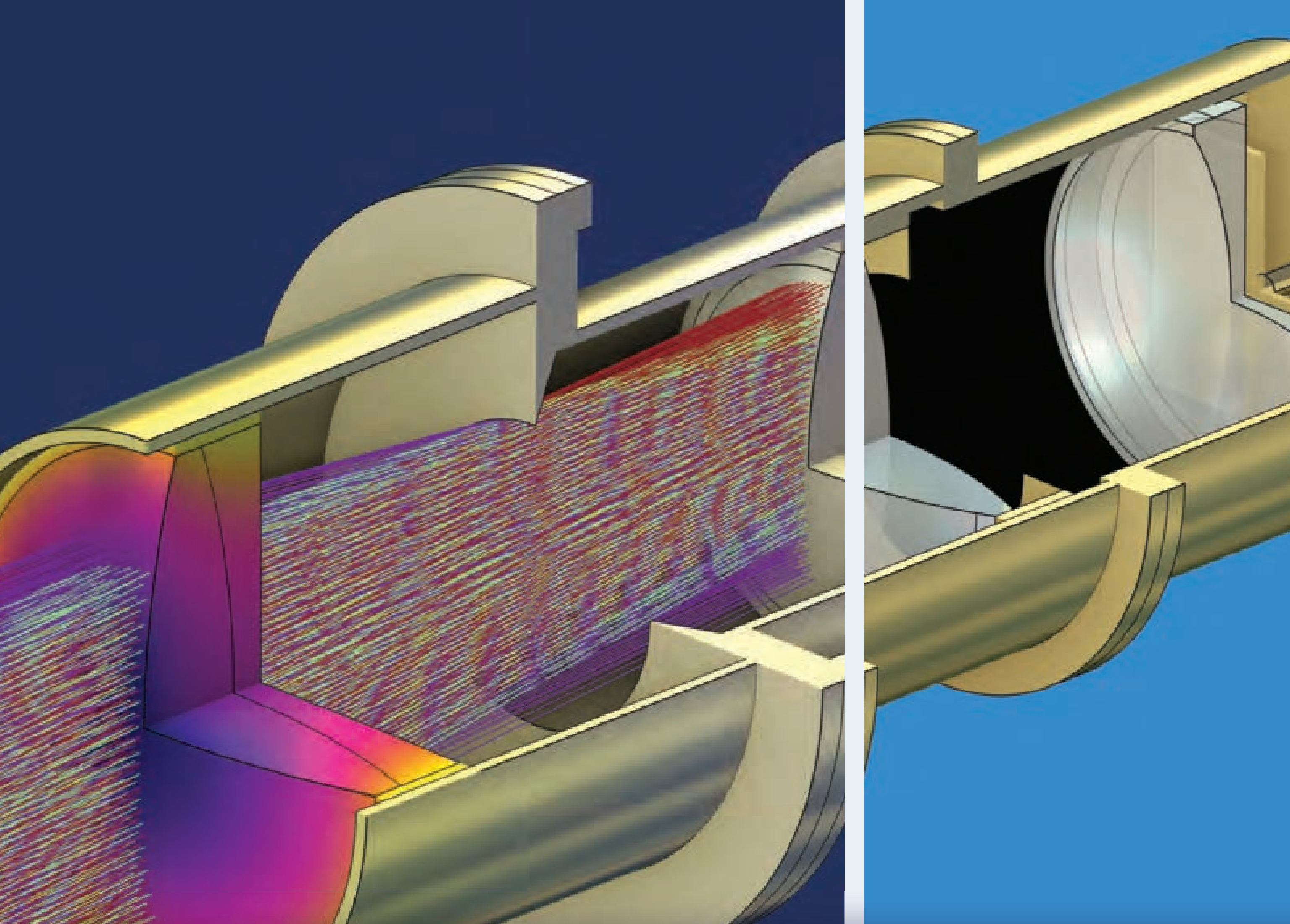

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Butterflies in *flight*

The human influence on extreme weather

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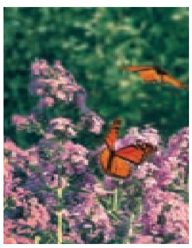
FEATURES



ON THE COVER: Some monarch butterflies migrate thousands of kilometers for the winter. Aiding that flight are microscopic scales covering their wings: The arrangement of the scales reduces the aerodynamic drag by as much as 45%, compared with wings with their scales removed. To learn more about the roller-bearing effect that the scales produce, turn to the Quick Study by Amy Lang on **page 54**. (Photo by Cynthia B. Cummings.)

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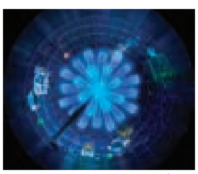

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Franklin currency

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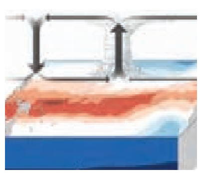

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El Niño

Anomalously warm temperatures in the tropical Pacific Ocean mark the return of El Niño for the first time in five years. Climate scientist Emily Becker offers a primer on the El Niño–Southern Oscillation and explores how the phenomenon and its impacts may change as the planet warms.

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Commentary

Capturing the history of GE Lighting

In 1913 General Electric (GE) opened Nela Park, the US's first industrial park, outside of Cleveland, Ohio. The complex thereafter served as GE's headquarters for its lighting business, which was a successor of the lighting company founded by Thomas Edison in 1878.

In March 2022 several GE Lighting retirees, including the authors of this commentary, were recruited as volunteers to find museums that would welcome many traditional lighting artifacts that had accumulated since 1913. Over the years the operation at Nela Park played a leadership role in the world lighting industry, arguably developing more new lamps and light sources than anyone else.

As onetime colleagues at Nela Park who had loved our work, we represented many different facets of the business, including technology, manufacturing, and commercialization. Nela Park had an open college-campus-like environment in which it was easy for colleagues from different business functions to meet casually, or deliberately when needed. The once 3000 employees had a common cafeteria, an employee store, a library, a bank, and numerous other amenities.

The oldest of our recruited group had started at GE in 1952, and each member knew pieces of the company's history, but certainly not all of it. During our careers, our jobs had been to look forward, not backward. Moreover, the range of the collection that had accumulated at Nela Park was overwhelming. Much of it was of historical significance, but none of it had retained commercial importance in the new world of LEDs. The items included a vast collection of historic light bulbs; dozens of filing cabinets full of previously classified internal technical reports documenting 20th-century GE product developments; bulbs from Joseph Swan, who independently of Edison also developed incandescent lamps; and advertising and training materials for new products. There were also many photographs and film reels capturing the design, manufacture, and commercialization of more than a century of products.

One group of artifacts included four shadow boxes, which Edison took to the International Exhibition of Electricity in Paris in 1881.[1] They show how the earliest Edison light bulbs were made, starting with pieces of bamboo, which were turned into carbonized fibers that were shaped into filaments and sealed inside glass bulbs. Francis Jehl, one of Edison's assistants, documented how their lab tried 6000 different sources of plant fibers before settling on a bamboo from Japan.[2] Edison's exhibit in 1881 was such a success that the shadow boxes remained in Europe to promote his early commercialization there. They finally made it back to Nela Park in 2007. Our retiree group, with our outward-looking network, was able to establish their provenance.

We connected with several museums eager to accept significant parts of our historic treasure. We focused on museums that were of a regional or national stature and that had an online presence, including searchable catalogs of their collections. As we worked with museums and their curators came to Nela Park, we found that different museums were interested in different types of items. The artifacts ended up in several locations, including the Smithsonian Institution's National Museum of American History in Washington, DC; the Western Reserve Historical Society in Cleveland; and the Corning Museum of Glass in New York.

The GE artifacts serve as a reminder of the era when bright indoor electric lighting at the flick of a switch really captured people's attention and changed their lives. Before electric lighting, people had been making do with candles, oil lamps, and gas lighting. The dramatically brighter, cleaner, safer, more efficient, and more convenient electric lighting didn't start to significantly displace those sources until the very late 1800s. Some of the oldest light bulbs in the collection, including those of competitors like Swan, and some early gas and oil lamps went to the San Antonio Museum of Science and Technology.

AN 1881 EDISON SHADOW BOX showing different bamboos considered for sources of light-bulb filaments.

Indoor electric lighting has enabled our modern 24/7 economy and lifestyles in ways that were previously unimaginable.[3,4] While LEDs now offer significant improvement in energy efficiency and electronic control, their impact on our lives is nowhere near as dramatic as that of the traditional products in those first 100 years after 1879, the year of Edison's first significant prototype.[3] The GE commercial materials, now in museums, reflect the public excitement with the new products and GE's engagement in all aspects of their application.

The GE internal technical reports also provide a new perspective on the technological developments themselves. Advances in electric lighting occurred in step with the advances in basic and applied sciences during those same years. (See the article by John Anderson and John Saby, Physics Today, October 1979, page 32.) The advances seldom occurred in isolation but rather in harmony with new products and new science developed around the world.

The record of those advances in technology in a century and more of progress has been known publicly through advertisements, product specifications, patents, academic papers, public presentations, published books, and other sources.[3,4] Access to the internal GE technical reports provides future scholars with a behind-the-scenes perspective on those advances. The documents now reside at the Hagley Museum and Library in Delaware, except for those involving glass, which are at Alfred University in New York.

We are grateful to the management team of GE Lighting, now a Savant company, who recruited us, provided logistical support in important ways, and made the preservation project possible. We hope that our experience inspires others who see history and technology moving forward and might know of artifacts worth preserving. Such items help the general public appreciate the rich history of scientific progress and enable scholars to study and interpret that history.

