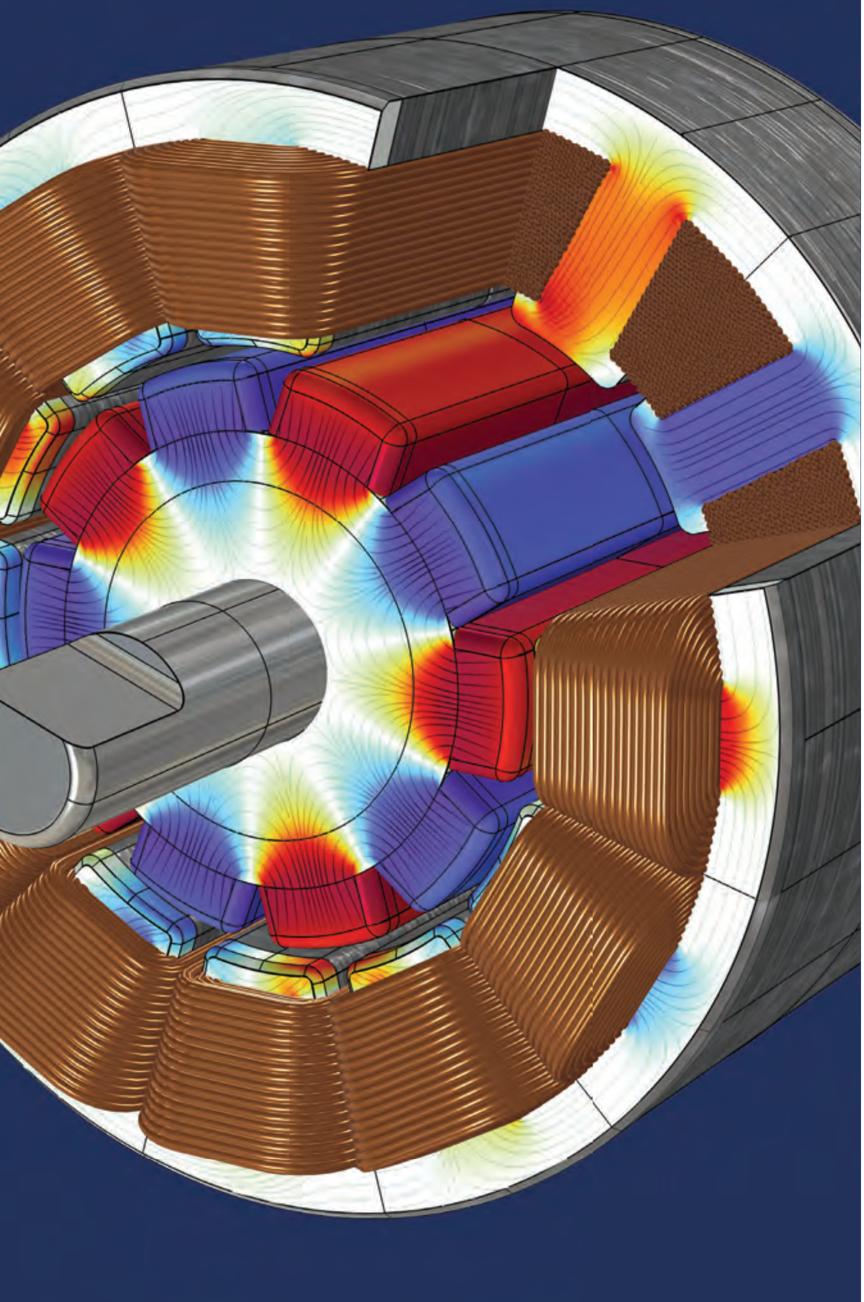

PHYSICS TODAY

January 2022 • volume 75, number 1

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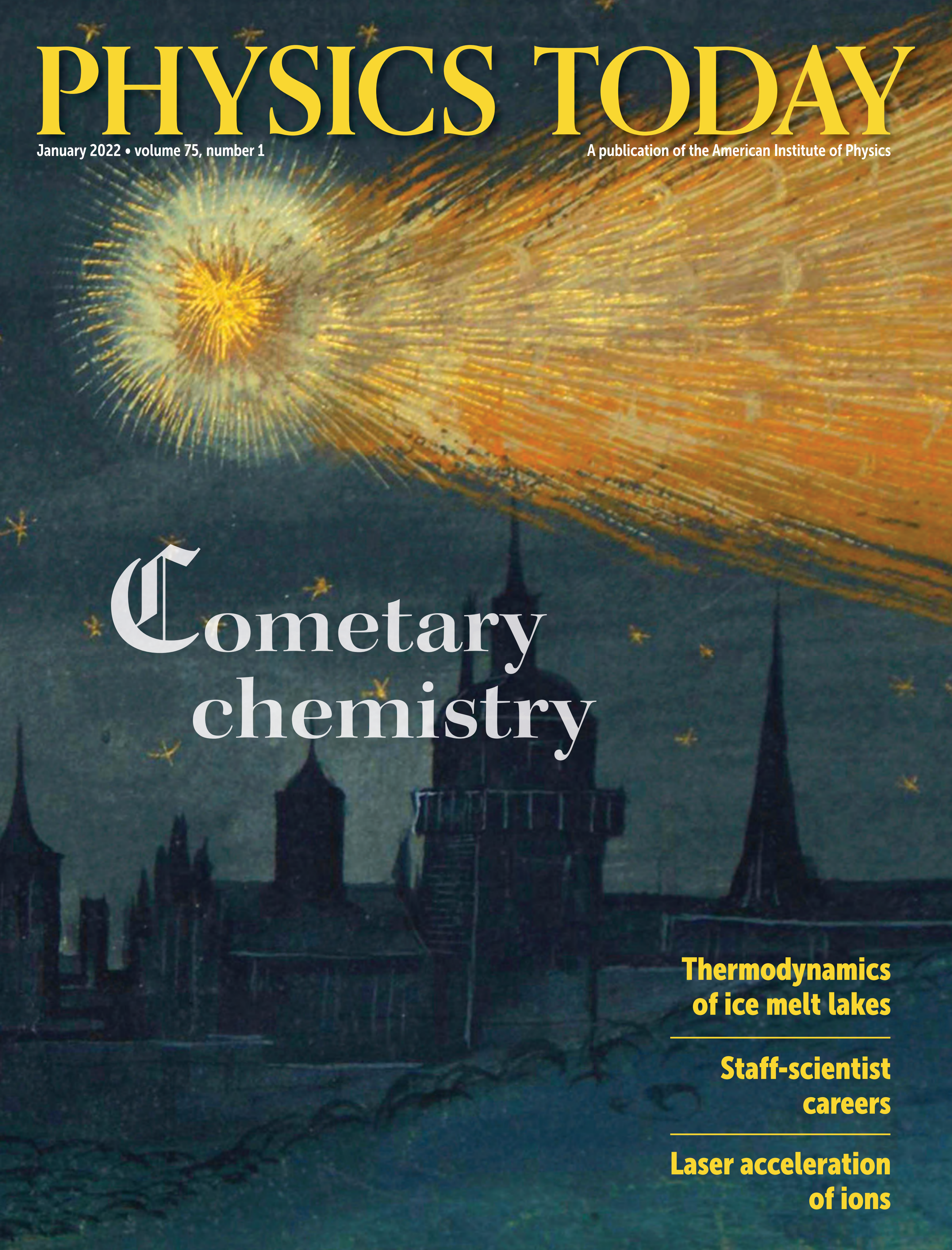

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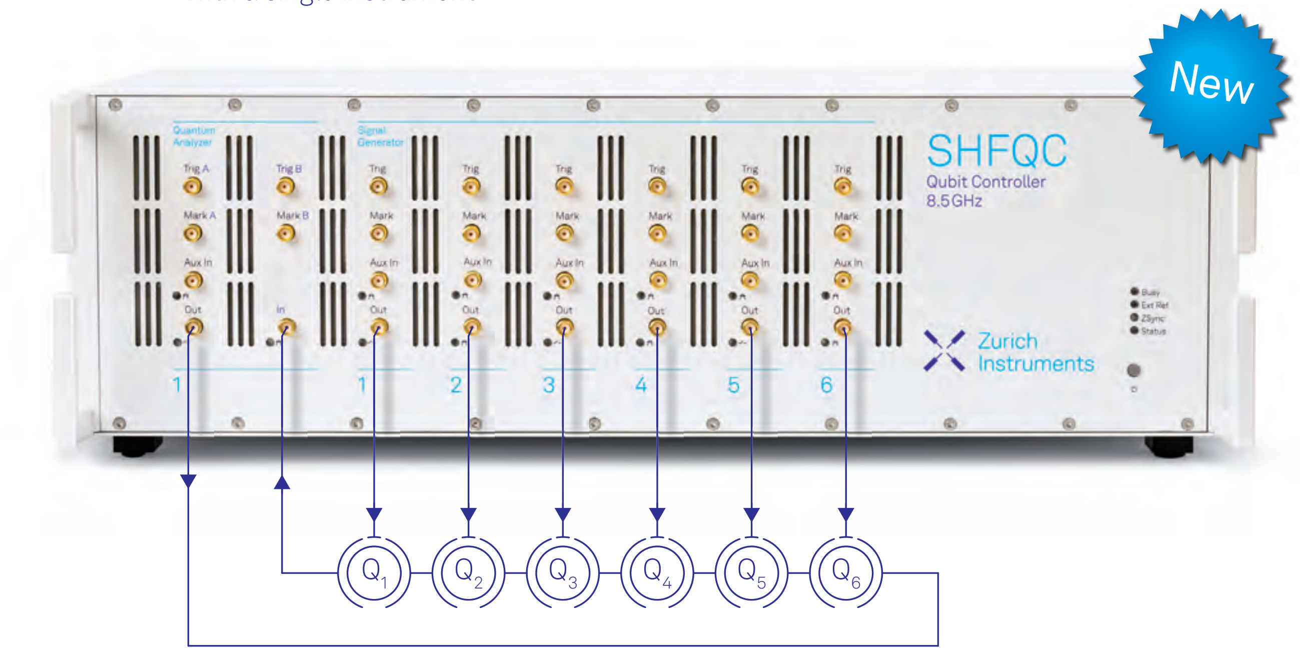

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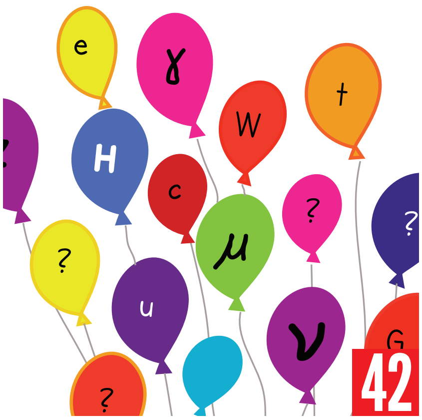
FEATURES



ON THE COVER: Comets have been observed for millennia, and their appearances were long thought to be harbingers of floods, famines, and other disasters. This illustration from the 16th-century *Book of Miracles* shows a comet that appeared in 1401 and was followed by a plague in the German region of Swabia. Though not actually omens, comets do carry a wealth of information. On **page 34**, Kathrin Altwegg describes how *in situ* cometary measurements have uncovered details about the bodies’ compositions and the solar system’s history. (Image from steeve-x-art/Alamy Stock Photo.)

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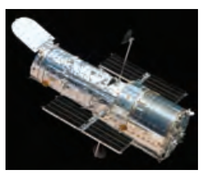

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Dual-anon review

Since the adoption of dual-anonymous peer review for the *Hubble* telescope, higher percentages of women and early-career researchers are getting observing time. Now NASA and other agencies are trying out the approach, in which neither applicant nor reviewer knows the other’s identity.

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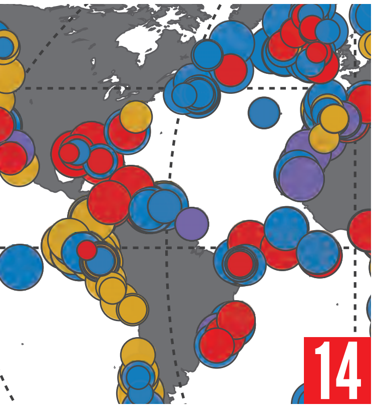

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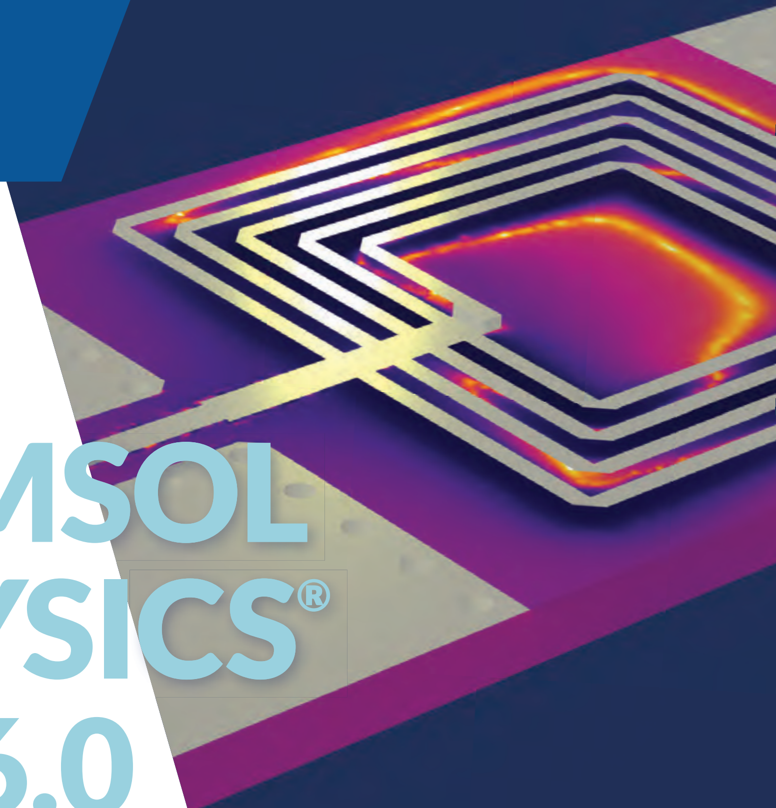

FROM THE EDITOR

Elementary, my dear physicists!

Charles Day

"It is an old maxim of mine that when you have excluded the impossible, whatever remains, however improbable, must be the truth."

Spoken by Sherlock Holmes, that line appears in "The Adventure of the Beryl Coronet." The short story by Holmes's creator, Arthur Conan Doyle, first appeared in the *Strand Magazine* in 1892. But my first encounter with the quotation was in a 2005 paper by Igor Mazin and Michelle Johannes entitled "A critical assessment of the superconducting pairing symmetry in $Na_xCoO_2 \cdot yH_2O$."[1]

The symmetry of the title belongs to the Cooper pairs of electrons that underlie sodium cobaltate's superconductivity. With a modest T_c of no more than 5 K, the state exists only when water molecules are intercalated between the compound's sodium atoms and cobaltate layers. Cooper pairs are composite bosons whose total spin S is an integer. When pairing up, spin-½ electrons have two choices for S, 0 and 1. They are also constrained, as a pair of fermions, to have an antisymmetric wavefunction. Fixing S, therefore, fixes the pair's total orbital angular momentum L: If $S = 0$, L must be an even integer; if $S = 1$, L must be an odd integer.

How electrons satisfy those constraints to form pairs depends on the symmetry of the lattice and on what fluctuations polarize the electrons and nudge them together. The superconductivity of $Na_xCoO_2 \cdot yH_2O$ intrigues physicists because the CoO_2 layers have hexagonal symmetry unlike the CuO_2 layers of the high-T_c cuprates, which have square symmetry.

Kazunori Takada and his colleagues reported their discovery of the superconductivity of $Na_xCoO_2 \cdot yH_2O$ in 2003.[2] Two years later when Mazin and Johannes wrote their Holmes-quoting paper, more experiments had been conducted on the compound and more explanations for its superconductivity had been proposed. In their paper, Mazin and Johannes set out to deduce which of 25 possible pairing symmetries was the most consistent with the strongest evidence. They eliminated all but two suspects, both of which are f wave—that is, $L = 3$. "$Na_xCoO_2 \cdot yH_2O$ may be the most exotic superconductor discovered so far," they wrote.

According to Guinness World Records, Sherlock Holmes is the most portrayed literary character in the history of theater, film, and television. Among recent adaptations is *Sherlock*, a BBC TV series that ran for four three-part seasons in 2010–17, starred Benedict Cumberbatch as Holmes, and took place in present-day London.

In the first episode of the series, "A Study in Pink," Holmes examines the worn-looking wedding ring of a dead woman. "Ten years old at least," he tells a forensic examiner. "State of her marriage right there. . . . The only polishing it gets is when she works it off her finger." The woman, Holmes deduces, has had a string of extramarital affairs.

My wedding ring is 27 years old. Its inside is shiny because I've removed it over the years for rowing, swimming, and cooking. Its outside is dull and scratched because I like its evident age to connote the length of my happy marriage.

The fictional Holmes does not consider plausible alternatives to his theories lest they undermine his evident brilliance. Nonfictional physicists, however, have to weigh alternative explanations. What's more, they have to consider the possibility that their data are uncertain or even spurious.

Until I read that yet another Holmes adaptation, the movie *Enola Holmes*, would be getting a sequel, I had forgotten about $Na_xCoO_2 \cdot yH_2O$. A search for the latest research on the topic yielded a paper from this past May by Niklas Witt and his collaborators.[3] The researchers used a numerical approach called FLEX-IR and applied it to the compound to explore its electronic properties. Like Mazin and Johannes before them, they concluded the pairing is f wave, although they favored the other of Mazin and Johannes's two suspects. A definitive answer, the two groups agreed, would come from further experiments.

Whether those experiments will be performed is not clear. Research in $Na_xCoO_2 \cdot yH_2O$ has become "unfashionable," Mazin told me in an email. That fate befalls a problem, he continued, "either because people believe it's solved or because solving it is so hard and too unprofitable." Neither possibility afflicted Sherlock Holmes.

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Commentary
Teaching quantum concepts

Quantum mechanics is one of the pillars of modern physics. Although quantum computing seems to grab the headlines, quantum mechanics lies at the heart of a vast array of fields, including modern electronics and modern medicine—not to mention all of chemistry. But it is also a notoriously obtuse subject in many ways. In fact, there's no clear consensus on what represents the bare-minimum competency in quantum mechanics, and there is even less consensus on the best formalism to use.

Classical mechanics can be understood entirely within the context of the conservation of momentum and energy. That is, we can derive the basic rules of classical mechanics, such as Newton's laws, from those conservation laws. But what is the equivalent foundation of quantum mechanics? The answer to that question—whether it is probability, discreteness, nonclassical correlation, or something else—has ramifications for how it is taught, for how it is communicated to the public, and even for how it is communicated to other physicists.

It's easy to fall down a rabbit hole when attempting to convey quantum ideas to an audience for the first time. Analogies only go so far in the quantum world, since it is so far removed from our everyday experience. For example, I have found that some people have difficulty even grasping the notion of discrete energy levels, let alone understanding the notoriously murky subject of entanglement. And yet both of those ideas are important enough that they *should* be understood by more people.

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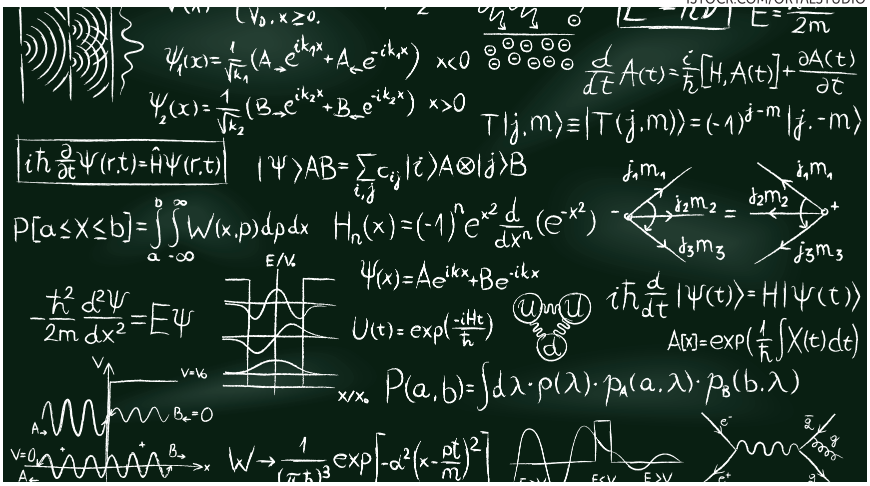

Consider climate change, for example. It is an existential problem for humanity, and it is attributable to a basic quantum mechanical phenomenon. As someone who works in quantum information, I suppose it's fair to say that quantum mechanics colors the way I view the world. But there's no denying that the only reason the atmosphere retains any heat at all is that carbon-based compounds absorb and reemit IR radiation while oxygen and nitrogen molecules, which constitute the majority of the atmosphere, do not. That's a purely quantum mechanical effect. In fact, it is arguably one of the two critical physical processes behind climate change (the other being the biosphere's conversion of the Sun's broad spectrum of energy to IR).

When you teach about quantum mechanics, a lot depends on the audience itself. Some ideas are inevitably simplified or wholly abandoned in certain settings. The climate change course I taught in the fall of 2021 was open to all majors, so in addition to physics majors, I had students from history, English, criminal justice, peace and justice studies, environmental science, and politics. Concurrently, I also taught a standard modern-physics course, which covered special relativity and quantum mechanics, to second-year physics majors. It introduced students to concepts such as spin and entanglement. Although entanglement may have a role in photosynthesis,[1] which is a key component of the global carbon cycle, it's tangential to the main point that I was trying to convey in my climate change course, so I never discussed it in that setting.

The importance of quantum mechanics outside of certain specialties is not limited to climate science, of course. With the rise of quantum computing and quantum information, there is a growing need for computer science and mathematics courses to introduce basic quantum concepts. In a computer science setting, it's much easier to introduce basic quantum concepts by using linear algebra than, say, a strict calculus-based formalism that emphasizes differential equations. In fact, I tend to find that the algebraic approach is easier even with physics majors.

Unlike climate change, quantum computing and quantum information don't represent existential crises, but they do have the potential to greatly affect humanity. Yet they are built around a handful of extremely counterintuitive ideas. Getting people to understand those ideas for the first time often requires a creative approach that sometimes sacrifices rigor in favor of a certain level of conceptual understanding. The fact is that we live in a highly complex world, and not every-

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one can be an expert in everything. So we have to find some way to convey those complex ideas in a manner that doesn't require years of study but that is effective enough to allow for sound judgments to be made both at the personal level and at the policy level.

Unfortunately, there is no simple, one-size-fits-all method. It would certainly help matters if people were introduced to quantum concepts at multiple points through a variety of techniques during their K–12 education, but that would require changing standards and increasing the number of teachers who have been exposed to those ideas.

Several initiatives are working to introduce more quantum mechanical topics into K–12 and undergraduate curricula. This past summer I participated in the Quantum Undergraduate Education and Scientific Training (QUEST) workshop. As the name suggests, it was aimed at quantum information science education at the undergraduate level, and several of the participants were from computer science and mathematics departments. Currently I am cofacilitating a faculty online learning community that is taking a deeper dive into some of the themes discussed at the workshop. A related initiative is the National Q-12 Education Partnership. The program, spearheaded by the White House Office of Science and Technology Policy and NSF, is compiling resources for use in the classroom. The general public and policymakers represent an entirely different cohort from those of either QUEST or the Q-12 partnership, which will necessitate yet another approach.

So what have nearly two decades of teaching quantum concepts taught me? They have taught me to be creative and to try multiple approaches. They have taught me that sometimes rigor must be sacrificed in service to the bigger picture. And much to the chagrin of family and friends at holidays and weddings, they have taught me to be annoyingly persistent. But there are few things I would rather do than talk about physics. What about you?

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LETTERS

Subtle historical connections between Magritte and Einstein

In the recent letter "Einsteinian subtleties in Magritte's *Time Transfixed*" (PHYSICS TODAY, April 2021, page 10), the author, Robert Fleck, candidly admits that "there is no evidence that [René] Magritte intended to represent . . . Einsteinian ideas in his painting" (shown below). The temptation to dismiss the whole piece as a purely subjective and arbitrary association is rather strong, but there are perhaps tenuous links that might save it from scorn.

The word *durée* in the French title of the painting, *La durée poignardée*, would have had for Magritte and his contemporaries the unmistakable association to the French philosopher Henri Bergson. Before World War I, Bergson was something of a superstar: His lectures were attended by large crowds, and just about everybody knew the buzzword *durée*.

Bergson's *durée* is not time but rather something else: What his philosophy emphasized is that personally experienced time (*la durée*) is totally different from objective time. "Bergson sees spatialization as the hallmark of the inauthentic, mechanized time of science," wrote a commentator,[1] and that idea seems to fit Magritte's picture rather well.

A mirror mechanically sends back inverted images but does not turn back time: "Reading the picture" spatially from left to right, the spectator notes that the reflection of the second candleholder is missing in the otherwise realistic representation. The locomotive, another mechanical device, irreversibly transmutes the internal energy of coal into external movement. The original thoughts that Bergson developed at length were badly damaged when Einstein's special theory of relativity became known. To say that they were stabbed (*poignardées*) could be an eloquent image.

Jimena Canales recently published a book about a confrontation between Bergson and Einstein[2] that took place in April 1922. Later that year Bergson published the monograph *Durée et simultanéité* (*Duration and Simultaneity*) about Einstein's theory. The book, if not the historical meeting, is something that Magritte might have known about. So perhaps there is a roundabout way to connect more convincingly the picture and Einstein.

Magritte commented on the association to Bergson in a letter he wrote decades after he had finished the painting and given it the title *La durée poignardée*: "You think of Bergson and Proust when you look at this painting," he said. However, he had already discussed the title in an earlier letter he sent to his friend Marcel Mariën sometime around the painting's production. A pen-and-ink sketch of the painting occupies the upper part of the sheet, and on the last line of text below it, Magritte asks his friend if he would like to "meditate" about it.

For avid readers of popular-science articles, trains and clocks have become suggestive of Einstein's

TIME TRANSFIXED, by René Magritte, oil on canvas (1938), Art Institute of Chicago. (Image from Peter Barritt/Alamy Stock Photo.)

theory of relativity, but there is no evidence of Magritte's interest in such matters. "Nevertheless, the associations between Magritte's art and Einstein's science are striking," Fleck notes in his conclusion. At that point, it seems that the linking is his own personal construct, prompted apparently by an invented English translation. But the full story might be more subtle: "Einstein Meets Magritte" was the title of a 1995 interdisciplinary conference, held in Brussels, that became the basis for a series of volumes published over the years.[3] The pairing of the two names is indeed striking, even if it has not been found to be particularly productive. "I believe that Einstein and Magritte would not have much to say each to the other," drily noted Nobel laureate Ilya Prigogine during the original conference.[4]

"The chance encounter on an operating table of a sewing machine and an umbrella"[5] became a popular quote in the history of surrealism, as bringing together widely disparate objects has been a major occupation for surrealists. The method was also adopted by Magritte, who argued that it is the clash of images that generates ideas.

So we might recapitulate: The image came first, followed by the title and its translation, then the conference, Fleck's letter, and, finally, this note.

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▶ **Fleck replies:** Alexandre Losev's intriguing suggestion of a René Magritte–Albert Einstein connection through the French philosopher Henri Bergson and his idea of "personally experienced time (*la durée*)" would, if confirmed, locate "Einsteinian subtleties in Magritte's *Time Transfixed*" more firmly within contextual, historical evidence, thereby elevating the subtle connections I point out beyond the level of mere coincidence. A more thorough search for possible links between Magritte and Einstein—such as may be recorded in the multivolume *Einstein Meets Magritte*, referenced by Losev; Magritte's *Écrits complets* (1979), edited by André Blavier in French; and the multivolume *René Magritte Catalogue Raisonné* (1992–2012)—certainly seems warranted.

The influence of Einstein and modern physics on other surrealists, most notably Salvador Dalí, is well documented. Both artists and scientists observe and interpret the world around us; we should not be at all surprised to find commonalities in their creations.

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PT

24 000 years of climate change, mapped

A numerical model combines with proxy temperature data to produce the most complete paleoclimate picture yet.

