updrafts or equations for statistical moments. In either case, the closure functions that represent processes such as turbulent exchange of fluid between cloudy updrafts and their environment are excellent targets for learning from data.

A similar approach that coarse-grains microphysical laws appears promising for the nonequilibrium thermodynamics that produces supercooled liquid cloud droplets, rather than ice crystals, at temperatures below freezing in rapidly rising updrafts. Nonequilibrium thermodynamics is responsible for the strong global warming response seen in some recent climate models.[10] Observations are particularly useful for providing information about coarse-grained models of cloud microphysics because the processes involved are not yet amenable to direct simulation.

Polar climates

All of the challenges that confound climate models play out simultaneously in polar regions. Turbulence in the often stably stratified polar boundary layer is intermittent and notoriously hard to model, and so are the clouds it sustains. The polar oceans are covered by sea ice, the extent of which depends on convection and clouds in the atmosphere above, turbulence and heat transport in the oceans below, and the nonlinear rheology of the ice itself.

In climate models, the amplitude of the seasonal cycle in Arctic temperatures can deviate several degrees from observations. As figure 5b shows, the discrepancies are especially large in winter, when stable boundary layers are prevalent. Figure 5c indicates that Arctic sea-ice extent likewise often strays far from observations, with biases in the tens of percent.

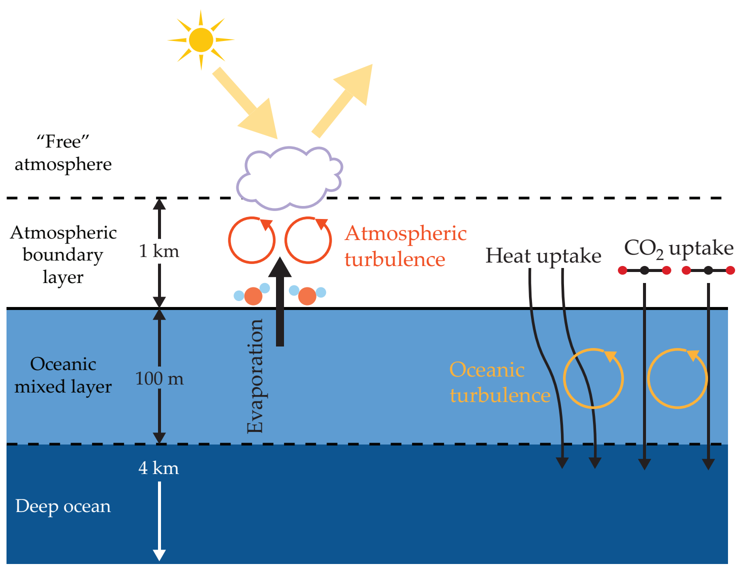

FIGURE 4. TURBULENCE in the atmosphere and ocean connects the surface and the fluid interiors. Turbulent motions govern the sequestration of heat and carbon in the deep ocean and the transport of energy and water vapor into the atmosphere. (Illustration by Nadir Jeevanjee and Freddie Pagani.)

Importantly, in simulations of recent decades, the amplitude of the seasonal cycle for Arctic temperature and sea-ice extent correlates with a model's climate sensitivity—that is, the average warming after a sustained doubling of the CO_2 concentration. More-sensitive models tend to have a lower seasonal-cycle amplitude and less sea ice. They are also more similar to observations than less-sensitive models, which bodes ill for the future of Arctic sea ice. Calibrating models with seasonal data is likely to make their predictions of polar climate changes more accurate.

Finely detailed space-based observations of polar cloud cover, distributions of sea ice, melt ponds on ice surfaces, and fractures in sea ice are now available. Autonomous robotic floats are beginning to give an unprecedented view of ocean properties and turbulence near the edge of and under sea ice, where warming waters are most effective at melting ice. The small-scale but important fluid dynamics of ocean waters under floating ice and along continental shelves is becoming amenable to local, targeted high-resolution simulations. Exploiting high-resolution simulations together with observational data much more systematically than has been done so far may bring the needed qualitative improvements in polar-climate modeling and prediction.

Land biosphere

Earth's land biosphere removes about 30% of the human CO_2 emissions from the atmosphere[11] (see the article by Heather

COARSE-GRAINING FLUID EQUATIONS

Theodore von Kármán deduced the "Law of the Wall" by averaging the Navier–Stokes equation for turbulent flows traveling past a wall. (See the article by Alexander Smits and Ivan Marusic, PHYSICS TODAY, September 2013, page 25.) Von Kármán decomposed velocity components parallel to the wall u and perpendicular to the wall w into mean values ($\bar{u}, \bar{w}$) and turbulent fluctuations (u', w'), so that $(u, w) = (\bar{u} + u', \bar{w} + w')$. Turbulent fluctuations lead to the appearance of a turbulent shear stress $\tau = -\bar{\rho}\,\overline{u'w'}$ with density $\bar{\rho}$ in the equation for the mean velocity $\bar{u}$, which therefore is not closed.

The equation for $\bar{u}$ can be closed by assuming that τ depends only on local flow conditions. Where turbulence is strong enough that viscosity can be neglected and if density is uniform, the only local quantities on which the turbulent shear stress can depend are the density, derivatives of the mean velocity $\bar{u}(z)$, and the distance from the wall z. Dimensional reasoning yields $\tau = \kappa^2 z^2 \bar{\rho}\,|\delta\bar{u}/\delta z|\,\delta\bar{u}/\delta z$. The only parameter in that closure function is κ, now known as von Kármán's constant and measured to be 0.4. Given the turbulent shear stress, the equation for the mean velocity profile is closed and yields the law of the wall: $\bar{u}(z) = u_*/\kappa \ln(z/z_0)$. Here u_* and z_0 are boundary terms known as the friction velocity and roughness length. The effects of small-scale turbulence on the along-wall velocity profile have been reduced to the parameters κ and z_0, which can be determined from data, and the variable u_*, which can be inferred from the velocity $\bar{u}(z)$ at some height z. Earlier measurements had suggested $\bar{u}(z) = u_0(z/z_0)^{1/7}$. This empirical "one-seventh" law is analogous to many empirical closures found in climate models that are not strongly rooted in theory and do not generalize well.

The theoretical reasoning underlying the Law of the Wall generalizes to the real atmosphere. Accounting for vertical density variations leads to Monin–Obukhov similarity theory, which is used to model near-surface turbulence in climate models. The theory contains an additional dimensionless height parameter and unknown functions of that parameter, which can be learned from data. In yet more complicated situations with nonlocal dependencies, such as atmospheric moist convection, theory may lead to systems of coarse-grained differential equations and closure functions that depend on functions of several nondimensional parameters. Such closure functions are natural targets for machine-learning approaches.

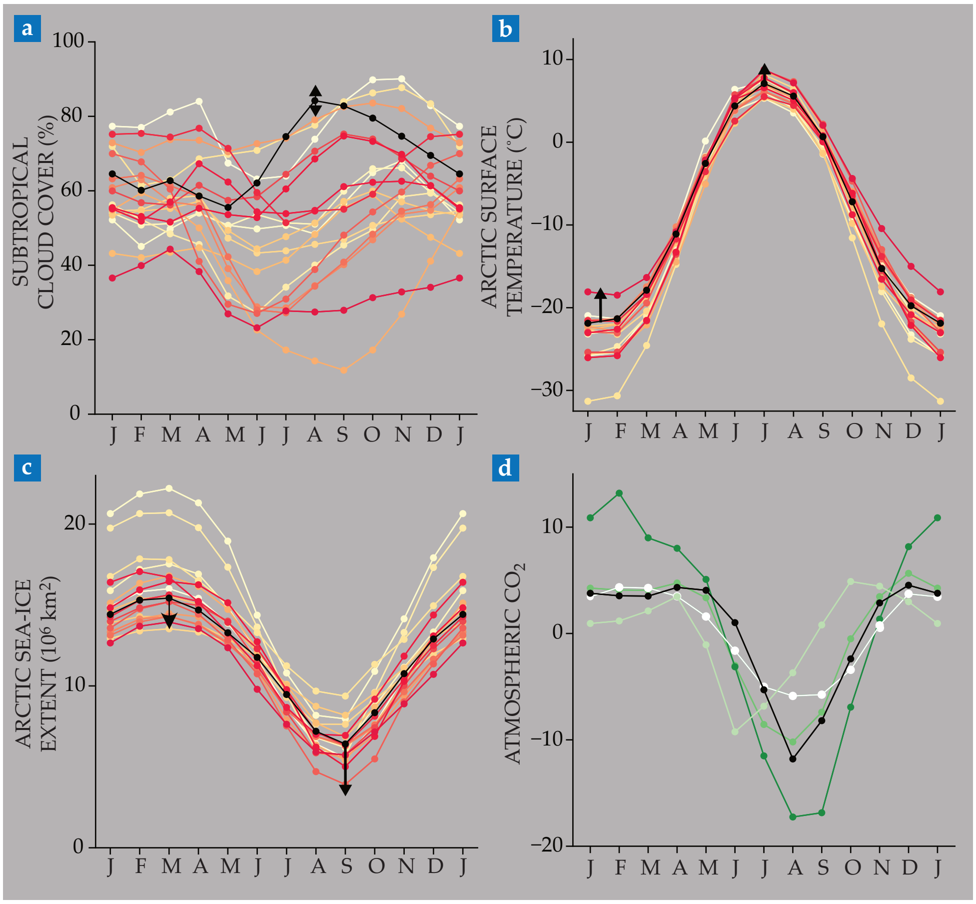

FIGURE 5. SEASONAL CYCLES (monthly data from January through January) in models (colors) and observations (black). **(a)** This plot shows cloud cover over the ocean off the coast of Namibia (10–20 °S, 0–10 °E). The models are colored from yellow to red in order of increasing climate sensitivity. **(b)** Similar to panel a, but this plot presents near-surface air temperature over the Arctic (60–90 °N). **(c)** Similar to panel b, but this plot shows Arctic sea-ice extent. The arrows in panels a–c indicate the magnitude and direction of the expected global warming response by 2050 under a high carbon dioxide emissions scenario; in panel a, the sign of the expected change is unclear. Models and observations in panels b and c are averaged over the years 1979–2019 (except for the cloud observations, which are averaged over 1984–2007). **(d)** Atmospheric CO_2 concentration is shown as deviation from the annual mean for 1994–2005 at Point Barrow, Alaska.[15] Models are colored from lighter to darker green in order of increasing global carbon uptake by the land biosphere in a CO_2 doubling simulation.[16] (Data processing and plotting courtesy of David Bonan and Alexander Winkler.)