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LETTERS

Nineteenth-century women and physics across the pond

Joanna Behrman's article "Physics . . . is for girls?" (Physics Today, August 2022, page 30) provides a refreshing antidote to today's stereotypes. For most of its history, Western science has been essentially a men's club, evolving in "a world without women," to borrow the title of David Noble's 1992 book that traces the male dominance of science to Christian clerical heritage.[1]

Behrman reports that in the 19th-century US, girls and young women were encouraged to study natural philosophy. But the situation at the time was quite different in Britain. Girls and women were thought incapable of "ascent up the hill of science," which Cambridge University geologist Adam Sedgwick said was "rugged and thorny, and ill-fitted for the drapery of a petticoat."[2] (Though, ironically, it is said that the cloth wrapping of the ring with which Michael Faraday discovered electromagnetic induction in 1831 was made from strips of his wife's petticoat.)

The Scottish physicist David Brewster, who worked on polarized light and invented the kaleidoscope, was explicit in his views toward women in science: "The mould in which Providence has cast the female mind, does not present to us those rough phases of masculine strength which can sound depths, and grasp syllogisms, and cross-examine nature."[3] J. J. Thomson, the Cambridge physicist who discovered the electron, expressed a similar worldview. In an 1886 letter to a family friend, he complained that a female student in one of his advanced classes did "not understand a word." He went on to state, "my theory is that she is attending my lectures on the supposition that they are on Divinity and she has not yet found out her mistake."[4]

The law of conservation of energy, established at midcentury with major contributions coming from the Englishman James Joule and the Scot William Thomson (later Lord Kelvin), was held by many to explain why women should not do science or indeed even be educated: A woman's body contained only a finite amount of energy, and trouble would befall those who channeled it away from childbirth and nurturing.[5]

In the 1800s, only a few women were accepted into Britain's scientific sphere. One of the most notable was the self-taught Mary Somerville, who wrote several treatises and translated and expanded Pierre Simon Laplace's *Mécanique céleste* (Celestial mechanics; see the article by James Secord, Physics Today, January 2018, page 46). Fortunately, the station of women in the still predominately patriarchal social arena of science steadily improves.

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► **Behrman replies:** Robert Fleck astutely notes that despite significant cultural exchange between the US and Britain, the histories of women in physics in each country took very different paths. In her book *A Lab of One's Own*, Patricia Fara discusses the difficulty faced by British female scientists in obtaining employment and carving out spaces for themselves in science.[1] In contrast, the relative encouragement for girls to study science in the US paved the way for strong communities of female scientists at many of the country's numerous women's colleges. Miriam Levin chronicles one such community at Mount Holyoke College in *Defining Women's Scientific Enterprise*.[2]

This is not to say that female physicists in the US didn't face plenty of barriers as well—they certainly did! Rather, it is a telling confirmation of how contextual and changeable culture is.

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Hope for CO_2 air capture

John Tanner's summary of carbon dioxide air-capture costs (Physics Today, February 2023, page 12) takes the glass-half-empty approach to an extreme. At the average US retail price for electricity (12¢/kWh), the thermodynamic energy demand of direct air capture[1] would indeed add $15 to the cost of collecting a metric ton of CO_2 from air. But large power consumers, such as aluminum smelters, get much better pricing.[2]

Moreover, removing 8 billion metric tons of CO_2 for a mere $120 billion would be a good deal. It would cancel past emissions from about 20 billion barrels of oil. The world buys that much oil every 200 days for $1.6 trillion. Prices for such a quantity have fluctuated between $200 billion and $3 trillion over the years. The implied surcharge of $6 per barrel seems cheap for fixing the climate.

Can air capture achieve such economics? The bad news is that current costs are above $500 per metric ton of CO_2. I agree with Tanner that thermodynamic limits plus unavoidable raw-material inputs set a lower bound around $10–$20 per metric ton.[3] The good news is that no physical law prevents approaching that bound through learning by doing. Betting against an order-of-magnitude cost reduction ignores the two-orders-of-magnitude reduction in wind and solar. It collides with the frequently expressed optimism that batteries will get cheaper if we produce a lot of them. Mass production has proven over and over that costs can drop 10-fold if cumulative capacity increases 1000-fold.[4] For air capture, which needs to grow more than a millionfold, that represents just the beginning of the growth curve.[5] Obviously, success is not guaranteed, but closing the door to the opportunity without trying is self-defeating.

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PT

High-energy neutrinos originate in our own galaxy

High-energy cosmic rays, long suspected of interacting with matter in the dense galactic plane, are almost certainly the source of the Milky Way's neutrinos.

The least interactive particles ever observed in the universe are neutrinos. Their neutral charge makes them unaffected by electromagnetism, and their lack of color charge means that they don't participate in the strong force. They are affected by the weak force, but it has an exceedingly short range, roughly the diameter of a proton. With those properties, neutrinos can travel through normal matter more or less undetected—every second, a trillion neutrinos from the Sun pass through your hand.

The lack of interactions makes neutrinos an ideal messenger of information on various astrophysical processes (see, for example, "The elusive Glashow resonance was observed deep within Antarctic ice," Physics Today online, 8 April 2021, and the article by Francis Halzen and Spencer Klein, Physics Today, May 2008, page 29). Because neutrinos don't interact much with other matter, their detection can be used to trace the direction from which they came and to reconstruct the events that produced them.

Most astrophysical neutrinos seen so far have come from somewhere beyond our galaxy. But now the IceCube Collaboration has identified a high-energy neutrino flux in the Milky Way that originates predominantly in the galactic plane.[1] The finding reinforces previous theoretical hypotheses about the origins of cosmic rays. It also shows how multiple messengers—neutrino measurements, gamma-ray emissions, and other radiation—can be used together to better investigate our own galaxy.

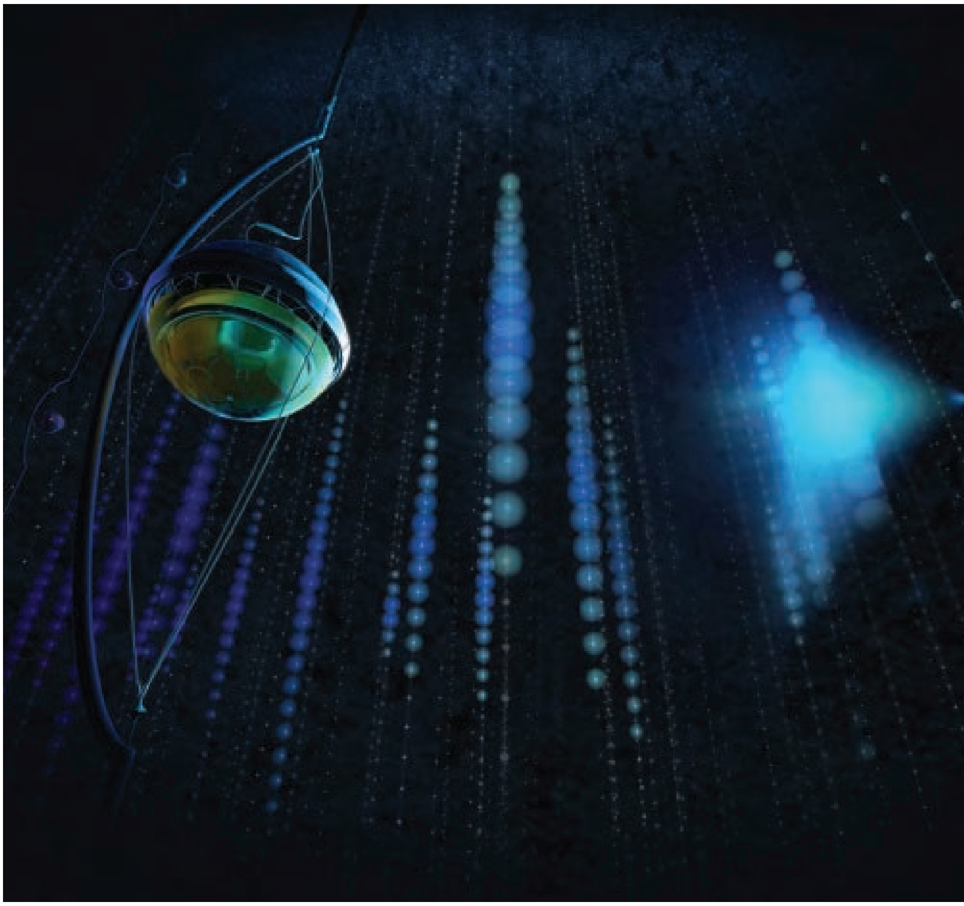

FIGURE 1. CHERENKOV RADIATION. High-energy neutrinos racing through Earth's atmosphere sometimes reach the IceCube Neutrino Observatory in Antarctica and collide with the nuclei of frozen water molecules. The impact produces charged particles that, if energetic enough, travel faster than the speed of light in ice, yielding blue-hued Cherenkov radiation. The optical sensor in the foreground and the dozens more in the background of this artistic illustration are a fraction of the thousands that hang on cables drilled as deep as 2500 m into the ice. By measuring the radiation and its trajectory, researchers estimate the neutrino's arrival direction and its intensity. (Courtesy of the IceCube Collaboration.)

A muddled path

Cosmic rays are high-energy particles that move through space with an energy range that roughly spans from a few GeV to several PeV, although most have energies on the lower end of the range. They're constantly bombarding Earth's atmosphere and are responsible for some chip-level errors that can flip the value of memory cells in electronic devices. Outside the planet's protective atmosphere and magnetic field, the highly ionizing radiation poses dangerous acute and chronic health risks for astronauts.

Even if space technology advances enough to quickly and reliably carry people to Mars and beyond, cosmic rays may limit how long and thus how far humans can travel through space, if the shuttles lack radiation-hardened shielding. (See the Quick Study by Larry Townsend, Physics Today, March 2020, page 66.)