Earth's changing climate is typically summarized with a single number: the average surface temperature. That's the quantity that has already risen by 1.1 °C since preindustrial times—and that parties to the Paris climate agreement hope to limit to a maximum rise of 2 °C.

But the average surface temperature doesn't describe how any specific location experiences climate change. Some regions, such as the Arctic, are warming much faster than average, while other regions warm more slowly. Temperatures change differently in different places, and they always have.

Now Matthew Osman and Jessica Tierney (both at the University of Arizona) and their colleagues have reconstructed Earth's spatially changing temperature tens of thousands of years into the past. Using a technique called data assimilation—a statistical method for melding measurement data with numerical models—they mapped the temperature at 200-year intervals over the past 24 000 years, the entire period since the Last Glacial Maximum.[1] Figure 1 shows a few snapshots of their time-varying map.

The work increases climatologists' confidence in how present-day climate change fits into historical context. According to the results, never in the past 24 millennia has Earth been warmer than it is today, and never has it warmed faster than it's warming today. And the vast majority of Earth's temperature change—even in preindustrial times—is attributable to atmospheric greenhouse gases and to the reduction in albedo that accompanies deglaciation.

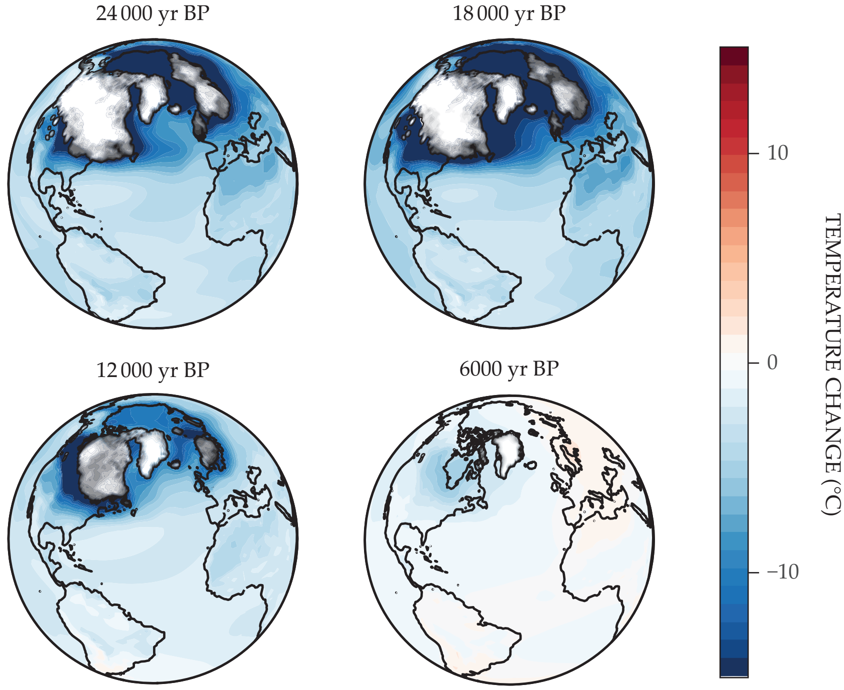

FIGURE 1. GLACIERS COVERED the northern latitudes 24 000 years before present (BP). As they receded, the planet warmed, but not evenly. New research assimilating temperature proxy data with climate modeling has reconstructed the temperature change across both time and space. Changes are relative to the average over the period 1000–1850 CE. (Figure by Matthew Osman.)

Model and measurement

Data assimilation methods are the engine of weather forecasting. Meteorologists have detailed models of atmospheric dynamics, but the models are only as good as their initial conditions. Even with thousands of instruments continuously monitoring the weather around the world, the complete state of the atmosphere is never precisely measured.

In its simplest form, data assimilation works like a weighted average: When a model and a measurement give conflicting values for the same scalar quantity, data assimilation outputs the best estimate of the quantity's true value that accounts for the respective uncertainties of the model and measurement.

The state of the atmosphere is not a scalar, but it can be represented as a vector with billions of components. For vector quantities, data assimilation is similar but more complicated. Uncertainty is represented by a covariance matrix that describes correlations among the vector components, and the measurement probes only part of the vector state. Still, data assimilation solves for the most likely state given the combined model and measurement information.

Forecast meteorologists use what's called an online approach to data assimilation: They repeatedly rerun their weather models with newly acquired data to refine their knowledge of the atmosphere's current state. Then they propagate that state forward to forecast the weather of the next several days.

Tierney, a geochemist with an interest in Bayesian statistical methods, sought to use a similar method to look into the past rather than the future. "The math is actually pretty simple—just a few lines of code," she says. "But everything that went into it was really complicated."

Plankton geochemistry

There weren't any weather stations collecting data 24 000 years ago, so researchers need to rely on temperature proxies to infer the climate at that time. For the recent past, they can use tree rings: Trees grow faster in warm years than in cold ones. (See the article by Toby Ault and Scott St. George, PHYSICS TODAY, August 2018, page 44.) But not many trees that were alive more than a few hundred years ago are still around.

Fortunately, single-celled ocean plankton leave geochemical records of temperature that date back not just thousands but millions of years. (See PHYSICS TODAY, December 2001, page 16.) Tiny organisms with calcium carbonate shells draw in varying amounts of oxygen-18 and magnesium from ocean water, depending on the temperature. And other organisms have evolved to alter their oily membranes' chemical composition—changing the number of carbon rings or double bonds—to keep them optimally pliable in changing water temperatures. Dead plankton are preserved in seafloor sediment, where researchers can dig them up to gauge Earth's past climate.

Many research teams have collected and analyzed plankton proxies over the years. But they've all done so for their own purposes—usually to study local climate, not global—so the data haven't all been stored in any central database, nor even in any standardized format. "The data were all over the place, like in the supplemental parts of research papers from the 1980s," says Tierney. She and her colleagues had to track them all down, compile and reformat them, account for changing calibration standards, and in some cases correct errors.

The proxy locations are shown in figure 2. They're concentrated near coastlines because that's where sediment accumulates fast enough to create a time-resolved record. Few proxies have been collected from the Southern Ocean, because storms and high waves make access to the region difficult.

The researchers used the same National Center for Atmospheric Research flagship climate model as the Intergovernmental Panel on Climate Change does for its future projections. Even on a supercomputer, modeling 24 000 years of climate evolution took so much computer time that Tierney and colleagues had to replace the meteorologists' online approach to data assimilation with an off-line one. Rather than incorporating new data at every time step, they ran the model in its entirety and assimilated the data afterward. To check the validity of their reconstruction, they excluded a few measurement records from the assimilation, then checked the withheld data against the output. The temperatures agreed well.

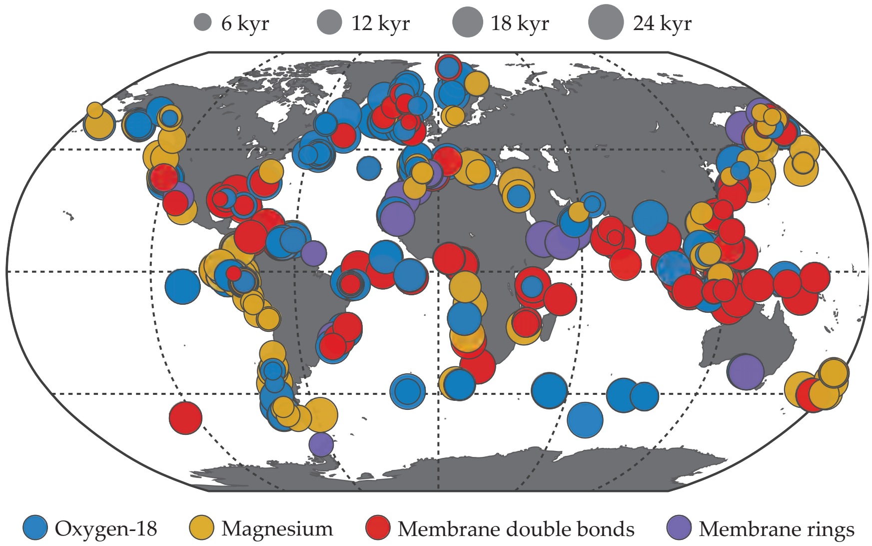

FIGURE 2. OCEAN PLANKTON preserved in seafloor sediments provide some of the best records of Earth's past temperature. Shown here are the locations of plankton sampling sites. The circle colors represent the type of geochemical data, and the sizes represent the duration of each temperature record in kiloyears (kyr). Relative to the rest of the world, the Southern Ocean—an important but inaccessible region—is poorly sampled. (Adapted from ref. 1.)

A simple story

A big benefit of having a spatiotemporally resolved climate map is that the researchers can decompose it into its principal components of variance to see where temperature changes are correlated. In the past 24 000 years, warming has been concentrated in the northern latitudes—in northern Europe and present-day Canada—where glaciers dominated the landscape at the time of the Last Glacial Maximum and have retreated the most since then. In fact, more than 90% of the global temperature variance is described by that Arctic-dominated mode, which in turn is almost perfectly correlated with atmospheric greenhouse gas levels and glacial extent.

It's well established that modern-day climate change is driven by greenhouse gas emissions and compounded by deglaciation. But to see the same effect in play before humans made their mark on the climate is a new and striking result. Plenty of other factors could conceivably have influenced global climate on millennial time scales—including changes in vegetation and windblown mineral dust—but it turns out that they haven't. "The cleanliness of the signal was a bit of a surprise," says Tierney. "There may be more complicated things going on at the regional level, but globally, the story is quite simple."

The data assimilation also sheds new light on the so-called Holocene temperature conundrum, the puzzle of how Earth's temperature has changed over the past 7000 years. Previous temperature reconstructions, including the red dotted line[2] in figure 3, show a slight cooling over that period—meaning that 7000 years ago, Earth was as warm as or warmer than it is today. When Osman, Tierney, and colleagues calculated a proxy-only average, without assimilating the data into the climate model, they found the same thing (red solid line). The cooling is difficult to explain, because ice-core records clearly show that greenhouse gas levels were increasing, not decreasing, over that period.

The data-assimilation reconstruction (blue) shows the opposite trend—a slight but definite warming across the entire period—more consistent with greenhouse gas records. Through statistical analysis, Osman, Tierney, and colleagues attribute the discrepancy with the proxy-only reconstruction to the undersampling of the Southern Ocean: With so little temperature data from that part of the world, the proxy-only reconstructions may have been filling in the gaps incorrectly.

The data gaps may yet be remedied directly. Temperature records exist in the Southern Ocean sediments, and researchers willing to brave the stormy seas could collect important new pieces of the climate puzzle. "When I've given talks to colleagues who specialize in the Southern Ocean, they've been pleased to see that the region is so important," says Tierney. "So maybe this will inspire new research cruises to go down there."

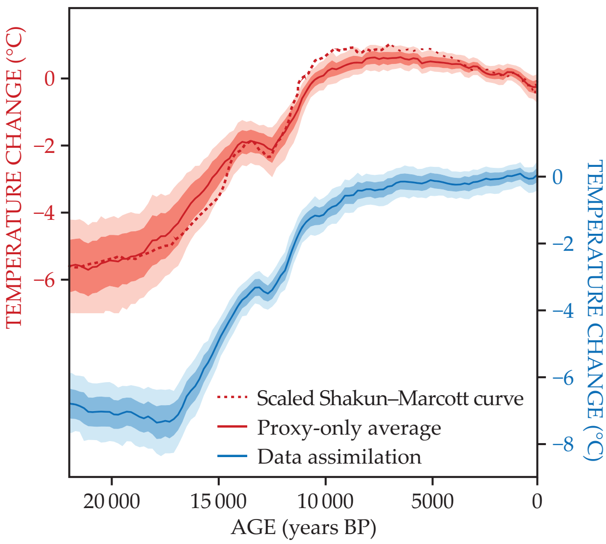

FIGURE 3. EARTH'S WARMING from 24 000 years before present (BP) until now has not been subtle. But the temperature trend during the Holocene epoch—especially the past 7000 years—is less certain. Previous work, including an estimate created by Shaun Marcott, Jeremy Shakun, and colleagues[2] (red dotted line), shows a cooling trend over that period. A weighted average of the temperature proxies from figure 2 (red solid line) shows the same. But assimilation of the proxy data with a climate model (blue) yields a slight warming trend, a result more easily reconciled with greenhouse gas records. Note that modern-day warming, which has increased Earth's temperature by 1.1 °C over the past 150 years, is not shown. (Adapted from ref. 1.)

Digging deeper

One of the main motivations for reconstructing past climate conditions is to look for clues about what's in store for Earth's warming future. But by that standard, the time since the Last Glacial Maximum is an imperfect guide: The temperature, rate of warming, and greenhouse gas levels are all higher now than at any other point in that period.

But that wasn't always the case. Looking back millions rather than thousands of years, one can find plenty of times when Earth was hotter and greenhouse gases were more abundant than they are today. In particular, the Paleocene–Eocene Thermal Maximum, an anomalous temperature spike some 55 million years ago, is an ominous analogue for present-day warming, although the rate of temperature change was still far slower then than it is now.

One goal on the researchers' minds is to turn their data-assimilation techniques to the more distant past to get a more complete picture of how Earth's climate behaved—and may behave again—under those extreme greenhouse conditions.

Johanna Miller

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X-ray observatory spots a possible planet in another galaxy

Even if the discovery is never confirmed, the method it uses may spawn a new generation of exoplanet searches.

In 1995 Michel Mayor and Didier Queloz detected a hot Jupiter-sized planet 50 light-years from Earth that orbits its host star more closely than Mercury orbits our Sun. That discovery—the first exoplanet confirmed around a sunlike star—recast the thinking about how planets form. It also so captivated the imagination that efforts to search for them soon became mainstream astronomy (see PHYSICS TODAY, December 2019, page 17).

Just five years later, 34 exoplanets had been spotted around sunlike stars. Nearly all of them were observed by Doppler spectroscopy, which measures the periodic redshifts and blueshifts in a star's wobble from an exoplanet's gravitational tug. In 1999, Harvard University's David Charbonneau debuted a complementary approach—the transit method, in which an observer looks for the brief dip in the brightness of a star when an exoplanet passes in front of it.

Together, the two methods are responsible for more than 4800 confirmed exoplanets. All of them are in the Milky Way and less than 3000 light-years from Earth. The vast majority were spotted by the *Kepler* and *TESS* (*Transiting Exoplanet Survey Satellite*) space telescopes. The more recently launched *TESS* looks for Earthlike planets by monitoring 85% of the sky every 27 days. (See PHYSICS TODAY, March 2019, page 24.)

Planets are ubiquitous in the Milky Way, and astronomers estimate that one third of all sunlike stars host planetary systems. But they've also found hot Jupiters, icy giants, and smaller rocky planets orbiting more exotic stars. An important goal is to explore planetary diversity in all its forms and settings.

In 2018, Rosanne Di Stefano and Nia Imara, both then at the Harvard–Smithsonian Center for Astrophysics, made a bold proposal: To find planets in exotic or extreme environments, astronomers should turn their attention toward x-ray binary systems.[1] Each binary consists of a collapsed star—a black hole, neutron star, or white dwarf—that accretes plasma from a much larger companion star. Spiraling inward through an accretion disk, the plasma reaches temperatures high enough to emit x rays.

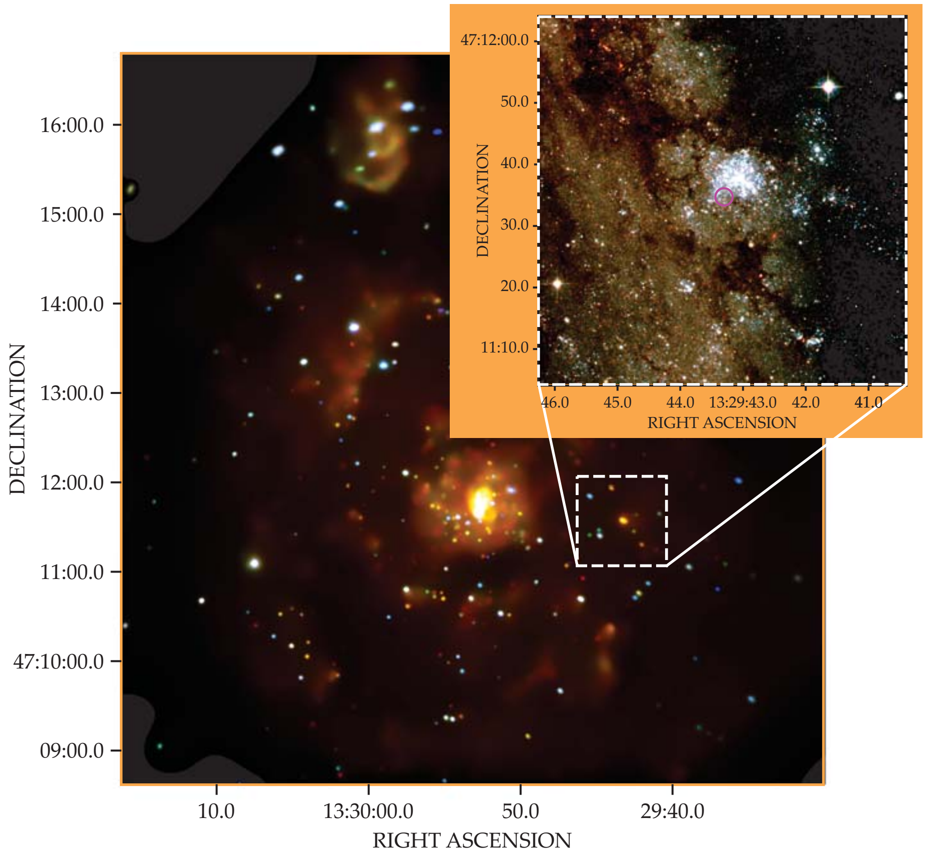

FIGURE 1. *CHANDRA* AND *HUBBLE*. This *Chandra X-Ray Observatory* image of Messier 51, known as the Whirlpool galaxy, reveals discrete x-ray light sources. The boxed region near a cluster of young stars contains an x-ray binary system. In the inset, the *Hubble Space Telescope* reveals an optically more crowded environment (the binary is circled in magenta). Insensitive to those optical signals, *Chandra* isolates the dip in the binary's x-ray flux when a putative planet blocks it along Earth's line of sight. (Adapted from ref. 2.)

The x-ray-emitting region is exceedingly compact, possibly even smaller than the diameter of Jupiter. If the binary hosts a planet, the dip in the x-ray light curve during a transit could be huge. It could even produce a total eclipse. Planets orbiting ordinary stars typically cast a far smaller shadow from the host star, which makes them more difficult to spot.

Di Stefano, Imara (now at the University of California, Santa Cruz), and their collaborators now report finding what may be a planet orbiting one of the brightest x-ray binaries in Messier 51, the Whirlpool galaxy.[2] Shown in figure 1, the binary resides 31 million light-years from Earth, about 400 times as distant as the far edge of the Milky Way's disk.

To find it, the astronomers mined the vast archives of the *Chandra X-Ray Observatory*, NASA's flagship satellite x-ray telescope. Their automatic search of 2640 point sources in three galaxies yielded the features of an exoplanet transit in a 2012 light curve (see figure 2). The researchers could not distinguish whether the compact, accreting star was a black hole or a neutron star, but in either case it was gravitationally bound to a blue supergiant companion whose luminosity and spectrum is that of a 20–30 solar mass star.

If the accreting object is a black hole, the exoplanet (M51-ULS-1b) would be the first ever spotted in orbit around one.

And the companion would be the highest-mass host star of any exoplanet yet discovered. From the light curve, the researchers estimate that the new exoplanet candidate is comparable in size to Saturn. And using Kepler's laws, they estimate its distance from the binary's center of mass to be tens of astronomical units—about 45 AU multiplied by a scaling factor that depends on the binary's mass. That inference puts the planet up to a quarter of a light-day from the stars—roughly equal to the distance between the Sun and the outer Kuiper belt in our own solar system—and its orbital period around 70 years.

The burden of confirmation

That orbital period would be the longest ever found for a transiting exoplanet. And it likely puts the exoplanet's confirmation—either from a repeat transit observation, Doppler spectroscopy, or both—out of reach for the current generation of astronomers. It's not alone: Beyond the confirmed exoplanets in the Milky Way—4878 as of December 2021—are thousands of candidates that require more observations to be considered authentic.

"Much of our paper is devoted to analyzing the transiting object's identity," says Di Stefano. Irregular blobs of gas and dust can affect light-curve data, for instance, as the density enhancement elicits spectral changes. But the *Chandra* data exhibit no changes in x-ray color. Di Stefano and her colleagues reasoned that only planets and white dwarfs could have produced plausible dips in the range of likely transiter radii. But they eliminated a white dwarf from consideration because its gravitational-lensing effect would have increased, not decreased, the amount of light received from the x-ray source.

The data shown in figure 2 exhibit a well-defined baseline before and after the photon count dips to zero and recovers mere hours later. But other possibilities for such a drop beyond the presence of a planet cannot be ruled out. For example, the x-ray emission could be interrupted if a flare or coronal mass ejection from the companion star diverted the flow of plasma fuel.

The uniqueness of the observation unsettles some astronomers. Of the 2640 light curves in the survey, only that one three-hour segment revealed a transit signature. "We may have been lucky to have caught this planet in the act," admits Di Stefano. Indeed, accounting for the number of light curves examined, the planet's long orbital period, and detections that can occur only along Earth's line of sight, the chances of finding it are about one in a million. "Despite discouraging odds the method is sound," says MIT's Andrew Vanderburg. "And I think it's sure to find multiple candidates if it were to be adapted into a search scheme that, like *TESS*, scans hundreds of thousands of stars at a time."

Although finding extragalactic planets is unsurprising, establishing an extragalactic search campaign is still important. Different galaxies present different snapshots in cosmic history. The planets in each one would be representative of the age and gas composition of that galaxy. Questions abound: What's the earliest time a planet could have formed in the universe? How many stars must have died and gone supernova before rocky planets started to emerge? Vanderburg puts the significance of the questions more generally: "How does the location in which you're born affect the planet you become?"

R. Mark Wilson

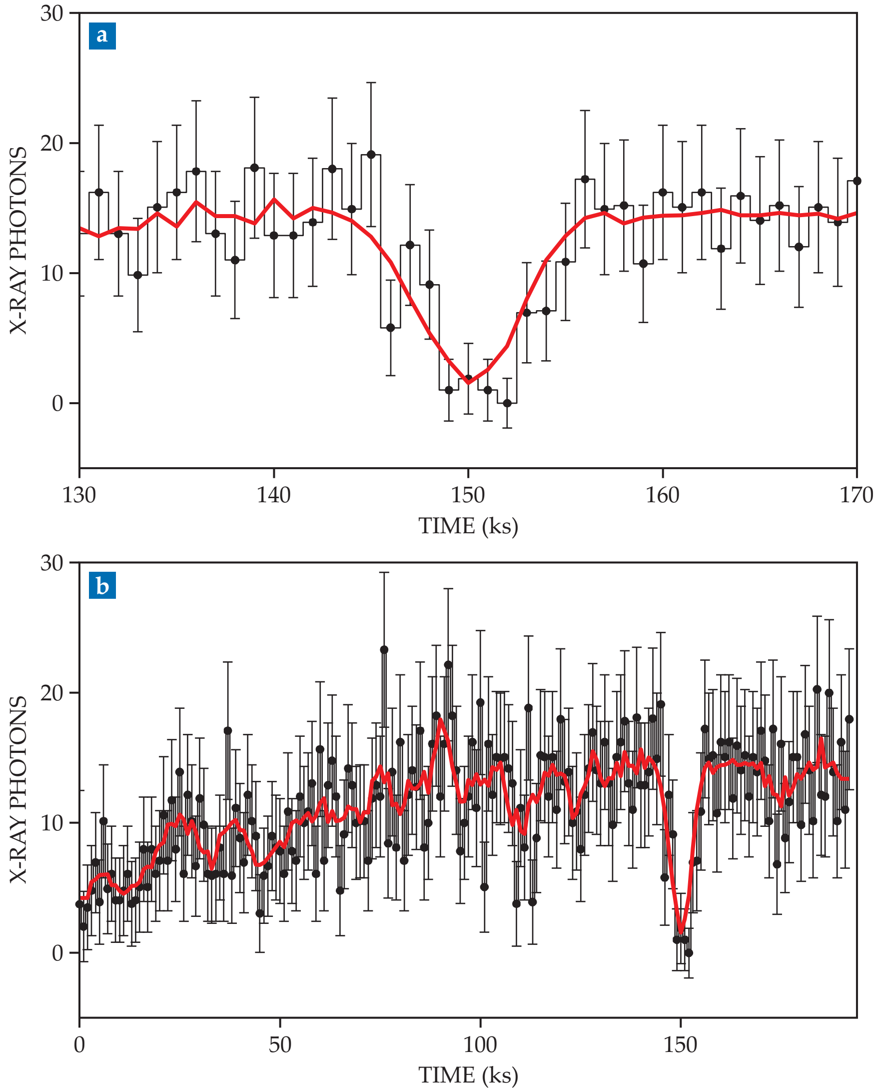

FIGURE 2. LIGHT CURVES. A short-duration eclipse is observed in the x-ray flux from the accretion disk around a black hole or neutron star that siphons gas from a massive companion star. **(a)** The telltale feature of a planetary transit—an abrupt dip and subsequent rise in flux—is consistent with the presence of a Saturn-sized planet. **(b)** In this entire duration of the observation, intrinsic variability can cause the flux rate to drop to zero even during periods not associated with the transit. (Adapted from ref. 2.)

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A laser selectively kicks carbon out of a foil

Experiments and simulations show how the shape of a laser's profile determines which target atoms make up the resulting ion beam.

FIGURE 1. THE GEMINI LASER at the Central Laser Facility, part of the UK's Rutherford Appleton Laboratory, provided pulses for a recent experiment on laser-driven ion acceleration. Here researchers check the alignment before they send the laser beam to the target chamber. The shape of the pulses' temporal profiles resulted in the preferential acceleration of carbon ions over proton contaminants that usually dominate ion beams. The short, high-flux burst of carbon ions could be useful for research into more efficient radiotherapy treatments. (Courtesy of the Central Laser Facility, STFC.)

An intense laser can ionize matter and accelerate the resulting ions into a beam. Creating and accelerating ions in a single compact system offers an advantage over the bulky conventional combination of a separate ion source and a cyclotron or synchrotron. Such laser-driven ion beams could be useful in various applications, including radiotherapy, that benefit from short high-flux pulses of ions.[1] (See the article by Jerimy Polf and Katia Parodi, PHYSICS TODAY, October 2015, page 28.)

But controlling what ions end up in the beam can be difficult in laser-acceleration systems. The problem is that the target materials inevitably contain contaminants, primarily hydrogen. When the laser hits, protons from the ionized hydrogen dominate the beam and prevent heavier ions from accelerating.

Although proton therapy is currently the most widespread ion radiotherapy, a treatment that employs larger ions, such as carbon, interests medical researchers because the ions' extra mass means they do more damage to a cancerous cell's DNA as they pass through. A reliable source of carbon-ion beams that is small enough to fit in a typical laboratory would facilitate more research on potential carbon-ion therapies. (See PHYSICS TODAY, June 2015, page 24.)

Now Marco Borghesi of Queen's University Belfast in Northern Ireland and his colleagues have developed a laser method to selectively excite heavier ion species.[2] Their complementary simulations demonstrate how the shape of their laser pulse preferentially moves protons out of the way so that carbon ions can be accelerated.

A new regime

Lasers can accelerate ions out of a material in a few ways. The most common method is known as target normal sheath acceleration (TNSA). In it, the laser ionizes surface atoms and produces free electrons that work their way through the material and escape out the back. As they leave, they create a strong electric field that ionizes and accelerates atoms on the back surface. Because TNSA acts on the surface atoms, it disproportionately accelerates contaminants, which sit primarily on the surface and are difficult to avoid or remove.

Radiation-pressure acceleration, on the other hand, acts on the bulk of the material. With sufficiently high intensity, the light pulse applies pressure directly on the electrons and ions and pushes them out of the material. Such acceleration happens in two regimes that depend on the target thickness. For thicker samples, the hole-boring regime prevails: Light pressure dents the target, and the excited ions must push their way through the rest of the material.

For thinner samples, tens of nanometers thick, the acceleration enters what's known as the light-sail regime, in which the ions escape directly. Although that acceleration is more efficient than the hole-boring regime, thinner targets are difficult to work with. For example, the laser profile needs to be temporally smooth because any sudden spikes in intensity that precede the main pulse can prematurely destroy a thin target.