Graven, PHYSICS TODAY, November 2016, page 48). But how the land carbon sink changes as CO_2 concentrations rise remains unanswered. Models differ widely in their simulation of past, present, and future carbon uptake. Consider, for example, the seasonal cycle of CO_2 in high northern latitudes, which mirrors the seasonal cycle of boreal vegetation. Photosynthesis predominates during the growing season and draws carbon from the atmosphere. Respiration predominantes during wintertime and releases carbon back to the atmosphere. Figure 5d shows that the amplitudes and phases of the high-latitude seasonal CO_2 cycle differ among models and often do not fit observations well.

The discrepancies among seasonal cycles in the models percolate into the responses of the land carbon sink to rising CO_2 emissions. Elevated CO_2 concentrations fertilize plants by enhancing photosynthetic carbon uptake, unless water and nutrient availability limit the uptake. At the same time, increased temperatures enhance respiration and also affect photosynthetic uptake, which leaves uncertain the magnitude of the net effect of rising CO_2 on the land carbon sink.

When the atmospheric CO_2 concentration doubles, some models produce a global land uptake of 7% of the emissions (light green model in figure 5d), whereas others suggest a 30% uptake (dark green model in figure 5d). The global carbon uptake by the land biosphere under rising CO_2 scenarios appears to correlate with the amplitude of the high-latitude seasonal cycle in the models, so seasonal data may constrain model responses to increased CO_2 concentrations.

The land biosphere's net uptake of CO_2 is the small residual of the much larger gross carbon fluxes associated with photosynthesis and respiration. Modeling progress has been hindered by poor knowledge of the gross fluxes. But new satellite data are upending the status quo. Soil moisture and vegetation cover are now being measured in unprecedented, hyperspectral detail. It has also become possible to estimate photosynthesis from space by measuring chlorophyll's solar-induced fluorescence (SIF), which detects the excess near-IR solar energy that chloroplasts cast off during photosynthesis.[12] (See the opening image.) Combining satellite measurements of SIF and CO_2 is now enabling scientists to disentangle the gross fluxes associated with photosynthesis and respiration.

Models of the biosphere are more difficult to design than models for physical aspects of the climate system. There is no straightforward way to coarse-grain the land or ocean biosphere. As a result, how to describe the biosphere is less clear: Should it be described at the level of genomes, plant functional types, biomes, or somewhere in between?

Nonetheless, the biosphere also obeys conservation laws, from energy to carbon mass, and small-scale processes—for example, photosynthesis, stomatal conductance, and plant hydraulics—are understood from first principles. The task for theory is to incorporate what is known on small scales into coarse-grained models that can effectively learn from data. Given the less-certain structure of biosphere models, ML techniques for data-driven model discovery, within the constraints of conservation laws, may improve biosphere models. Advances in computing and the use of GPU accelerators enable increased resolution and additional variables. A substantial improvement in land models can be anticipated, with the seasonal cycle as an obvious first target for model discovery and calibration.

Time for a broader effort

Our understanding of and ability to model clouds, polar climates, and the land carbon sink should improve substantially in the next decade. Ancillary benefits may be expected for activities such as seasonal to subseasonal prediction of extreme weather risks. Improved models and predictions of melting land ice, connected with sea-level rise, and of the deep-ocean circulation and its associated heat and carbon uptake may also be achievable. Reducing uncertainties in climate sensitivity by at least a factor of two may be in reach—a feat whose socioeconomic value is estimated to be trillions of dollars.[13]

Paleoclimates that are the closest analogue of what awaits us are a natural next test for models of the climate system. The last time CO_2 concentrations exceeded today's level of 415 ppm was 3 million years ago, when Earth's continental configuration looked as it does today but temperatures were 2–3 °C higher.[14] Cooling since then triggered the ice-age cycles, which are driven by variations in Earth's orbit (see the article by Mark Maslin, PHYSICS TODAY, May 2020, page 48). But it remains a mystery how the subtle orbital variations, amplified and modulated by feedbacks involving clouds, ocean turbulence, and the carbon cycle, work their way through the nonlinear climate system to produce the glacial–interglacial climate swings Earth has experienced.

Progress in one of the defining scientific challenges of our time requires well-funded collaborative teams with expertise ranging from the natural sciences—physics, biology, and chemistry—to engineering, applied mathematics, statistics, computer science, and software engineering. The rate of progress will be determined by the rate at which new talent joins the field. Come on in!

Many members of the Climate Modeling Alliance (CliMA.caltech.edu), which is pursuing the approach outlined here, provided valuable feedback on drafts, as did Venkatramani Balaji and Mitchell Bushuk at the Geophysical Fluid Dynamics Laboratory and too many others to name here. David Bonan, Christian Frankenberg, Clare Singer, and Alexander Winkler made invaluable contributions of figures and data.

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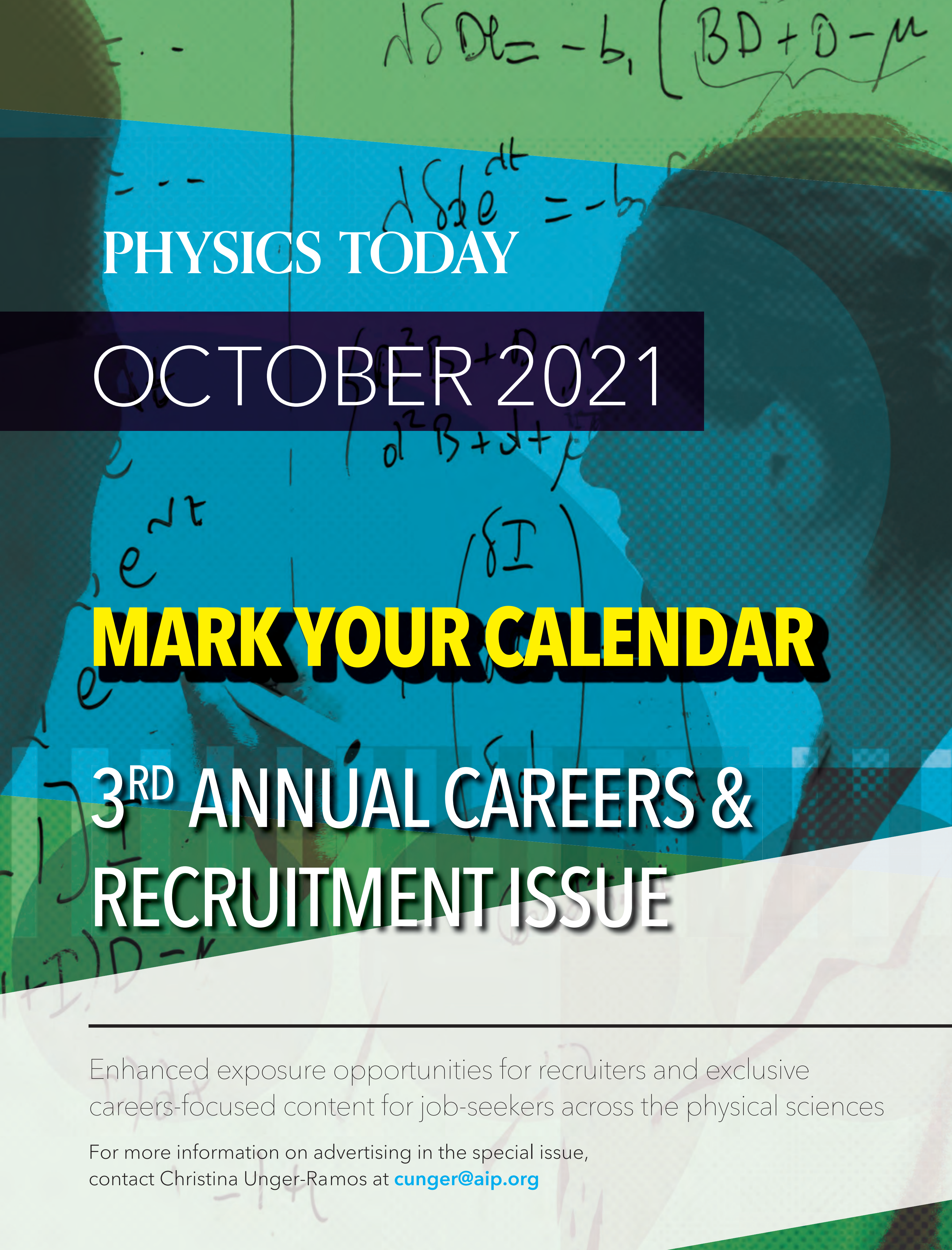
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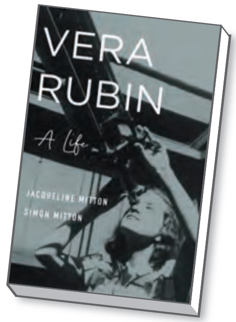
ASTRONOMER VERA RUBIN pictured during the 1980s with her collection of antique globes.