Despite their discovery more than 100

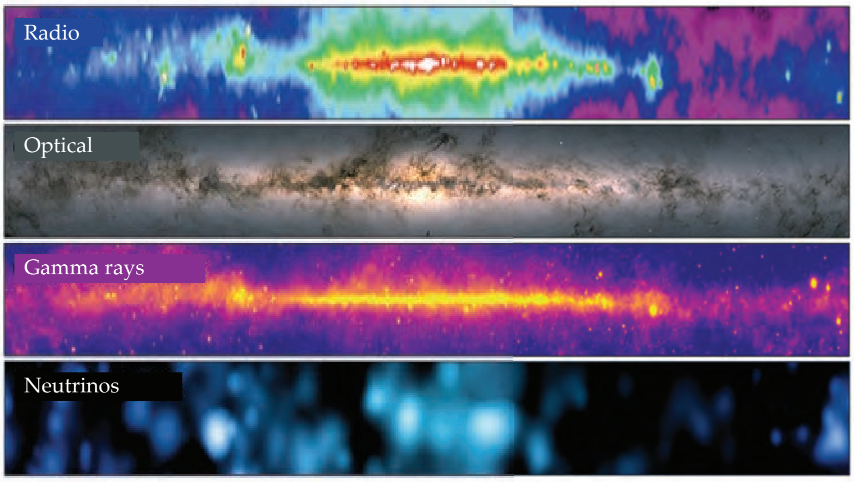

FIGURE 2. NEUTRINO VISION. For years, astronomers have viewed the Milky Way through radio, optical, and gamma-ray emissions. Images taken with all three clearly show the galactic center and surrounding plane. After carefully analyzing 10 years of data from the IceCube Neutrino Observatory, an international collaboration found that the Milky Way is a source of neutrinos, and the diffuse neutrino signal across the galaxy, shown here, is statistically consistent with gamma-ray emission. (Courtesy of the IceCube Collaboration.)

years ago, cosmic rays remain mysterious. Astronomers do know that some GeV cosmic rays originate from the Sun's coronal mass ejections and other solar eruptions. But the theoretical hypotheses for where the high-energy flux comes from—supermassive black holes, active galactic nuclei, supernovae, or something else—are difficult to evaluate with much statistical certainty because of what happens to the cosmic rays as they travel through space.

Along their path to Earth, high-energy cosmic rays often encounter strong galactic magnetic fields, which scramble their trajectories so much that it's impossible to determine where they came from. Some of the cosmic rays interact with the gaseous interstellar medium and produce particles whose trajectories are easier to track. Those interactions produce both charged and neutral pions. Neutral pions quickly decay and most commonly produce gamma rays. Although observations of the gamma-ray emission hint at where cosmic rays come from, the evidence isn't conclusive because gamma-ray photons are readily absorbed by other matter in the interstellar medium. One solution to the origin question comes from the other product of cosmic-ray interactions: charged pions, which produce neutrinos.[2]

Under the ice

Most visible mass in the Milky Way lies in its galactic plane, and in the interstellar space, hydrogen nuclei are spread out at an average density of one per cubic centimeter. When cosmic rays interact with interstellar hydrogen, gamma rays are produced; and they've already been observed by the Large Area Telescope aboard NASA's *Fermi Gamma-Ray Space Telescope*. The cosmic-ray interactions also make neutrinos, which are most visible in Earth's southern sky if atmospheric noise is minimized, according to calculations of the estimated neutrino flux. In part for that reason, the Amundsen–Scott South Pole Station in Antarctica hosts the IceCube Neutrino Observatory.

The detector is a cubic kilometer of ice with more than 5000 spherical optical sensors, which hang on cables drilled as deep as 2500 m. Most neutrinos pass through the detector area without interacting, but when one slams into a water molecule, it produces muons and other charged particles. If any of them are energetic enough, they travel faster than light does in the ice, which results in the emission of blue-tinged Cherenkov radiation, as illustrated in figure 1. (The effect is similar to the sonic boom that's heard when a supersonic jet travels faster than the speed of sound.)

By measuring the Cherenkov radiation picked up by the optical sensors and the blue light's spatial pattern, researchers can infer the particle's energy and from what direction it arrived. One of the biggest challenges, however, is the overwhelming number of neutrinos and muons produced in Earth's atmosphere by cosmic rays. For every astrophysical neutrino that IceCube observes, the facility measures 100 million atmospheric muons.

To filter the immense background noise from the astrophysical neutrino signal, the IceCube Collaboration had developed an event-selection protocol. A neutrino signal measured by IceCube is categorized either as a track event, in which a neutrino creates a muon that then leaves an energetic trail as it races through the ice, or as a cascade event, in which the neutrino releases most or all of its energy at a single location. Many atmospheric neutrinos leave track events in the IceCube detector, so selecting for just cascades greatly reduces the background noise.

The approach is computationally expensive. Many neutrino events need to be excluded, including those found in certain detector regions that are known to witness many atmospheric muons and neutrinos with energies close to those of atmospheric neutrinos. The exclusions have left the IceCube Collaboration with a high-quality data set that it has used for previous analyses—for example, in 2013, the team discovered an extragalactic source of neutrinos.[3] The data set, however, was too small to draw conclusions with high statistical confidence about galactic neutrino emission.

Deep learning

To better analyze the 10 years of data collected from IceCube so far, the collaboration developed a hybrid artificial-intelligence technique, spearheaded by Mirco Hünnefeld of the Technical University Dortmund and Steve Sclafani of Drexel University.[4] The first part of the technique uses a deep-learning neural network to identify cascade neutrino events. The neural network runs through the data quickly, and the resulting time savings allows more events, including those at the lower end of the energy range, to be included in the data set. Compared with earlier analyses, the neural network also improves by a factor of two the angular resolution of the direction of incoming neutrinos.

The second part of the technique uses the light patterns collected by the detectors to reconstruct the neutrino's direction and energy. The previous reconstruction method was based on a computationally expensive set of Monte Carlo simulations, but the neural network approximates those simulations more efficiently. The new data set of 60 000 neutrino events is 20 times as large as previous sets. Francis Halzen, a theoretical physicist who is a member of the IceCube Collaboration, says that "given the new machine-learning techniques, it almost looked easy in retrospect, especially given our unsuccessful efforts to see our galaxy over the last decade."

With those improvements, the collaboration found a signal of diffuse high-energy neutrinos from the galactic plane. Figure 2 shows the Milky Way as it's typically been seen through radio, optical, and gamma-ray emissions. Those three wavelength regimes show a clear, bright galactic center flanked on either side by a thin plane of more diffuse emission. The Milky Way's neutrino signal is about 10% of the total flux at 30 TeV, and although it may not be immediately clear, the signal is consistent with the gamma-ray emission. In fact, the IceCube Collaboration found that the chance for the neutrino signal to arise randomly from background noise is less than 1 in 100 000, or a statistical confidence level of 4.5 standard deviations.

Guide to the galaxy

The neutrino picture of the Milky Way so far shows a diffuse pattern of emission that arises when cosmic rays interact with interstellar gas. But neutrinos could be coming from galactic point sources of cosmic rays. To figure that out, the team will need to review more data. Similar to how the atmospheric background overwhelms the astrophysical signal, the suspected point-source neutrino signal may be masked by the diffuse neutrino signal shown in figure 2.

Astronomers already have some ideas for where galactic cosmic rays, and by extension neutrinos, could come from. Supermassive black holes could produce them (see Physics Today, August 2022, page 14), but the one at the center of the Milky Way may not be active enough to generate such high-energy particles.

Neutrinos could also be sourced from active galactic nuclei (see "IceCube pinpoints an extragalactic neutrino source," Physics Today online, 12 July 2018), and some have already been spotted in an extragalactic supernova (see "A supernova for the ages, 30 years later," Physics Today online, 23 February 2017). In the Milky Way, says Halzen, "finding the sources are our next priority, and we are on it."

Alex Lopatka

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Toward faster, safer proton therapy

Most facilities for zapping tumors with protons are extremely inefficient. But perhaps they don't have to be.

In the fight against cancer, the global medical community is placing an increasingly big bet on protons. Of the just over 100 proton-therapy facilities worldwide, more than half began operation in 2016 or later. Currently they treat some 50 000 patients per year, with a cumulative total of around 300 000.

The treatments are eye-wateringly expensive. A new facility can cost more than $200 million just to build, not counting the cost of upkeep, operation, and doctors' time. Because of the high price tag, plenty of critics are putting pressure on proton-therapy proponents to justify the expense with results. (See, for example, Physics Today, October 2015, page 8.) For some applications—such as treating eye tumors, as shown in figure 1—proton therapy has shown clear advantages over other treatments. For others, achieving its potential is still a work in progress.

At the Paul Scherrer Institute in Switzerland, home to one of the oldest operating proton-therapy centers, a team of researchers led by Vivek Maradia and his PhD adviser, Serena Psoroulas, is working to lessen a major source of inefficiency: In a typical treatment facility that accelerates its protons with a cyclotron, between 70% and 99.9% of the accelerated protons get thrown away.[1]

Wasted protons don't directly translate into wasted dollars. But getting protons more efficiently into patients could lead to faster treatments, happier patients, and eventually more economical facilities. And it could allow proton therapy to better benefit from a powerful but counterintuitive phenomenon called the FLASH effect: Delivering a lot of radiation to a tumor all at once could lessen the side effects on the surrounding healthy tissue.

Low transmission

Proton therapy's appeal stems from the physics of how protons interact with matter. The goal of radiotherapy—and indeed of all forms of cancer treatment—is to kill cancer cells while sparing healthy ones. But a beam of radiation (of any form) sent into the body encounters not just the tumor but also the healthy organs in front of and behind it. X rays, still the tool for most radiotherapy, deposit their energy everywhere along their path, in tumor and healthy cells alike.

Protons, on the other hand, have scattering cross sections that depend inversely on their kinetic energy. So a proton passing through the body slows down little by little, until it finally leaves most of its energy—and does most of its damage—right before it stops. By controlling the proton beam's direction and initial kinetic energy, clinicians can position the radiation-affected region in all three dimensions.