Hit the target

The Borghesi group has worked on laser techniques for accelerating ions since 2005. In 2013 the group joined A-SAIL (Advanced Strategies for Accelerating Ions with Lasers), a consortium of several UK universities established to explore whether those techniques could be used for medical applications. Several years later Borghesi and his A-SAIL collaborators were the first to publish convincing results that they were reaching the light-sail acceleration regime for amorphous carbon foil targets.[3] The researchers found that carbon ions were accelerated efficiently, but the beam still contained a mix of ion species, with the protons, because of their lighter masses, at higher energies per nucleon. Although the target had about a sixth as many protons as carbon ions, at high energies the ion beam had around 500 times as many protons as carbon ions.

Borghesi and his then graduate student Aodhan McIlvenny decided to try

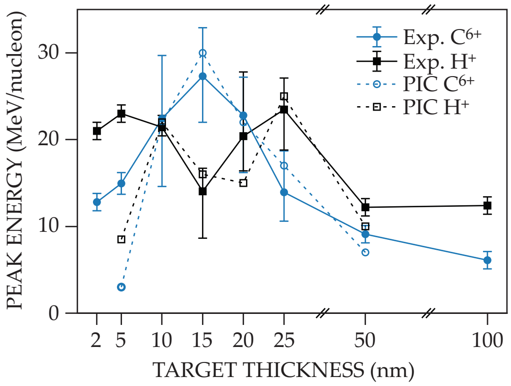

FIGURE 2. CARBON IONS (C^{6+}) reach a peak energy per nucleon in experiments (solid blue line) and in particle-in-cell (PIC) simulations (dashed blue line) when laser accelerated out of a target that's 15 nm thick. That optimal thickness strikes a balance of thin enough that a laser can easily push ions out of the material but not so thin that the laser has trouble interacting with it. Surprisingly, proton contaminants (H^+) in the material have a local energy minimum for the same target thickness (solid and dashed black lines). In previous experiments, the protons always had higher energies per nucleon than carbon ions did. (Adapted from ref. 2.)

again with more targets at a wider range of thicknesses than they used with the previous work. They performed the study at the Central Laser Facility, shown in figure 1, at the UK's Rutherford Appleton Laboratory. They used a 40 fs pulse of circularly polarized IR light to irradiate targets that were 2–100 nm thick. (Circular polarization results in less heating of the material's electrons than linear polarization does and thus maximizes the radiation pressure's steady push on the target.)

The researchers were looking for the optimal target thickness. Intuitively, the thinner the sample is, the more energy each ion will get from the laser. But to experience radiation acceleration, the material must reflect the laser beam.

Reflection happens only when the material exceeds a critical density at which it becomes opaque to the laser frequency. For highly intense laser pulses, the electrons in the plasma move at relativistic speeds, and their effective masses thus increase. The critical density consequently increases, so a target that was once opaque becomes transparent. That so-called relativistically induced transparency sets in at lower laser intensities in thin samples than in thicker ones.

In the new study, McIlvenny measured the maximum energy of the ejected carbon ions as a function of target thickness and found that the peak occurred in a 15-nm-thick target, as shown by the solid blue line in figure 2. What the researchers didn't expect was that for the same foil thickness, the proton contaminants (solid black line) had a local energy minimum and reached energies per nucleon only about half those of the carbon ions. The protons' disappearance from the beam was unusual: In all previous experiments, the proton energies per nucleon always surpassed those of carbon. The result was so surprising that, Borghesi explains, "we didn't really believe it. We thought maybe it was a limitation of the detector we were using."

In theory

To understand and verify the atypical behavior, McIlvenny performed particle-in-cell simulations of the carbon and proton energies as a function of target thickness and laser intensity for an idealized pulse and for one matching the experimental pulse. In the case of an idealized Gaussian temporal profile, the carbon ions' and protons' energy trends roughly matched, although the protons' energies were 30% higher.

The realistic laser profile, on the other hand, had a shoulder before the peak intensity. That shoulder resulted from the two plasma mirrors that the researchers used to smooth the laser profile and increase its intensity contrast. A plasma mirror is a polished surface that when excited by a high-intensity laser forms a plasma, which acts as a highly reflective active optical element. For the leading edge of the laser pulse, the plasma mirrors suppress the intensity until the laser is powerful enough to make them reflective, as happened a few picoseconds before the peak intensity.

The pulse shape creates three stages in the laser–foil interaction. First, the low-intensity shoulder causes the target to expand radially out from the center of the laser spot. Protons, with their lighter masses, race away from the central region faster than carbon. Next, the rising intensity causes the material in the central region to contract, but few protons remain in the region by that point. Finally, the peak arrives and accelerates ions, which are primarily carbon, in the central region. Protons are accelerated afterward by a less-efficient mechanism similar to TNSA.

The simulations showed that the same species-selective acceleration should be possible with a pair of pulses.

In practice

Other methods exist to reduce the contaminants in ion beams, including running an electric current through the target before irradiation and ablating the material first with another laser. Most of the methods, however, are complicated to implement and too destructive for the sorts of thin samples needed to access the efficient light-sail acceleration regime.

In the future, Borghesi and his colleagues' technique could be used for studying the effects of irradiation in cell cultures and other biological samples to help develop more efficient radiotherapy treatments. To get meaningful and reproducible results that can be compared with those from conventional sources, researchers need a well-defined ion species with a well-defined energy distribution. The light-sail acceleration setup offers those benefits in a system compact enough for a typical lab. The technique also accesses unique regimes of cellular irradiation—in particular, shorter bursts of ions than are possible with a conventional accelerator. Shorter doses offer the advantage of less damage to nearby healthy cells.

Borghesi and his collaborators are already exploring those research topics. Right now, the ion beam is useful for planar cell cultures, but moving to three-dimensional *in vitro* or even *in vivo* studies will require higher-energy carbon ions. The team members are exploring ideas for how to boost the energy: employing recently developed high-power lasers, gaining better control of the temporal and spatial shapes of the laser pulse, and finding ways to delay a thin target from becoming relativistically transparent. They are also exploring techniques for focusing the ion beam, which would offer even higher doses.

Heather M. Hill

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A windfall for US carbon capture and storage

How wisely will the billions of dollars in new funding for commercial-scale demonstrations be spent?

NRG ENERGY INC

THE PETRA NOVA facility in Texas is the sole commercial fossil-fuel power plant in the US capable of capturing its carbon dioxide emissions. The retrofitted capture equipment was switched off in 2020 because of economic conditions, including a drop in demand for CO_2 used for enhanced oil recovery.

A flood of additional financing became available for carbon capture, utilization, and storage (CCUS) when President Biden signed the $1.2 trillion bipartisan Infrastructure Investment and Jobs Act on 15 November. The Department of Energy, which had requested $531 million for CCUS in its budget for the current fiscal year, suddenly finds itself charged with administering more than $10 billion over five years for demonstration projects and R&D for those programs. Of that amount, $3.5 billion is allotted to support technologies for extracting and storing carbon dioxide from the atmosphere, an activity for which the administration last year had requested all of $66 million.

The appropriations, much of which are available immediately, include $3.5 billion for direct air capture (DAC), a fledgling technology that many experts say will be needed on the gigaton scale. And even after fossil fuels have been nearly extinguished, CO_2 removal from the atmosphere will still be necessary if humans are to keep concentrations below dangerous levels. One gigaton is equivalent to a year's emissions from the nation's 250 million cars.

Another $3.4 billion is allocated to commercial-scale demonstration plants and large-scale pilots of technologies for capturing CO_2 from fossil-fuel power plants and industrial facilities. The measure provides another $2.5 billion for CO_2 storage demonstrations.

DOE will have its hands full. The new law instructs the agency to create an office to administer demonstrations of CCUS, advanced nuclear reactors, and clean hydrogen production. The agency is required to spend $2.5 billion on six commercial-scale carbon capture demonstrations: Two will be for coal power plants, two for natural gas plants, and two for large industrial emitters such as cement, steel, and chemical manufacturers. The infrastructure act requires DOE to issue an initial solicitation for proposals within six months.

On 6 December DOE asked industry, academia, research laboratories, and others for suggestions on potential carbon management demonstration projects and their locations. Although it doesn't solicit specific proposals and offers no funding, the request seeks a wide range of information, including advice on potential carbon capture and DAC technologies, validation of carbon storage resources, pipeline infrastructure locations, and technologies for converting carbon into products. The comment period closes on 24 January.

Chicken and egg

Some questions are unanswered: How will DOE avoid repeating its experience with past CCUS demonstrations, most of which were abandoned? And how will the agency address the chicken-and-egg situation of companies waiting to commit to either CO_2 transport and storage infrastructure or CO_2 capture projects until the other exists or is in the works?

To help with that dilemma, the infrastructure act provides $1.5 billion for a low-interest loan program to finance shared CO_2 transport infrastructure. Also included are grants to incentivize pipeline builders to provide excess capacity for future CO_2 volumes.

Various proposals have been floated on where pipelines and connections should be located. Emissions sources in the Ohio River valley include 29 fossil-fuel power plants, 19 steel mills and aluminum smelters, 5 chemical manufacturing plants, and 2 refineries, according to a 2021 report from the Labor Energy Partnership, a joint effort of the Energy Futures Initiative and the AFL-CIO. Another concentration of industrial emissions is along the Texas and Louisiana coast, where the report identified 47 chemical plants, 31 power plants, 25 refineries, 23 natural gas processing facilities, and 21 ammonia and hydrogen producers.

ExxonMobil and other Houston-area businesses have expressed interest in forming a CCUS hub that would capture emissions from refineries and other industrial sources along the Houston Ship Channel. The CO_2 would be transported to the Gulf of Mexico, where ExxonMobil says multiple geological locations could store 500 gigatons. Denbury Inc and Gulf Coast Midstream Partners recently announced plans to develop geological carbon storage and injection operations near Houston in a property that could hold 400 million tons of CO_2. A Denbury news release says the company could begin injection at the Houston site in 2025 at an initial rate of 1.5 million tons per year.

The infrastructure act designates funding for the Environmental Protection Agency to establish a new permitting operation to accelerate applications for injection wells that are dedicated to geological storage of CO_2. The EPA has approved only two such wells to date. Nearly all the relatively small amount of CO_2 captured in the US today is injected into depleted oil fields to force out additional petroleum, a process known as enhanced oil recovery.

The CCUS and DAC programs, together with demonstrations funded in the infrastructure act for nuclear reactors, hydrogen production, and geothermal energy, are expected to cumulatively reduce CO_2 emissions by 1.4–2.5 gigatons over the next 17 years, says a report by ClearPath, a nonprofit advocacy group. In 2019, before the coronavirus pandemic, the country emitted 5.1 gigatons of CO_2, according to the US Energy Information Administration.

Scaling up

The act's $3.5 billion for DAC is specifically to create four "regional hubs." A hub is defined as a network of DAC projects, companies with CO_2 offtake agreements, a dedicated CO_2 transport infrastructure, subsurface storage resources, and other carbon sequestration infrastructure. Each hub must have a minimum extraction capacity of 1 million tons of CO_2 per year. That's two orders of magnitude more than the 4000-ton annual capacity of the world's first commercial DAC plant, built by the Swiss company Climeworks, that began operating in Iceland last September. A consortium of Carbon Engineering, based in Canada, and Occidental, a US-based firm, last year announced plans for a million-ton-scale facility in the Permian Basin in western Texas. Half of that total capacity is expected to become operational in 2024.

The infrastructure bill directs DOE to begin soliciting proposals for DAC hubs within six months. The hubs are to be geographically diverse, and at least two must be located in economically distressed areas with high levels of coal, oil, and natural gas resources. "You can imagine cross-pollination between heavily industrial areas that could potentially capture CO_2 and that have storage locations," says Jessie Stolark, public policy and member relations manager at the Carbon Capture Coalition, whose members include oil, gas, and electricity producers; environmental groups; and labor unions.

CLIMEWORKS

CLIMEWORKS began operating the world's first commercial plant to capture carbon dioxide directly from air in Iceland last September. The Swiss company says the plant, run with geothermal energy, has a capacity to capture 4000 tons of CO_2 per year. The purified gas is injected deep underground, where it mineralizes with subsurface rock.

Another factor in hub location should be access to clean electricity, since operating DAC on fossil energy will likely result in a net increase in CO_2, notes Robert Socolow, an engineering professor emeritus at Princeton University. But, he adds, "if you build a large solar field to power a DAC plant . . . you could ask why aren't you using that solar to close down a gas or coal power plant." Until most fossil-fuel plants are shut down or their emissions captured, Socolow says that DAC should be pursued as R&D and kept in reserve.

Although DAC isn't explicitly defined in the new law, Giana Amador, cofounder and policy director of the DAC advocacy group Carbon180, says the hubs are intended to support engineered chemical CO_2 extraction technologies, such as those of Carbon Engineering, Climeworks, and Global Thermostat, based in New York. Not qualifying, it appears, are the less-glamorous and more natural air-capture methods that include carbon mineralization, reforestation, and bioenergy with carbon capture and storage. (See the article by David Kramer, Physics Today, January 2020, page 44.)

A report released in November by the Japan-based Innovation for Cool Earth Forum says that with strong and sustained policy support from governments around the world, carbon mineralization processes could remove 1 gigaton of CO_2 annually from the atmosphere by 2035 and 10 gigatons per year by 2050. Since 2014 the forum has put on an annual conference on technological innovations to mitigate climate change. The most recent report notes that unlike DAC, the chemical reactions that occur with mineralization require no energy input, and resources of the type of rock needed exist widely throughout the world.

This past November, Energy secretary Jennifer Granholm announced a "carbon negative shot" with the goal of removing gigatons of CO_2 from the atmosphere and permanently storing it for less than $100 per ton. Amador says the current cost ranges from $200 to $600 per ton. The DOE program is to encompass R&D and demonstrations of DAC and other methods of atmospheric carbon extraction.

Carbon capture

It's unclear whether any of the three dozen US CCUS projects that have been announced, are in the planning stages, or are under construction can qualify to become demonstrations. Many of them have already been awarded DOE grants for front-end engineering and design work. One, NET Power, in November announced its delivery of CO_2-emission-free power from natural gas to the grid from a pilot plant that uses the Allam–Fetvedt cycle, which combusts natural gas with pure oxygen, instead of air, and employs supercritical CO_2 rather than steam as the working fluid to drive a turbine.

DOE's record on CCUS demonstrations has been far from stellar. Of the nine projects the agency backed—with a total of $1.1 billion from 2010 to 2017—only three were completed successfully, according to the Government Accountability Office. The Petra Nova coal power plant in Texas is the only functional CCUS-equipped fossil energy plant in the US; it's backed with $195 million in DOE funding. It shut down capture operations in 2020 because of declining demand for CO_2 in enhanced oil recovery.

Still operating are a hydrogen production facility in Texas run by Air Products and Chemicals, the recipient of $284 million in federal support, and an ethanol plant in Illinois operated by Archer Daniels Midland, which received at least $140 million from DOE. That plant injects the CO_2 into dedicated geological storage located nearby; Air Products' CO_2 is used in enhanced oil recovery.

FutureGen, a 2003 demonstration of capture and geological storage, was scrapped in 2008, and then redesigned as an oxygen-combustion plant and renamed FutureGen 2.0 in 2010. After $200 million in public funding was spent, the project was suspended in 2015 when DOE concluded that it couldn't be completed before the funding authority expired, as required by the 2009 American Recovery and Reinvestment Act. The agency had expected to contribute a total of $1 billion.

Perhaps the worst debacle was in Mississippi, with Southern Company's Kemper coal CCUS project, to which DOE contributed at least $270 million. Originally estimated to cost $2.4 billion, its construction ballooned to $7.5 billion before it was abandoned in 2017 and the plant was converted to natural gas without carbon capture.

David Hart, senior fellow at the Information Technology and Innovation Foundation, agrees there is a risk of more failures if projects aren't managed properly. Some past projects tried to demonstrate too many new technologies at once or to scale up too fast, he says. "With all the money pouring in, it's important to do front-end studies and take things one step at a time rather than go for the moon all at once."

More to come?

Absent from the infrastructure act are tax incentives that advocates say must work in tandem with the above measures to broaden adoption of CCUS. The House-passed version of the partisan Build Back Better bill proposes boosting the current credit for CO_2 capture with geological storage from $50 per ton to $85 per ton. Capture with utilization—whether for enhanced oil recovery or other purposes—would increase from $35 per ton to $60 per ton. The bill also proposes to increase the $50 per ton credit for DAC to $180 per ton. Equally important, the legislation would provide for the direct payment of credits to DAC startups that aren't yet profitable. At press time, the Senate had yet to act on its version of the bill, which will then have to be reconciled by a House–Senate conference committee.

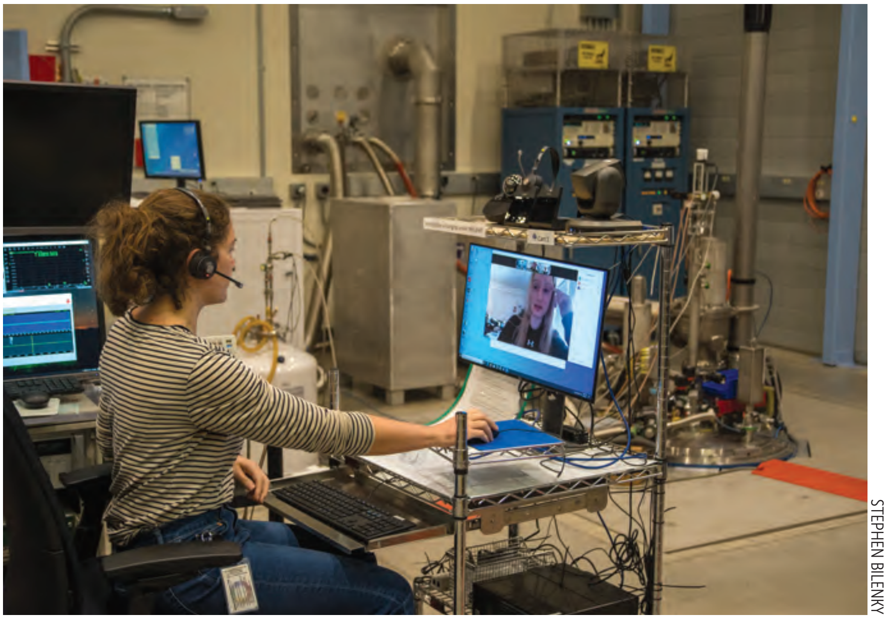
David Kramer

Staff scientists in academia and government labs follow rewarding careers

Being a faculty member is not the only way for scientists to stay in basic research.

"I was dead sure I'd end up as a university professor. I surprised myself by taking this position," says Archana Raja, who in 2018 turned down tenure-track offers from prestigious universities to join the Molecular Foundry at Lawrence Berkeley National Laboratory as a staff scientist.

Raja's time is split 50-50 between running her own research group and working with outside users. Her research centers on tuning bandgap, charge, energy transport, and other electronic properties of two-dimensional materials by modulating the local electromagnetic environment through substrate engineering. "I manage three labs," she says, "with optics, lasers, and cryogenics. We do sample fabrication and characterization." In work-



STEPHEN BILENKY

ELIZABETH GREEN (left) is a staff scientist at the National High Magnetic Field Laboratory in Tallahassee, Florida. Here she virtually assists Ingrid Stolt, at the time a PhD student at Northwestern University, with NMR measurements on a single crystal of a cuprate superconductor using the lab's 32-tesla superconducting magnet. When she is not working with external users, Green conducts her own research on exotic spin states of frustrated magnetic compounds.

ing with outside users, Raja looks for projects that are "scientifically adjacent" to her own research. "That's how I can best support them," she says. Typically, users come to the Molecular Foundry, one of five Department of Energy nanoscale research centers, for stays of up to several months. "I've been exposed to other fields through the users," she says.

Clinching her decision to accept the job, Raja says, were the Molecular Foundry's wide range of facilities, its emphasis on teamwork, and its mission to democratize science. "We foster collaborations with researchers from 30 states and 27 countries," she says.

At the Molecular Foundry, staff scientists receive startup funds, raise money to support students and postdocs, and pursue career tracks that culminate in permanent positions. They are also evaluated on their research records and may be paid more than their university faculty counterparts.

More generally, though, staff-scientist positions come with myriad titles and responsibilities. Jobs might involve running a lab for an individual faculty member, writing code, or overseeing the budget for a user facility. With the notable exception of government laboratory positions, the pay tends to be lower and more precarious than for either faculty or industry jobs.

Despite their variety, the roles of many staff scientists share some broad-brush similarities. For the most part, staff-scientist positions involve helping other scientists either directly by working alongside them or indirectly through maintaining or developing equipment. They are key to the functioning of a facility but often have low visibility. Staff scientists stay closely connected to the nitty-gritty of research throughout their careers, and many of them have their hand in a wide spectrum of research topics. Few teach courses, but many serve as mentors. Competing for grant money is seldom required—and it can be tricky on account of staff scientists' status or agency restrictions.

Skill sets and job security

Kris Hagel became a staff scientist through chance and circumstance. In the early 1990s, while he was a postdoc in nuclear physics at Texas A&M University's Cyclotron Institute, he applied for faculty positions. After two years, his adviser offered to keep him on as a staff scientist. "We had a gentleman's agreement," says Hagel. "I would split my time 50-50 between taking care of the computing facility at the cyclotron and doing research."

A large portion of his job is being the help desk, Hagel says. On the research side, he helps graduate students with their experiments and analysis, but he doesn't serve on thesis committees. He publishes original research and attends conferences; the research directions are set by his group leader.

As an undergraduate in the 1970s, Ron Fox worked at Michigan State University's cyclotron laboratory. He then headed to the University of Illinois at Urbana-Champaign intending to do a PhD. Instead, because he missed developing software, he completed his master's in experimental nuclear physics and then returned to Michigan State as a staff scientist. He's still there.

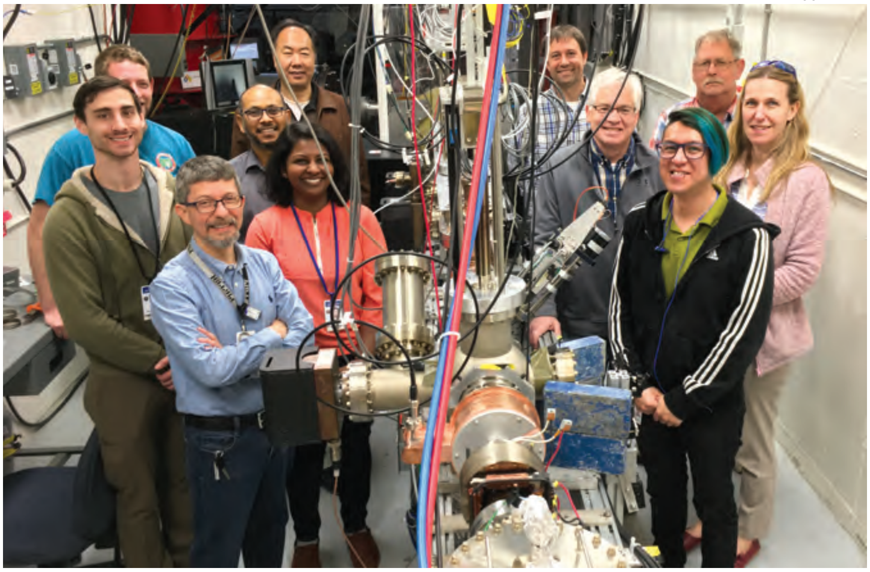
Fox writes and maintains code for the facility and for individual users. "I interact with users to iterate so they get what they need. I like being able to develop something useful from nothing and making it well structured." His day-to-day activities vary. "It can be immersive development. It can be chatting with people about what they need me to do. It can be running around responding to requests." The least enjoyable part of his job? "The high interruption rate. There are days when responding to requests is all I do."

Fox says he's respected for what he delivers. He and his colleagues support

K. RAMIREZ

ANAMARIA EFFLER (left), a staff scientist at the Laser Interferometer Gravitational-Wave Observatory's site in Livingston, Louisiana, and a colleague conduct measurements on one of the detector's many vacuum-system chambers.

R. SULEIMAN



STAFF SCIENTISTS, senior scientists, and students at the Thomas Jefferson National Accelerator Facility. Carlos Hernandez-Garcia (front left) is the staff scientist responsible for the facility's four electron-gun high-voltage systems. The pictured electron-gun test stand generates magnetized electron-beam pulses intended to cool relativistic ion beams in electron–ion collider accelerators.

more than three-quarters of a million lines of code. But, he adds, the experimental science staff and administrators "for the most part don't comprehend what it takes to produce this stuff." That lack of understanding, he says, "has made it difficult to adequately staff" the programming group.

A purposeful trajectory

As an undergraduate at Caltech in the 2000s, Anamaria Effler knew that a career in academia wasn't for her. She saw professors dealing with bureaucracy, serving on committees, and applying for grants. "A lot of them don't actually do research—they guide their students and postdocs," she says. "To me, it seemed like a headache. It didn't seem like a fun way to live."

After graduating with her bachelor's, Effler took a job as a technician at the Laser Interferometer Gravitational-Wave Observatory (LIGO) facility in Hanford, Washington. "I fell in love with the detector. I really liked the project, the science, and the people," she says. "But without a PhD, I didn't have the background to do a lot of the cool stuff." At LIGO, she saw firsthand the role played by staff scientists, and she went to Louisiana State University for her doctorate with the goal of landing such a position. She succeeded.

Since 2018 Effler has been a staff scientist at LIGO's site in Livingston, Louisiana. "I work on mechanics, optics, lasers and quantum noise, magnetic coupling," she says. Her main responsibility is to identify and reduce ambient noise in the interferometer. "We try to predict and characterize the different noise contributions, and to see which ones we can squash." LIGO employs roughly 60 staff scientists in total; for an early career scientist with a PhD the starting salary is $70 000–$90 000.

Like Effler, Sandra Bruce knew early that she was uninterested in a traditional academic career. After earning her bachelor's in physics at Harvey Mudd College in 2008, she took a job in industry working in optics. When she realized that "doors are much harder to open without a PhD," she went to the University of Texas at Austin to earn her doctorate working on the Texas Petawatt Laser, the flagship facility of the university's Center for High Energy Density Science. In 2018 she joined a startup company to work on high-power laser design. After being laid off during a rough patch for the startup, she ran her own consulting business for a while but then returned to the center as a staff scientist in 2020.

Bruce started off designing a clean room and additional beamlines for the petawatt laser and managing upgrades to its electrical, chilled-water, and vacuum systems. "There was a lot of creative liberty to decide what the space should look like and how to use the funds. I was given a budget to design the space," she says. She recently became the center's associate director.

"I have the best of all worlds," says Bruce about her role as a university-based staff scientist. "I make sure the machine runs, I interact with academics, and I don't have to do the publish-or-perish thing." The pay is less than in the commercial sector, she says, but she "didn't take a big hit." Her salary comes out of grants, but she has health insurance and retirement benefits through the university. If the petawatt laser lost its funding, she'd be out of work.

Research, support, service

The National High Magnetic Field Laboratory in Tallahassee, Florida, employs 80 staff scientists. In general, they split their time equally among research, user support, and service. But some staff scientists have vibrant research programs, while others focus on supporting users and maintaining equipment or developing experimental techniques, says Scott Hannahs, a staff scientist at the lab since 1993. Many of them appreciate the access to students that comes with the lab's close connection to Florida State University.

When Hannahs went on the job market in the late 1980s and early 1990s, few faculty positions were available. After a postdoc and a stint as a visiting professor, he took a staff research position at MIT's Francis Bitter Magnet Laboratory. As NSF phased out funding for the lab by 1995, he moved to Tallahassee to help set up the new one. The job aligned with his interests and ability to design experiments, he says. Now the lab's director of scientific instrumentation, he says he's "paid higher than most full professors."

Elizabeth Green has been a staff scientist at the magnet lab for about two years. She studies frustrated magnetic compounds with NMR. "I love the exotic spin states," she says. "They may have applications in quantum computing." Before she started at the magnet lab, her future boss told her she could choose what type of career to forge. "I like to publish, and I want grants to support postdocs and students," she says. "Also, in the US, very few people do condensed-matter NMR, so my hope is to teach people the technique and see it grow."