The queen of dark matter

When I was an undergraduate at Princeton University during the early 1970s, the astrophysics department was abuzz with talk about dark matter. Two faculty members, Jeremiah Ostriker and James Peebles (see PHYSICS TODAY, December 2019, page 14), had recently completed a series of computerized *N*-body simulations of rotating disk galaxies, and the results were as-

Vera Rubin
A Life

Jacqueline Mitton and Simon Mitton
Belknap Press, 2021. $29.95



tonishing. The models, whose mass distribution reflected canonical estimates of luminous material seen in photographs, proved to be grossly unstable, which conflicted with the Milky Way's acknowledged long-term stability. To steady the rotating disks, Ostriker and Peebles superimposed on each a weighty spherical "halo" of matter—a plumped-up version of the seemingly sparsely populated haloes around observed galaxies.

It was at that time that I first heard of Vera Rubin, a researcher at the Carnegie Institution for Science in Washington, DC, whose observations of galactic rotation substantiated the models' unexpected findings. Taken together, they provided sound evidence for the presence of a great abundance of dark matter in the universe. Even as a callow undergraduate, I sensed scientific history in the making.

Rubin's long and illustrious career—and how her name became synonymous with dark matter—is chronicled in *Vera Rubin: A Life*. The authors, Jacqueline Mitton and Simon Mitton, have each published prolifically on astronomy and its history, and their latest book is a scientific narrative told from the human perspective.

The book alternates between biography and semitechnical exposition. Thus we encounter tutorials on celestial spectroscopy and Kepler's laws along with descriptions of life stressors faced by dual-career couples; notably, Vera and her husband, mathematical physicist Robert Rubin, faced the "two-body problem" of securing employment in the same locale. The opening chapters span the 1950s and 1960s, and given the time period, it's no surprise that Robert's career initially took precedence, at times to the detriment of Vera's. In one job inquiry, she felt compelled to explain that science was "too large an interest for me to ever stop work, even though my family will always be uppermost in my life."

When Rubin began her career in the 1950s, dark matter had long been the Bigfoot of astronomy: rarely glimpsed, and then only inferentially. Its observable ramifications were articulated in 1844 by astronomer Friedrich Bessel, who 10 years earlier had detected a periodic undulation in the proper motion of the bright star Sirius and which he had since concluded was gravitationally tugged by an unseen companion. (In 1862 telescope maker Alvan Graham Clark observed the elusive object—not what we now take to be dark matter but, rather, a dim white dwarf star—while field-testing a new objective lens.) As Bessel wrote to naturalist Alexander von Humboldt, "The visibility of countless stars is no argument against the invisibility of countless others." Nevertheless, observational astronomers of the late 19th and early 20th centuries paid little heed to the presence of matter they could neither see nor photograph through their telescopes.

In 1932 astronomer Jan Oort reported an unexpectedly large velocity dispersion perpendicular to the galactic plane among stars in the solar neighborhood. To explain that phenomenon, he proposed extrapolating the local stellar mass function to stars below the threshold of visibility. Concurrently, astronomer Fritz Zwicky found a hugely discordant velocity dispersion in members of the Coma galaxy cluster; assuming the system to be gravitationally bound, he asserted that dark matter must be present in a much greater amount than luminous matter.

Other studies followed, with like conclusions, but it was not until the 1970s that dark matter emerged from the shadows. The observational impetus for that belated recognition was the galactic rotation curve—namely, the tendency of a galaxy's rotation speed to remain relatively constant with distance from the galactic center. The curve's "flatness" was the ostensible manifestation of copious amounts of dark matter, as predicted by galaxy models of that period. Rubin, in collaboration with Kent Ford, became the key figure in extending rotation curves based on optical-wavelength studies to large galactic radii, where their prevalent flatness dovetailed neatly with results from radio-wavelength observations.

Rubin's life story is one of perseverance in the face of occupational and societal obstacles. As the Mittons' meticulous account of Rubin's career arc demonstrates, no single breakthrough vaulted her to prominence; rather, it was a string of self-directed efforts to wring research results out of cataloged data and to acquire suitable observational data where they did not yet exist. She networked tirelessly on her own behalf and secured access to large telescopes traditionally closed to women astronomers.

The authors vividly depict Rubin's formative early-career huddles with astrophysical luminaries, such as Margaret Burbidge, Geoffrey Burbidge, George Gamow, Walter Baade, and Allan Sandage. They also describe how she later mentored a younger generation of astronomers. Astronomy enthusiasts will enjoy the book's behind-the-scenes peeks into the profession—several of them cringeworthy.

PRINCETON UNIVERSITY PRESS

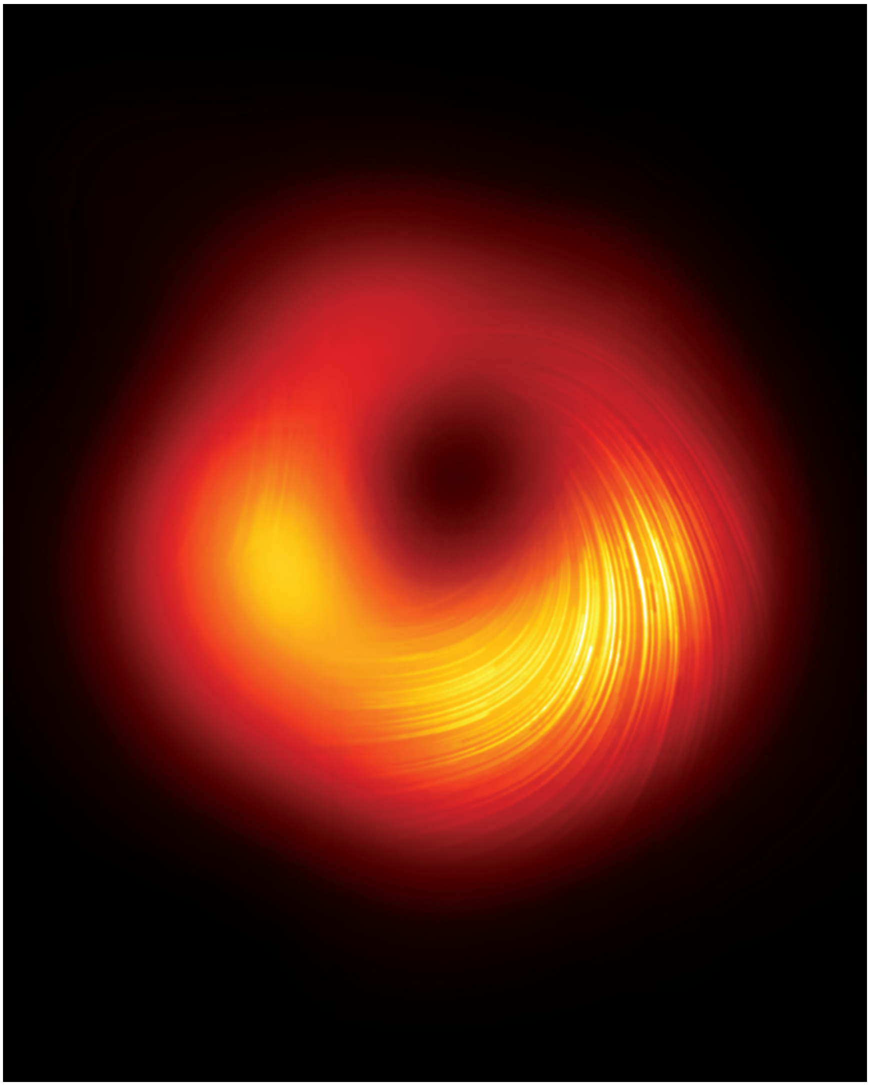
"Extraordinarily impressive."
—Malcolm Longair, *Nature*

"A magnificent achievement."
—Edward Witten, *Physics Today*

Kip Thorne and Roger Blandford's monumental *Modern Classical Physics* is now available in five stand-alone volumes that make ideal textbooks for individual graduate or advanced undergraduate courses on statistical physics; optics; elasticity and fluid dynamics; plasma physics; and relativity and cosmology. Each volume teaches the fundamental concepts, emphasizes modern, real-world applications, and gives students a physical and intuitive understanding of the subject.

Rubin's story illustrates the resistance of the scientific community to altering an established paradigm—that light is the essential gauge of mass in the universe. Chapter by chapter, one senses the gathering force of theoretical and observational evidence for the existence of dark matter, until its impact on an array of astrophysical problems could no longer be dismissed. How does scientific transformation occur? To quote Ernest Hemingway: "Gradually and then suddenly."

Alan Hirshfeld
University of Massachusetts Dartmouth



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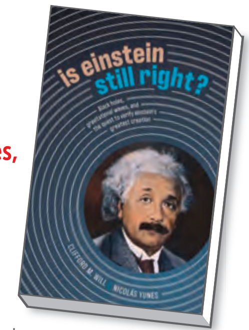
AN IMAGE of galaxy Messier 87's supermassive black hole in polarized light, which was released by the Event Horizon Telescope collaboration in March 2021.

Testing the theory of general relativity



Is Einstein Still Right?
Black Holes, Gravitational Waves, and the Quest to Verify Einstein's Greatest Creation

Clifford M. Will and Nicolás Yunes

Oxford U. Press, 2020. $21.95

Twice in the past four years, the Nobel Prize in Physics has been awarded for research into phenomena predicted by Einstein's theory of general relativity: in 2017 for the first direct detection of gravitational waves and in 2020 for theoretical and experimental work on black holes. The awards epitomize how general relativity has been empirically confirmed to an unprecedented extent in the past few years. We are a far cry from what historian of science Jean Eisenstaedt aptly called the "low water mark of general relativity": a period from the mid 1920s to the mid 1950s when the theory was considered little more than a mathematical curiosity.

Is Einstein Still Right? Black Holes, Gravitational Waves, and the Quest to Verify Einstein's Greatest Creation outlines the recent history of precision tests of general relativity and describes the current state of those experiments. Each chapter is devoted to either a physical effect or astronomical object that has been used to test the theory, including gravitational redshift, gravitational effects on light, geodetic precession and frame dragging in gyroscopes, pulsars, black holes, and gravitational waves. The final chapter describes gravitational-wave observatories that are currently being planned—both on Earth and in space—and are expected to be crucial to the future development of multimessenger astronomy.