In practical terms, however, controlling proton kinetic energies is not so easy. Clinicians need proton energies ranging from 60 MeV (for tumors close to the body surface, such as those in the eyes) to 230 MeV (for tumors tens of centimeters deep in the body). But a single cyclotron produces proton beams at just one energy. It would be far too expensive to have a separate cyclotron for every possible proton energy. A few facilities have opted for low-energy cyclotrons for treating eye tumors, with the consequence that they can't treat anything else. Most proton-therapy centers, however, use cyclotrons at the top of the energy range, at either 230 MeV or 250 MeV. And that's where the inefficiency comes in.

One can turn high-energy protons into lower-energy protons by passing them through a chunk of solid material, usually carbon. But that energy-degradation process also turns a monoenergetic proton beam into one with a considerable energy spread—no longer suitable for clinical use, because the protons' localized depositions of energy, known as Bragg peaks, are no longer all in the same place. The standard approach is to use a dipole magnet to disperse the protons by energy and then pass them through a slit to select protons with as close to a single energy as possible. Most of the protons, as a result, are thrown away.

The waste is worst at low clinical energies. The more the cyclotron protons need to be degraded, the larger their energy spread, and the lower the fraction transmitted through the energy-selection slit. For target energies greater than 200 MeV, perhaps 10% or more of the initial protons can be salvaged. But for target energies less than 100 MeV, less than 1% can.

The low transmission makes it hard to treat eye tumors at facilities without low-energy cyclotrons. Delivering a radiation dose takes about a minute, which may not sound like much. But patients need to be kept from blinking or moving their eyes for that time, which is challenging and uncomfortable.

For tumors in parts of the body such as the lungs and abdomen, which inevitably move around despite the patient's best efforts, treatment can take even longer—up to 45 minutes—because clinicians need to continually rescan the patient's body to track the tumor's position. Again, the patient needs to stay as still as possible for the duration of the procedure.

Momentum cooling

Are the low transmission efficiencies and long treatment times an inherent limitation of cyclotron-based proton therapy? Much of the community thought so, says Maradia. "For years, it's been widely believed that there was no feasible way to enhance transmission," he says. "But Serena Psoroulas challenged that notion, and she conceived the idea for my PhD project."

For the first year of his PhD studies, Maradia tinkered with simulations of beamline ion optics, and he discovered some new ways to wrangle more protons from the cyclotron to the patient.[2] In a nutshell, existing ion-optics setups treat the two dimensions perpendicular to the beam symmetrically, and they apply the same focusing and defocusing forces in both directions. But the dimensions aren't symmetrical—in part, because the protons are dispersed by energy in one direction but not the other. Maradia and colleagues predicted that by accounting for that asymmetry, they could improve transmission by up to a factor of six.

There remained the greatest source of inefficiency: the protons discarded at the energy-selection slit. The solution, it turned out, was deceptively simple. The protons were already dispersed by energy, and their momentum can be slowed by passing them through solid material. So Maradia proposed sticking a wedge into the beam, as shown in figure 2. The fastest protons pass through the thickest part of the wedge and are slowed most; the slowest pass through the thinnest part and are slowed least.

Maradia came up with the momentum-cooling idea on his own, but he noticed afterward that wedge-shaped absorbers had been used before in other areas of particle physics, such as muon experiments.[3] They'd not been considered before for proton therapy, perhaps

FIGURE 1. EYE CANCER is rare, but it's extremely difficult to treat. At the OPTIS2 beamline at the Paul Scherrer Institute in Switzerland, where eye tumors are treated with proton-beam therapy, patients must keep their eyes open and immobile for the duration of the minute-long radiation delivery. The treatment time could be shortened by increasing the fraction of protons transmitted through the beamline. (Courtesy of the Paul Scherrer Institute.)

because when the protons scatter off the wedge, their momentum spread perpendicular to the beam increases. But Maradia and colleagues' improved ion optics were equipped to handle the increased spread.

Proposing and simulating improvements is one thing; actually implementing them can be quite another, especially in an active medical facility. "No one wanted to disrupt the ongoing clinical treatments," says Maradia. But with persistence, he eventually got permission to try out his wedge on the Paul Scherrer Institute's eye-treatment beamline.

The results were positive but modest: From an initial fraction of 0.27% of protons, the wedge increased transmission almost twofold, to 0.5%. Why such a small improvement? The beamline as a whole was designed on the basis of the assumption that only protons with one specific energy would ever make it through to the patient. After being dispersed by the dipole magnet, most of them crash into the beamline walls before they even reach the wedge.

If the dipole magnet deflected the protons at a shallower angle, the loss could be mitigated, and the researchers estimate that transmission at the lowest energies could be boosted to perhaps 7%. Making such a change to an existing beamline is probably not feasible. "However, it would be relatively easy to incorporate momentum cooling into future proton-therapy centers during their design and construction," says Maradia. Several dozen new proton-therapy facilities are currently in development around the world.

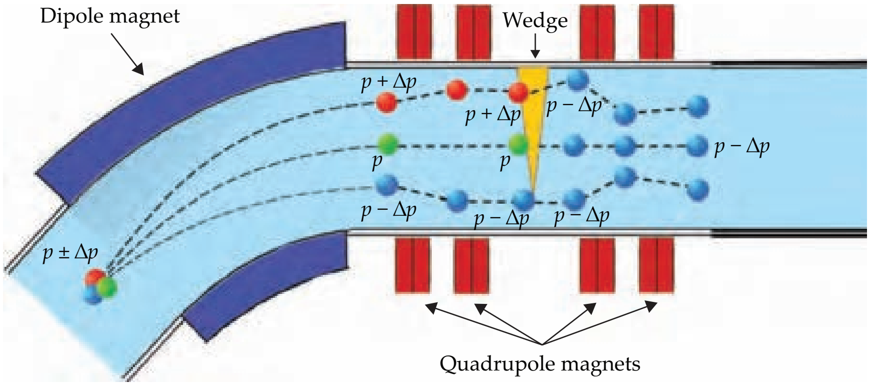

FIGURE 2. WHEN PROTONS from a cyclotron are tuned to the energies required for proton-beam therapy, they end up with a momentum spread $p \pm \Delta p$ that's too wide for clinical use. The conventional approach is to use a dipole magnet (dark blue) to disperse the protons by momentum and then pass them through a slit to select out the protons with just one momentum value, p. But if, instead, a wedge-shaped absorber is used to cool all the protons' momentum to $p - \Delta p$, more protons can make it through the beamline and into the patient. (Adapted from ref. 1.)

FLASH therapy

Increasing the fraction of protons that make it through the beamline has more implications than just reducing treatment times proportionally. For example, if proton treatment of a lung tumor could be sped up so much that the entire radiation dose is delivered while patients hold their breath, clinicians might no longer need to take elaborate steps—and employ expensive equipment—to track the motion of the tumor during treatment.

Alternatively, if the treatment times that are available today are considered acceptable, they could be achieved with much smaller and less powerful cyclotrons. A more modest cyclotron produces less radiation overall, so it requires less concrete shielding and could be built at less cost.

But perhaps the most intriguing potential implication concerns the FLASH effect. Proton therapy's appeal is that most of the proton beam's energy is deposited at the Bragg peak. But most is not all, and proton-therapy clinicians have to go to great lengths to design treatments that avoid harming healthy tissues, especially when tumors lie close to critical organs or arteries. (See the article by Jerimy Polf and Katia Parodi, Physics Today, October 2015, page 28.)

So when, in 2014, experiments started to show[4] that if radiation is delivered very quickly, it does less harm to healthy tissues—despite being just as effective at killing the tumor—the radiotherapy community was captivated.

FLASH radiotherapy is still far from ready for clinical use, and much remains unknown. For example, researchers still don't know how the effect works—and not every experiment even agrees that it does. One popular hypothesis is that the fast delivery of radiation induces a temporary oxygen deficiency in healthy tissue, which protects it from damage because radiation works by creating oxygen radicals. The tumor, on the other hand, is already starved of oxygen, so it doesn't become more oxygen-deficient than it already is. But much more study is needed to see if that picture holds up.

It's also not known exactly how fast radiation must be delivered to produce the FLASH effect, but a rough consensus is that it needs to be several orders of magnitude faster than current treatments allow. That is, instead of lasting minutes, delivery should take a fraction of a second.

The FLASH effect appears to be equally applicable to all forms of radiation: protons, x rays, electrons, and carbon ions. Out of all clinical radiation sources, proton-accelerating cyclotrons are the closest to being able to achieve FLASH intensities. But the catch is, they can do so only with the full-strength high-energy beam straight out of the cyclotron—which means forgoing all the advantages of the Bragg peak and its tunability.[5]

In their simulations, Maradia, Psoroulas, and colleagues estimate that with a beamline optimized for their momentum-cooling approach, they could reach FLASH intensities across the entire range of clinically relevant proton energies—as long as the beam is focused to a small enough spot. For tumors more than a few millimeters in diameter, however, the FLASH beam would need to be scanned over the tumor volume more rapidly than is currently possible.