Research occupies about one-third of Green's time. The rest is divided between supporting users and developing instruments—all on a 32-tesla superconducting magnet. New users typically start on Mondays and work at the lab—remotely during the pandemic—for a week. "I like getting to know the people and learning about new science," she says.

Green's previous position was at the Dresden High Magnetic Field Laboratory in Germany, where she spent seven years—first as a postdoc and then as a staff scientist—after she earned her PhD at Florida State in 2012. The work in Germany was similar, but her job was more secure because of that country's employment laws. Trading a permanent position for one that depends on grants was the main hesitancy she had about returning to Florida. "But as long as the magnet lab is funded by NSF, I'll get paid. And the lab does great work."

Theory and practice

Staff-scientist positions are predominantly in experiment because of the user-support component. But theorists also work as staff scientists. One is Sinéad Griffin, who since 2018 has been a staff scientist at Lawrence Berkeley National Laboratory's Molecular Foundry and its materials science division. "A big part of my research is designing the next-generation dark-matter detectors," she says. The condensed-matter theorist works with high-energy physicists. In her computations and simulations, Griffin applies models of dark matter to predict how it might interact with different materials. Her work yields recommendations for what could make good detector media.

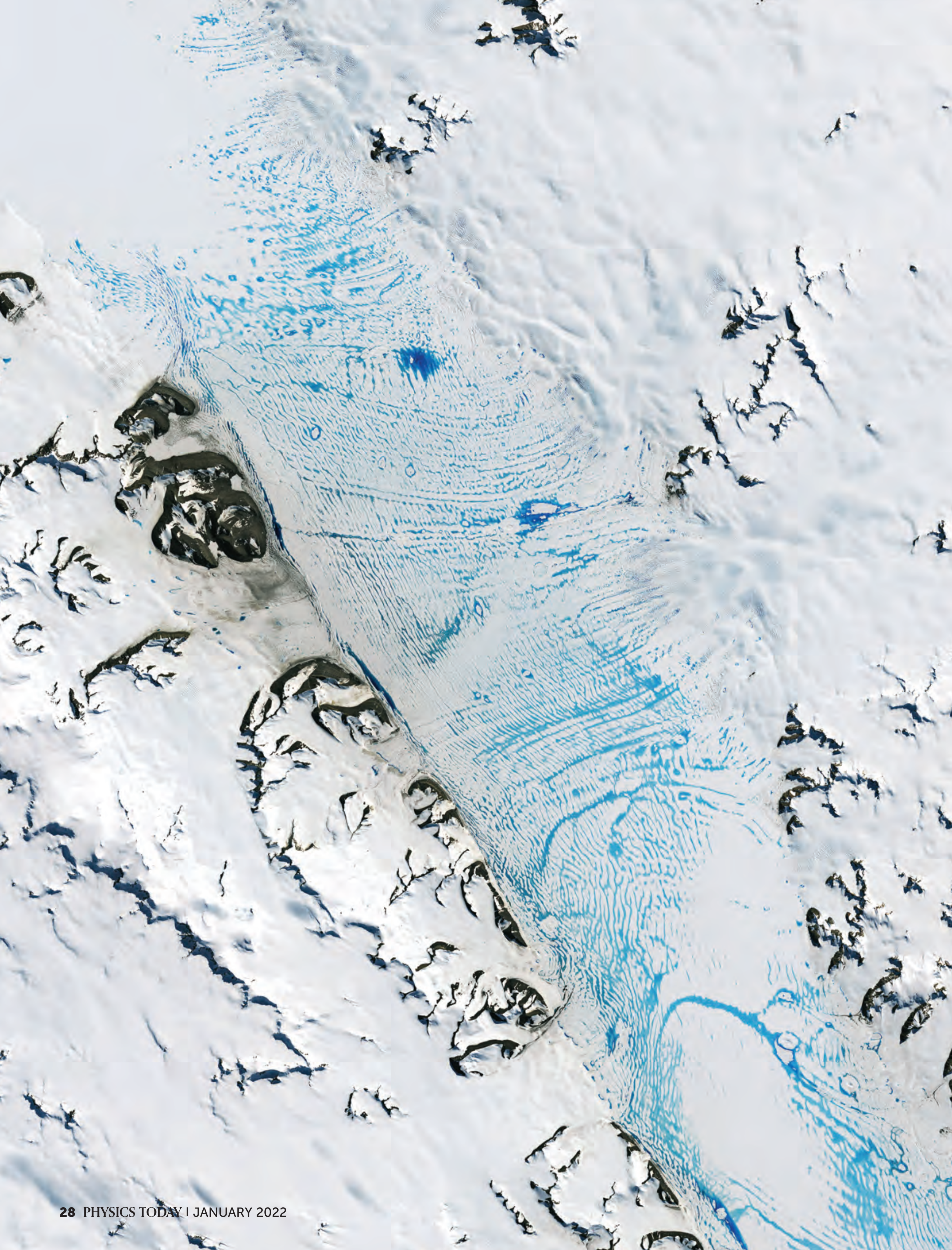
As a DOE facility, the Molecular Foundry is mission driven. "What we work on is dictated by the host lab and DOE," says Griffin. "Built into that is pivoting your research accordingly. That's great if your interests align." A plus, she says, is the team-based approach. "There is more emphasis on collaboration at national labs than in most university departments." A minus, she says, is the confusion among some peers about what a staff scientist does: "There is some outward appearance that we are more like technicians, rather than scientists who forge and lead research projects."

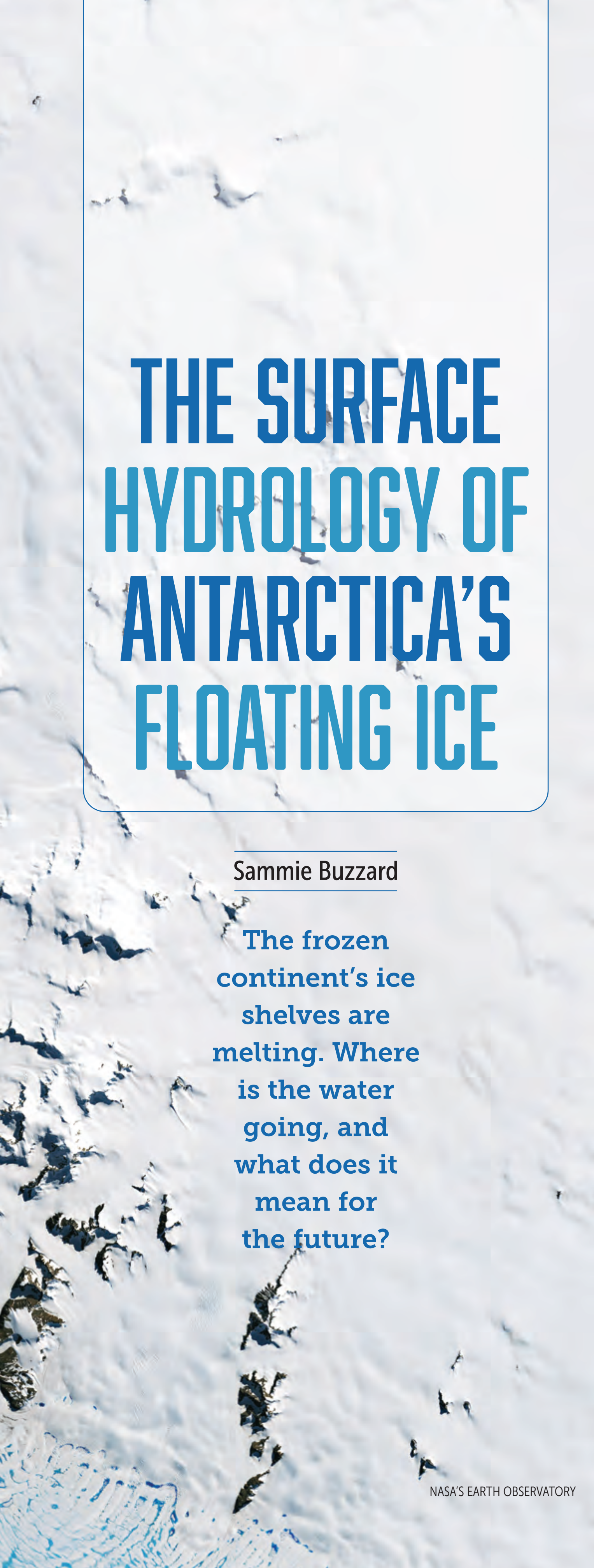
Agham Posadas is a rarer breed of staff scientist in that he works for an individual professor, Alexander Demkov at the University of Texas at Austin. A theorist, Demkov started a lab where one current focus is electro-optically active oxides on silicon for potential applications in neuromorphic and quantum computing. Posadas joined the lab as a postdoc in 2007, and after a couple of years the job morphed into a staff-scientist position.

Lab management—including equipment maintenance and mandatory safety reports—takes about 60% of his time, Posadas says. The rest goes to conducting his own research and mentoring students. "I don't have to worry about writing grants to get funding," he says.

Posadas says his pay falls short of a new professor's. And he doesn't know whether he'd keep his job if Demkov moved or retired. All around, though, he appreciates the work–life balance. To physicists on the job market, he says: "If you are not intent on a faculty position, a staff-scientist position is a good option."

Toni Feder PT





NASA'S EARTH OBSERVATORY

THE SURFACE HYDROLOGY OF ANTARCTICA'S FLOATING ICE

Sammie Buzzard

The frozen continent's ice shelves are melting. Where is the water going, and what does it mean for the future?

Sammie Buzzard is a lecturer in climate science at Cardiff University in Wales.

Imagine an area the size of the US state of Rhode Island, some 3000 km^2, breaking off from the land, collapsing, and floating away. Picture Brown University completely submerged and houses falling into the Atlantic Ocean. Luckily for the residents of Providence and the rest of the state, Rhode Island is a relatively stable land mass, so such a collapse is an unrealistic scenario. But if it were built on an Antarctic ice shelf, the story would be a little different.

Ice flows across Antarctica and continues to do so as it reaches the edge of the land mass and extends over the ocean. The huge floating tongues of ice often remain attached to the continent. Anything that remains grounded on the land is part of the Antarctic ice sheet; the floating part is an ice shelf. Floating ice shelves surround three-quarters of Antarctica's coast and make up about 11% of its total area. One of the largest, the Ross Ice Shelf, is roughly the size of France. The George VI Ice Shelf is shown in the opening image, taken by NASA's *Landsat 8* in January 2020.

It may seem intuitive that all the ice added to the ocean from melting ice shelves would raise global sea level, but that's not the case. By Archimedes's principle, ice shelves floating on the water have already displaced their own weight, so their disintegration or melting won't change the water level. Ice shelves do, however, regulate the speed of glaciers on Antarctica's land. As shown in figure 1, ice shelves act to hold glaciers back. Take the shelf away, and the glaciers are free to speed up and flow into the ocean. Any ice and liquid water that the glaciers take with them will raise sea level. Of Earth's fresh water, 70% is stored in Antarctica's ice; that is the equivalent of about 58 meters of sea-level rise if all of it were to melt.

Although ice shelves are located thousands of kilometers away from anywhere else on Earth, their loss has global consequences. It can change ocean circulation, temperature, and salinity when the cold, fresh water from a collapsed shelf floats into the ocean and melts. Furthermore, sudden collapses destroy habitats for penguins and various other creatures.

In 2002 the Larsen B Ice Shelf, an area roughly the size of

Rhode Island, suddenly disintegrated spectacularly. It shattered into smaller pieces and was dispersed to the surrounding ocean in less than a month. Scientists have observed several major ice-loss events over the past few decades, including on Larsen B's next-door neighbors. The Larsen A Ice Shelf collapsed in 1995, and in 2017 the Larsen C Ice Shelf lost an iceberg larger than the areas of Larsen A and Larsen B combined.[1]

In the case of Larsen B, the ice shelf was located on the Antarctic Peninsula, the most northern part of the continent. The region is one of the warmer areas of Antarctica, and the surface of the ice is melting. The water from it accumulates to form lakes up to 4 km long. Larsen B was covered in those lakes, but just before the ice shelf collapsed, the lakes started to drain one after another. Scientists suspect that the chain reaction of draining lakes was key to the sudden collapse of the ice shelf.[2] Figure 2 shows NASA satellite imagery of the breakup: The small blue-colored features in the middle of the photo are lakes.

Between 2012 and 2016, the Antarctic ice sheet lost 199 ± 26 gigatons of ice per year.[3] Researchers in the climate-science community hotly debate how much of the sheet will melt in the future and at what rate. Part of the debate focuses on whether the direction of the bed slope beneath the ice sheet will influence the melt rate, which is known as marine ice-sheet instability. The ice sheet is considered unstable when the bed slopes downward from the point that the sheet becomes afloat toward its center. Another possibility, known as marine ice-cliff instability, arises when unstable ice cliffs form as ice shelves collapse.[4] Both instabilities are theoretical possibilities that have yet to be observed, and the choice to include them in ice-sheet models produces a wide range of future predictions of Antarctica's contribution to sea-level rise.[5]

Although many ice shelves currently remain relatively unscathed, researchers are investigating which of them may be at future risk and which collapse events may be related to human effects on the climate.[6] Lakes and other features caused by melting snow and ice have been observed on other ice shelves in Antarctica,[7] in the Arctic on the Greenland Ice Sheet, and on the frozen sea ice in the Arctic Ocean. To understand what the future may hold for the planet's frozen regions, researchers need to understand more about the melting. How well are computer models capturing the thermo-

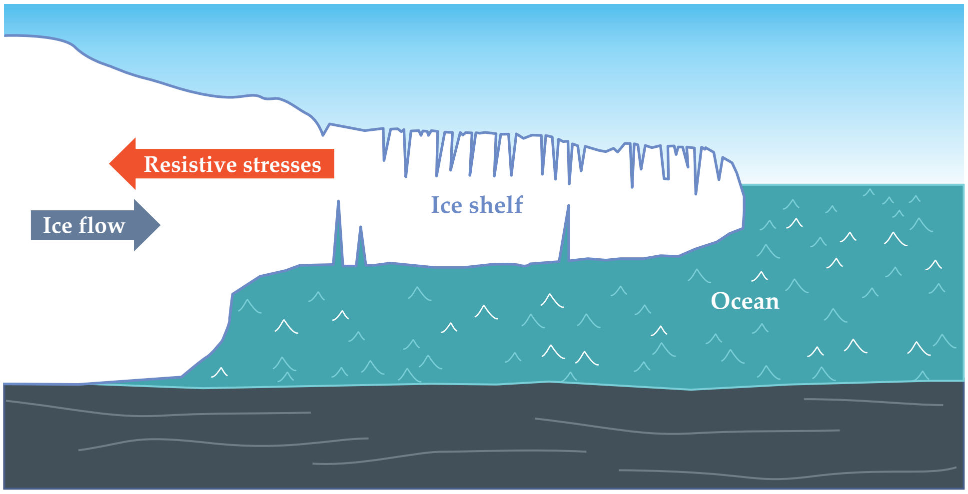


FIGURE 1. RESISTIVE STRESSES restrain ice from flowing into the ocean. Some of the ice from the grounded sheet on the left floats on the ocean surface, where it prevents more ice from accelerating into the water and contributing to increased global sea level. (Image by Sammie Buzzard and Donna Padian.)

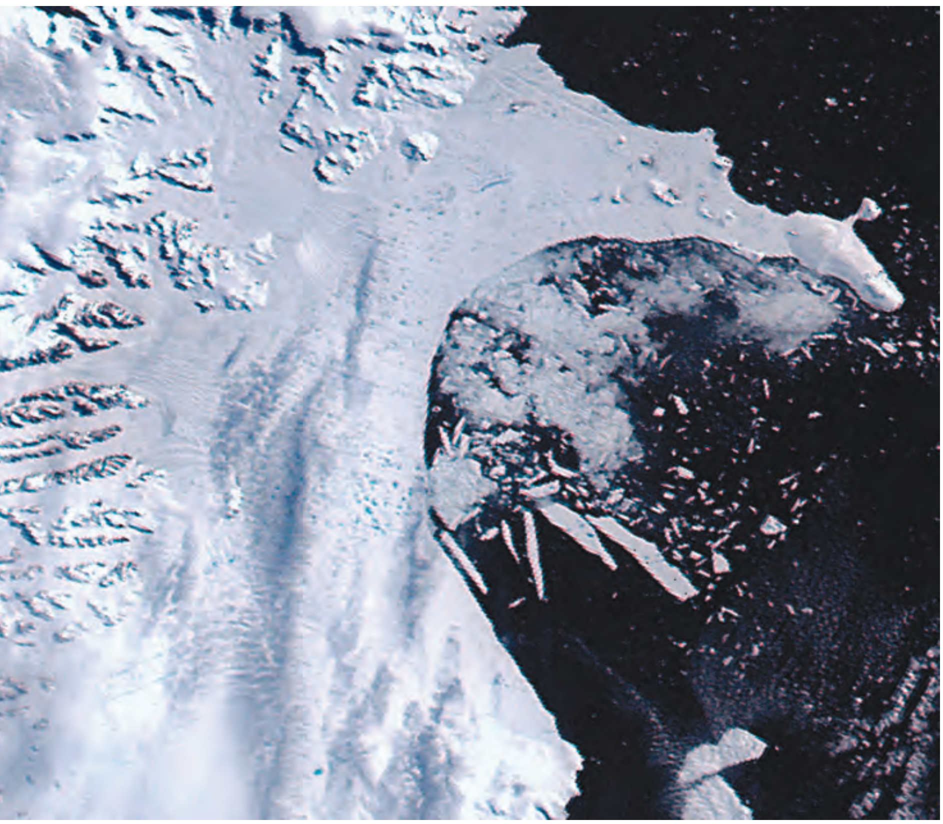


FIGURE 2. THE LARSEN B Ice Shelf, which totaled some 3000 km^2, collapsed from Antarctica's land surface in February 2002. The solid white areas are the ice shelf, the dark area to the right is ocean, and the white fragments are disintegrated ice shelf or sea ice. The speckled blue-colored features on the ice shelf are melt lakes that were present at the time of the collapse and that likely contributed to the shelf's instability. (Courtesy of MODIS, NASA's Earth Observatory.)

dynamics of ice shelves? How and where are they melting, and where is the water going?

Antarctica's changing surface

The ice shelves and ice sheets of Antarctica are made of more than solid ice. In many areas, a layer of snow, sometimes tens of meters thick, lies on top of the ice. Over time, that snow forms ice sheets. As more snow falls on the surface, the older snow below becomes more compacted and is eventually dense enough to form solid ice. Called meteoric ice, it is derived from precipitation, which in Antarctica almost always means snow.

The snow layer complicates estimates of ice-shelf melting because any water produced through melting at the surface will drain down into the snow. Although some satellite methods can detect water on the surface and in the snow, observations are limited and don't always provide accurate values. Many estimates of the amount of melting are based on regional climate models, and scientists still have a lot to learn about the snow itself: how deep it goes, how dense it is, and how those properties change over space and time.

One thing glaciologists can be sure about is that Antarctica gets quite cold. When water drains into the snow, it often refreezes, which causes two important changes to the ice shelf. The frozen water alters the shelf's density and its temperature. The density change is intuitive: Filling lots of fluffy, airy snow with water that freezes will make the snow denser than it was originally. In some cases, enough water refreezes in the snow to form lenses, or layers, of solid, impermeable ice. They can be a few centimeters to several meters thick.[8] Figure 3 shows some examples of ice lenses, which can be important for lake formation in ice shelves.

The second change, the ice shelf's temperature, occurs because of the release of latent heat as water freezes and becomes ice. The phase change heats up the surrounding snow enough that when the ambient temperature reaches 0 °C, a layer of constant-temperature, or isothermal, snow develops that extends from the surface to the depth that the meltwater has reached.

For lakes to form, the snow has to become completely saturated with meltwater. The isothermal layer would need to extend down to where the snow becomes so dense that water can no longer percolate through it. The maximum depth that water can reach is known as the pore-closure depth of the ice shelf. The formation of ice lenses can expedite the saturation of the snow. Because the lenses are mostly impermeable to meltwater, any water that reaches them is then stuck and can't permeate farther. The water begins to saturate the snow from the ice lenses upward, which means that a much smaller melt volume is needed for the snow to become fully saturated and for lakes to form on top of the snow–water mixture.

Once lakes form, they can accelerate the melting of the surrounding ice through multiple processes. First, the lakes are darker than the ice and thus have a lower albedo, or reflectivity. Consequently, they absorb more shortwave solar energy than the ice, heat up, and melt more of the surrounding snow and ice. The positive feedback loop leads to more melting.

Second, the water itself causes additional melting if it gets into existing crevasses on the ice shelf. The weight of the shelf—known as overburden or lithostatic pressure—acts to close crevasses. But the water pressure can counteract the lithostatic pressure and open the crevasse horizontally and vertically. With enough water, the crevasse penetrates the whole ice shelf, a consequence of which may be sudden collapse, depending on the stresses the shelf is experiencing. In addition, researchers have observed that the weight of the water in the lakes bends the ice shelf. That process may have contributed to the instability of Larsen B.[2]

Science at the poles

Given the size of Antarctica and the logistics of getting there and taking measurements, observing ice processes is especially difficult. Satellites provide some information. Lakes are visible, for example, in optical images, but as soon as their surfaces refreeze, it is no longer possible to determine whether they contain water or to distinguish them from surface ice. Other complicating factors include clouds blocking the satellite's view for a substantial proportion of time and the 24 hours of darkness the South Pole experiences for five months of the year.

FIGURE 3. GLACIOLOGIST HEÏDI SEVESTRE points to lenses of solid ice in a snow wall that separates two snow pits on the Larsen C Ice Shelf in Antarctica. (Courtesy of Project MIDAS, Swansea University, and Aberystwyth University.)

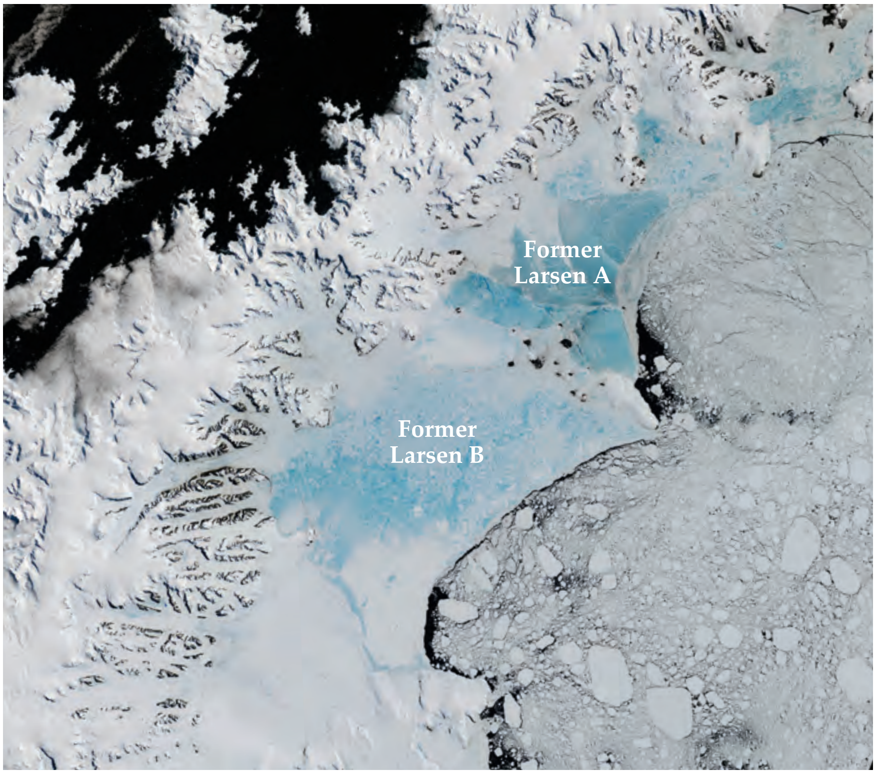


FIGURE 4. TWO ICE SHELVES, Larsen A and Larsen B, collapsed from the east coast of the Antarctic peninsula in 1995 and 2002, respectively. Sea ice now fills their place. Recently the Larsen C Ice Shelf (not shown) has experienced potentially unstable conditions, including the loss of a huge iceberg in 2017. (Courtesy of NASA's Earth Observatory.)

Researchers at the UK's Halley VI Research Station farther north on Antarctica's Brunt Ice Shelf have to endure "only" around 100 days of darkness a year.

Automatic weather stations provide information about ice-shelf conditions even when people aren't there to monitor them. Only a limited number of locations, however, are monitored by the network of instruments, which people still need to maintain and retrieve the data from. With the 2020 and 2021 field seasons disrupted by the COVID-19 pandemic, operations have been severely curtailed, including travel. To date, Antarctica has had only a few coronavirus cases. The majority of data-gathering fieldwork was canceled or postponed in the 2020–21 field season, and the limited personnel who have traveled to the continent are mostly maintaining existing instrumentation rather than doing any new science.

Although researchers have been allowed to continue with some fieldwork during the 2021–22 season with stringent quarantine requirements, they will have to wait at least another year to collect valuable measurements such as those taken from radar surveys, which reveal the inner structure of the ice shelf and where they should drill for ice cores. They can learn about past climates by looking at the air bubbles trapped in the cores (see the article by Mark Maslin, PHYSICS TODAY, May 2020, page 48).

Simulating Antarctica's water

Given the lack of direct water observations on Antarctica, computer models are essential to predicting the future of the continent's ice shelves. Researchers at Cardiff University and Georgia Tech are currently collaborating to develop MONARCHS, the first comprehensive model for surface meltwater across Antarctica's ice shelves. (The acronym stands for Model of Antarctic Ice Shelf Surface Hydrology and Stability. Scientists do love a tenuous acronym.) The collaborators will use it to assess what areas of Antarctica are vulnerable to collapse events.

One ice shelf of particular interest is Larsen C. The next-door neighbor of the former Larsen B, it is Antarctica's most northern ice shelf and the continent's fourth largest. The Larsen Ice Shelves, of which there were originally four, were named after Carl Anton Larsen, a Norwegian whaling captain who sailed along the ice front in 1893. Although Larsen A and Larsen B have mostly collapsed (see figure 4), Larsen C and Larsen D still remain.

Larsen C hit headlines in 2017 when a huge iceberg broke away from the shelf.[9] Although the production of an iceberg is a natural event and doesn't necessarily indicate climate change, researchers are concerned about the lakes that satellite images have revealed on part of the ice shelf.

The snow on Larsen C that sits on top of the ice is several meters deep, and water from snow melting at the surface will drain downward into the remaining snow. For a lake to form, it would take a lot of water, likely several times more than would be provided in any one location by the melting snow at the surface of the ice shelf. The large volume of water that would be needed suggests that something else is contributing to lake formation. Scientists need to understand whether the water accumulates in certain areas because of the shape of the ice shelf's surface or if the processes involving the refreezing of water have an effect.

To simulate ice-shelf processes, computer models need to include not just the energy balance at the surface of the ice shelf and the heat transfer through the ice and snow, but also the changes in the density of the snow as it melts and refreezes and the path of any water produced across the ice shelf's surface.[10] A significant amount of computing power has to be dedicated to certain processes. The vertical percolation of meltwater, for example, happens on scales of a few centimeters to meters, whereas water can travel laterally across the ice shelf for many meters or even kilometers. A simulation of horizontal water transport across several kilometers of an ice-shelf surface takes just a few minutes on a laptop. But including the water percolating vertically down into the snow and refreezing can mean running computer simulations for several days on a supercomputer.

Although the refreezing of meltwater to form ice lenses can be important for the formation of melt lakes and can cause lakes to refreeze,[11] a lot of work remains to determine how water moves laterally across ice shelves and how it affects their stability. Could the future of the Larsen C Ice Shelf be headed for a fate similar to that of Larsen B?

The future of polar regions

Much of the work mentioned in this article is applicable beyond Antarctica's ice shelves. In the Arctic, the Greenland Ice Sheet is melting, and lakes have formed. In many ways, the surface behaves similarly to that of ice shelves. Most of Greenland's ice is grounded, but if water drains to the bed of the ice sheet, it can lubricate the base. The sheet then slides across its bed faster, reaches the ocean more quickly, and accelerates sea-level rise.