Theoretical physicists Clifford Will and Nicolás Yunes are the ideal authors for a book about verifying Einstein's theory of general relativity. Will has long been the world's leading expert in experimental confirmations of the theory and has dedicated his 50-year career to the topic. Yunes, part of a younger generation, is internationally renowned in the experimental testing of general relativity with gravitational waves.

The present volume is a sequel to Will's

1986 book *Was Einstein Right? Putting General Relativity to the Test*. In that tome, Will coined the term "renaissance of general relativity" to describe how attempts to verify the theory beginning in the late 1950s gradually brought it into science's mainstream. The precision of such experiments has increased in the intervening years, as has their popular appeal: The first image of the supermassive black hole at the center of galaxy Messier 87 made the front page of many world newspapers when it was released on 10 April 2019. *Is Einstein Still Right?* is thus intended to chronicle developments in the field that have occurred since Will's first book was published.

The two authors have not only the broad spectrum of knowledge and personal experience necessary to master the subject, but also the writing skills needed to provide a fresh and witty narrative that is comprehensible to a wide audience. Without employing a single mathematical formula, Will and Yunes succeed in building a simple and highly intuitive picture of the abstruse theory's physical effects, all of which challenge common sense views of space and time. Particularly useful are the figures, which offer easy-to-grasp visual representations of experiments and effects. Many are bidimensional analogies of four-dimensional spacetime phenomena. Although the authors continuously remind readers that those analogies are imperfect, anyone unfamiliar with the theory will find them extremely helpful.

Since I am a historian of science, I cannot refrain from commenting on the book's use of history, which is important to the narrative. The historical passages are generally well written and fair, although they—perhaps inevitably—lack sophistication and, at times, accuracy. For example, the authors perpetuate the myth that Einstein gave four lectures to the Prussian Academy of Sciences on progressive developments of his theory during the crucial weeks of November 1915. In reality, those four lectures were actually four articles Einstein published in the academy's house journal that month. He did present one of the four papers in a formal lecture to academy members, but the other three appeared solely in print.

Will and Yunes consulted the historical literature and provide a useful list of their sources. However, they occasionally focus too heavily on anecdotes—for example, how a discussion between three naked scientists in a California pool eventually led to the *Gravity Probe B* experiment—rather than stressing the epistemic and socio-institutional elements of the theory's resurgence, which I believe are far more interesting. The authors acknowledge the help of several scientists who commented on parts of the book. Given the role history plays in it, one wonders whether consulting a few professional historians of science might have helped them avoid some inaccuracies.

Besides those minor reservations on the historical aspects of the book, I strongly recommend it to all those interested in general relativity. Although nonspecialist readers may find it challenging, they will surely be rewarded by its compelling descriptions and fascinating narrative.

Roberto Lalli
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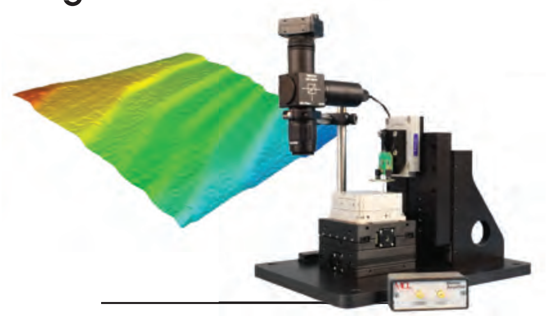
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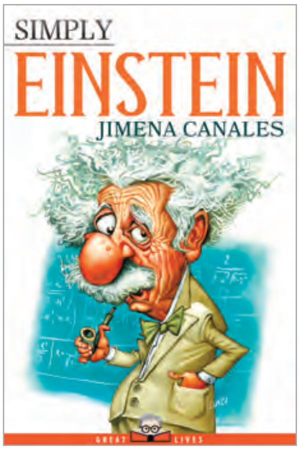


Simply Einstein

Jimena Canales

Simply Charly, 2021. $9.99 (paper)

Given the ever-growing pile of books devoted to Albert Einstein, readers might reasonably wonder whether yet another volume about the most famous physicist of the 20th century is necessary. Yet Jimena Canales has made *Simply Einstein* worth the read by drawing on recent scholarship and providing a concise and incisive introduction to his science, politics, and personal life. Part of Simply Charly's Great Lives series, the book provides a rigorous overview of special and general relativity for the lay reader. Canales effectively places the theories in historical context by describing how Einstein's work built on contributions from Henri Poincaré, Hendrik Lorentz, and David Hilbert. Outside the scientific realm, her portrayal of Einstein's poor treatment of his first wife, Mileva Marić, does not pull any punches. In the end, Canales rightly concludes that his life of celebrity serves as a lens through which 20th-century history's "changing mores and values" can be discerned. The book contains a helpful list of suggested reading for those who want to learn more about Einstein.

–RD

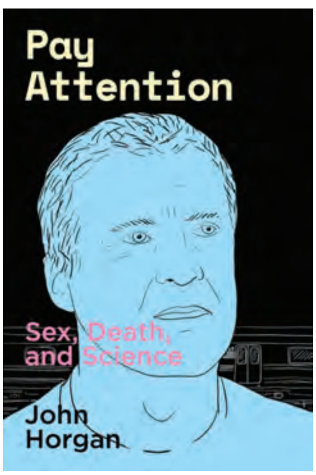
Periodic Table of Videos

Brady Haran, host

YouTube, 2008–

To provide a more visual representation of the periodic table, filmmaker and video journalist Brady Haran and researchers at the UK's University of Nottingham have created a series of videos about all 118 elements. The videos are a mix of description, experiments, and demonstrations, and are designed to provoke viewers' interest and curiosity. New videos are continually being posted on various chemistry topics, such as the chemical composition of acid rain and how to make plutonium. Presenter Martyn Poliakoff received the Royal Society's Michael Faraday Prize and Lecture in 2019 in recognition of his work on the videos.

–CC



Pay Attention

Sex, Death, and Science

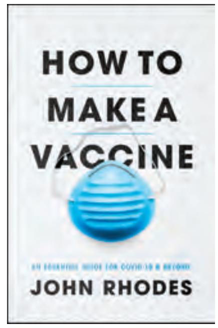
John Horgan

Terra Nova Press, 2020. $25.95 (paper)

This intensely personal book by well-known science journalist John Horgan describes a day in his life—or rather, the life of his thinly veiled alter ego, Eamon Toole: He commutes to work to teach an introductory humanities course at an engineering school; has lunch with colleagues; and meets his girlfriend, Emily, for dinner. It is written in a stream-of-consciousness style that feels almost voyeuristic at times, especially when Toole/Horgan ruminates about his personal struggles and the dissolution of his marriage. A particular highlight is Toole's lunchtime debate with his colleagues François, an engineer who is a philosophical realist; Jim, a postmodern historian of science; and Dave, a mathematician with a philosophical position somewhere between those two opposites. Although *Pay Attention* assumes a certain degree of familiarity with historians of science like Thomas Kuhn and philosophers like Bruno Latour, even readers without that prior knowledge will be intrigued by the unique work.

–RD

How to Make a Vaccine



An Essential Guide for COVID-19 and Beyond

John Rhodes

U. Chicago Press, 2021. $15.00 (paper)

In the midst of the COVID-19 pandemic comes *How to Make a Vaccine*, in which immunologist John Rhodes sheds light on the world of vaccine research. Covering some 300 years of immunization history, Rhodes uses stories of past pandemics to launch a discussion of viruses and how they operate, the history of immunology and some of the principal researchers involved, the different types of vaccines, the lengthy clinical trials required before a vaccine can be administered to the public, and the difficulties associated with rolling out mass vaccines during a global emergency. The author's fascination with vaccines is apparent, and the result is a highly readable introduction to the subject of disease and immunization for the general reader.

–CC

Science History Podcast

Frank A. von Hippel, host

2017–

The interface between science, history, and societal issues is the focus of this podcast hosted by ecotoxicologist Frank A. von Hippel of the University of Arizona. An ongoing topic of discussion is chemical contaminants, von Hippel's own area of expertise; for example, a recent episode with epidemiologist Shanna Swan discusses how environmental toxins are affecting humans' ability to reproduce. Other episodes cover obesity, gravitational waves, whistleblowers, and the ways in which corporations sow doubt in scientific findings. A new episode is released every month.

–RD PT

Focus on software, test, measurement, and instrumentation

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

Andreas Mandelis

Extra-long-scan noncontact thickness gauges

Bristol Instruments has added two models to its line of noncontact optical thickness gauges. The 157XLS (extra-long-scan) and 137XLS systems extend the maximum measurement limit to 80 mm. The new capability was added primarily to accommodate thicker, multielement optical components and assemblies and large-diameter medical devices. According to the company, the gauges deliver industry-leading accuracy: as high as ±0.1 μm for the 157XLS, with long-term repeatability of up to ±0.02 μm, and as high as ±1.0 μm for the 137XLS, with long-term repeatability of ±0.05 μm. The instruments use the properties of light to measure the thickness of a material without damaging or deforming it. Total thickness and up to 31 individual layers can be measured simultaneously. ***Bristol Instruments Inc**, 770 Canning Pkwy, Victor, NY 14564, www.bristol-inst.com*

Cryogenic software with remote control

Innovative Cryogenic Engineering (ICE) Oxford developed version 3 of its LabVIEW-based software to provide a user-friendly computer interface to remotely control temperature and pressure via sensors, heaters, and needle valves. The new capability also facilitates remote diagnostics and improved support from the company's factory in Oxfordshire, UK. The software permits the simultaneous plotting, logging, and control of a maximum of eight temperature sensors at any given time. By monitoring performance graphs while the system runs, it observes system progress and reduces errors. The modular software allows for additional features such as magnetic field control, a ^{3}He dipper, and the company's ICE Mini Cube gas-handling system. ***ICE Oxford**, Ave Four, Station Lane, Witney, Oxford OX28 4BN, UK, www.iceoxford.com*