Johanna Miller

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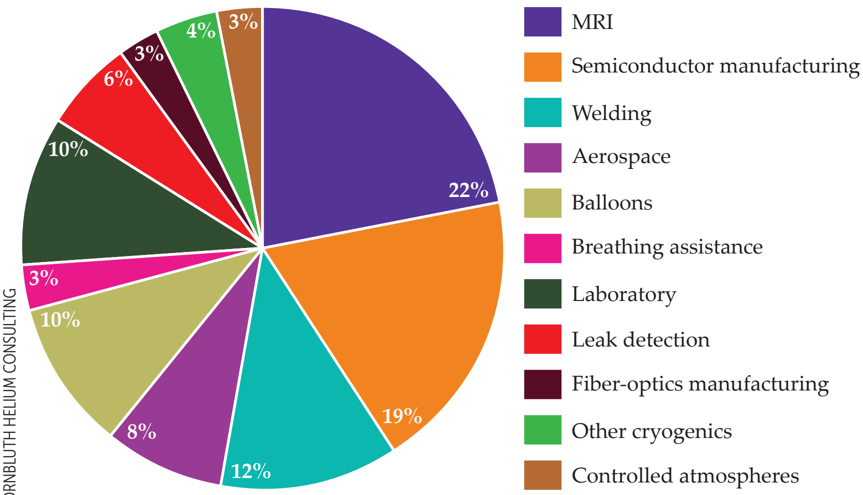
Helium prices surge to record levels as shortage continues

The shortfall may end if a new supply from Russia reaches the market. Growing numbers of universities and labs are recycling their supplies.

Nancy Washton, who looks after 28 Pacific Northwest National Laboratory instruments that use superconducting magnets, was forced to shut down five NMR spectrometers last year when her supplier began rationing liquid helium, cutting deliveries from 2400 L to 962 L per month. Although all five NMRs are back in operation, the lab now pays \$39/L, double the cost from two years ago. Washton says that at one point she was forced to pay \$55/L to cool a magnet back to its superconducting state and keep it there.

William Halperin, a physicist at Northwestern University, says the university pays on average \$30/L for helium today, in comparison with \$7/L a decade ago. Christopher Nicholson, a chemist at Marian University in Indianapolis, Indiana, says he's paid \$45/L for the 9 L per month he needs to keep the campus's sole NMR spectrometer cold. But since his supplier's rigid delivery schedule doesn't align with what it takes to keep the instrument operational, his department will pay even more by signing up for a service contract from the NMR manufacturer. "They do charge a little more for the helium, but not so much more that it's not worth it," he says. Many small liberal arts colleges with one or two instruments face similar helium predicaments, he adds.

The helium shortage that last year forced many scientific users to get by with less than half of their pre-2022 usage levels has eased a bit, according to a wide variety of users. (See "Helium is again in short supply," Physics Today online, 4 April 2022.) Yet prices continue to soar above the already high levels of a year ago, they say.



KORNBLUTH HELIUM CONSULTING

HELIUM IS CRITICAL to low-temperature physics, chemistry, and life-sciences experiments, yet laboratory usage accounts for just 10% of helium consumption worldwide, well below medical MRI and semiconductor manufacturing.

The situation is no better outside the US. Donald Thomas, a chemist at the University of New South Wales in Sydney, Australia, says he's heard that researchers in Western Australia and New Zealand are paying suppliers up to Aus\$100/L (\$68/L), "if they even bother to promise to deliver." He says other Australian universities have had NMR magnets come close to warming up and quenching their superconductivity. "I know of three magnets that were in trouble and at least as many where conversations were had about shutting down magnets."

At the University of Crete, chemist Apostolos Spyros says he paid €44/L (\$49/L) for his most recent shipment of liquid helium, up from the €24/L charged last year. That doesn't include a 23% value-added tax. "We've gone from something like €7000 to €8000 per year to €17 000 or €18 000. It's very difficult for the department to get that money," he says. The price is only a couple euros lower in mainland Greece, he notes.

A recent survey conducted by the Canadian Helium Users Group, an organization of NMR spectroscopists, found that 72% of facilities had difficulty procuring liquid helium within the last nine months. It also found many labs have been subjected to unscheduled price increases, ranging from 25% to as much as 400%.

Still, there are always exceptions to the rule with helium: Gregory Wylie, the NMR facility manager at Texas A&M University, says he pays \$19/L, up from \$16/L two years ago. Like other institutions, the university has had to deal with helium rationing by suppliers, Wylie says, but he's never had a problem obtaining enough to get by. "We are a big user, so we have pretty good contracts."

Declining production

The immediate cause of last year's helium supply pinch, from which the market has yet to fully recover, was the five-month-long shutdown in early 2022 of the Cliffside crude helium enrichment plant in Amarillo, Texas. That followed an extended outage in 2021.

A CRYOPLANT newly commissioned at SLAC will feed the superconducting RF cavities of the Linac Coherent Light Source-II with helium cooled to 2 K. The closed system circulates 4 tons of helium between the linac and the cryoplant, with very low losses.

Cliffside feeds helium from the US helium reserve and other privately owned helium sources into the 684 km pipeline that has long been the source for about half of US helium supply. The pipeline is tapped at various points along its length by four privately owned helium refineries. Cliffside has operated without further interruptions since resuming operation in June 2022 under new private-sector management.

The General Services Administration is now scheduled to auction off both the pipeline and associated assets, plus the 51 million cubic meters (51 billion L) of helium left in the reserve, in mid-November. The sale, first ordered by Congress in 1996, has been delayed repeatedly, most recently last year.

The American Physical Society has petitioned lawmakers in recent years, to no avail, to require that buyers of reserve assets pledge to continue fulfilling scientists' ongoing needs on a preferential basis. At press time, those efforts were continuing with staff on Capitol Hill.

Despite helium's indispensability in low-temperature physics, chemistry, and life sciences, research accounts for only 10% of overall helium consumption (see the chart on page 18).

No matter who buys the reserve, the flow of helium is unlikely to change immediately, says helium market consultant Phil Kornbluth. But the flow will naturally diminish each year as the remaining helium, and the corresponding pressure in the formation, continually decline. He estimates that it will take 10 years or more to empty the reserve.

In the short term, a monthlong maintenance shutdown at Exxon Mobil's natural gas processing plant in Shute Creek, Wyoming, will exacerbate the shortage for a couple of months, says Kornbluth. After that, the market should return to its previous condition of relatively mild shortage. Shute Creek is the largest US helium source and accounts for about 20% of global supply. Helium occurs in varying proportions in natural gas. It is separated cryogenically when its fraction is economically viable, generally over 0.3%.

The wild card for the near-term global supply picture is the status of Gazprom's Amur natural gas processing complex in eastern Russia. The complex hasn't operated since an October 2021 fire and explosion, a month after its commissioning. Amur could add 21–42 million cubic meters per year of helium to the global supply. But that depends on whether Gazprom can operate the plant and can get the helium to the international market as the war in Ukraine continues. Gazprom was planning to begin commissioning Amur last month, Kornbluth says, but the company had also promised to open last year. In any case, there is no scenario in which Amur will reach full production immediately, he adds.

"If and when Amur puts a substantial amount of gas into the market, the shortage should end," says Kornbluth. To date, Western nations have not imposed sanctions on Russian exports of helium. Should they do so, helium from Amur could be shipped to China, India, or other countries that haven't imposed sanctions, he says.

A complicating factor for Amur, however, is a US export restriction on domestically manufactured containers that are used to ship large quantities of liquid helium. The US manufacturer Gardner Cryogenics produces the bulk of the global supply of those superinsulated cylinders, and there are limited spares available around the world that could transport helium from a new source.

The opening of another liquefied natural gas plant in Qatar in 2027 could add as much as 42 million cubic meters to the world's helium supply, Kornbluth says. Depending on what comes out of Russia, helium could be in oversupply by the end of the decade. In that case, he adds, prices are likely to moderate.

Development of new helium sources around the globe has picked up in response to rising prices. One major new source could be Blue Spruce Minerals, a gas-processing plant that's being planned to commence operations on land adjacent to Exxon Mobil's Wyoming plant by 2028. Robert Ferguson, Blue Spruce's managing partner, says the hope is to produce 22 million cubic meters of helium annually, about half the output of Exxon Mobil's plant.

Helium recycling grows

The prolonged supply and price squeeze has driven more large consumers of helium—and increasingly many smaller ones—to acquire recovery and liquefaction systems. The efficiencies of those systems vary from 75% to 95%, according to users.

Physicists require helium for conducting experiments at low temperatures and for cooling quantum computers. They also need it for some scientific instruments, including some superconducting magnets, superconducting quantum interference devices, and accelerators—the last of which uses copious quantities. The newly commissioned helium recovery system at SLAC's Linac Coherent Light Source-II is among the largest cryoplants in the US. (See the photo on page 19.) The closed-loop system will circulate 4 tons of helium (equivalent to 32 000 L liquid at 4.5 K) to cool the LCLS's 23 superconducting RF cavities to 2 K, says Eric Fauve, SLAC's cryogenic division director. He notes that the Large Hadron Collider at CERN circulates a helium inventory of 96 tons (768 000 L liquid equivalent). The circulating helium in both systems is part liquid and part gaseous.

With the purchase of an Aus$5 million helium liquefier from Linde five years ago, the University of New South Wales now can provide much of the 20 000 L used by its quantum computing group and the 2000 L needed for its 11 NMRs annually. Because nearly all the helium from the NMRs is recovered and liquefied, Thomas says his cost is an "embarrassingly low" Aus$5/L. Before it began liquefying helium, the university had been capturing helium and selling it to the party-balloon business, he notes.

McMaster University's Brockhouse Institute for Materials Research has been recycling liquid helium since the 1960s, when physicists were looking at Fermi surfaces of metals and helium cost just Can$3–Can$4 ($3.20-$4), says Paul Dube, manager of research facilities. He cites a recovery rate as high as 95%.

The Brockhouse recapture system allows researchers who may need just 10 L of helium at a time for their experiment to get it without having to buy a 60 L or 100 L dewar. "Purchasing 100 liters and using only 20% of it never made fiscal sense," Dube says.

Halperin has been managing a recovery and liquefaction facility at Northwestern since 1983. Today it recovers about 70% of the helium used by physicists, chemists, and materials scientists on campus. He keeps an inventory of about 5000 L. Installing a similar system today would cost a medium-to-large campus $3–$5 million, he says.