Meltwater processes also apply to sea ice, the frozen layer of seawater that sits on the surface of polar oceans, although on a smaller scale and with added salt. Ponds on the surface of sea ice contribute to its seasonal retreat and breakup as it disappears each summer with increasing temperatures.

As global temperatures continue to rise because of climate change, knowing more about the role of meltwater and the thermodynamics of the ice in Earth's frozen regions is becoming increasingly important. Scientists are discovering new features of meltwater, such as fast-flowing rivers and waterfalls, which complicate their understanding of Antarctica's hydrology. Additionally, they need to fully comprehend the effect of a warming ocean on the base of ice shelves. As Earth continues to warm, those effects will likely continue to develop, damage ice shelves, and raise sea level. Antarctica's contribution to global sea level is increasing: Between 1992 and 2017, Antarctica is estimated to have contributed 7.6 mm to global sea level,[12] with two-fifths of that amount occurring since 2008.

The sizes of ice sheets and ice shelves and water's high heat capacity mean that polar regions are slow to respond to climate change. It appears that humanity has committed to centuries of ice-sheet melt and sea-level rise that will continue until the polar regions reach a new equilibrium state. Understanding the polar regions better, however, will allow society to plan for that change, protect the most vulnerable communities from the consequences, and ensure that humanity's actions going forward do not make the problem worse.

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COMETARY CHEMISTRY

Kathrin Altwegg

Celestial messengers carry a link between interstellar matter and life on Earth.

Although comets can appear extremely bright to observers, cometary nuclei are the darkest objects in our solar system. Their albedos are around just 4%. Their apparent brightness is caused by solar light scattering from their tails—micrometer-sized dust grains ejected from the nuclei. Although the nuclei are tiny, just a few kilometers in diameter, their visible tails can span the night sky, as seen here for comet McNaught behind Mount Paranal in Chile in 2007.

Despite their small size, comets receive significant research attention. Since ancient times, they have been recognized as special—and often as messengers announcing imminent doom. Today we know that comets actually carry a wealth of information about the solar system's early history.

To the best of our knowledge, comets formed far from the young Sun in a cold part of the protosolar disk. They were then scattered by the giant outer planets either into the Kuiper belt, a ring of objects that lies outside Pluto's orbit but still in the ecliptic plane, or into the isotropic Oort cloud, a collection of objects understood to reside 20 000 AU from the Sun. And there they remain unless collisions or other gravitational disturbances scatter them to the inner solar system.

Temperatures in cometary reservoirs are below 30 K, so comets contain well-preserved material from the earliest stage of solar-system formation. When they warm upon entering the inner solar system, they shed their icy surface layers through sublimation, which continually exposes fresh material until the comets break up or lose all their volatile material and become dormant. That fresh material dates back to the solar system's formation and can provide evidence of nucleosynthesis, the formation of complex organic molecules, and other chemical processes that happened along the way.

Cometary exploration

Remote sensing of cometary tails and comae, the atmospheres around comet nuclei, started with the appearance of Halley's comet in 1910 (see figure 1). The first *in situ* exploration, however, came when the European Space Agency (ESA) launched the *Giotto* spacecraft, which approached comet 1P/Halley during its 1986 return. The spacecraft's observations showed that comets are much more than dirty snowballs, as postulated by Fred Whipple[1] in 1950. Rather, they contain a plethora of molecules with atomic masses of 100 or more.

The appearances of two big comets—Hale–Bopp and Hyakutake in 1995 and 1996, respectively—led to a major step forward in cometary research. In the years since Halley's transit in 1986, Earth-bound telescopes have become more powerful, capable of covering wider frequency ranges and detecting many new chemical species in the bright

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comets' comae. Those telescopes now can also observe a larger population of comets—so many that ones from different families, such as long-period Oort-cloud comets (OCs) and short-period Jupiter-family comets (JFCs), can now be compared.[2]

Such species as diatomic nitrogen remain elusive, however, as they lack or have only weak optical transition lines. And even the most powerful telescopes observe mostly comets with strong outgassing—that is, active comets that travel relatively close to the Sun. Data therefore show a strong bias toward more active OCs relative to JFCs and toward comets with small perihelion distances.

In situ observations have come mostly from flyby missions targeting one or two comets at a predetermined distance from the Sun; for example, *Giotto* encountered comets 1P/Halley in 1986 and 26P/Grigg–Skjellerup in 1992. Missions are generally limited to flybys because of the high velocities the spacecraft would have to reach to keep up with the comets. Only the ESA's *Rosetta* probe[3] followed a comet, 67P/Churyumov–Gerasimenko, over a large part of its orbit around the Sun (see figure 2). It launched in 2004 and, after three flybys of Earth and one of Mars, reached comet 67P/Churyumov–Gerasimenko in 2014. *Rosetta* stayed within a few kilometers of the comet for more than two years and finally crash landed on its surface in September 2016.

Rosetta carried 11 instruments and the landing unit *Philae*. It was the first probe to monitor a coma's evolution. Several instruments analyzed refractory material—the size, mass, speed, and composition of dust. Others were optical spectrometers that measured wavelengths from UV to microwave, and some, of course, were cameras. *Philae* itself had nine instruments on board, including two mass spectrometers and a drill.

Because of the comet's small size and low density, it exerts gravitational forces that are one hundred-thousandth the size of Earth's, so harpoons were used to anchor the lander to the surface. But they malfunctioned, and *Philae* hopped around, landing not once but four times. It ended up in a tilted position in the shadow of a ledge. Results from *Philae* are therefore scarce, but nonetheless extremely important, as they provide some ground truth. A summary of the mission and its main scientific results can be found in reference 4.

Why study comets?

Cometary material originated well before the solar system's formation 4.6 billion years ago. It contains tracers of all stages of formation, from the interstellar medium to planets to, maybe, the origin of life.

Figure 3 shows a sketch of the developmental stages of material in the solar system. The tenuous interstellar medium, with a density of less than 10^3 cm^{-3}, is composed of gas and dust released from long-dead stars, such as supernovae and red giants. Those objects are responsible for the nucleosynthesis of atoms heavier than helium and for producing submicrometer refractory grains composed of silicates, graphite, aluminum oxides, and other minerals. Each stellar source produces a specific isotopic signature.

Chemical reactions eventually arise in the interstellar medium, albeit slowly because of the low densities and temperatures. Simple gas-phase molecules, such as diatomic hydrogen, cyanide, and hydroxide, start to form. Dark molecular clouds—dense agglomerates of dust grains and gas—form by gravitational forces. They can be huge, up to 600 light-years in diameter and 100 million solar masses. At 10^3 cm^{-3} and 10–20 K, the clouds are slightly denser and warmer than the surrounding interstellar medium.

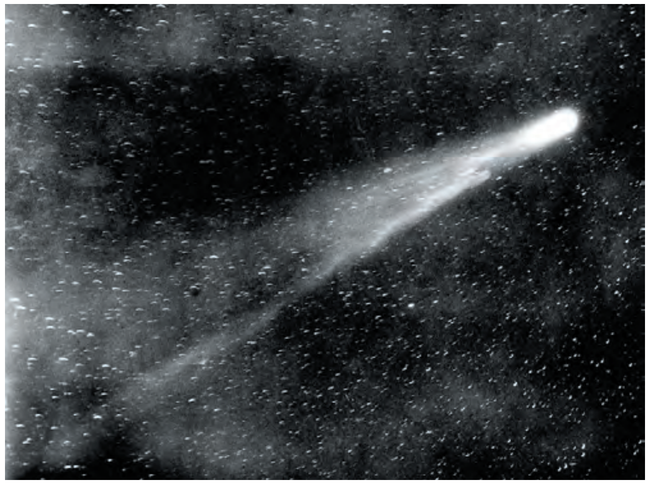


FIGURE 1. COMET 1P/HALLEY was first photographed during its 1910 traverse. (Courtesy of the Yerkes Observatory/public domain.)

Although interstellar-medium chemistry is governed by ion–neutral reactions in the gas phase, the ionization in dark clouds is low because of the absorption of radiation by dust. The tiny dust grains can act as catalysts for chemical reactions: Atoms or radicals condense onto the grains and then become joined. For example, carbon monoxide condenses and, over time, is converted to methanol with the addition of hydrogen. Dust grains therefore accumulate icy layers composed of different molecules. Condensation and subsequent sublimation and recondensation, which may be mass dependent and are driven by changes in surrounding radiation fields, cause isotopic fractionation.

Once gravitational forces collapse part of the dark cloud into a disk, the density increases as material flows toward the disk's center. Eventually it becomes high enough for a star to start forming. Temperatures in such regions show strong gradients. Before a star ignites, temperatures are around 10–20 K a few astronomical units from the protostellar disk's center along the midplane and 100 K in the densest part. Molecules near the center can sublimate from the icy layers of the dust grains, undergo chemical transformation, and then flow out into colder regions and recondense, leading to even more complex species.

Even after a protostar has formed and ignited, it's shielded by dust, so the midplane of the protoplanetary disk just a few astronomical units away remains dark and cold. Along the z-axis, however, bipolar jets originating from the star extend perpendicular to the plane and allow ions and hot material to mix with cold midplane material. That process may lead to additional chemical reactions, although the extent to which it does is still debated.

Material then aggregates into planetesimals from which planets form. Depending on a planetesimal's size and its distance from the star, any memory of the material's origin may already be partly or mostly lost. The material has already undergone sublimation, ionization, and chemical interactions with other species before recondensing. Large planetesimals are subject to considerable heating by radioactivity—mainly from

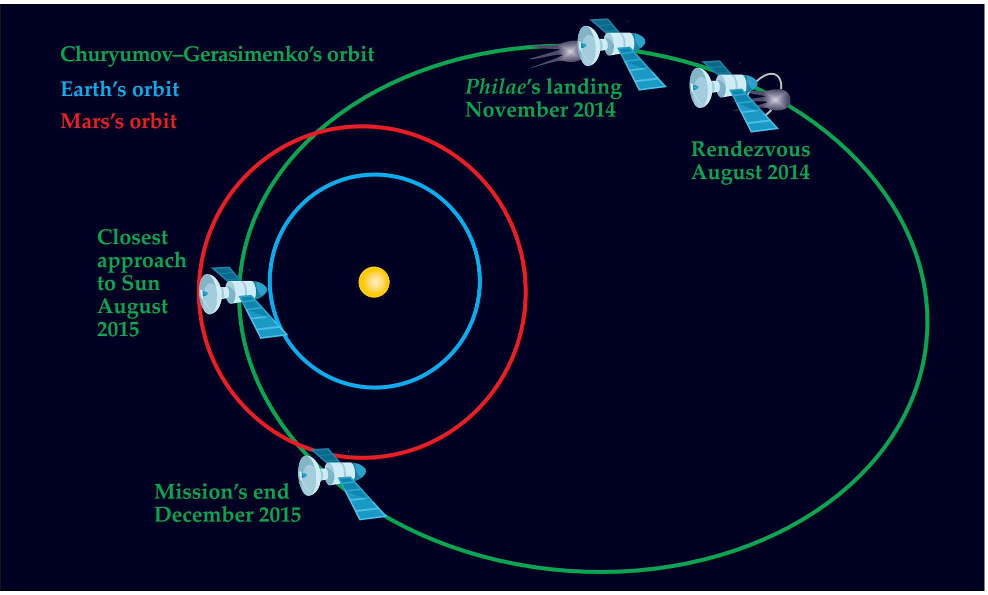


FIGURE 2. THE *ROSETTA* PROBE met comet 67P/Churyumov–Gerasimenko in 2014 when it was 3.8 AU from the Sun. It followed the comet for more than two years, including going through the comet's perihelion at 1.29 AU. (Adapted from a schematic by the ESA.)

the decay of ^{26}Al—which leads to liquid water in their interiors that can alter their minerals. The liquid phase also leads to differentiation, particularly in planets, big asteroids, and moons, with denser material sinking to the center. Small asteroids are often fragments of larger bodies and show signs of high-temperature processes with liquid water. The nature of the original material from which the solar system emerged is therefore nearly impossible to detect in planets, moons, and even asteroids.

In comets, however, evidence from the early solar system is preserved because the bodies experience little chemical activity in the solar nebula. Comets form in the outer protoplanetary disk, probably 30–50 AU from the center, and their sizes remain so small—a few kilometers in diameter—that heating by radioactivity is moderate at most. No aqueous alterations can be found in cometary material, although some high-temperature minerals have been detected, which is proof of some mixing with the protoplanetary disk. Comets' porous structures also have very low thermal inertia, which keeps their interiors cold.

Blast from the past

Once a comet enters the inner solar system, and during each orbit around the Sun, it sheds its damaged surface layer and exposes fresh, unaltered material. That material originates from the prestellar stages and can be sampled remotely or *in situ*. Comets also transport material from the cold outer edge of the solar system to the inner parts, including Earth. From the number of craters on our moon, it is evident that small bodies did impact planets and moons in quite large numbers well after the larger bodies formed and may therefore have changed or complemented terrestrial material by supplying water and organics.

Noble gases in cometary material undergo few chemical interactions, which makes the gases important for understanding how the material that makes up our solar system evolved. Their isotopic fingerprints reflect the earliest stage at which the elements formed by nucleosynthesis and point to certain stellar origins. The abundances of volatile molecules, such as CO, methane, argon, and diatomic sulfur, present a record of the temperatures experienced by the material throughout its evolution.

Isotopologues—molecules with the same chemical formula that differ by at least one isotope, such as $C^{16}O$, ^{13}CO, and $C^{18}O$—have different sublimation and condensation rates that lead to isotope fractionation. The rates and temperature dependences of their chemical reactions are also often slightly different, which again leads to fractionation. Studying isotopologues of different molecules provides clues about the molecules' formation temperatures. It also points to the kind of cold-temperature chemistry that may have occurred. Detecting evidence of such processes as gas-phase, gas–grain surface, and ion chemistry provides information about the stage at which the compounds were formed.

The deuterium-to-hydrogen ratios in cometary water (HDO/H_2O and D_2O/HDO) are sensitive to external factors, including temperature and the type of chemistry that produced the water. Comparing those ratios in terrestrial and cometary water indicates how much water could have been delivered to Earth by comets.

Comparing the degree of organic-molecule complexity in comets with that in the interstellar medium, dark clouds, and star-forming regions hints at how much chemistry is inherited from those cold prestellar environments rather than from the protoplanetary disk. Prebiotic molecules and other species essential for life that are found in comets might provide clues about how life got started on Earth.

A cometary portrait

The comet 67P/Churyumov–Gerasimenko is a JFC with a period of 6.45 years, an aphelion distance of 5.68 AU, and a perihelion distance at 1.24 AU. It has a mass of about 10^{13} kg and a density of 533 kg m^{-3}. The comet has a bilobed shape—its longest dimension is 4.3 km—that suggests it was once two cometesimals that gently collided. When *Rosetta* arrived in 2014, 67P was spinning with a period of 12.4 hours around an axis tilted relative to the ecliptic. Over the following two years, the comet's period decreased to 12.0 hours, a result of nongravitational forces from its sublimating gas.

Rosetta's CONSERT and radio science instruments probed the interior of 67P's nucleus. Those data point to a homogeneous mixture of ice and dust with a density slightly higher at the surface than in the interior. It is unclear whether ice and dust are intimately mixed or the ice fills the voids between the dust grains. Water is scarce on the comet's surface—the temperature on the sunlit parts is around 200 K, even at large heliocentric distances. But the body's high porosity, about 75%, causes a huge thermal gradient. Subsurface temperatures can reach 120–160 K just a few millimeters to centimeters below the surface, where ice sublimation happens.

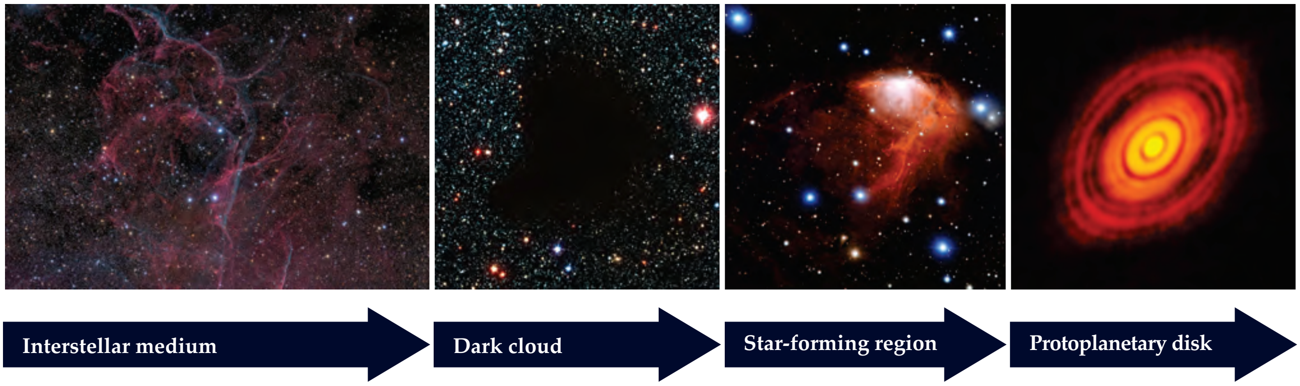


FIGURE 3. A STELLAR SYSTEM'S DEVELOPMENT starts with the interstellar medium. Once the material starts undergoing chemical reactions, it aggregates through gravitational forces and forms dark clouds, which eventually become dense enough to form stars surrounded by disks of protoplanetary material. That material comes together to form planets where life can potentially evolve. Information about all those stages can be gleaned from cometary material. Pictured from left are the Vela supernova remnant (courtesy of ESO/José Joaquín Pérez); the dark cloud B68 (courtesy of ESO); the star-forming cloud RCW 34 (courtesy of ESO); the protoplanetary disk around HL Tauri (courtesy of ALMA/ESO/NAOJ/NRAO); the solar system (image by Withan Tor/Shutterstock.com); and compounds that enable life (courtesy of ESA).

During 67P's perihelion passage, *Rosetta* witnessed many violent, short-lived—less than a half hour—outbursts of cometary material (see figure 4). The mechanism for those outbursts is not yet fully understood. Over the course of its orbit, the comet lost 0.1% of its mass by sublimation of ice and dust carried away by gas drag. Half of that measured mass loss was from volatiles, which means the comet lost an equivalent amount of dust. But ejected dust may not be lost; it can fall back onto the nucleus. That process was observed in many images of the comet's dust-covered northern hemisphere, where dust ejected from the southern hemisphere during perihelion returned to the surface. It's therefore hard to say whether comets are dirty snowballs, icy dirtballs, or, most likely, a mix of ice and refractory dust grains in approximately equal amounts.

Dust grains observed in the coma range from micrometers to decimeters in size.[5] They are agglomerates made of subunits that can be as small as 100 nm. On impact, the agglomerates often fragment, a sign of their low tensile strength. They are composed of about equal parts minerals and organic refractory macromolecules. Those observations point to a gentle agglomeration of dust and ice at comet formation.

In situ mass spectrometry by *Rosetta*'s ROSINA instrument yielded the most sensitive analysis to date of the chemical composition of a comet's icy part. In particular, the high mass resolution (9000 at $m/z = 28$) and sensitivity of the double-focusing mass spectrometer, a classical magnetic spectrometer in Nier–Johnson configuration, led to many detections of molecules and isotopologues never seen before in cometary comae.[6] More than 66 parent molecules, including some minor isotopologues, could be identified. Data analysis is still ongoing, and more results from the mission are expected.

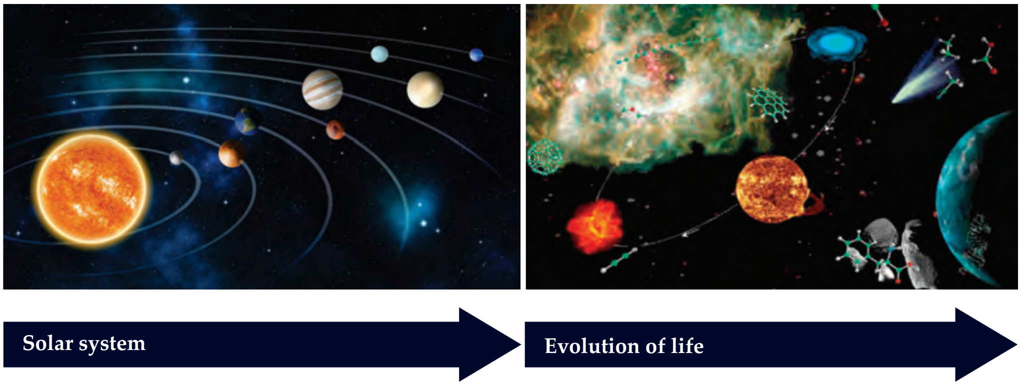
Chemical composition

One of the biggest surprises from *Rosetta* was the detection of abundant O_2, which is highly volatile, is extremely chemically active, and should not survive as a gas in such hydrogen-dominated environments as the solar nebula and protoplanetary disks. Strikingly, in 67P, the O_2 sublimation followed the same trajectory as H_2O sublimation, which occurs around 140 K. Other highly volatile chemicals instead followed that of CO_2 and had much lower sublimation temperatures, around 60 K. The different sublimation temperatures were evident from large compositional inhomogeneities in the coma, where the CO_2/H_2O ratio changed by a factor of 20 but the O_2/H_2O ratio remained constant.

Several mechanisms, such as the radiolysis of water ice, were proposed to explain the formation of O_2 and the constant ratio of the highly volatile O_2 to H_2O. But the $^{16}O/^{18}O$ ratios of H_2O and O_2 are incompatible,[7] which leaves only a primordial origin for the O_2, either in the gas phase or on the surfaces of grains. The O_2 was then incorporated in a water-ice matrix of dust grains and never sublimated before it ended up in the coma of 67P.

Rosetta also detected the first neutral N_2, another molecule that is hard to detect remotely because it lacks a dipole moment. But the amount of N_2 found does not explain the missing nitrogen that had already been noticed during the *Giotto* mis-

FIGURE 4. A SHORT-LIVED OUTBURST from comet 67P/Churyumov–Gerasimenko was captured by *Rosetta*'s OSIRIS narrow-angle camera on 29 July 2015. No signs of the jet are seen in the left image, taken at 13:06 Greenwich Mean Time (GMT). It is strong in the middle image, captured at 13:24 GMT. Residual traces are only faintly visible in the right image, taken at 13:42 GMT. (Courtesy of ESA and the OSIRIS team.)



sion. Comets seem to have less nitrogen than would be expected based on its cosmic abundance. Nevertheless, the detection of N_2, together with CO, CH_4, and Ar, shows that comets accumulate frozen, highly volatile species from their environments. That means temperatures during comet formation would have been around 25 K.

Molecular formation

Isotopes have different fingerprints depending on what stellar environment—for example, a low-mass star, supernova, or neutron-star merger—hosted their nucleosynthesis. Those fingerprints can change or even disappear, however, because sublimation, condensation, and other chemical reactions often have small but nonnegligible isotopic dependences, especially at the cold temperatures encountered in space. Still, comparing the isotopic ratios of different chemical species can provide clues about the physical and chemical conditions in which the species formed.

Noble gases undergo few chemical reactions. They therefore retain the best-preserved isotopic distribution from nucleosynthesis. A good example is xenon, which has nine stable isotopes. One of the most important results from the ROSINA instrument is the isotopic distribution[8] of Xe in 67P. Compared with the solar distribution, it is depleted in the heavy isotopes ^{134}Xe and ^{136}Xe (see figure 5). The relatively high amount of ^{129}Xe can be explained as the decay product of iodine-129, which has a lifetime of 1.57×10^7 years. To get that result, the solar nebula was probably poorly mixed when 67P and other comets formed; if it was, the isotopic makeup of cometary Xe should be the same as solar Xe.

The Xe isotopic ratios on Earth highlight a long-standing puzzle about the element's sources. Earth has two Xe reservoirs: its interior and its atmosphere. The material inside Earth is chondritic, meaning its makeup is consistent with that of stony, nonmetallic chondrites—meteorites that have not been modified by melting or differentiation. The atmospheric reservoir, however, is neither chondritic nor solar. Over time, Earth has lost Xe, mostly light isotopes, from its atmosphere to space. But even after correcting for that fractionation, the atmosphere is unexpectedly depleted of heavy Xe isotopes.

Mixing $(22 \pm 5)\%$ cometary Xe with chondritic Xe yields the isotopic ratios of Earth's atmospheric Xe. Achieving that composition would require roughly 100000 cometary impacts. With that number of impacts and considering the ratio of Xe to water in comets, researchers have concluded that less than 1% of today's surface water was brought by comets. The quantity of organics relative to Xe in 67P, however, indicates that the amount of organic matter brought to Earth by comets surpasses today's biomass. That enormous amount of organics may have helped to spark life on Earth.

Other evidence supporting the idea that most of Earth's water did not originate in comets comes from the D/H ratio, which is mostly a product of chemical fractionation. Earth's water is enriched by a factor of 10 compared with the interstellar medium and the Sun, which have D/H ratios of 1.5×10^{-5}. Still, researchers already realized from the *Giotto* mission to Halley that comets have a higher D/H ratio than Earth, and 67P has a value of 5.3×10^{-4}, even higher than the 3×10^{-4} of Halley and other Oort-cloud comets. The average value for all comets measured so far is 3.6×10^{-4}, which makes it highly unlikely that most terrestrial water comes from comets, as was once postulated.

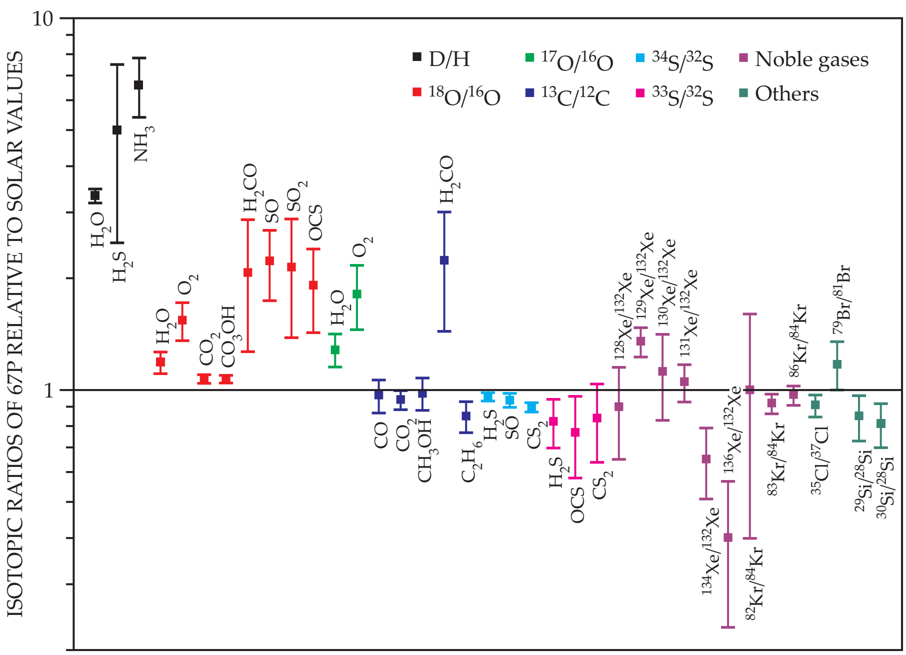


FIGURE 5. ISOTOPIC RATIOS of elements and compounds found in comet 67P/Churyumov–Gerasimenko differ from solar values. The deuterium/hydrogen ratios are shown relative to terrestrial values. (Courtesy of *Rosetta*'s ROSINA team.)

FIGURE 6. THE COMETARY ZOO is filled with gases detected by the ROSINA instrument on *Rosetta*. Identification of complex molecules on 67P/Churyumov–Gerasimenko dispelled the myth that comets contain only simple substances and cast doubt on whether certain biosignatures could serve as evidence of life. For more details about the menagerie, see https://blogs.esa.int/rosetta/2016/09/29/the-cometary-zoo. (Adapted from an illustration by ESA.)

Doubly deuterated water, D_2O, is abundant in 67P compared with what would be statistically expected. The fraction of deuterated water that is doubly deuterated is compatible with what is measured in the interstellar medium.[9] But the fraction of water that is deuterated is nearly 70 times as high as would be expected at thermal equilibrium. That means the comet's water is the result of highly nonequilibrated chemistry that could only have happened in the extremely cold interstellar medium. The comet's ice was therefore inherited as solid ice from the prestellar stage and never released into the gas phase, a process that would have immediately lowered the ratio by isotopic exchange reactions with the gas-phase hydrogen, which has a low D/H ratio.