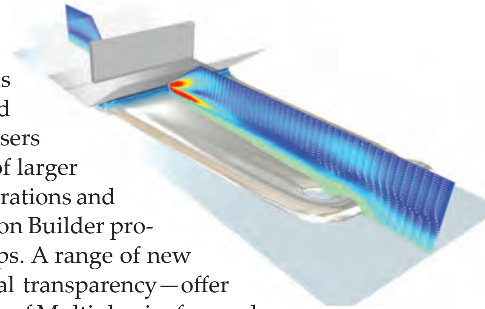
Dynamic vertical positioning system

Physik Instrumente now offers its V-308 voice coil PIFOC, a magnetic direct-drive-based vertical positioning system with a 7 mm travel range, magnetic-weight-force compensation, and exceptional dynamics, according to the company. At its core is a single-axis slider with high-precision lateral-crossed roller guides placed on the base body. It is driven by a centered PIMag voice coil motor specifically developed for high dynamics. The system features optical focusing, scanning, and height adjustment of sensors. Acceleration up to 8 m/s2 and a maximum velocity of 200 mm/s yield step-and-settle times of below 15 ms for 100 nm and 250 nm step sizes with a ±15 nm error band for fast data acquisition and high productivity. The magnetic-weight-force compensation ensures a levitation of the slider and mounted load without power supply and prevents an uncontrolled crash in case of a power failure or when the controller is switched off. Applications for the V-308 PIFOC include multiphoton fluorescence microscopy, magnetic tweezers, laser materials processing, and wafer inspection. ***Physik Instrumente LP**, 16 Albert St, Auburn, MA 01501, www.pi-usa.us*

Event-based power-analysis software

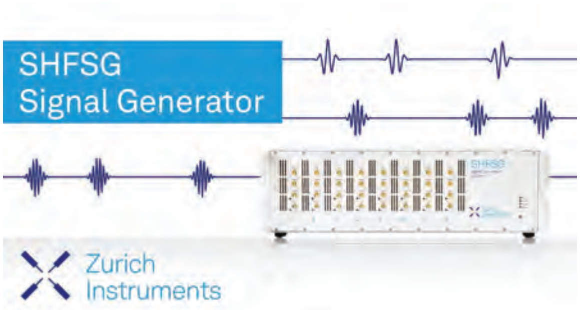
Keysight Technologies has enhanced its X8712A system for device battery-life optimization by adding KS833A2A event-based power-analysis software. The X8712A can help optimize the battery life of internet-of-things (IoT) devices by delivering an accurate view of how the devices behave to the subsystem level and of their charge-consumption profile. The software offers an easy-to-use visualization tool via the company's PathWave software and a new continuous data-logging mode with measurement and data collection. To better understand device behavior and charge-consumption profiles over many operating cycles, users can employ patented seamless current-ranging technology from A down to nA. That technology can capture the dynamic current consumption of an IoT device over up to eight days as it transitions between active, idle, and sleep modes. The software automatically calculates battery life based on the charge-consumption profile; eliminating manual calculation speeds analysis time. ***Keysight Technologies Inc**, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Modeling and simulation software



Comsol has updated its Multiphysics software for creating physics-based models and simulation applications. Among the additions in version 5.6 are faster and more memory-lean solvers for multicore and cluster computations designed for users working with large models that have millions of degrees of freedom. Handling of larger computer-aided design assemblies has been improved with more robust solid operations and easier detection of gaps and overlaps. New application templates in the Application Builder provide a quick, intuitive way to create organized user interfaces for simulation apps. A range of new graphics features—including clip planes, realistic material rendering, and partial transparency—offer enhanced visualization for simulations. Four new products expand the capabilities of Multiphysics for modeling fuel cells and electrolyzers, polymer flow, control systems, and high-accuracy fluid models. ***Comsol Inc***, *100 District Ave, Burlington, MA 01803, www.comsol.com*

Signal generators for quantum computing



According to Zurich Instruments, its SHFSG Signal Generator is the first instrument of its kind on the market. Designed to control superconducting and spin qubits and reach higher gate fidelities with less overhead time, the SHFSG operates directly at qubit frequencies without mixer calibration. It delivers state-of-the-art spectral purity and stability. The SHFSG generates freely programmable pulse sequences on up to eight outputs with a signal bandwidth of 1 GHz and a variable output frequency of up to 8.5 GHz. Such microwave signals, required to control the state of qubits in quantum computers, previously had to be generated using a combination of arbitrary waveform generators, microwave signal generators, and mixer circuits. The SHFSG brings those instruments together in a single box and eliminates the need for time-consuming and error-prone calibration routines. The versatile instrument can cover the various approaches pursued in diverse quantum technology endeavors. ***Zurich Instruments AG***, *Technoparkstrasse 1, 8005 Zürich, Switzerland, www.zhinst.com*

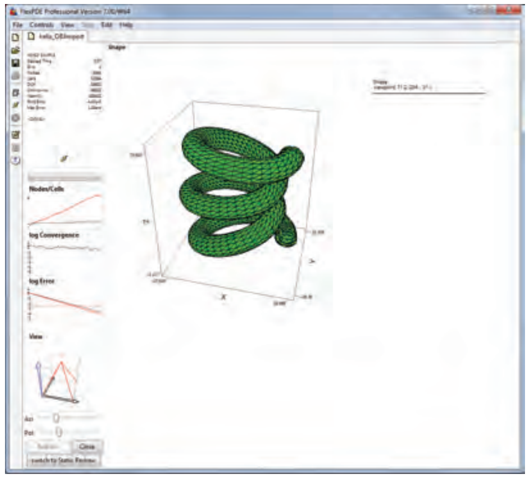
Mathematical programming software

MathWorks has introduced version 2021a of its MATLAB and Simulink software. In addition to updates to various products, new capabilities in MATLAB include dynamic controls in live scripts and a task for adding plots to live scripts without writing any code. Simulink updates enable users to import C code as reusable Simulink libraries and to speed up simulations. The new Satellite Communications Toolbox in MATLAB can help equipment makers and operators model, simulate, analyze, and verify satellite communications systems and links. The Radar Toolbox includes algorithms and tools for the design, simulation, analysis, and testing of multifunction radar systems. The Simulink add-on, Data Distribution Service (DDS) Blockset, offers a full model-based design experience for system and algorithm engineers developing software for DDS-based embedded systems. According to the company, it can help users find errors sooner while performing faster design and coding iterations. ***The MathWorks Inc***, *1 Apple Hill Dr, Natick, MA 01760-2098, www.mathworks.com*

Basic power supply with linear accuracy

The R&S NGA100 series of basic power supplies from Rohde & Schwarz offer a performance level and extra functions not usually associated with that instrument class, according to the company. Four models provide a choice of single and dual outputs, with a maximum voltage per channel of 35 V at 6 A or 100 V at 2 A per output. Single-output models supply up to 40 W power, dual-output models up to 80 W. The dual-model outputs can be combined to provide up to 200 V or 12 A. A linear design throughout the output circuits improves performance compared with the switched-mode circuits often found in basic power supplies. The standard level of readback resolution, 1 mV or 100 μA, is enhanced for currents under 200 mA to a resolution of 1 μA. The R&S NGA100 has the necessary dynamic range for power and current spikes when switched to active mode. ***Rohde & Schwarz GmbH & Co KG***, *Muehldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*

Software for partial differential equations



PDE Solutions has released version 7.18 of its FlexPDE finite element solution, an unlimited, scripted, multiphysics environment for partial differential equations. New features have been added and errors repaired. Version 7.18 increases the argument limit for function definitions from 3 to 10 and improves solver behavior for very small meshes and error estimation in quadratic models. The preconditioner selection algorithm and parser error location diagnostics are also improved. The Status legend window is no longer a floating frame. Occasional errors in the Find dialog box and in the XBOUNDARY, YBOUNDARY, and ZBOUNDARY functions have been corrected. Other miscellaneous problems, such as an error on Linux that causes sockets to remain open after the computer has connected to the internet, have also been addressed. ***PDE Solutions Inc**, 9408 E Holman Rd, Spokane Valley, WA 99206, www.pdesolutions.com*

Flexible miniature temperature sensor

With a footprint of less than 1.0 mm × 0.6 mm and a low height of 50 µm, the miniaturized temperature sensor from Heraeus Nexensos can be placed in extremely small spaces very close to heat sources. That minimizes thermal diffusion lengths and significantly speeds up temperature detection. The sensor can, for example, monitor temperature peaks between thermal interface material layers such as those in power electronics, microprocessors, and batteries. Its bendable structure enables close contact with curved and flexible surfaces, such as smart textiles or smart-linked medical applications and helps improve heat-transfer rates. A high measuring accuracy of ±0.1 °C and the small thermal mass enable fast, precise sensing of temperature changes. ***Heraeus Nexensos**, Reinhard-Heraeus-Ring 23, 63801 Kleinostheim, Germany, www.heraeus.com*