Smaller-scale recovery and liquefaction systems can capture the boil-off from three or more NMRs. Texas A&M's chemistry department installed a $240 000 helium recovery and liquefaction system three years ago. It recycles the helium boiled off from nine instruments. The installation lowered the department's annual helium expenditures from $40 000 to $8000. That includes the purchase of amounts needed to maintain three NMRs that are too distant to be connected to the system.

The payback for the chemistry department was immediate, says Wylie. A National Institutes of Health grant paid for most of the system cost, while the university administration picked up the rest. Wylie says the combined costs for equipment, staffing, and maintenance will likely be too large for many small universities that have three or fewer instruments.

Plumbing and power

Martha Morton, director of research instrumentation at the University of Nebraska–Lincoln, operates a liquefaction system that recovers 1200 L per year, about 80% of what's needed for her four NMR spectrometers, a Fourier transform ion cyclotron resonance mass spectrometer, and a scanning tunneling microscope. The system was installed in 2021 with a $250 000 grant from NIH. The university kicked in $50 000 for the 400 m of pipes that collect gas from four floors in the laboratory building. "It's all about plumbing," Morton says, noting that leaks are often hard to find because much of the piping is hidden in the walls.

NIH has discontinued its support for helium-recovery systems, but NSF received new authority under last year's CHIPS and Science Act for grants in support of them. As Physics Today went to press, NSF was reviewing proposals it solicited early this year offering anywhere from $100 000 to $4 million for new helium-recovery systems. An NSF spokesperson declined to comment on the number of grants the agency expects to award, saying the grants will be announced by this fall.

For the single-NMR institution, manufacturers offer a recovery system as an option for a new machine. But the feature costs around €100 000, says Spyros, and it would reduce, but not eliminate, the need for helium replenishment. He estimates his payoff period for such a system would be 15–20 years.

Liquefaction systems do have drawbacks: They consume lots of power, need chilled water lines and other supporting infrastructure, and require servicing. "NMR spectroscopists are struggling to keep up" with the additional costs, Morton says. "They've been asked to install the systems. They were expecting them to be more turnkey, and they're not." She says that keeping the liquefier system functioning properly takes 4–10 hours each week—time that could have been spent on research.

Cryogen-free systems can eliminate the need for helium altogether. Also known as dry fridges, they are well-suited for certain applications, such as in quantum information science, where the vibration they create isn't an issue. But some other low-temperature applications, such as scanning tunneling microscopy, are vibration sensitive. "Maybe commercial suppliers will be able to better mitigate vibration, but it's not available now," says Halperin. "If you work at the nanoscale, dry fridges may not be usable."

Cryogen-free systems are also expensive. A "bare-bones" system will cost $500 000, Halperin says. Still, manufacturers Blue Force and Oxford Instruments are now building them at the rate of one a day, he says.

David Kramer

Impending ship retirement leaves ocean-drilling researchers adrift

Scientists may have to wait more than a decade for the launch of a new vessel capable of collecting samples below the ocean floor.

THOMAS RONGE/IODP JRSO

THE *JOIDES RESOLUTION* cruises on the Aegean Sea earlier this year.

After nearly 40 years, the *JOIDES Resolution* (*JR*) will quit drilling into Earth's oceanic crust for scientific research at the end of 2024, four years earlier than expected. NSF announced the ship's retirement this past March. Despite the vessel's continued contributions to exploring Earth's history and climate, the US and its 20 international partners can no longer sustain the ship's increasing costs for drilling operations, says Jim McManus, director of NSF's division of ocean sciences. The unexpected decision leaves scientists who rely on ocean drilling wondering what is next for their research, careers, and community.

The *JR* got its start in 1985 under the US Ocean Drilling Program, which became the Integrated Ocean Drilling Program in 2003 and then the International Ocean Discovery Program (IODP) in 2013. The *JR* is one of three ocean drilling projects operating under the IODP. The others are Japan's *Chikyu* and the European Consortium for Ocean Research Drilling (ECORD), which conducts missions through various hired vessels. The *Chikyu* and ECORD have completed 17 and 8 expeditions, respectively, compared with the *JR*'s nearly 200.

The *JR* brings together scientists from multiple disciplines, including environmental science, geoscience, and sedimentology. The vessel can carry up to 50 scientists and technicians in addition to 65 crew members. Every year the *JR* averages four or five expeditions, each lasting two months.

To collect samples, researchers lower a long pipe into the oceanic crust, drill a hole, and collect a core of material. The pipe can reach depths up to 7 kilometers below sea level. The cores, which measure about 9.5 meters in length and 6 centimeters in diameter, are brought back to the ship and analyzed in one of its five onboard labs. Researchers collect hundreds of cores during each expedition. "There is this incredible moment of wonder when you are bringing a core off a new blank spot on the map and splitting it open for the first time," says Luan Heywood, an IODP research associate based at Texas A&M University and a *JR* marine-science technician. "You're seeing some rocks that are probably millions of years old and have never been seen by a human."

Over the years, researchers aboard the *JR* have, for example, found microbes in encrusted ocean rock; discovered pollen in the Arctic and Antarctic, which indicates tropical plants once existed there; and analyzed sediments from the crater formed by the asteroid impact that killed the dinosaurs. The findings collectively advance the understanding of Earth's evolutionary and climate history. During a recent *JR* expedition, scientists pulled up a record-breaking amount of rock from the mantle, which, more than a kilometer beneath Earth's crust, is difficult to access.

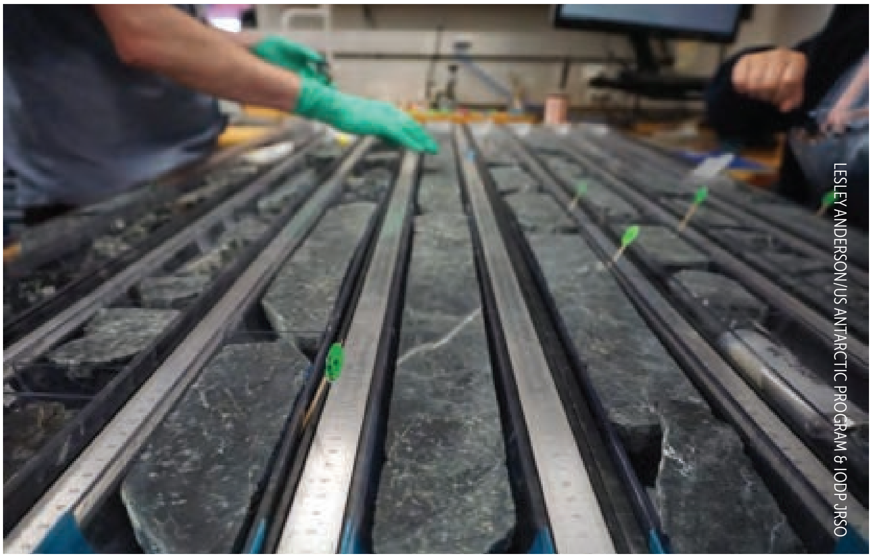
The current annual operational costs of the *JR* are $72 million; NSF representatives would not say how much the cost has gone up. In a virtual town hall meeting on 6 July, McManus said that the contributions from international partners decreased from $16.5 million in 2015 to $12.5 million in 2023. The US covers about two-thirds of the operational costs but receives only about one-third of the allocated science spots on expeditions, McManus tells Physics Today.

A jolt to research

The loss of the *JR* will hit early-career scientists especially hard; roughly one-third of the scientists on board are graduate students. "So many of the people that I know and am connected with on social media have started their careers by going on the *JOIDES Resolution*," says US Science Support Program (USSSP) communications officer Maya Pincus, who disseminates information about the

LUAN HEYWOOD

***JOIDES RESOLUTION* technician** Luan Heywood holds a rock that was deposited by a long-ago melted Antarctic iceberg. The sample is about 30 microns thick.



RESEARCHERS EXAMINE a sample of mantle rock that was pulled up from more than a kilometer below the ocean floor.

JR to the public. Because operations on the *JR* are 24/7 for 60 days straight, participants tend to have many networking opportunities.

"Sailing on board the *JOIDES Resolution* as a young scientist changed my career, as we uncovered unexpected materials and I started new collaborations with colleagues that will remain lifelong friends," says Sietske Batenburg, a stratigraphy lecturer at the University of Barcelona. "I will miss the sense of camaraderie and adventure."

The USSSP ran workshops in August to help redirect early-career scientists in the ocean-drilling community, Pincus says. Although there are no concrete plans for the younger scientists, NSF said in its March announcement that future mission-specific expeditions conducted through alternative platforms are a possibility.

"It's hard to know what is going to come next in terms of where all my coworkers are going to go," says Heywood. Those who are visiting members on *JR* expeditions can go back to their jobs. Others who work on the technical staff, like Heywood, may still be employed at core repositories, which contain hundreds of kilometers of previously drilled material available for study. Downsizing is almost certain, she adds, and it is unclear what future scientific ocean-drilling efforts will look like.

Researchers will also be more limited in where they collect new data. Many will be able to turn to stored cores. The IODP places cores in repositories at Texas A&M, the University of Bremen in Germany, and Kochi University in Japan. But legacy cores aren't an option for everyone. When a core is brought up to the ship, microbiologists get their samples first before the core is split and exposed to microbes in the surrounding environment, says Jessica Labonté, a marine microbiologist at Texas A&M. Without the *JR*, researchers in microbiology and in other disciplines will have to rely on other scientific ocean-drilling expeditions, meaning researchers will have fewer opportunities to sail each year.

Replacing the *JR* was always on the horizon. Even if NSF had continued its funding, the *JR* would have operated only until 2028, the end of the period covered by its environmental impact statement. In the town hall meeting, McManus said retiring the *JR* in 2024 would give NSF more time to plan for the future of ocean drilling rather than scramble at the end of 2028. It will take at least 15–20 years to gain financial backing and construct a new ship available for expeditions, he added.