As seen in figure 5, the isotopic ratios of many elements in 67P deviate from solar values by at least one standard deviation. Silicon's heavier isotopes are underrepresented, another hint that the solar nebula was not well mixed. Sulfur is likewise depleted in heavy isotopes in all molecules that could be measured.

Oxygen isotopic ratios on the comet vary. Whereas CO, CO_2, and methanol show solar-like values, formaldehyde is enriched in ^{18}O. Methanol's formation can be explained by grain-surface reactions, with CO freezing out of the gas phase onto grains and then being hydrogenated. The freezing enriches ^{18}O in CO while leaving behind an ^{18}O-depleted gas phase. But H_2CO is enriched in heavy oxygen and has a high $^{13}C/^{12}C$ ratio compared with methanol and CO, which means it cannot stem from an intermediate step in the CO hydrogenation process. Nor does a gas-phase-chemistry origin fit, as the H_2CO would then be depleted in the heavy isotopes. The riddle remains unsolved.

Water on 67P is slightly enriched in heavy oxygen (^{17}O and ^{18}O) compared with solar abundances, and the O_2 is more enriched in the heavy isotopes than the water. Self-shielding models[10] predict primordial water to be enriched in ^{18}O because of UV photodissociation of CO, whereas the solar wind is expected to be depleted in ^{18}O. The data therefore favor an interstellar origin for O_2 in comets and are not compatible with radiolysis of water ice, a commonly accepted source for O_2 on other bodies, such as Jupiter's moon Europa.

From stars to life on Earth

Although the mass spectrometers on *Giotto* were built to detect water and simple molecules with a limited mass range (1–56 Da) and resolution ($m/\delta m \approx 40$), the Picca instrument[11]—an energy analyzer—detected masses up to 100 Da. The molecules' thermal velocities were well below the 68 km/s flyby speed, so species could be separated by their mass-dependent energies. The resolution was insufficient to identify the molecules, but it became clear that complex organic molecules were present in Halley's coma.

Rosetta's close proximity to 67P allowed it to detect many new species, shown in a cometary zoo in figure 6. Among them are several molecules that could participate in prebiotic chemistry. The detection of long carbon chains of up to seven carbons (giraffes), aromatic hydrocarbons (elephants), oxygenated hydrocarbons (exotic birds and monkeys), and a diverse population of sulfur-bearing molecules (skunks and frogs) changed the perception that comets contain only simple molecules like CO, CO_2, NH_3, and water.

One of *Rosetta*'s highlights was the lion—glycine, the simplest amino acid. Such complexity probably stems mostly from the presolar stages of the solar system, specifically from dark clouds and star-forming regions. The abundances of cometary parent molecules and those observed in the interstellar medium show a striking similarity for many of the species.[7]

Recently, traces of ammonium salts of the form $NH_4^+R^-$ (saltwater crocodiles) have been detected in ROSINA data.[12] The salts are formed in reactions between ammonia and acids such as hydrogen cyanide, hydrochloric acid, and formic acid. Their sublimation temperatures are higher than those of the individual parts, and upon sublimation, they mostly dissociate again into NH_3 and acid. The presence of ammonium salts provides a likely explanation for the missing nitrogen, as they lock nitrogen in a refractory state in which it escapes detection.

Ammonium salts also have astrobiological relevance: They are involved in the formation of amino acids and of the nucleobase adenine from NH_4CN. The salts form cyanamide, which then reacts with glycolaldehyde to form natural nucleotides. Both prebiotic molecules—cyanamide and glycolaldehyde—were found in the coma of 67P.

Another important result is the detection of phosphorus monoxide. Early Earth had plenty of phosphorus, but most was probably tied up in minerals and therefore not available for biological processes. But life as we know it needs phosphorus for, among other things, DNA and the energy carrier ATP (adenosine triphosphate). Recently, an international collaboration of researchers sketched the cosmic journey of soluble phosphorus from a massive supernova where phosphorus is formed by nucleosynthesis, to the observation of PO in star-forming regions, to comets where PO is enclosed in the cometary ice, and—potentially—to Earth, where it was a necessary component for life to start.[13]

The material in comets is not specific to the solar system or Earth. The processes that happened here can happen everywhere. Thousands of planets have been found orbiting a wide variety of stars, and those discoveries have triggered significant interest in finding life elsewhere in the universe. The *Rosetta* mission's results make that search more difficult: Molecules that could serve as biosignatures, such as O_2 together with CH_4 or amino acids, are now known to exist in the nonliving world of cometary ice. Such biosignatures are therefore insufficient evidence for life on a planet, since they can have a nonbiogenic origin. Still, knowing that complex prebiotic molecules exist and how they could be delivered to planets may help focus the search for life.

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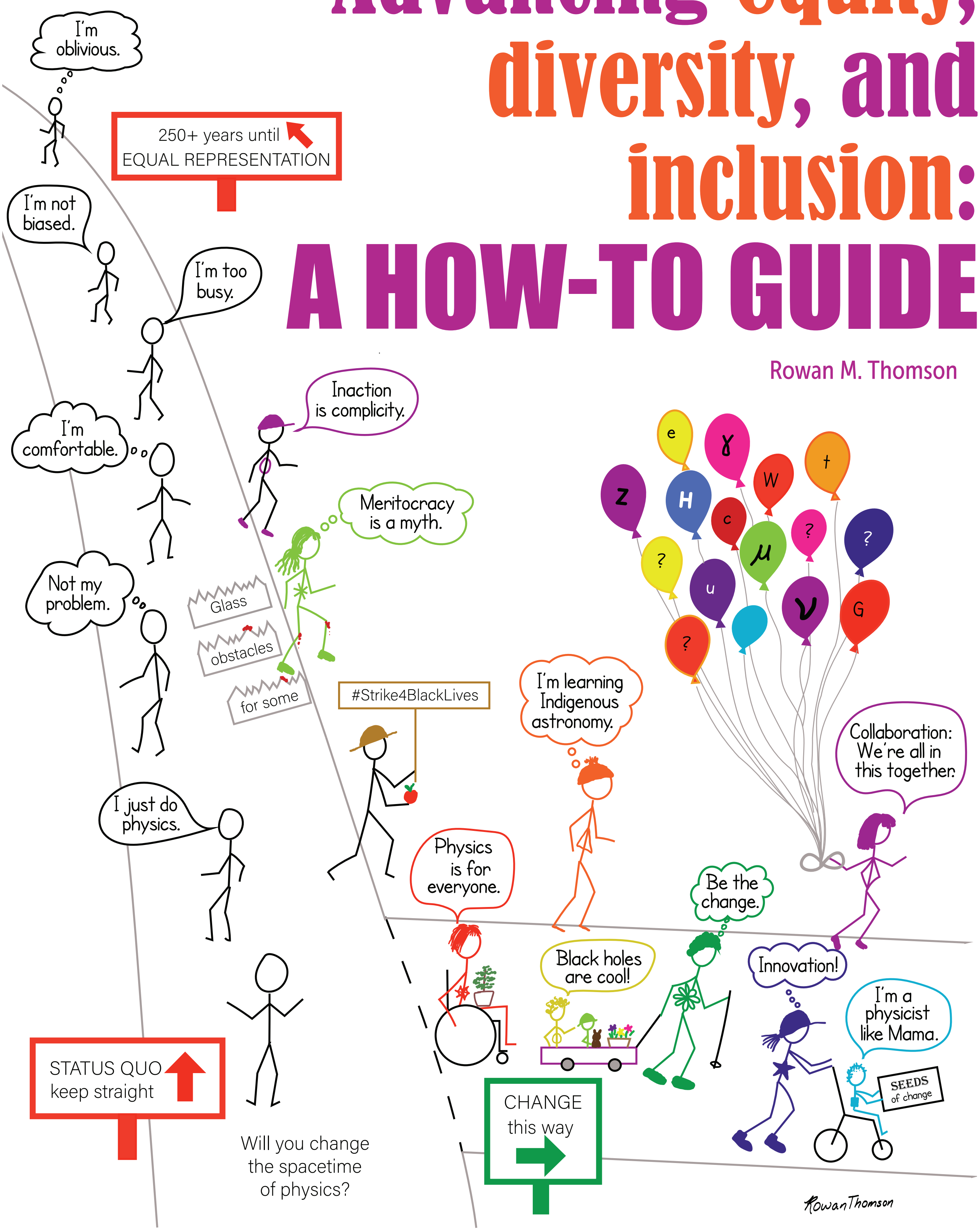
Advancing equity, diversity, and inclusion: A HOW-TO GUIDE

Rowan M. Thomson



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Physics remains one of the least diverse fields in science. Here's how individuals at all career stages can contribute to fostering an inclusive environment for everyone.

Looking around the lunchroom on my first day at my first job in physics—as a summer student in a Canadian national laboratory—I was shocked to see that almost all the scientists present were white men! I loved that job and was thrilled to be paid to do physics, but I was disappointed in the lack of diversity at the lab. I expected that things would get better as I continued in my career. Surely, I thought, the diversity of the general population would begin to be reflected in physics. But 20 years later, my optimistic expectation has proven naive. The lack of diversity in physics is still striking. Moreover, the issues in the field go beyond representation. Insidious inequities, pernicious discrimination, and systemic barriers continue to prevent the inclusion of everyone in physics.

The numbers confirm that many groups are underrepresented in physics: Data from a recent NSF report demonstrate that among recent PhDs awarded in physics, Black, Hispanic, and Indigenous people, women, and individuals with disabilities are underrepresented by factors of about two to five.[1] The representation of individuals in physics identifying as lesbian, gay, bisexual, transgender, queer, intersex, asexual, and additional identities (LGBTQIA+) has received less attention, but those groups are certainly underrepresented too.[2,3] And representation gaps seem set to persist for a long time. To take just one example, currently only 13% of senior authors of articles in physics are women. That number is rising by only 0.1% per year—at that rate, it will take 258 years to come within 5% of gender parity![4]

What factors lead to those disparities in representation? What are the challenges faced by equity-deserving groups? Why should physicists be motivated to effect change? What can physicists do to help the field improve? This article is a call to action for all physicists to work together on concrete and sustained efforts to advance equity, diversity, and inclusion (EDI; see the box on page 46) through awareness, collaboration, and engagement.

Awareness: Molehills and mountains

Both academic research and lived experience have shown that individuals from underrepresented groups face a pattern of barriers that can be conceptualized as "molehills"—namely, challenges that may be individually surmountable but that add up over time to create a substantial cumulative effect.[5] Even a single molehill may be sufficient to deter an individual from entering the field or to motivate their departure. Individuals who do persist face disadvantages that compound over time. The summative effect of molehills creates a mountain that members of underrepresented groups must overcome (see figure 1). The result is a loss of talent, a lack of recruitment, and other inequities that hamper the full realization of human potential in physics.

Young children are often described as little scientists, but their joy for experimentation and discovery may be adversely affected by negative stereotypes and cultural beliefs. Gender identity, sexuality, and race or ethnicity are strong and persistent social bases for stereotyping. Students with disabilities also face accessibility barriers—particularly the high financial costs of disability accommodations in STEM (science, technology, engineering, and mathematics).[6] All of those obstacles result in enrollment gaps in physics among underrepresented groups.[2]

The sense of belonging felt by students with diverse backgrounds is important in determining their persistence and success. Factors affecting that sense can include their peer group, the presence of role models, and the pedagogical approaches used by instructors.[2,7] Perhaps the biggest negative factor those students face is discrimination or exclusion because of their race, ethnicity, gender identity, socioeconomic class, disability status, or sexual identity. Given that today's student body is more diverse than ever—16% of physicists ages 17–25 identify as LGBTQIA+—such discrimination may have a significant effect on overall retention.[3]

Individuals who have been sexually harassed are particularly likely to feel like they don't belong.[7] One recent survey of attendees at a US conference for undergraduate women in physics revealed that 74% of the 455 respondents had experienced sexual harassment. Most of them probably experienced gender harassment, which comprises a range of put-down behaviors, including sexual and sexist remarks and inappropriate jokes. Gender harassment is often deemed less severe than similar types of behavior, but it, too, has serious ramifications. Its pervasiveness is alarming.[7]

Other research indicates that scientists who identify as members of multiple marginalized groups, like women and people of color who are also part of the LGBTQIA+ community, face greater risks of harassment.[2,3] Members of those groups are also likely to face microaggressions, subtle and often unconscious actions that express prejudicial views toward marginalized people. Microaggressions negatively affect individuals' experiences in the field and the likelihood of whether they will ultimately choose a career in physics.[2,8,9]

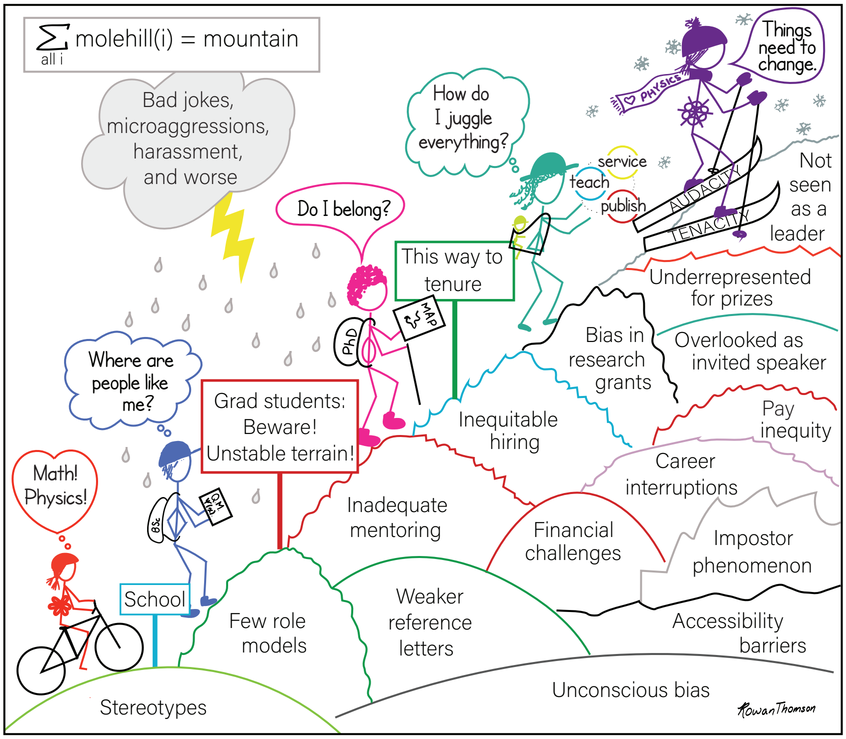

FIGURE 1. AWARENESS. "Many molehills make a mountain."[5] Members of underrepresented groups in physics experience disadvantages that have a substantial cumulative effect.

Myth of equity

The gender, race, and ethnicity of graduate students entering the job market have been shown to influence perceptions of their abilities and have ramifications on both their hirability and the salary they are offered.[10] In one recent study, a curriculum vitae (CV) was created for a hypothetical doctoral student applying for postdoctoral positions. Eight versions of the CV were produced. All were identical except for the name, which was changed to reflect gender (female or male) and race (Asian, Black, Hispanic, or white). A total of 251 physics and biology professors at eight large US research universities were each sent one of the CVs and asked to rate the candidate for competence, hirability, and likability.

The physics faculty had more gender bias than their counterparts in biology. Although they rated the female candidates as more likable, they ultimately viewed male candidates as more competent and hirable than female candidates. Race and ethnicity affected ratings too: White and Asian candidates were rated as more competent and hirable than Black and Hispanic candidates. Black female and Hispanic male and female candidates were rated lowest in hirability, which demonstrates how race and gender intersect in physics.

Biases undermine the advancement of individuals from underrepresented groups.[5] They are shortcuts formed by our brains based on our culture, experiences, and external influences. Such automatic associations make information processing more efficient, but they are often incorrect.[11] Biases are labeled as unconscious or implicit to indicate that we may be unaware of their role in distorting our decisions. Common biases relate to gender identity, race, ethnicity, age, sexual identity, religion, and disability.[2,5,11] Sometimes called second-generation discrimination,[8] biases may underpin the disadvantages faced by individuals from underrepresented groups, including receiving inadequate mentoring, unequal pay, weaker reference letters, and fewer speaker invitations; having fewer citations; being overlooked for prizes; and not being seen as a leader.[2,5]

A strong indication of the bias encountered, for example, by scientists identifying as women comes from a recent study that considered 24 000 grant applications received by the Canadian Institutes of Health Research.[12] For years the funding agency has awarded project grants, which are allocated mainly on the proposal's scientific merit. But in 2014 it introduced a new award, the foundation grant, intended for research leaders and based on the "excellence" of the candidates who applied.

The study compared the success rates of male and female principal investigators for both types of grants. They found that female applicants were 0.9% less likely than men to succeed at winning project grants. But when the foundation grants were introduced and reviewers were explicitly instructed to focus on researcher excellence, that gap widened to 4%. Although that number may sound small, it is not: Only about 10% of such grant applications are successful. The authors concluded that gender gaps in grant funding stem not from the quality of women's proposals but from the tendency of reviewers to evaluate women less favorably when they are principal investigators. Because most research begins with winning a grant, that bias damages both individual careers and the collective potential for scientific excellence.

Physicists like to believe that the field is meritocratic and that it grants power and resources to individuals in accordance with their abilities, talents, and achievements. But as quantita-

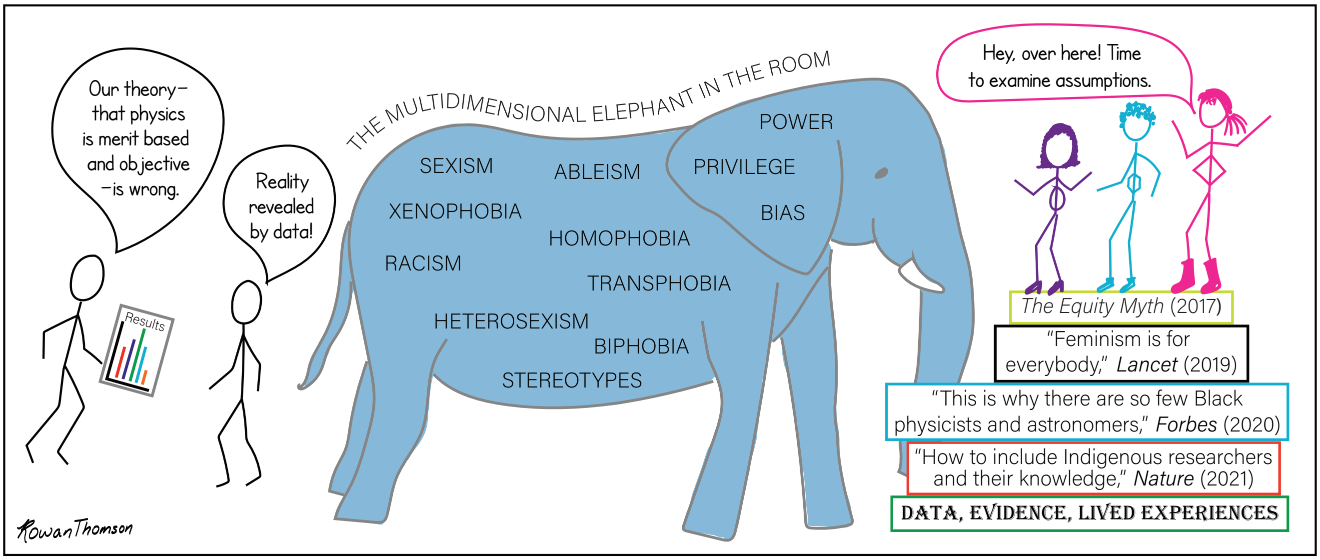

FIGURE 2. CONFRONTING IDEAS WITH DATA. Mounting evidence demonstrates that contrary to what some may choose to believe, the field of physics is not a meritocracy.

tive scientists, we must follow the data, which clearly demonstrate that our so-called meritocracies are not so meritocratic. In fact, they often reinforce the privilege of those who are already established in the field[11] (see figure 2).

Impetus for change

The "business case" is sometimes cited as a motivation for diversity initiatives. The term comes from the private sector, where it describes how employers can improve their business opportunities and gain economic and competitive advantages by employing the broadest possible field of talent.[13] In the scientific world, there is analogous evidence that diverse teams of researchers are smarter and more creative. One recent analysis focused on gender diversity in teams and determined that it is positively linked to collective problem solving, that diverse teams more effectively draw on each member's expertise and help members overcome biases, and that diversity broadens the range of research questions that a group might choose to address.[14] Because the majority of physics research is conducted by teams, the business case presents a good argument that diversifying physics would open the door to new discoveries.

The trouble with the business case is its implication that inclusivity needs to be justified. Why does it need to be shown that including underrepresented groups adds value?[13] Requiring proponents of diversity to demonstrate its positive effects implicitly sets the bar higher. After all, teams of white men are not asked for a business case to justify their team's composition.[11] The potential for scientific excellence in a fully equitable, diverse, and inclusive system remains not just unrealized but unknown.

Powerful voices for change have emerged in the physics community (see the Commentary by Ann Nelson, PHYSICS TODAY, May 2017, page 10, and the #BlackInPhysics Week essay series, PHYSICS TODAY online, 26 October 2020 and 25 October 2021). Those individuals have courageously shared their experiences and stories of persistence in the face of adversity, and their ideas illuminate paths forward. And in 2020 a task force chartered and funded by the American Institute of Physics (the publisher of PHYSICS TODAY) released a comprehensive report, *The Time Is Now: Systemic Changes to Increase African Americans with Bachelor's Degrees in Physics and Astronomy* (see PHYSICS TODAY, February 2020, page 20).

International human rights treaties commit governments worldwide to take measures to address stereotyping and eliminate inequities. Restrictions in access to STEM education and careers impose a limitation on a person's right to full participation in society and are thus a matter of human rights as defined by those treaties.[6] In short, advancing EDI is a moral imperative: We must focus on action (see figure 3).

Collaboration and innovation

Now that we are fully aware of the magnitude of the problem, let's put advancing EDI at the top of the list of open questions in physics and address it as we would any other challenge: through collaboration (see figure 4). That makes advancing EDI into an innovation challenge, which is something that we are very familiar with. As physicists, we know how to experiment, collect data, try different tactics, and learn from our successes and failures—all of which are needed to advance EDI. "Experimental" (real-life) evidence has shown that the "perturbation" (incremental) approach to EDI that the field has taken up to now has failed. That must motivate us to disrupt the established ways of doing things and make systemic changes. Only then will the field of physics achieve equity.[8]

To do our part in that field-spanning collaboration, we must each engage in concrete and sustained actions to effect change—which need to be made part of all things physics. In the following list, I present eight ways that physicists can help to advance EDI. The ideas are expressed in general terms, and their implementation should be tailored to each specific context. Because some ideas are more relevant at certain points in a physicist's career, I have indicated appropriate career stages for each of them. They are intended to stimulate reflection and spark action, but the list is by no means exhaustive. Think of it as a starting point.

Adopt EDI as core values (everyone). EDI must become an integral part of our field's spacetime. Committing to the principles of EDI means that we need to use them as a guide for all our activities as physicists. Making that commitment to address them implicitly acknowledges the field's ongoing deficiencies in EDI. It affirms "inclusive excellence" as a guiding principle—namely, the philosophy that true excellence is unattainable without EDI.[2,15] It emphasizes that all physicists need to be mobilized in collective and intentional actions to advance EDI and that each physicist must take personal responsibility for change. And it underlines the importance of adopting a culture of care in physics that emphasizes respect, honesty, compassion, and fairness.

Practice allyship (students, early-career physicists, and onward). Physicists who come from more privileged groups should become allies, which involves speaking up in support of individuals from underrepresented groups, amplifying their voices, and calling out bias and discriminatory actions and behaviors. Anyone can be an ally; many universities and other organizations offer allyship training.[9,15] As allies progress in their careers, they may expand their work to help members of marginalized groups dismantle oppressive structures and enact sustainable institutional and societal changes. Practicing allyship requires concerted and sustained efforts to disrupt cycles of injustice.

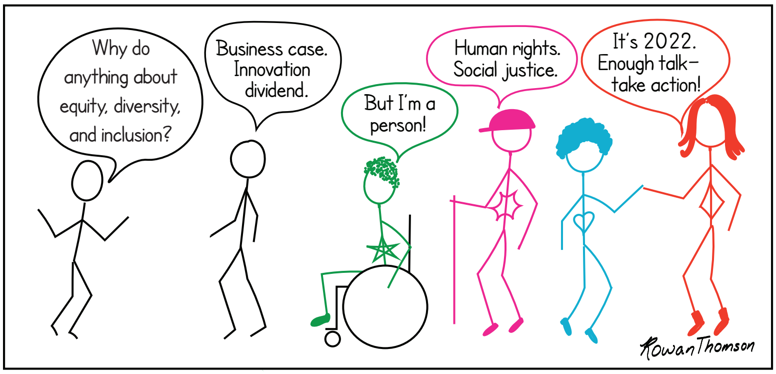

FIGURE 3. ENOUGH TALK—TAKE ACTION. There are compelling reasons to advance equity, diversity, and inclusion. It's time to end the discussion and focus on innovative solutions.

Serve as a role model or mentor (students, early-career physicists, and onward). Physicists of all identities need role models and mentors who can show that people from diverse backgrounds can flourish in the field. Being a role model involves sharing stories of personal and scientific trajectories with less senior members of the field, including early-career physicists, students, and even children. A physicist at any stage of their career can be a role model: Undergraduate physics students can be effective role models for high schoolers and younger children, who may more readily relate to them than more senior physicists.

Mentors provide guidance, support, and opportunities to nurture the development of others. Peer mentoring is highly effective and can take place at all career stages. Upper-year students can help their first-year counterparts; senior postdoctoral fellows can mentor new postdocs; and senior faculty can assist junior professors.[6] Both formal and informal mentoring programs typically pair a more senior physicist mentor with a junior mentee. Such programs should be explicitly inclusive of underrepresented groups, such as the LGBTQIA+ community,[3] because members of those groups often have a difficult time finding appropriate mentors. Strategies for being an inclusive mentor[2,6] include listening actively, being approachable, reflecting on biases, working toward cultural responsiveness, creatively addressing issues faced by the mentee, and being supportive of the mentee as they navigate obstacles and transitions.

Teach equity, inclusivity, and accessibility (instructors). Students can become agents of change if we expand the curriculum to incorporate topics relating to EDI. One way of doing that is by developing courses dedicated to EDI. Biologists have already begun to incorporate such classes into their curriculum: In a recent article, Amy Reese describes a course she developed that focuses on how women's and men's scientific work have been treated differently throughout history. In the course, she also discusses how the scientific community has dealt with individuals from such marginalized groups as racial minorities, the LGBTQIA+ community, and those with disabilities.[16] Adapted for physicists, such a course would empower students with the tools to recognize, challenge, and change persistent inequities.

Another example of diversifying the curriculum would be an astronomy course that uses "two-eyed seeing" as a guiding framework—namely, one that weaves Indigenous astronomical practices together with Western scientific principles (see, for example, the Native Skywatchers initiative at https://nativeskywatchers.com). Such a class would provide an opportunity for students to learn about Indigenous history, ways of knowing, decolonization, and reconciliation.

EDI considerations and education may also be incorporated into traditional courses. Several of my colleagues and I at Carleton University recently released a toolkit for instructors that aims to make the classroom more inclusive, diversify science education, and incorporate EDI in all courses (see https://science.carleton.ca/toolkit). It provides ideas for actions both small and large that instructors can take to advance EDI in their teaching.

Along similar lines, Abigail Daane, Sierra Decker, and Vashti Sawtelle present a set of activities that instructors can use to teach racial equity in introductory physics courses.[17] They acknowledge that instructors may be hesitant to tackle sensitive topics in the classroom but note the importance of addressing and not ignoring them. Student responses to the activities have been generally pos-

CONCEPTS OF EQUITY, DIVERSITY, AND INCLUSION

▸ **EQUITY:** Treating people of all identities and backgrounds fairly and respectfully with regard to opportunities, access, treatment, power, outcomes, and resources.

▸ **DIVERSITY:** Embracing differences, which may include race, ethnicity, gender identity or expression, family status, disability status, sexual orientation, age, and socioeconomic situation.

▸ **INCLUSION:** Intentionally creating welcoming and respectful environments and systems in which inequities in power and privilege are addressed and everyone is given an opportunity to flourish.