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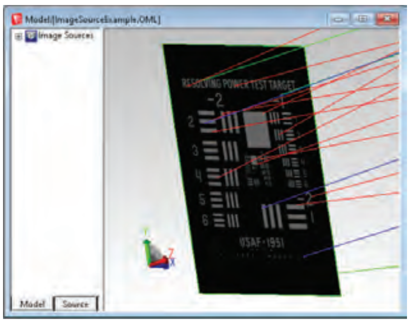
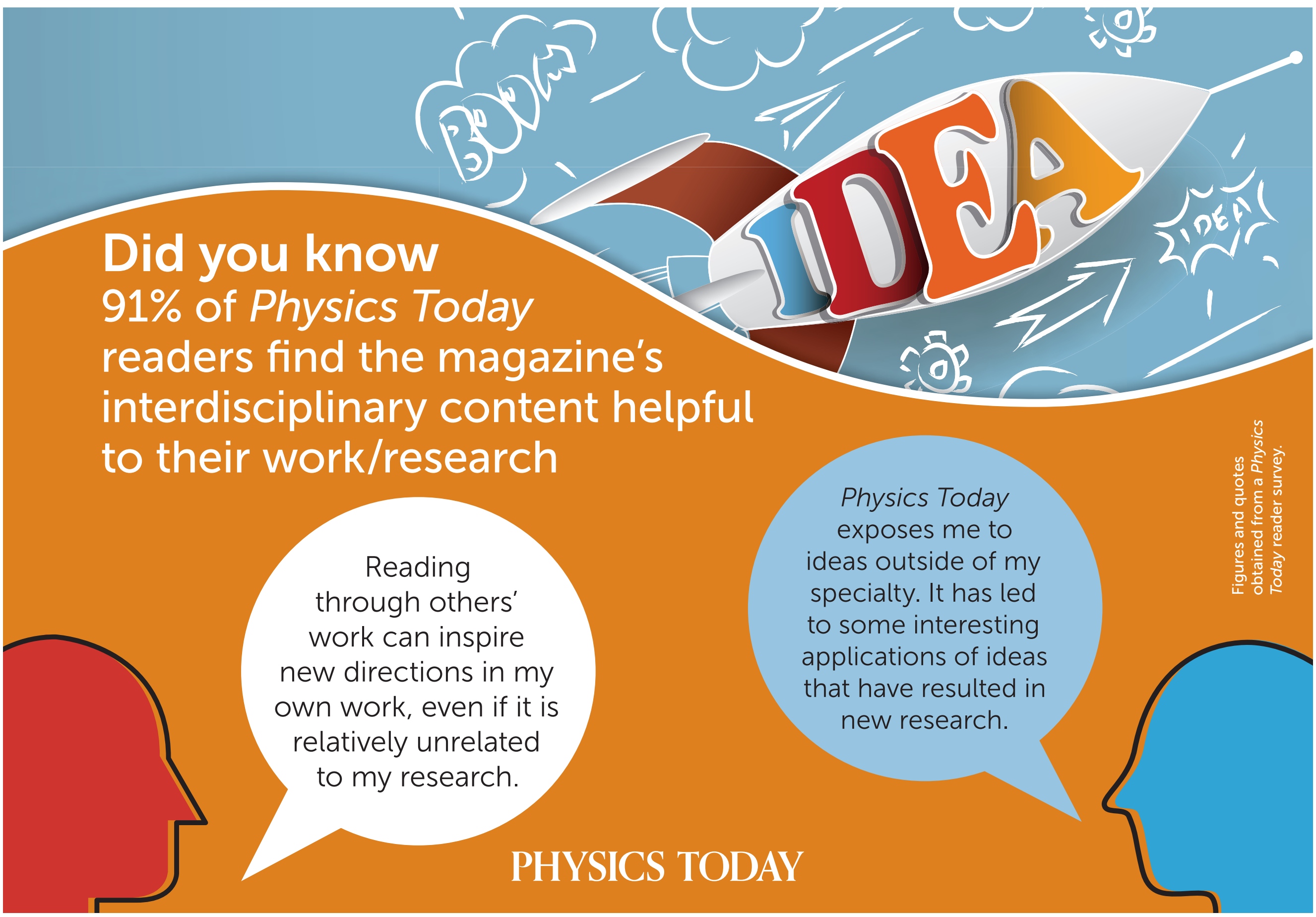
Data-sharing software

Tektronix says its TekDrive is the first native oscilloscope-to-cloud software solution to allow global data collaboration directly on an oscilloscope, PC, phone, or tablet. It eliminates the need for cumbersome data-sharing practices by allowing data to automatically become accessible, usable, and shareable across teams and partners, but it also incorporates robust security practices. And TekDrive is the first general-purpose test-and-measurement file system with scope-like data visualizations, according to the company. It provides smooth visualization and analysis capabilities that support any modern browser, including options to view, zoom, pan, measure, decode, and analyze full test-and-measurement data on any device with no need for additional software. ***Tektronix Inc****, 14150 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com*



Optical design software

Lambda Research has unveiled TracePro 2021 version 21.2, the latest iteration of its software for the design and analysis of illumination and optical systems. The main improvement in TracePro 21.2 is the new Image Source, which enables TracePro users to employ image files as light sources. Image files can be inserted into a model, and rays are emitted from the image with flux and wavelength determined by the color and intensity of each pixel. The Image Source, which works with all ray tracing and analysis features, is especially useful for accurate image source modeling. The Interactive Optimizer has been further developed with user interface improvements and conveniences, and the Lighting Toolkit has been enhanced with the addition of Federal Motor Vehicle Safety Standards number 108 regulations to its built-in Regulation Table. ***Lambda Research Corporation****, 25 Porter Rd, Littleton, MA 01460, www.lambdares.com* PT



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Paul Josef Crutzen

Paul Josef Crutzen, for decades the creative, global leader in atmospheric chemistry, died in Mainz, Germany, on 28 January 2021, after a protracted struggle with Parkinson's disease. Having made astonishing discoveries from Earth's surface to the mesosphere and from the tropics to the poles, Paul profoundly influenced global and national environmental policy, but he never lost his childlike wonder at the natural world, and he delighted in guiding young scientists and students.

Born on 3 December 1933 in Amsterdam to a Dutch father and a German mother, Paul was in grade school during the *Hongerwinter* of World War II; he recalled a nagging belly and neighbors reduced to eating tulip bulbs. After the war, he studied engineering and spent a short time working in bridge construction. In 1954, while on vacation in Switzerland, he met Terttu Soininen, a student of Finnish history and literature at the University of Helsinki who would become his lifelong partner, foil, and inspiration.

In 1958 Paul took a job as a computer programmer at Stockholm University, where his fascination with the atmosphere blossomed. He joined the department of meteorology and earned a PhD in 1968, with Bert Bolin as his adviser, and a DSc in 1973, with John Houghton and Richard Wayne as advisers. His research for both degrees shocked the scientific world.

DNA-based life is possible on Earth's surface only because the atmospheric ozone layer shields us from harmful UV radiation. The approximate amount and location of that ozone has been known since at least 1912, when Charles Fabry and Henri Buisson first measured it, but the chemistry and physics leading to its steady state remained a mystery until Paul's 1970 paper showed that oxides of nitrogen, NO_x, were responsible for most of the destruction and that man-made pollutants were a threat to life's delicate balance. Paul shared the 1995 Nobel Prize in Chemistry with F. Sherwood Rowland and Mario Molina, who had discovered the role of chlorine compounds in ozone destruction. The Nobel citation reads, "The three researchers have contributed to our salvation from a global environmental problem that could have catastrophic consequences."

After his stint at Stockholm, Paul took a postdoc at the University of Oxford and then moved to Colorado to work at the National Center for Atmospheric Research (NCAR), where he was director of the atmospheric chemistry division when I met him in 1977. He always found time to help us graduate students put our work in perspective and offer insightful guidance. He taught us that even enormously complicated systems usually have key, controlling processes—and it was our job to find them.

Paul loved sports. We played on the NCAR softball team, named the NOxSOx. One evening after a game, Paul was being driven back to work—he was too much a theorist to be behind the wheel—when he suddenly shouted, "That's it! That's it!" An agricultural fire had been set to clear away winter wheat stubble. Paul realized that was the solution to the missing source of carbon monoxide in his global model. Biomass burning of tropical forest was indeed the major source of CO and other pollutants, as predicted by his numerical simulation, and is now recognized as a serious threat to global ecosystems and climate.

Ozone has been called the godfather of atmospheric chemistry. In the 1960s ozone in the troposphere, outside large cities, was viewed as a basically inert gas descending from the stratosphere and blowing around until destroyed by contact with Earth's surfaces. Paul and his colleagues proved that photochemistry was not only the dominant sink but also the dominant source for ozone in the troposphere—and subject to adverse changes as man-made pollutants reached global proportions.

In 1980 Paul moved to the Max Planck Institute for Chemistry in Mainz, Germany, where he served as director of the air chemistry division until his retirement in 2000. He issued an early warning about the global climate consequences of nuclear war that inspired work on "nuclear winter" and popularized the term Anthropocene to describe the current geological era dominated by humans. He recommended studying geoengineering to avert a climate disaster, but only as a last, desperate measure if humans are unable to shake off their addiction to fossil fuels. He held adjunct professorships at the University of Chicago and the Scripps Institution of Oceanography. With support from an NSF Science and Technology Center, Paul co-led INDOEX (the Indian Ocean Experiment), which showcased the interaction of clouds, chemistry, and climate and brought international attention to the Asian brown cloud.

© UCAR/PHOTO BY GINGER WADLEIGH

Paul Josef Crutzen

Approachable, communicative, and modest, Paul once remarked, "You Americans are easily impressed. Someone speaks five languages, and you think he's a genius." He was comfortable speaking in English, French, German, and Swedish, in addition to his native Dutch. But Finnish got the better of him; he lost a bet with Terttu that he could become fluent in it, and he had to give up his beloved spicy foods. Despite his myriad accomplishments, Paul never took himself too seriously. He showed kindness, humility, and a sense of humor that goes with knowing that even if you have added many pieces, the puzzle will never be complete.

Russell R. Dickerson
University of Maryland
College Park

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Rudolf Zahradník

Rudolf Zahradník, whose defining work was in quantum chemistry, died on 31 October 2020 in Prague, Czech Republic.

Born on 20 October 1928, Rudolf made his first chemical experiments in his early teens; he was driven by a sense of adventure fostered by his membership in the Boy Scouts. After World War II, he graduated from a vocational high school and attended Prague's Institute of Chemical Technology. For his 1956 PhD, which he received from the Institute of Occupational Medicine, Rudolf discovered new organizing principles for the toxicity of aliphatic compounds and the stability of sulfur heterocycles. In his other early groundbreaking work, he found correlations between the electronic spectra of conjugated systems and the energy gaps between their highest occupied and lowest unoccupied molecular orbitals.