Japan and the countries involved in ECORD plan to continue working together in ocean drilling after the IODP cooperative agreement ends late next year. NSF is in talks about US participation in future international collaborations in ocean drilling, McManus says, but the agency does not want to rely on such a collaboration to be sustainable.

Hannah H. Means PT

THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

TENURE-TRACK FACULTY POSITIONS IN PARTICLE PHYSICS AND COSMOLOGY

The Department of Physics invites applications for several tenure-track faculty positions at the Assistant Professor level in experimental and theoretical physics. The target areas of the search are Theoretical High Energy Physics and Cosmology, Experimental Particle Physics and Observational Cosmology. Applicants must possess a PhD degree in physics or a related field. The successful candidates should have a strong track record of research (the ones with an interdisciplinary background are especially encouraged to apply). Appointments at the rank of Associate Professor or above will be considered for candidates with an exceptional record of research excellence and academic leadership. In addition to pursuing a vibrant research program, appointees are expected to engage in effective teaching at the undergraduate and graduate levels.

The current faculty in the particle physics and cosmology group at The Hong Kong University of Science and Technology include Professor Andrew Cohen, Professor Tao Liu, Professor Kam-Biu Luk, Professor Kirill Prokofiev, Professor George Smoot, Professor Henry Tye, and Professor Yi Wang. The department is expanding its effort in this area by hiring additional new faculty in theory and experiment. Further information about the Department can be found at http://physics.ust.hk.

Starting salary will be highly competitive and commensurate with qualifications and experience. Fringe benefits including medical and dental benefits, annual leave and housing benefits will be provided where applicable. The initial appointment prior to tenure will normally be on three-year contract terms. A gratuity will be payable upon successful completion of a contract.

Application Procedure: Applicants should submit their applications along with CV, cover letter, complete publication list, research statement, teaching statement, and three reference letters.

High Energy Theory and Cosmology (PHYS1017H):
https://academicjobsonline.org/ajo/jobs/16291

Particle Physics Experiment (PHYS1017P):
https://academicjobsonline.org/ajo/jobs/16292

Observational Cosmology (PHYS1017C):
https://academicjobsonline.org/ajo/jobs/16293

Screening of applications begins immediately, and will continue until the positions are filled.

Helping the PANDEMIC GENERATION

Brad R. Conrad and Matthew J. Wright

Physics undergraduates have returned to classrooms, but pandemic trauma has endured. How can the community assist?

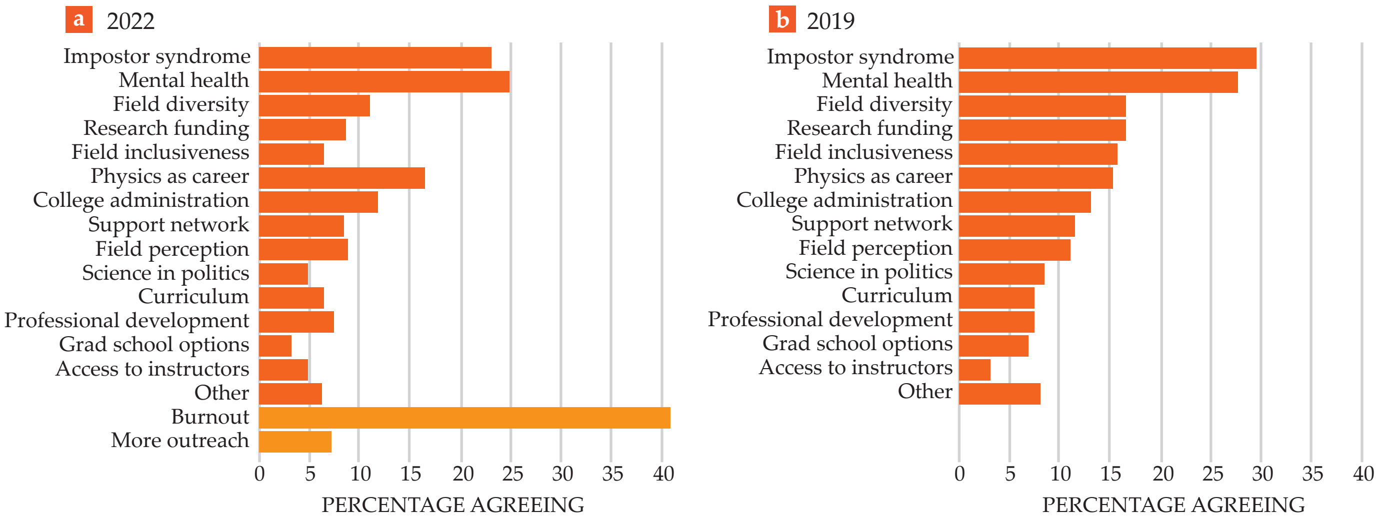
Brad R. Conrad is the former director of the Society of Physics Students (SPS) and Sigma Pi Sigma, the physics and astronomy honor society. **Matthew J. Wright** is an SPS zone councilor and an associate professor of physics at Adelphi University in Garden City, New York, where he is a coadviser of the SPS chapter.

Although the COVID-19 health emergency of the past three years is fading, its effects will be felt on college campuses for many years to come. It shouldn't come as a surprise to anyone that a global pandemic that shut the world down for years significantly impacted students' educational journey. Although the extent of the disruption is still being measured, the pandemic clearly affected aspects of the physics undergraduate experience, such as experimental courses and summer laboratory internships. It also made it hard for students to build an identity as part of a cohort and develop relationships with faculty.

The pandemic's effects were not uniform and will likely not be fully understood for decades. Studies have shown that some students fared no worse during the health emergency[1,2] and have gotten back to business as usual now that in-person instruction has returned.[3] But many others have struggled.[4,5] Students' experiences have been uneven because the abrupt changes to university instruction during the pandemic affected them at different stages of their professional development. Students who are now beginning their fourth year of college likely experienced their first year of college mostly virtually.

For many students, college is their first extended time away from home. It is where they develop foundational skills in communication, studying, prioritization, and managing stressful situations. The pandemic generation was removed from support systems that are traditionally vital to undergraduates—for example, physics club meetings, in-person study sessions, and informal hallway discussions—and that are especially crucial for first-generation college students and those who come from underrepresented groups.[6]

Departments should be commended for how they helped students continue their



(a) THE RESULTS of a student survey at the Congress Workshop at PhysCon 2022. Participants were asked to list the two most important issues facing them and their Society of Physics Students chapter. **(b)** The results of a similar survey at the previous congress, in 2019. Although the survey posed the same question, the provided responses differed slightly. Nevertheless, it is clear that the pandemic worsened existing mental health issues among students.

"Burnout and impostor syndrome affect nearly every single physics and astronomy major."

studies as best they could in the face of a public-health crisis. Moving an entire college-level course sequence from in-person to virtual instruction essentially overnight is something most physics and astronomy departments didn't see coming and likely didn't even think was possible. Universities have now largely returned to in-person instruction, but it shouldn't surprise anyone that students missed out on things that previous generations would consider to be normal or even fundamental. Our students are very bright, and they are looking for ways to show us they missed out on those experiences. We need to listen to them.

Lessons from PhysCon

Every few years, the physics and astronomy honors society, Sigma Pi Sigma, hosts PhysCon (short for "Physics Congress," although going forward the event will be formally called the "Physics and Astronomy Congress"). It brings together current undergraduates—mostly juniors and seniors—from over 250 colleges and universities to share in three days of community building, professional-development activities, leadership training, and workshops. The conference seeks to understand how the physics and astronomy community needs to evolve so its members can best support each other and build a better future for the physical sciences.

One of the most important parts of the meeting is the Congress Workshop, which asks attendees to consider their undergraduate experience so far and identify the most important issues that they or their chapter are facing. The workshop focuses on how attendees can support each other and make progress on the issues students are facing in their capacities as individuals, as representatives of their departments, and as part of the broader community.

Originally planned for late 2021, the most recent PhysCon was held in fall 2022 because of a pandemic postponement. Panel a of the figure shows the results of a survey conducted at the Congress Workshop in which the authors of this article asked students to list the two most important issues facing them and their chapter. The most common response was burnout, with 40.6% of the students in the room who responded stating that it was the biggest challenge. That should not be surprising. It's rational to feel burned-out after a global pandemic, and the prevalence of the response is a strong indicator of the issues students are dealing with.

Comparing that result with a similar survey conducted at the previous PhysCon in 2019 (see panel b of the figure) is instructive. Although that survey was slightly different, we can still learn much from it. Tellingly, burnout was not even listed as a potential concern in 2019, and it wasn't written in by anyone either. At that time, the largest issue of concern was impostor syndrome (29.6%), and mental health was a close second (27.9%). Of course, mental health and burnout are linked.

The PhysCon survey touches on an array

of deep-seated issues that we as a community can help to address. They were exacerbated by both the rapid transition to online learning environments and the prolonged changes to student support structures such as undergraduate groups and faculty connections. For many students, those issues were compounded by a loss of access to research, summer experiences and income, and even housing. Similarly, course expectations were changed in ways that often conflicted with educational goals.

The pandemic also robbed the current generation of students of one of the most important aspects of the college experience: connections to their peers. Many students stay in physics and astronomy because of those connections, which help them develop their identity as budding scientists. If students are removed from their course-related cohorts, their self-identity and support networks suffer. That is especially true for students from underrepresented backgrounds.[6] In many cases, the pandemic also physically isolated students or stunted their opportunities for connection and learning outside of the classroom, such as research experiences or interactions with faculty. Lack of connections probably also hampered recent graduates: New degree holders employed in the private sector report that teamwork is the most-used skill they learned as a physics major.[7] Feeling disconnected might be part of the reason why 36% of physics and astronomy undergraduate students who completed their degrees in 2020–21 reported that they changed their postgraduation plans because of COVID-19.[8]

Differentiated experiences

For instructors, it is important to realize that not all students were affected by the pandemic equally, and that will create difficulties in the classroom for some time. On the one hand, some students came through the pandemic unscathed or even empowered. For example, when freed from the distractions of campus life, one student the authors of this article have worked with was able to dive deeper into studying and make rapid improvements. Despite receiving poor grades in the first semester of college, that student ultimately earned admission into a PhD program. Another student formed a pod of study partners and benefited from increased time with family.