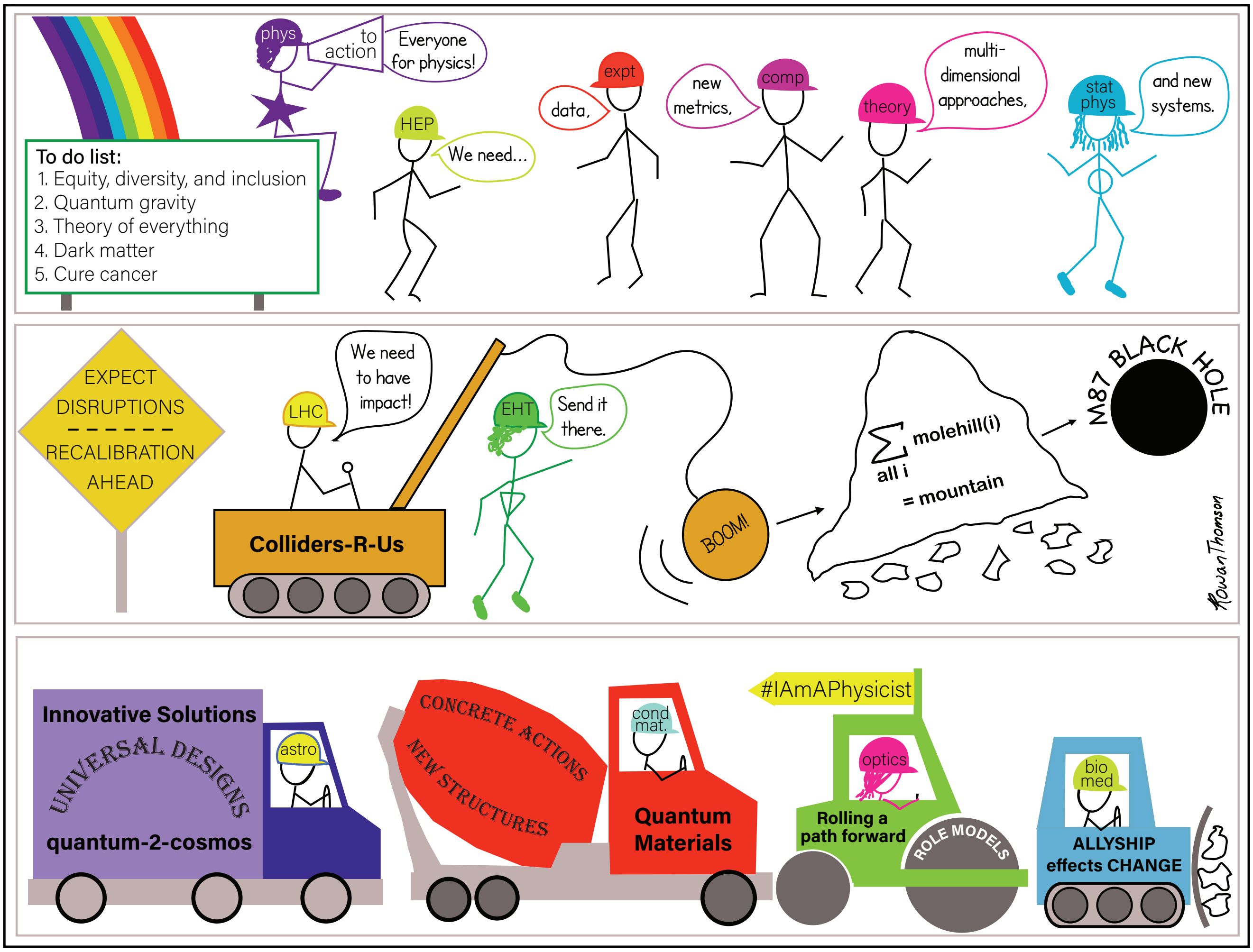

FIGURE 4. COLLABORATION. All physicists need to work together to advance equity, diversity, and inclusion.

itive. Instructors can preempt resistance from students by pointing to published data on the physics field's glaring EDI deficiencies and thereby emphasizing the importance of integrating EDI into courses.

Changing the curriculum, adopting inclusive teaching practices, and supporting students' development of a physics identity all promise to improve student recruitment, retention, and overall success (see the article by Jennifer Blue, Adrienne Traxler, and Ximena Cid, PHYSICS TODAY, March 2018, page 40). Physics graduates will then be prepared for a professional work environment in which awareness of EDI is the new cultural norm.

Train in EDI (early-career physicists and onward). All professional physicists should engage in ongoing EDI training as part of their career trajectory. A first step is building one's awareness of current EDI deficiencies. Learning about the framework of intersectionality, for example, can help physicists understand how different facets of an individual's personal identity interact with privilege and dominant belief systems in STEM and society.[15] Developing foundational skills, such as cultural sensitivity, knowledge of inclusive language, and strategies to deal with problematic interactions, will help physicists build inclusive, respectful, and welcoming environments.

For example, training to improve Indigenous cultural awareness might involve learning about the impacts of colonialism, appropriate language, and the experiences of Indigenous students, scientists, and elders.[8] Training to better support the LGBTQIA+ community, on the other hand, might involve learning how to use gender-neutral pronouns, create safe spaces, and develop strategies to make classrooms and events welcoming.

Creating an environment where everyone can thrive requires recognizing and addressing discrimination in all its forms. Microaggressions are especially challenging to identify and address because they are subtle and nuanced.[8] In a 2019 paper, Derald Wing Sue and several coauthors introduce a strategic framework for disarming racial microaggressions that incorporates the "microintervention" strategies they developed for targets of microaggressions, for white allies, and for bystanders.[9] The framework has four goals: To make the "invisible" visible, to disarm the microaggression, to educate the offender, and to seek support or intervention from an external party. Sue and his colleagues' microintervention strategies should be adapted for other targets of microaggressions, including women, LGBTQIA+, and physicists with disabilities.[9]

Organize inclusive scientific meetings (senior physicists). Women and other members of underrepresented groups are

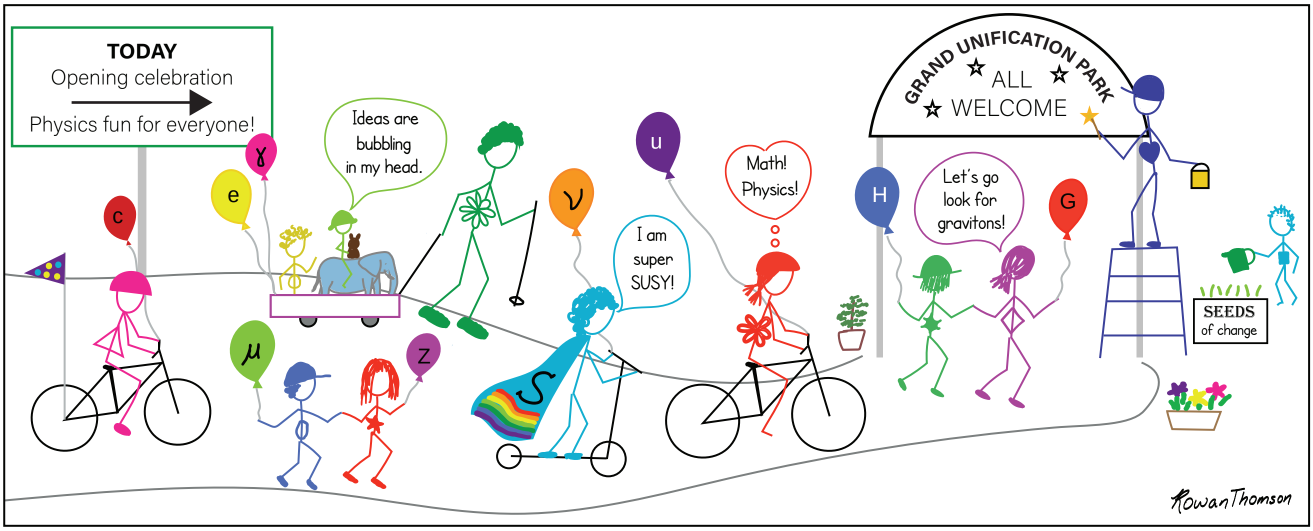

FIGURE 5. ENGAGEMENT. Physicists can be leaders in effecting broader change toward a more equitable and inclusive society.

often overlooked as invited speakers at conferences, workshops, and seminar series. Seeking balance in representation enriches the development of highly qualified personnel, enhances the career progression of researchers, and spurs research and innovation. Specific practices that organizers of scientific meetings can use to encourage EDI include collecting data on diversity at meetings and conferences, publicly reporting that data, mandating that a proportion of speakers come from underrepresented groups, ensuring that the organizing committee is diverse and informed, building databases of diverse speakers, responding to resistance, accommodating speaker needs, and being family friendly.[18] Organizers should also adopt a code of conduct that supports respectful and ethical behavior and creates a safe environment for all.[3,18] Conference participants should pledge to proactively check if the conference has a policy to ensure a diverse set of participants and speakers before accepting an invitation to speak.

Planning an inclusive event means being aware of inclusive design principles and budgeting accordingly, which might include covering costs related to captioning, dietary restrictions, accessible facilities, childcare, nursing rooms, and travel and registration (for students and low-income attendees).[18] Organizers should make EDI sessions part of the conference's core programming. In addition to having their travel and accommodation costs covered, EDI-focused speakers should be provided with honoraria to explicitly recognize the value of their contributions.

Integrate EDI into committee work (senior physicists). All physics committees must intentionally integrate EDI into their activities (see the Commentary by Alexander Rudolph, PHYSICS TODAY, June 2019, page 10). Committee members should undergo appropriate EDI training and be made aware of strategies to mitigate bias, and members of underrepresented groups should be present on such panels. Inclusive recruitment and hiring actions can include the following:

▶ Drawing candidates from underrepresented groups with job advertisements that appeal to a broad applicant pool.

▶ Critically examining the criteria, evaluative metrics, and their relative weight before reviewing applications and interviewing candidates. That should include recognition that traditional metrics place individuals from underrepresented groups at a disadvantage because they fail to account for their unequal starting points and career barriers.

▶ Considering holistic core competencies to ensure that recruits have the potential to succeed in all facets of physics, from mentoring and teaching to innovation and research. Hiring committees for faculty positions should, for example, evaluate candidates' abilities to integrate EDI best practices into research teams and teaching.

▶ Using structured interviews and a standardized rubric for admission and hiring.

▶ Fostering collegiality among committee members so that they collectively work to mitigate biases.[2,6,8]

Leaders need to be aware of the burden often placed on members of underrepresented groups to fulfill service roles. Many of those roles are less visible and are done without compensation. Senior physicists should implement strategies that ensure an equitable distribution of labor, which might include strategically assigning individuals from underrepresented groups to serve on important committees, such as hiring and award selection; limiting other service activities, such as taking minutes or ordering lab supplies; monitoring total time spent on service; and shifting responsibilities to ensure fairness.

Celebrate and raise the visibility of diverse physicists (senior physicists). Are diverse physicists visible in your organization, community, and society? Or are imbalances perpetuated by a lack of diversity in the images on classroom walls, on departmental websites, and in the names of buildings, research chairs, and awards? Are diverse physicists included in textbooks and classroom examples? We need to overhaul outdated images and textbooks and find balance in the naming of theorems, buildings, and awards. Annual events such as the International Day of Women and Girls in Science and Black in Physics Week provide natural venues for celebrating the contributions of underrepresented groups. Social media can also be invaluable, as demonstrated by such viral hashtags as #NativeInSTEM, #IndigenousSTEM, #POCinSTEM, #IAmAPhysicist, #WomenInSTEM, and #HispanicinSTEM.

Leaders can champion the advancement of protégés from underrepresented groups, provide them with access to opportunities, connect them with networks, and help propel them into leadership positions. They can also use their privileged positions to nominate outstanding physicists from underrepresented groups for prestigious prizes.[2,5]

Engagement with society

Physics does not take place in a vacuum; it exists within the context of the broader society. The inequities and injustices experienced by physicists from underrepresented groups exist across the globe. But we need to try and ACE EDI: With growing *awareness* of barriers (see figure 1) and *collaborative* work to address them (see figure 4), all physicists can *engage* in debunking societal stereotypes and drive change in our communities, cities, and countries (see figure 5). We cannot settle for the status quo: We must take ambitious strides toward a more equitable future. Underrepresented groups deserve to be full members with equal opportunities and rights not just in physics but in all organizations, communities, and societies. As we work to integrate EDI in physics, let us spread a culture of care and inclusive excellence beyond the confines of our field so that everyone can flourish.

This article is dedicated to my family, with thanks for their ideas to improve the cartoons, and it is also in memory of Chris. Additionally, I acknowledge support from the Natural Sciences and Engineering Research Council of Canada, the Canadian Institutes of Health Research, and the Canada Research Chairs Program.

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DESPITE ITS SEEMING BEAUTY, the ivory tower has proven to be unwelcoming to many scholars with underprivileged backgrounds.

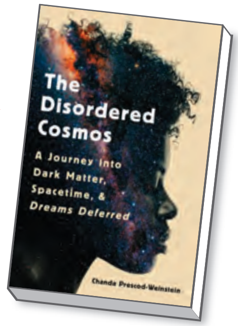
The social context of quarks

The Disordered Cosmos

A Journey into Dark Matter, Spacetime, and Dreams Deferred

Chanda Prescod-Weinstein

Bold Type Books, 2021. $28.00



Chanda Prescod-Weinstein loves quarks, but not the environment that produces the physicists who work on them. In *The Disordered Cosmos: A Journey into Dark Matter, Spacetime, and Dreams Deferred*, she lifts the curtains hiding the nasty truths about how science is done and lays bare the structure of the academic culture that puts up systemic barriers built on inequalities and injustices. But the book is more than just an exposé. Starting from the Big Bang and continuing to the here and now, it also weaves a beautiful picture of the universe from its building blocks—elementary particles, dark matter, and dark energy.

Prescod-Weinstein is an assistant professor in theoretical particle physics and a core faculty member in women's studies at the University of New Hampshire. In addition to her academic work, she writes extensively for a broader audience as a columnist in *New Scientist*, in the opinion pages of newspapers like the *Washington Post*, and on her blog. Descending from a long line of historians, union activists, authors, and journalists, Prescod-Weinstein's essays and articles span topics from axions and supernovae to labor rights and the racist history of academia.

Bolstered by her intellectual lineage and informed by her personal experience as a Black, queer physicist from East Los Angeles, Prescod-Weinstein's book opens a new, unique window into the ivory tower. It shows us the rot behind the beauty: A large part of the book grapples with why her existence as a Black woman in physics and her viewpoint in academia are so unique.

The Disordered Cosmos begins by outlining the physics of elementary particles and describing our current understanding of the universe before delving into a deep and multifaceted analysis of the human behavior behind scientific research. The book is divided into what Prescod-Weinstein aptly calls phases—not chapters—because the transitions between some of them are first order. In only a hundred pages, for example, the reader is swept from Prescod-Weinstein's daydreams about quarks on a school bus into the harsh reality of the misogynist, racist world where those quarks are ultimately studied.

That juxtaposition is intentional: Whether she talks about the quantum gravity model she most admires—no spoilers as to which one!—or rape culture in our scientific abodes, Prescod-Weinstein lets us into her life and allows us to feel both the excitement of doing science and the pain of working in academia as a Black, queer woman. That might sound antithetical for a work of popular science, but *The Disordered Cosmos* is the type of book that compels us to shatter our preconceptions about science, scientists, and academia. For instance, it forces readers to confront the fact that rape is part of the scientific story—it affects who does science and what kinds of scientific ideas are allowed to be pushed forward.

As a particle physicist, I'm somewhat embarrassed to admit that I don't normally enjoy reading popular depictions of my own field. Considering how much I adored books like Stephen Hawking's *A Brief History of Time: From the Big Bang to Black Holes* (1988) as a young girl, that is a sad admission of my current habits. Having followed Prescod-Weinstein's writing for several years, I knew her book would be about more than physics, so I thought I might end up skimming the first few physics chapters before delving into the bits dealing with the field's social aspects.

I was wrong. *The Disordered Cosmos* is more than your usual popular-science book, and the sections about physics are well worth the read, even for someone in the field. Among other things, they illuminate flaws in our physics terminology. Take, for example, dark matter. Why do we call it dark? Does that usage align with the physics of dark objects? Having gotten many questions about that terminology at lectures in the past, I have enjoyed being able to cite *The Disordered Cosmos* when asked about it during talks. In fact, I have started using several details from the book in my presentations, which my audience has greatly appreciated.

A far more troubling case she points out is that we call the *SU*(3)-charged particles "colored." In the US that word has a loaded, racialized meaning, one that the individuals who coined the terminology were surely aware of. Because my native tongue, Turkish, does not have a direct equivalent of the word colored, the word *renkli*, which literally means "colorful," is used to describe such particles. One happy consequence of that slight change in literal meaning is that in Turkish the racialized context is lost. A similar language issue I was not attuned to is the way physicists use the word "dark" when we name particles or concepts. In Turkish, the word used is *karanlık*, which one might use to describe the color of the night sky, but never to describe dark skin. But that ambiguity exists in the English word "dark," and it is a lot more obvious to a Black person than to a white person.

Prescod-Weinstein's writing has compelled me and my collaborators to be more mindful about language when writing papers. I also found some wonderful historical gems in the book that will help make my physics teaching more nuanced: I'm looking forward, for example, to bringing up Black physicist Elmer Imes in my quantum-mechanics class.

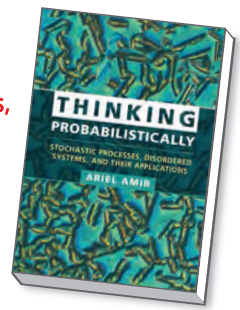
The Disordered Cosmos is the rare book that one returns to again and again. It is so interesting and varied that I almost hope Prescod-Weinstein writes several sequels that each expand on different aspects of the book. But I'm guessing she'd prefer it instead if the scientific world made space for more people who come from untraditional backgrounds—so that those individuals could enrich our worldview by shining their own unique light on the physics we do. Let us work so that her dream is realized sooner rather than later.

Seyda Ipek
Carleton University
Ottawa, Ontario, Canada


Brownian motion, or the random motion of particles suspended in a liquid or gas, was first observed in 1827 by botanist Robert Brown, who saw minuscule particles moving within pollen grains such as those pictured here.

Randomness unbound

Thinking Probabilistically
Stochastic Processes, Disordered Systems, and Their Applications
Ariel Amir
Cambridge U. Press, 2021. $105.00



The typical undergraduate statistical-mechanics course does not usually delve into advanced topics that require probabilistic reasoning to understand, such as extreme-value statistics, anomalous diffusion, and random-matrix theory. Nevertheless, many of those topics are closely linked to ongoing research trends in various fields. Ariel Amir, a professor at Harvard University, aims to remedy that situation in *Thinking Probabilistically: Stochastic Processes, Disordered Systems, and Their Applications*, a book of about 200 pages intended for advanced undergraduates and graduate students.

Amir's own work is at the vanguard of complex-systems theory, and his experience shows: One of *Thinking Probabilistically*'s main strengths is how it introduces many interesting and inspiring advanced topics, including barrier-escape problems, generalizations of the central limit theorem, and percolation. Each of those subjects has applications in several fields, which means that the book will appeal to students and researchers in a wide variety of disciplines.

Thinking Probabilistically assumes its readers have an undergraduate background in physics, that they are familiar with calculus and linear algebra, and that they have some background in probability theory and complex analysis. In that sense, the level of mathematical understanding required is on par with that of well-known textbooks such as *Mathematical Methods of Physics* (2nd ed., 1970) by Jon Mathews and R. L. Walker. Throughout, Amir is careful to prioritize physical intuition over mathematical rigor, and the author gives plenty of heuristic hints. For those who need help, the appendix contains brief reviews of probability theory, linear algebra, contour integration and Fourier transforms, some basic mechanics and statistical mechanics, and functional derivatives and Lagrange multipliers.

The book is a suitable springboard for self-study because it introduces a wide variety of topics and contains many references to current work. In the classroom, the book can function either as the basis for a course in special topics or as a source of material to spice up more traditional statistical-mechanics courses.

Chapters 1 through 3 cover random walks and the Langevin and Fokker–Planck equations. Because those topics lay the groundwork for the rest of the book, that portion should probably be read first. After that, the rest of the chapters can be digested independently. Many of the real-world examples presented in the later chapters come from physics, but Amir also includes interesting cases from other fields such as finance, biology, computer science, and even hydrology. It's not often that you see topics like the Black–Scholes equation for option pricing and the Google PageRank algorithm discussed in a physics textbook, but *Thinking Probabilistically* covers both in depth.

Amir has chosen exercises inspired by research questions to support and deepen the arguments made in the main text. They are designed to invite readers to think outside—sometimes far outside—the box. For that reason, they are more open-ended than those one would find in standard textbooks.

There are two minor points of criticism that I feel compelled to mention. First is that the level of technical detail is a bit overwhelming at several points, including, for example, the discussion of random-matrix theory at the end of chapter 8. In fairness, Amir does warn the reader that things are going to get tricky before he delves into such topics, but the difficulty spike is still notable.

Second, when describing Brownian motion, the author propagates a common error found in many physics textbooks: that Robert Brown observed the motion of pollen grains. But pollen grains are far too large to exhibit visible Brownian motion. What Brown actually observed in 1827 was the motion of small particles within pollen grains. It is pedagogically important to correct that error because, as David Layton noted in a 1965 article in the *Journal of Chemical Education*, failing to do so "fosters a misleading impression of the scale of the phenomenon." Making the correct statement also shows our friends in the life sciences that we physicists at least know a little bit of biology.

One of the book's explicit goals is to bridge the gap between the world of active research and the sanitized treatment of random phenomena found in the typical textbook, thereby enabling readers to follow contemporary research papers. The book succeeds in that aim, but making that leap will require hard work on the part of a reader not already familiar with the techniques being presented. A necessary consequence of the book's brevity is that the conceptual and technical jumps in reasoning are often quite large, and the reader will have to fill in many of the details.

Nevertheless, the methods for studying random phenomena introduced in *Thinking Probabilistically* will help readers understand reasoning techniques that may not be terribly familiar to physicists. Moreover, following the author's arguments is a rewarding intellectual exercise in its own right.

Rob de Ruyter
Indiana University Bloomington

NEW BOOKS & MEDIA

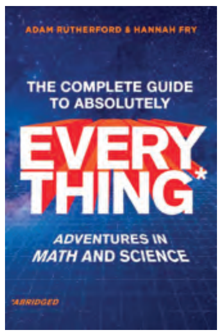
When We Cease to Understand the World

Benjamín Labatut; trans. Adrian Nathan West
New York Review Books, 2021. $17.95 (paper)

In his new book, Benjamín Labatut weaves together the scientific work and personal lives of legendary 20th-century scientific figures like Karl Schwarzschild, Erwin Schrödinger, Werner Heisenberg, and Fritz Haber into a meditation on both the meaning of life and the destructive potential of modern science. Labatut clearly did his homework on the figures he writes about, which makes it slightly disappointing that he repeats the common error of crediting the development of matrix mechanics solely to Heisenberg. In fact, Heisenberg had never heard of matrices when he began developing his theory; it was Max Born and Pascual Jordan who recognized that Heisenberg's initial work could be represented mathematically with that formalism. Historical quibbles aside, Labatut's truly unique blend of fact and fiction can only be described as a literary tour de force. It should not be missed. —RD

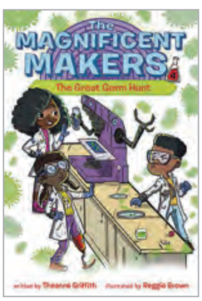
The Complete Guide to Absolutely Everything (Abridged)

Adventures in Math and Science



Adam Rutherford and Hannah Fry
W. W. Norton, 2022. $24.00

Obviously, no single book could possibly cover absolutely everything. The word "abridged" in the title is key: It hints at both the authors' curation of their subject matter and the tongue-in-cheek nature of the narrative. Over the course of some 300 pages, Adam Rutherford, a geneticist, and Hannah Fry, a mathematician, discuss such broad topics as the origin of the universe and life itself, what time is and how it is measured, and the strangeness of quantum behavior. Pooling their extensive knowledge in math and science, the authors explain not only what we know but how we know it. Through the use of pop-culture references, anecdotes, and humor, *The Complete Guide to Absolutely Everything (Abridged)* aims to be accessible and appealing to the general reader. —CC



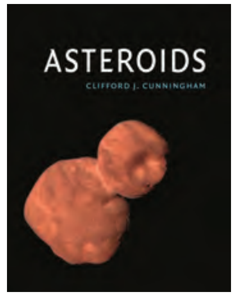
The Magnificent Makers #4

The Great Germ Hunt

Theanne Griffith; ill. Reggie Brown
Random House Books for Young Readers, 2021. $5.99 (paper)

The Magnificent Makers is a science adventure series aimed at readers in elementary school. It features a magical portal that leads to the Maker Maze, a laboratory that is run by the rainbow-haired Dr. Crisp and is filled with robots, purple microscopes, and other cool equipment. In *The Great Germ Hunt*, the fourth book in the series, Newburg Elementary third graders Violet, Pablo, and Aria complete a science worksheet, which opens the portal. They are whisked off to the Maker Maze, where they learn about bacteria, viruses, and fungi through a series of fun challenges. Like the Magic School Bus book series, the Magnificent Makers turns the study of science into an adventure while teaching the importance of such values as teamwork and intellectual curiosity. Each book in the series includes two science activities. —CC

Asteroids

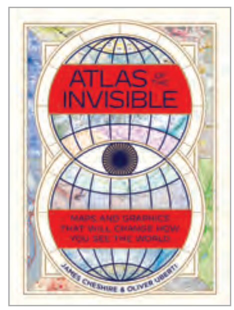


Clifford J. Cunningham
Reaktion Books, 2021. $40.00

This new book by astronomer and asteroid fanatic Clifford Cunningham is an all-in-one reference work about the unique heavenly bodies. Cunningham begins *Asteroids* with a lengthy description of the 1801 discovery of the first asteroid to be located by astronomers, Ceres, which is now considered a dwarf planet. He describes how other larger asteroids were soon found and how researchers gradually began to understand that the newly discovered objects were different from planets. An extensive overview of the various types of asteroids leads into a chapter on asteroid impacts. Particularly interesting are the last two chapters, which describe asteroids in popular culture and recent unmanned missions that have returned asteroid samples to Earth. —RD

Atlas of the Invisible

Maps and Graphics That Will Change How You See the World



James Cheshire and Oliver Uberti
W. W. Norton, 2021. $40.00

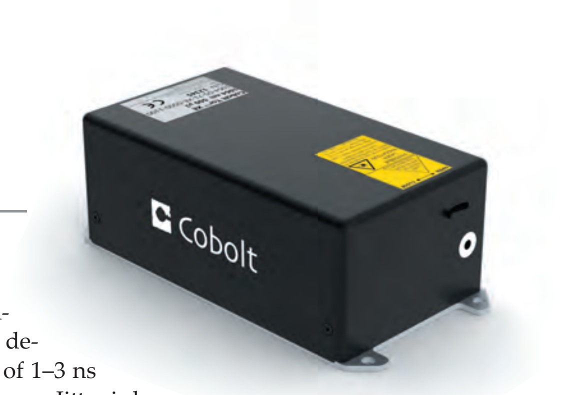
Patterns, not places, are the theme of this coffee-table book that authors James Cheshire and Oliver Uberti hope will not only entertain readers but also make them more aware of some of the problems facing humanity and inspire them to act. Be it the deportation paths of two Holocaust survivors, the geographic spread of disease, or the effects of climate change, they have found a way to visually depict them. Using information gleaned from written and computer records and from satellites, cell phones, and other sources, Cheshire and Uberti have created a plethora of colorful maps, diagrams, graphs, and more that reveal some surprising—and some not-so-surprising—insights. —CC PT