In 1961 Rudolf joined the Institute of Physical Chemistry of the Czechoslovak Academy of Sciences—now the J. Heyrovský Institute of Physical Chemistry of the Czech Academy of Sciences. But he was denied a professorship because the Czechoslovak Communist authorities regarded him as politically suspect.

The authorities' fears that Rudolf would corrupt the youth were more than justified: His noblesse, critical thinking, insight, and decency were truly contagious, and his sense of responsibility was a constant challenge to those who ruled the country after the Soviet-led invasion in 1968.

Rudolf did what was right and proper regardless: Principled, conscientious, and upright, he did his best to produce quality work with all-out dedication—and exhorted others to do the same. With Jaroslav Koutecký and his associates in the 1960s, Rudolf launched the Prague School of Quantum Chemistry. Despite the emigration in 1968 of some of its protagonists, among them Koutecký, Jiří Čížek, and Josef Paldus, the school continued to flourish through the dark 1970s and 1980s. Rudolf was a generous mentor and reliable friend to countless students and colleagues. During bad times, he could find encouraging words even in seemingly hopeless situations.

STANISLAVA KYSELOVÁ/CZECH ACADEMY OF SCIENCES

Rudolf Zahradník

Despite the political oppression, the authorities failed to forestall recognition of Rudolf's work by his colleagues at home and abroad. He would host in Prague and at his country house numerous living legends of quantum chemistry—among them Charles Coulson, Roald Hoffmann, and John Pople—whom the Czechoslovak community would not have otherwise been able to meet. Over time, Rudolf himself would become a living legend.

By the time the Velvet Revolution forced out the Communist government in 1989, Rudolf was ready for high office. He was elected director of the Heyrovský Institute in 1990 and spent the next three years transforming it into a modern institution. About 60 students and collaborators shared Rudolf's overarching interest in reactivity and spectroscopy. In his memoir, *Laboratorní deník: zač jsme bojovali* (*Laboratory Notebook: What We Fought For*), Rudolf referred to five of his students—Josef Michl, Petr Čársky, Pavel Hobza, Zdeněk Havlas, and Pavel Jungwirth—as his "doctoral sons." Angela Merkel was a postdoc of Rudolf's a year before the fall of the Berlin Wall.

In 1993 Rudolf became the founding president of the Czech Academy of Sciences and the following year the founding chairman of the Learned Society of the Czech Republic. But governmental positions, including the Czech presidency, did not materialize, to the detriment of the country. Václav Havel envisioned Rudolf as his successor, but to no avail.

Rudolf often compared the cultural policies and attitudes toward academia of the two totalitarian regimes he lived through: "national and real socialism" (self-descriptions of Nazism and Soviet-type Communism). Neither proved capable of extinguishing Rudolf's enthusiasm for science nor of precluding him from doing what's right. He was highly productive and respected, and during his career he authored about 370 papers and 20 books.

The list of problems Rudolf tackled is long and varied. Among them, he examined the electronic structure of nonalternant hydrocarbons and their tetracycles and found a formula for the relative stability of several classes of such compounds. His studies of the structure and properties of open-shell systems had implications for molecular spectroscopy and electron spin resonance spectroscopy, such as the equivalence of ESR signals for the radical cation and radical anion of an alternant hydrocarbon. He mapped out the stability and structure of clusters bound by weak interactions and the implications for solvation and biological catalysis. Another line of Rudolf's research involved the rates of benchmark ion–molecule reactions on an *ab initio* reaction profile.

Among Rudolf's gifts was the ability to listen to others. With his colleague Zdeněk Herman, he wrote a semisatirical piece about academia that was introduced with the motto "Everybody writes, nobody reads; everybody talks, nobody listens."

Rudolf's outlook developed through his symbiotic marriage to Milena, whom he met in a shelter during the Prague uprising in May 1945 and who died a week before Rudolf. Their shared approach to life also comes through in *Laboratory Notebook*: Rudolf plays with the metaphor that our natures are "a linear combination of good, less good, and not so good qualities" and that the point is to maximize, on the "coordinate of life," the coefficients standing in front of the good qualities. He adds that our self-improvement "has a chance of success only if we live for others."

Bretislav Friedrich
Fritz Haber Institute of the Max Planck Society
Berlin, Germany PT

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PHYSICS TODAY | JOBS

Varghese Mathai (vmathai@umass.edu) is an assistant professor of physics at the University of Massachusetts Amherst.

The air we breathe in a car

Varghese Mathai

Your typical commute hides complex fluid-dynamical pathways of disease transmission. Where you sit and the windows you open could heighten or suppress the risk of airborne infection.

In the single breath you take while reading this sentence, you have inhaled air that once passed through the lungs of everyone who has ever lived before us. That fact is a reminder of the astonishing ability of fluids such as air to spread and disperse the particles they carry. During the COVID-19 pandemic, we're all aware of the possibility of disease transmission through the air. Even so, the number of airborne, or aerosolized, particles that we exchange during social interactions is relatively small if we are in a well-mixed outdoor setting.

In a confined, poorly ventilated space, it's a different story. Respiratory diseases are transmitted primarily indoors, via the turbulent, multiphase clouds of air and droplets spewed when a person coughs, sneezes, or talks loudly (see the Quick Study by Stephane Poulain and Lydia Bourouiba, PHYSICS TODAY, May 2019, page 70). Even normal breathing can release up to a thousand airborne particles per liter of air exhaled. And those microdroplets can remain suspended for several minutes before evaporating or settling on a surface. The invisible, buoyant, thermal plumes ever present around us can also carry them far and wide.

That's especially concerning for those of us who commute to work in a passenger vehicle with someone outside our household, such as in a taxi or as part of a carpool. The setting can be considered the epitome of a close, social interaction. With a typical car interior's volume being four cubic meters—a tenth the size of a bedroom—social distancing is impossible.

Cabin microclimate

Most megacities host more than a million ride shares every day, with a median ride duration of about 15 minutes. Not surprisingly, taxis and ride-share companies worldwide have had to implement various mitigation measures, ranging from mask mandates and barrier shields to hand sanitizing. Such measures, however, are only partially effective against airborne particles. Even when a person wears a mask, aerosols can seep through the smallest of gaps between the fabric and their face; they can also travel well beyond the six-foot distance we're told to maintain from others. Within minutes, the tiny microdroplets can pervade the cabin space and expose passengers to a dose of virions.

The critical number and the critical exposure time remain unclear and are likely variables that are dependent on several biological, behavioral, and environmental factors. Can we possibly know the risk of airborne infection when sharing a car ride with a stranger? In the simplest approximation, cabin air quality—expressed in terms of the number of air changes per hour (ACH)—provides one metric. A more relevant measure would also include the number of passengers. The Centers for Disease Control and Prevention recommend a ventilation rate of at least 10 L/s per person.

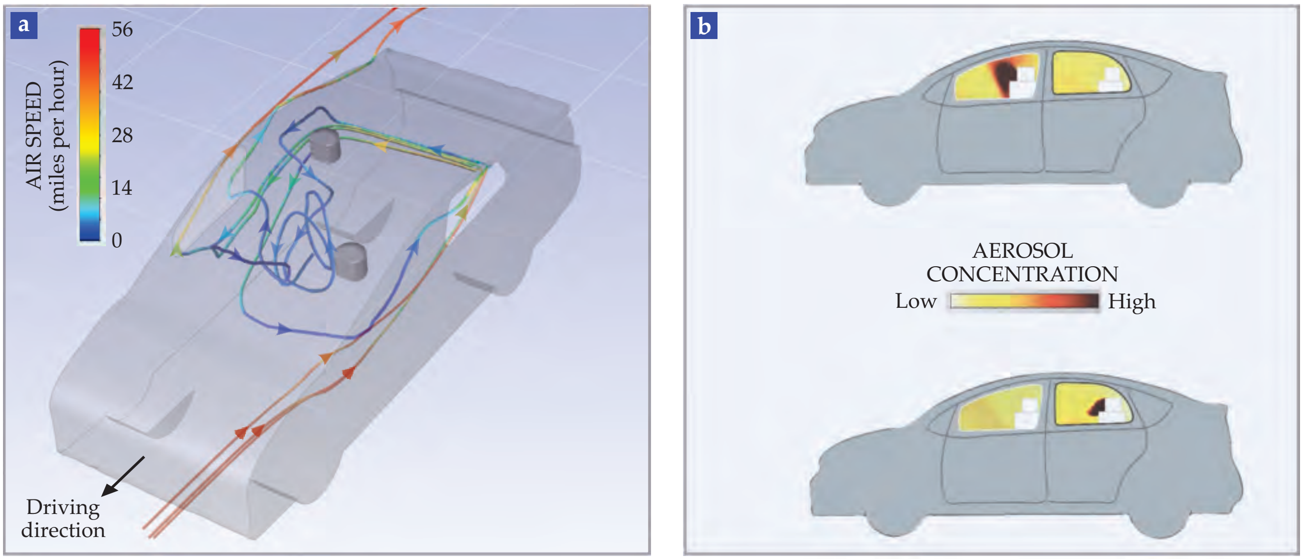
But what's also important for risk assessment are the specific air-flow patterns that become established when the air conditioning is turned on or windows are rolled down. To that end, I worked with colleagues Asimanshu Das, Jeff Bailey, and Kenny Breuer this past year to make sense of the fluid-dynamical pathways that exist inside a passenger car.

We were not the first. Other researchers have looked at those flow patterns—most commonly, to determine how to reduce cabin noise or to see how cigarette smoke dilutes. For our study, the first insights came from Breuer. He realized that when air flows around a car, it sets up pressure on the side windows that is lower in the front than in the rear. Fluid mechanicians have been aware of the effect since the 18th century, when Daniel Bernoulli deduced that pressure generally decreases when flow speed increases. If that's the case, we wondered, would the pressure gradient between rear and front windows also cause a rear-to-front air current inside the cabin if the windows are opened?

Field tests that combined smoke visualizations and a flow-wand technique in a moving vehicle bore out that hypothesis. To answer the more detailed questions about the interior airflow and the transport of potentially infectious aerosols, we turned to computer simulations. In particular, we solved a simplified (time-averaged) version of the Navier–Stokes equations, the same ones that govern the movement of almost all fluids around us.

Airflow patterns

We loosely based the car's exterior geometry on a Toyota Prius driven with a passenger in the rear-right seat. In this two-occupant configuration, we simulated several open and closed window combinations at a driving speed of 50 miles an hour. As expected, the best scenario was to open all four windows, which allows fresh air to enter the rear windows, circulate inside the cabin, and exit through the front windows. The upshot: an effective air exchange rate of 250 ACH, or 50 L/s per person. Were the car's speed cut in half, the exchange rate would also



COMPUTER SIMULATIONS of airflow patterns and aerosol concentrations inside a passenger car driven at 50 miles per hour with front-right and rear-left windows open. **(a)** An air stream (colored lines) enters the cabin through the rear-left window. It then flows across the back seat, turns sharply around the rear-right corner behind the passenger, and exits through the front-right window. A small fraction of the incoming air also circulates inside the cabin before leaving. **(b)** Cross sections of the car show a concentration of aerosols in the cabin that correspond to the driving configuration in panel a. At top is the concentration released by the driver, only a small fraction of which reaches the passenger. The fraction of aerosols released by the passenger (bottom) and reaching the driver is also small. (Image by Varghese Mathai.)

be roughly halved. In either case, the values are well above the ventilation rates recommended in the literature. Clearly, though, the discomfort of cold, hot, or wet air blowing on passengers during poor weather prevents such a drastic approach.

Fortunately, we found a few alternate configurations that provide a more practical compromise. For instance, opening only two windows—one in the rear, the other in the front—produces a cross-ventilation path from the rear to the front of the cabin. Surprisingly, we noticed a few key benefits to opening windows farthest from the two occupants, namely, the front-right and rear-left windows. That configuration, shown in panel a of the figure, creates an air current that enters the cabin from the rear-left window, moves past the back-seat passenger, and exits through the front-right window. Most of the incoming fresh air turns sharply at the rear-right corner, with a little of it circulating in the cabin.

To our surprise, we noticed an airflow barrier established between the occupants. The barrier flow shields the occupants from cross contamination, in much the same way that an air curtain prevents outside air from mixing with indoor air at a controlled temperature in the doorways of supermarkets and shopping malls. That airflow should also reduce the discomfort of fast-moving air blowing directly on the occupants and yet still ensure a good air exchange rate of 150 ACH—about 30 L/s per person.

Particles smaller than 10 μm in diameter follow that air path; they also get diluted by the incoming air stream. After accounting for the two effects—advection and turbulent diffusion—in our simulations, we found that about 5% of the aerosols exhaled by either occupant reaches the other, as shown in panel b of the figure.

Should you now feel safe hailing a ride share? To answer that question, one must consider not only the physical separation and ventilation rate, but also the actual duration of the ride. For a novel pathogen such as SARS-CoV-2, which is continuing to evolve even as vaccines are taking effect, we can only assess the relative risks. In fact, scientists may have initially underestimated the immense biological variability in the infectivity of people. COVID-19 appears to be a disease wherein the top 20% most infectious people produce 80% of all infections. With those issues in mind, the picture I present is a comparative one. To be wise, we cannot yet breathe a sigh of relief.

Additional resources

▶ K. L. Chong et al., "Extended lifetime of respiratory droplets in a turbulent vapor puff and its implications on airborne disease transmission," *Phys. Rev. Lett.* **126**, 034502 (2021).
▶ M. Abkarian et al., "Speech can produce jet-like transport relevant to asymptomatic spreading of virus," *Proc. Natl. Acad. Sci USA* **117**, 25237 (2020).
▶ J. Allen, J. Spengler, R. Corsi, "Is there coronavirus in your car? Here's how you can protect yourself," *USA Today*, 22 April 2020.
▶ F. Yang et al., "Towards improved social distancing guidelines: Space and time dependence of virus transmission from speech-driven aerosol transport between two individuals," *Phys. Rev. Fluids* **5**, 122501 (2020).
▶ P. A. Jensen et al., "Guidelines for preventing the transmission of *Mycobacterium tuberculosis* in health-care settings," *Morb. Mortal. Wkly. Rep.* **54(RR17)**, 1 (2005).
▶ V. Mathai et al., "Airflows inside passenger cars and implications for airborne disease transmission," *Sci. Adv.* **7**, eabe0166 (2021). PT

An ink for printed electronics

As demand rises for flexible and lightweight electronics, so does the need to develop industrial-scale, low-cost processes to fabricate them. One possible method to create printable electronics is to disperse a highly conductive, organic coating material on a flexible substrate. To date, a conducting polymer known as PEDOT:PSS has been at the heart of several prototype solar cells, LEDs, and other applications. The p-type organic thermoelectric material uses positively charged holes to conduct electricity. But various opto- and bioelectronic devices rely on complementary mixtures of p-type and n-type materials, the latter of which relies on negatively charged electrons for conductivity.

This picture shows an n-type conducting polymer ink in an ethanol solvent being sprayed on a surface. To make the ink, postdoc Chi-Yuan Yang and Simone Fabiano of Linköping University in Sweden and their colleagues started with BBL, a polymer known for its conductivity. They doped it with PEI, an insulating polymer that lowers the minimum thermodynamic work required to move an electron from a solid surface. The PEI dopant increased not only the conductivity but also the stability of the ink at ambient conditions. The researchers spray coated BBL:PEI and PEDOT:PSS onto the active layer of a solid-state thermoelectric generator. Its power output exceeded that of generators made with only p-type materials. (C.-Y. Yang et al., *Nat. Commun.* **12**, 2354, 2021; photo courtesy of Thor Balkhed.) —AL

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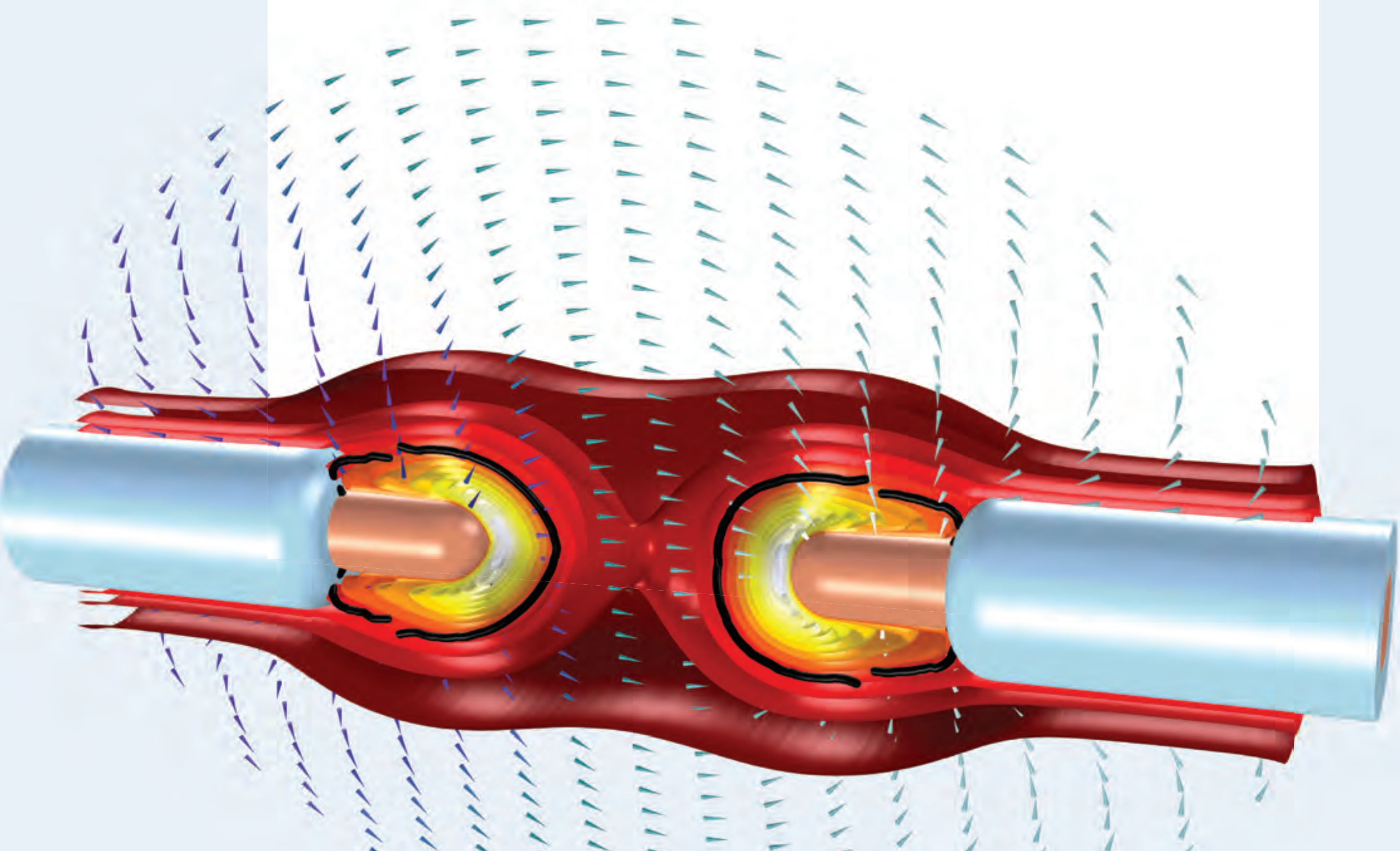

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