NEW PRODUCTS

Focus on lasers, imaging, microscopy, and nanoscience

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



Q-switched pulsed laser at 532 nm

Hübner Photonics now offers a new wavelength in its Cobolt Tor Series of high-performance, compact, air-cooled Q-switched lasers. The Cobolt Tor XE 532 nm delivers 0.25 mJ/pulse at up to a 1 kHz repetition rate. It offers short pulse lengths of 1–3 ns and excellent pulse-to-pulse stability for a passively Q-switched laser in a TEM_{00} beam. Jitter is less than 2 μs. Through advanced, fully integrated control electronics, the emission can be triggered from single pulses up to 1 kHz pulse trains, bursts of pulses using external or internal trigger signals, or a combination of both. The compact laser head contains all drive electronics. The Cobolt Tor XE 532 nm is designed for integration into instruments for marking, laser-induced breakdown spectroscopy, lidar, and photoacoustic microscopy applications. ***Hübner Photonics Inc****, 2635 N 1st St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com*

Laser power and pulse-width stabilization system

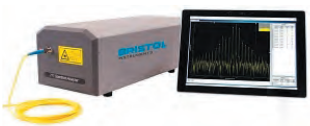
Calmar has introduced a power and pulse-width stabilization system for its Carmel X-series of femtosecond fiber lasers. The OptaPower system is designed for users who need to measure extremely small signal levels and require hours for data acquisition. It ensures ultrastable power and pulse-width performance from the laser system for extended periods of time and irrespective of variations in the ambient temperature. Over a room-temperature change between 17 °C and 32 °C, OptaPower provides a twofold improvement in the rms pulse-width stability and an order of magnitude improvement in rms power stability. Carmel laser systems are used for nonlinear microscopy, cancer diagnostics, phototherapy, metrology, and other applications. ***Calmar Laser****, 951 Commercial St, Palo Alto, CA 94303, www.calmarlaser.com*

Cryogenic Raman imaging system

WITec and Attocube have jointly developed a system that makes Raman imaging at low temperatures in high magnetic fields accessible at high spatial resolution. CryoRaman integrates Attocube's cryostat and nanopositioner technology with WITec's sensitive, modular alpha300 correlative microscope series. It offers excitation wavelengths from visible to near-IR with optimized spectrometers, operating temperatures of 1.6–300 K, patented cryogenic Raman-specific objectives, and a precise piezoelectric scan stage. Optional modules include multiwavelength excitation capabilities, automated switching from optical microscopy to spectroscopic imaging, and time-correlated single-photon counting modes. CryoRaman also introduces to cryogenic Raman microscopy the ability to detect low-wavenumber Raman peaks and full polarization control in excitation and detection. ***WITec Instruments Corp****, 130G Market Place Blvd, Knoxville, TN 37922, www.witec-instruments.com*

Compact laser-diode modules with ultrathin lines

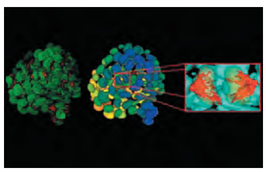
The HSML-E laser-diode module from Frankfurt Laser is very compact and delivers an ultrathin line. The laser head, whose dimensions are 12.6 mm × 44 mm, is 200 mm away from the laser driver, which is 12.6 mm × 40 mm. The laser driver operates at 24 V. As an example, the beam line can be focused to a thickness of just 10 µm at a distance of 40 mm. Standard fan angles are 10–90°. The wavelength ranges from 405 nm to 1060 nm with output powers of up to 50 mW. The power stability is typically less than ±5% over 8 h at an operating temperature range of 10–50 °C. The modules are optionally offered with a potentiometer for power adjustment, external transistor–transistor logic modulation up to 1 MHz, and analog modulation up to 100 kHz. The electrically isolated housing satisfies the protection class IP67, which means it can tolerate harsh conditions. Applications include laser triangulation, machine vision, scanning, and profiling. ***Frankfurt Laser Company***, *An den 30 Morgen 13, D-61381 Friedrichsdorf, Germany, https://frlaserco.com*



Laser spectrum analyzer for IR applications

To support the spectral analysis of IR lasers, Bristol Instruments has added the 771 NIR2 to its laser spectrum analyzer series. The new instrument uses the original 771 series' Michelson interferometer technology with FFT analysis and offers the benefit of fiber-optic input. It is suitable for use by scientists and engineers who need to characterize the spectral properties of CW lasers that operate from 1.0 µm to 2.6 µm. The 771 NIR2 provides spectral resolution up to 2 GHz and measures wavelength to an accuracy as high as ±0.0002 nm. Its convenient fiber-optic input ensures optimal alignment of the laser under test and allows it to be placed in an out-of-the-way location to conserve optical bench space. ***Bristol Instruments Inc***, *770 Canning Pkwy, Victor, NY 14564, www.bristol-inst.com*

Autonomous image analysis

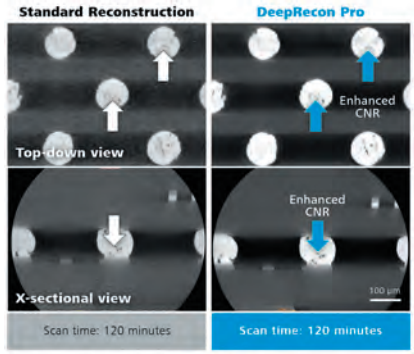


Leica Microsystems has announced that Aivia 10, the latest release of its artificial intelligence–powered image-analysis solution, is now available for a free trial on the Aivia Web platform. Featuring state-of-the-art machine-learning tools and deep-learning algorithms, Aivia software enables microscopy image visualization and analysis. Designed to allow researchers to get reliable results quickly by eliminating repetitive tasks, it provides a wide array of solutions, including 2D–5D image visualization and cloud-based model training modules. Trained by experienced human users, the new autonomous mode in Aivia 10 determines the parameters required for successful object recognition for each new image and makes expert-level segmentation and analysis of 3D images accessible for even untrained users. Upgrades in Aivia 10 include four new Active Tiles with optimized user interfaces for the most common tasks and improved file handling with faster image conversion and smaller file sizes for the fully documented Aivia TIFF 2.0 format. ***Leica Microsystems Inc***, *1700 Leider Ln, Buffalo Grove, IL 60089, www.leica-microsystems.com*

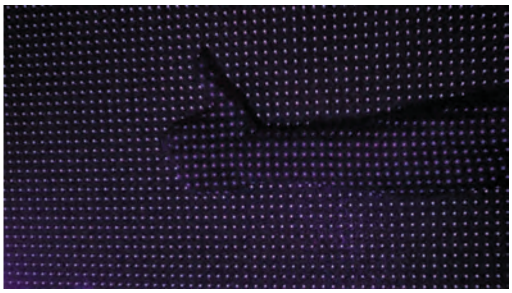
Software for surface analysis

Digital Surf has unveiled version 9 of its Mountains software platform for image and surface analysis in microscopy and metrology. Features include a new-look interface; analysis of multichannel cubes of compositional data; and surface-texture analysis on free-form surfaces, which makes it possible to calculate roughness on any type of nonplanar part, even on very complex shapes, such as shells. The company has also introduced several optional modules, including IV Spectroscopy, which uses scanning-probe microscopy to investigate electrical surface properties. Mountains 9 tools for statistical analysis can help users handle large quantities of measurement data and multiple data-population types. Version 9 comes with a new branch of Mountains software, MountainsSpectral, for correlation and spectroscopy analysis. ***Digital Surf***, *16 rue Lavoisier, 25000 Besançon, France, www.digitalsurf.com*

X-ray 3D image reconstruction



Zeiss has made available two reconstruction technologies for the Advanced Reconstruction Toolbox (ART) on its Xradia 3D x-ray platforms. The DeepRecon Pro and PhaseEvolve modules use artificial intelligence to improve data collection and analysis and speed up decision making. The DeepRecon Pro and its custom variant increase throughput while producing better image quality and significantly reducing scan times. PhaseEvolve, a postprocessing reconstruction algorithm, enhances image contrast by revealing the material property variations uniquely capable of detection by x-ray microscopy. Both modules can improve image quality for many applications, typically 3D nondestructive submicron-resolution imaging and 4D *in situ* studies. The ART is suitable for academic and industrial users in fields such as electronics, battery and engineering materials, pharmaceuticals, geosciences, and semiconductor failure analysis. ***Zeiss Research Microscopy Solutions***, *Carl-Zeiss-Promenade 10, 07745 Jena, Germany, www.zeiss.com*

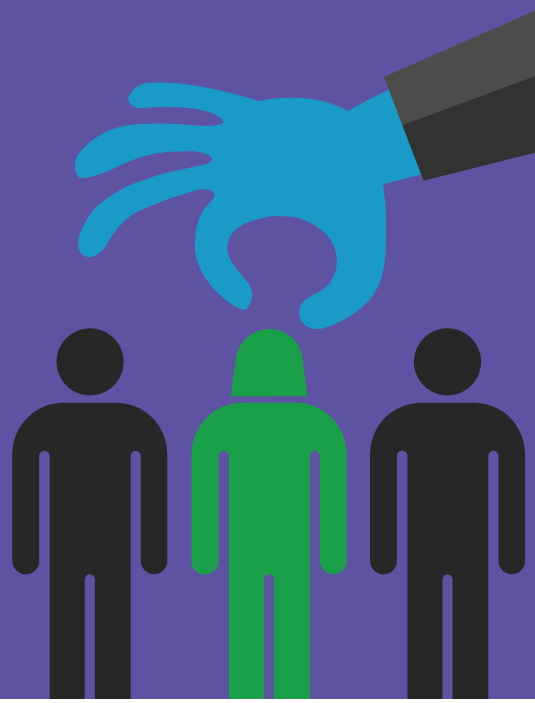


Metalenses for ultracompact optical sensors

Multifunctional metalenses from II-VI Inc are based on a proprietary platform that enables ultracompact optical sensors for a broad range of applications, including ones in the life sciences, consumer electronics, and industry. The metalenses are flat diffractive optical elements that can efficiently perform multiple optical functions on a single surface and operate over a broad range of wavelengths. In one implementation, II-VI's metalens both collimates and splits the light from vertical-cavity surface-emitting lasers (VCSELs) into a highly uniform grid of thousands of IR beams that are projected on a scene. Optical sensors reference those grids to accurately construct the scene in 3D. The metalenses can be used with the company's VCSELs to enable ultracompact 3D sensing cameras with high spatial resolution. ***II-VI Inc***, *375 Saxonburg Blvd, Saxonburg, PA 16056-9499, https://ii-vi.com*

Single-frequency deep-UV CW laser

CryLaS has extended its CW FQCW266 laser family by adding the frequency-converted 1000 model, which emits at the 266 nm wavelength with 1000 mW output power and $M^2 < 1.3$, for a single-mode TEM_{00} laser beam. The diode-pumped solid-state laser is air cooled. By means of a novel high-efficiency resonant ring cavity and ultrahigh-purity nonlinear optical materials, the FQCW266-1000 operates in the deep UV and is highly stable at a single frequency and single spatial mode. The OEM design helps maintain not only the absolute wavelength over a prolonged emission time but also the stable beam pointing and propagation parameters over the laser's life span. The noise-suppression module eliminates spontaneous and triggered dropouts, which actively compensates for parasitic power fluctuations and significantly reduces the relative intensity noise over a wide range of the frequency domain of interest. Applications for the FQCW266-1000 include spectroscopy, analytics, lithography, and inspection. ***Crystal Laser Systems GmbH***, *Ostendstrasse 25, 12459 Berlin, Germany, www.crylas.de* PT



QUICK STUDY

Kyle Angle is a doctoral candidate and **Vicki Grassian** is a distinguished professor, both at the University of California, San Diego, in La Jolla. **Andrew Ault** is an associate professor at the University of Michigan in Ann Arbor.

The rapid acidification of sea spray aerosols

Kyle J. Angle, Vicki H. Grassian, and Andrew P. Ault

The ocean has a nearly neutral pH. But the same can't be said of the microscopic drops churned up from its surface.

Atmospheric aerosols, tiny solid and liquid particles suspended in the air, have profound effects on the world. High in the atmosphere, they seed clouds and thus influence weather and climate. Closer to ground, aerosols in the US have been regulated for many years by the Environmental Protection Agency because breathing high aerosol concentrations is connected to negative effects on the lungs, brain, and tissues. And aqueous aerosols produced by speech and coughing have made the news in the past two years as the dominant route of the spread of SARS-CoV-2.

With oceans covering 70% of Earth's surface, sea spray aerosols (SSAs) are one of the most prevalent types of atmospheric aerosols. More than just salt water, SSAs contain a rich variety of compounds, including fatty acids and other organic molecules that originate from living creatures, in greater concentrations than the bulk ocean. The chemical makeup of SSAs is important because it affects their role in climate—only certain types of aerosols can efficiently seed clouds—and human health.

A fundamental chemical property is acidity. For human health, aerosol acidity is particularly important because more acidic aerosols are correlated with increased lung stress. Aerosol acidity also affects solid material solubility, aerosol reactivity, and gas transfer into and out of particles. For example, sulfur dioxide oxidization and conversion to particulate sulfate—a potential cloud seed—occurs at the interface of acidic aerosols only. Biogenic molecules in SSAs include active enzymes that function differently at acidic pH levels. Fatty acids in acidic SSAs can become protonated and act as surfactants. Despite the importance of aerosol pH, only recently have scientists begun to devise ways to measure it.

Studying sea spray with a smartphone

Fortunately, the same pH strips used in first-year chemistry labs can be used to measure aerosol pH! The strips are ordinarily thought of as a semiquantitative tool for estimating pH based on the color they turn when dipped into a bulk solution. But as one of us (Ault) and colleagues at the University of Michigan recently found, more detailed analysis can quantitatively relate color and acidity. By depositing aerosol particles onto pH paper and photographing the paper with a smartphone, one can calculate the acidity from the red, green, and blue values in the image. We found that pH decreases with size for atmospheric ammonium sulfate aerosols.

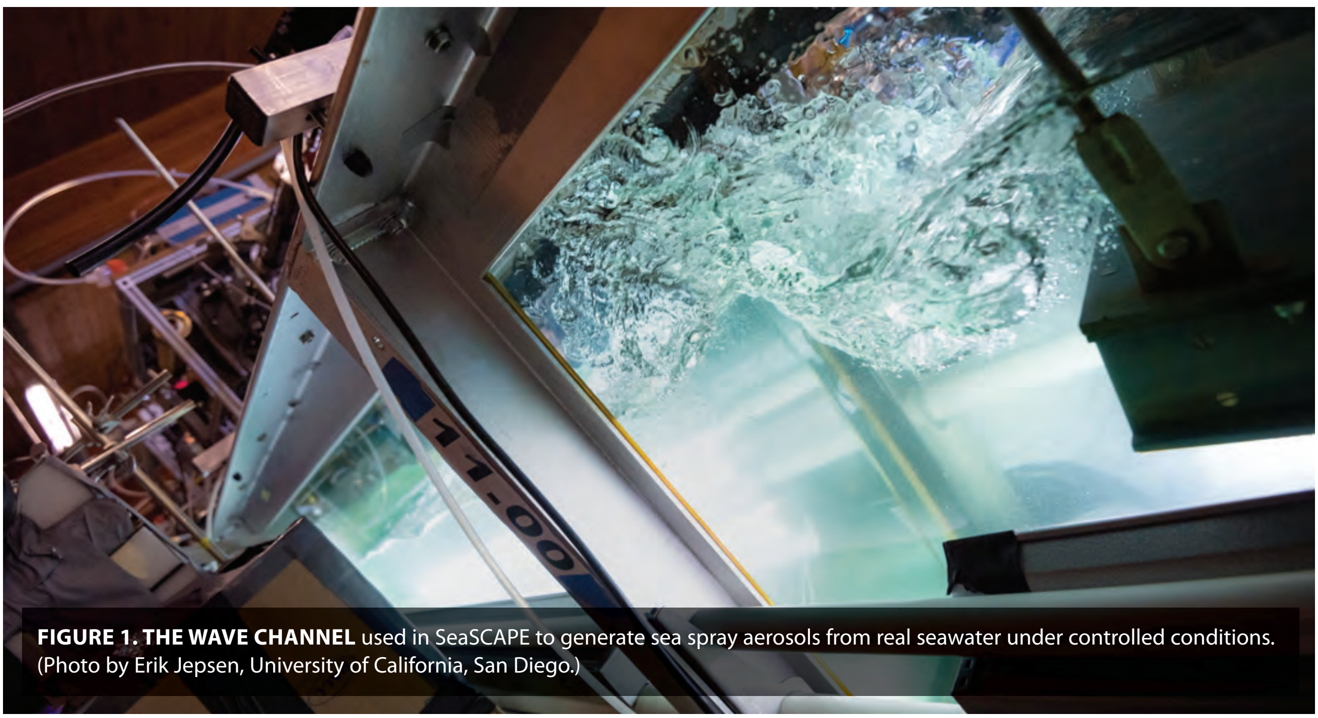


FIGURE 1. THE WAVE CHANNEL used in SeaSCAPE to generate sea spray aerosols from real seawater under controlled conditions. (Photo by Erik Jepsen, University of California, San Diego.)

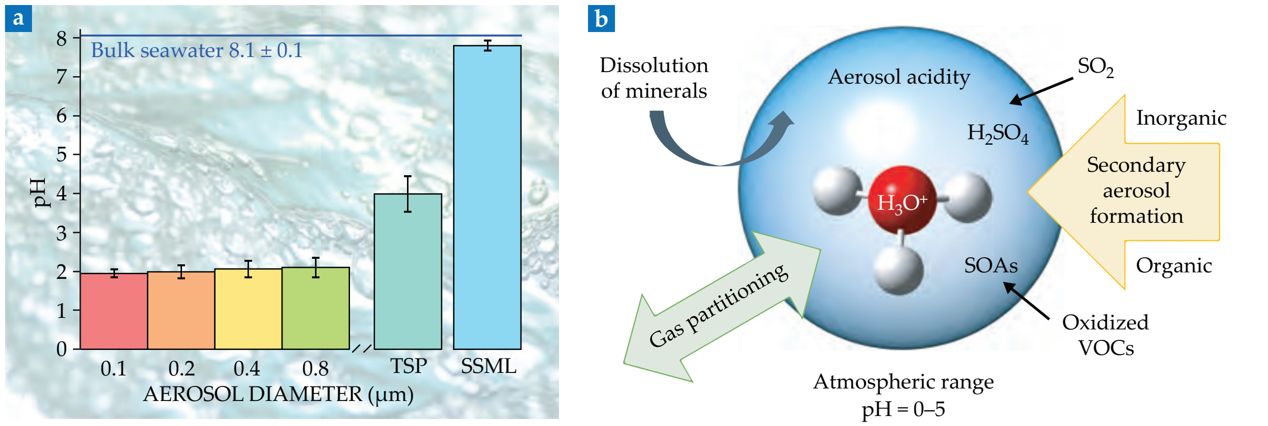


FIGURE 2. ACIDITY of sea spray aerosols (SSAs). **(a)** The pH of size-separated SSAs is shown by the four leftmost bars. Submicron SSAs are found to be orders of magnitude more acidic than the total suspended particles (TSP, mainly a measure of aerosols larger than 1 μm), the sea surface microlayer (SSML, the topmost layer of the ocean), and the ocean itself. (Background photo by Nigella Hillgarth.) **(b)** Aerosol acidity influences various phenomena, including the oxidation of sulfur dioxide into sulfuric acid, the dissolution of minerals, gas partitioning into and out of the aerosol, and the chemical reactions that produce secondary organic aerosols (SOAs) from volatile and semi-volatile organic compounds (VOCs) in the atmosphere.

Acidic aerosols have been observed in various contexts and by various methods, and researchers have found that aerosols that experience longer atmospheric aging often have lower pH levels. Inspired by Ault's simple and inexpensive way to determine aerosol pH, the other two of us (Angle and Grassian) at the University of California, San Diego, took on an unsolved question: What is the pH of *fresh* SSAs?

Seawater has a pH of 8.1 (a value that is slowly decreasing as more and more carbon dioxide dissolves in the ocean), so one might expect newly created SSAs to have the same pH. But as SSAs are emitted from the ocean surface when waves crash and bubbles burst, they quickly mix with the surrounding air, which contains gases and other aerosols. It is therefore difficult to determine their native acidity, and past studies were unable to distinguish between fresh and aged SSAs.

The solution was to mimic sea spray in a controlled environment. Measurements were performed during a sampling project called SeaSCAPE (Sea Spray Chemistry and Particle Evolution) carried out by the NSF Center for Aerosol Impacts on Chemistry of the Environment (CAICE). At the Hydraulics Laboratory at the Scripps Institution of Oceanography, the CAICE team filled a 33-meter-long glass tank, shown in figure 1, with real seawater. Aerosols were generated by a specialized paddle and were airborne for less than two minutes before being collected onto pH paper.

The results are shown in figure 2, with the measured pH plotted as a function of the aerosol-particle diameter. As the figure shows, even freshly created SSAs are far more acidic than the bulk ocean. Just as in a bulk solution, acidity in aqueous aerosols is measured on a logarithmic pH scale: A decrease in one pH unit means a 10-fold increase in acidity. The smallest aerosols, at pH 2, become a million times more acidic than bulk seawater in just two minutes!

Acid–base chemistry, microscopically

The rapid acidification of SSAs is likely due to several reasons, including their interaction with acidic atmospheric gases. Just as dissolved CO_2 acidifies the ocean, atmospheric CO_2, SO_2, and even hydrogen chloride produced by chemical reactions with salts in SSAs can all lead to more acidic aerosols. In fact, acidic gases are a major factor in controlling atmospheric pH levels in general. The gases dissolve in fog and cloud droplets, making them slightly acidic, and the effect is amplified for aerosols because of their greater surface-to-volume ratio.

If acidic gases create more acidic aerosols, one might think that alkaline gases such as ammonia—released into the atmosphere from ammonium nitrate fertilizer—could counteract the effect. Unfortunately, intuitions about acid–base balance do not necessarily hold for atmospheric aerosols. A recent publication in *Science* (see "Additional resources") demonstrated that ammonia can actually buffer aqueous aerosols and maintain their acidic pH.

Exciting progress has been made in recent years. But it remains an outstanding analytical challenge to measure the pH of individual SSAs on the fly in the real atmosphere. If portable, streamlined aerosol acidity sensors can be developed, they would enable more accurate assessments of aerosols as well as air quality.

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Additional resources

▶ K. J. Angle et al., "Acidity across the interface from the ocean surface to sea spray aerosol," *Proc. Natl. Acad. Sci. USA* **118**, e2018397118 (2021).

▶ A. P. Ault, "Aerosol acidity: Novel measurements and implications for atmospheric chemistry," *Acc. Chem. Res.* **53**, 1703 (2020).

▶ G. Zheng et al., "Multiphase buffer theory explains contrasts in atmospheric aerosol acidity," *Science* **369**, 1374 (2020).

▶ V. Grassian, "What's really in the air we breathe," TEDxSanDiego, www.youtube.com/watch?v=yWv18fV6tdQ.

▶ "Sea spray: Complex chemistry with big effects on climate," Science Nation, NSF video series, www.youtube.com/watch?v=kYQc2IjQqRU.

▶ K. A. Prather et al., "Bringing the ocean into the laboratory to probe the chemical complexity of sea spray aerosol," *Proc. Natl. Acad. Sci. USA* **110**, 7550 (2013).

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Nanoscale up-conversion

Photons in the mid-IR range of the electromagnetic spectrum have one-tenth the energy of those in the visible domain. Specialized detectors are capable of measuring those more feeble photons, but thermal noise and other engineering challenges limit the number of environments in which those detectors may be applied. One solution, up-conversion, pairs mid-IR photons with near-IR ones produced from a pump laser. The newly emitted IR photon has a higher frequency and thus a higher energy. The catch is that researchers must find suitable nonlinear crystals that are transparent at all of the involved frequencies and then carefully and painstakingly match the propagation phase of the two sets of photons. This artistic picture shows the polygonal crystalline surface of a new, alternative device for up-converting IR light and then detecting it with more cost-effective, off-the-shelf devices.

In the device shown, spherical gold nanoparticles, about 150 nm in diameter, reside in a similarly sized groove etched into a gold nanofilm. The mid-IR photons are resonantly captured in the groove, which acts as a slot antenna, and meet near-IR photons coming from an overhead pump laser. Those near-IR photons resonantly excite the nanoparticle–groove assembly. The confined, nanometer-wide channels house a monolayer of small organic molecules, which lie well below the diffraction limit of the setup's focusing microscope lens, so no matching of the propagation phase is necessary. The internal vibrations of the molecules in the channel mediate a nonlinear optical interaction that results in coherent up-conversion of mid-IR photons to visible ones. Those photons are then measurable with a conventional detector at ambient conditions. (W. Chen et al., *Science* **374**, 1264, 2021; image courtesy of Nicolas Antille, www.nicolasantille.com.) —AL

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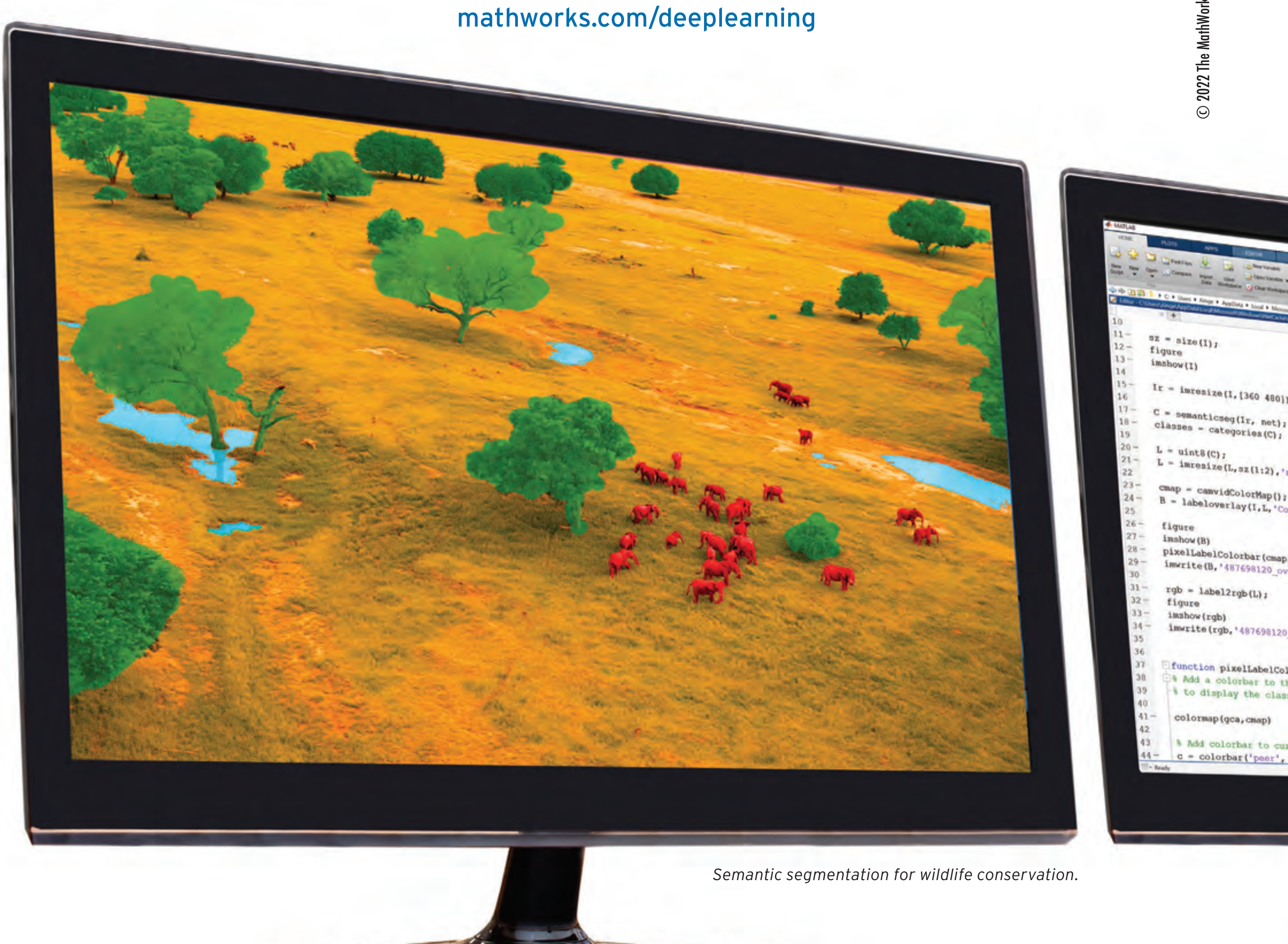

Semantic segmentation for wildlife conservation.