But many other students—often those from marginalized parts of society[4]—did not

“Imagine starting your career with no friends to meet up with.”

"The lack of outreach and connection creates a culture and a public reputation of elitism."

fare as well. Some of them may have had to drive to fast-food-restaurant parking lots so that they could access the internet to attend their class, or spent months living in their cars. Some may have had family members who lost their jobs or had to take on extra part-time work just to get by. Those experiences speak to inequities in resource access. Lower-income communities in New York City, for example, saw a disproportionately higher rate of COVID-19 infections, hospitalizations, and deaths.[9] Should we really be telling a student who lost multiple family members due to COVID-19 to focus on their homework?

That presents an important question for educators: How can they meet the needs of students who weren't affected by the pandemic and students who have fallen far behind? On the one hand, instructors may have classes filled with eager students prepared in the same way that many students were before the pandemic. Those students are generally tired of COVID-19 and ready to proceed to the next level in physics. On the other hand, educators may have classes filled with students who, during the pandemic, may have missed out on critical high-school mathematics, lost family members, or had to live in a small space with fewer resources than normal. Those students are also sick of the pandemic. The reality is that both sets of students are probably present in all classrooms.

Many of the students who are struggling have missed out on key academic-development opportunities. They don't just have low math scores: Often they don't possess the study skills[10] or expert-like thinking[11] necessary to succeed in physics and astronomy. Inequity and impostor syndrome were already major problems in physics and astronomy before the pandemic. Students would look at their high-achieving peers and wonder if they had the ability to succeed. Those problems may now be worse, because educators and employers sometimes assume that students have had certain experiences without understanding the reality of college life during the pandemic.[6]

The term "hidden curriculum" loosely captures the collection of unwritten skills for being successful in college that many students from the dominant-culture class have developed over the years.[10] Those skills might include understanding social messages and expectations or intuitively comprehending the appropriate behaviors or

values a student should have at a certain point in their educational journey. Having those skills can give a student a serious edge. Many students from underrepresented backgrounds gain knowledge of the hidden curriculum by connecting with the community through activities like internships, department work, and summer research projects. Although some students had opportunities to do so during the pandemic,[12] there were fewer openings.

Most students have felt anxious or depressed because of the pandemic.[13] The authors of this article have mentored academically high-performing students who faced extreme mental health conditions caused by, or amplified by, the COVID-19 emergency. One of the unfortunate situations is that because of their success, those students often appear as if their life is going along swimmingly. The outside observer might not see the emotional turmoil that is happening inside the student.

Those are the students who are often key members of student organizations in the department. They are the ones everyone goes to with their problems, questions, and concerns. Even faculty rely on them to accomplish important tasks: An undergraduate physics club president might be asked, for example, to attend a university open house. In moderation, those responsibilities are typically good for the student's career. But when they're giving everything they have and are on the verge of breaking down, a little extra work might push them over the edge. Mental health support for all students is critical because it encourages social connectedness.[13]

All members of the physics community can help to address the issues facing undergraduates and recent graduates today. As difficult as it is for our students, there are plenty of opportunities for us to help them out and give them the keys to success. Just a little bit can make a huge difference. The rest of this article will discuss some of the things we can do as a community to improve the situation for students.

Inside the ivory tower

College professors can help their students address burnout and the mental health consequences of COVID-19 in several ways.[14,15] In the classroom, they can promote mental health by designing the social aspects of active-learning activities in ways that reduce anxiety, increasing mastery-based learning,

"When a student gets burned out, they are encouraged to transfer majors instead of to keep going."

“Students are struggling with the world around them, and their mental health is in the gutter. . . . Often the source of their struggles are systemic issues that cannot be adequately addressed at the individual level.”

and providing students with more choice in course assignments.[14] They can also account for the inequality of students’ experiences and help them reacclimate to studying, overcome impostor syndrome, cultivate a sense of belonging, and learn about the hidden curriculum.[15]

Even before COVID-19, students came into physics classes with varying levels of preparedness. The spread in that gap is much bigger now. Not every student is going to catch up in one semester. Some of them will need to be pushed: We must make sure they are meeting their deadlines and are giving it their all. Telling those students they can miss class or homework assignments is not going to help them grow. But other students are really at an inflection point. An extra assignment or bad grade can have negative consequences for their mental health. We must identify those students early so that we can help right them when they get off course.

Departments and colleges also have an important role to play. Here we can take inspiration from a few programs already instituted at several universities. At Washington University in St Louis, for example, the diversity, equity, and inclusion committee has designed posters of physicists with a variety of career descriptions and hung them around their department. At Juniata College in Huntingdon, Pennsylvania, a program sponsored by the Society of Physics Students (SPS) created a mural in the department that depicts physicists and astronomers from a wide variety of backgrounds. Those initiatives communicate the various careers available to graduates with physics degrees and broaden perceptions of who is in the field. Indeed, studies have shown that expanding the culture of physics, which is quite narrow, and providing materials for both educators and students is necessary to create a wider classroom support structure.[16]

Another way departments can help is by hosting career events with alumni. They provide an excellent way for students to meet recent graduates who can teach them pieces of the hidden curriculum. Learning about career opportunities can also help motivate students who are struggling to find their career path. SPS’s online Careers Toolbox provides a collection of resources that faculty and departments can use to help students with their career search.

Mentorship is another area to focus on. Many SPS chapters or department-level physics and astronomy clubs support programs in which upper-level students help mentor lower-level students. Departments can arrange small meetups between students over coffee or a snack to chat about their studies. Invaluable information about how to succeed as a college student can be passed down in those forums. The value of student-

to-student and recent-alum-to-student interactions cannot be overstated. At the end of the day, education is a deeply personal journey that students undertake not as individuals but as a group: They learn just as much from classmates and friends as they do from giants in the field. In many ways, physics is a team sport: When one student is stressed, all of their classmates feel it.

Almost all campuses host a wealth of support services such as counseling and tutoring centers that students can take advantage of. But many students are afraid to ask for help. Participating in a mentor–mentee relationship can be one way a lower-level student can gain the courage to use those services. When mentors share how they used those services in the past and describe how they benefited from them, lower-level students learn that it's OK to get help.

Colleges and their physics departments should also provide a space for students to have fun, connect with their peers, and feel at home. A strong physics or astronomy club connected to SPS is an excellent way to do so. Such a club allows students to develop a space for themselves and gain a voice in the department. But it's important for SPS clubs to post and enforce codes of conduct so that they can provide a safe and encouraging educational atmosphere and avoid creating a toxic environment that excludes members of the department. That isn't easy. It takes effort and a lot of patience.

Outside academia

Individuals outside the ivory tower may not think that they can have a role in students' education. Somewhat counterintuitively, however, being outside of the academic world may actually give them hidden powers to reach students in a meaningful way. Students are often skeptical of career advice from faculty. But when someone in the so-called real world gives advice, it can really hit home—even if it is the same advice that students have received from their professors. Individuals outside academia have a unique opportunity to provide support that faculty are not able to.

Mentoring provides a one-on-one opportunity to help develop someone's career, and many of the American Institute of Physics' member societies have programs that aim to connect physics-trained professionals with hungry students who want to learn. (AIP is the publisher of Physics Today.) For example, the American Physical Society (APS) has a Career Mentoring Fellows program, which provides funds, resources, and training for professionals to give talks at colleges and universities about how students can build their careers. For those in industry, APS's Industry Mentoring for Physicists program connects students and early-career physicists with industrial physicists for career advice and guidance. Another important program is APS's National Mentoring Community, which facilitates relationships between underrepresented undergraduates and professionals. The American Astronomical Society also boasts several programs that aim to connect students and early-career astronomers with potential mentors in the community.

Strong mentors can be an excellent resource for students who are struggling with their studies and other life situations. A positive mentor might be able to even catch student problems before they become serious and help students overcome them. Mentoring can improve a student's physics identity and their success in physics. Mentoring can also have a huge effect as students transition into the professional world. Transitioning into the industrial world can be particularly daunting for students. One student at PhysCon 2022 remarked, "I am doing my own research on finding jobs and have not seen any way to get my foot in the door of industry." For that reason, senior industrial physicists can make a powerful impact by taking new employees under their wing, especially if those employees are recent graduates struggling with the transition into the working world.

Unfortunately, there is no magic pill that will solve all the problems students are facing. Professors can't change the landscape of mental health in physics all by themselves: It's going to take effort by the whole community. Although mental health issues and inequality have been made worse by the COVID-19 pandemic, they were issues before and will be issues afterward. Physics is hard, and when students push themselves to their limits, they will inevitably test themselves and require support.

But the world needs good physical scientists, especially now that we are facing an increasing climate crisis. We must work together as a community to create an enriching, challenging environment for our students to thrive in. Our students are struggling to handle the lasting impact of a pandemic, and they need our help. The first step is to reach out.

All photos and quotes in this article are from PhysCon 2022. The photos are courtesy of SPS, the SPS National Council, and Sigma Pi Sigma.

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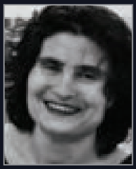

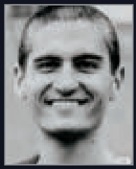

The dynamics and changes of the world's monsoons

Michela Biasutti, Mingfang Ting, and Spencer A. Hill

The seasonal rainy phase observed in many places across Earth is shaping the climate and is being changed by global climate trends.

If you have ever lived in Kolkata, India; Niamey, Niger; Darwin, Australia; or Tucson, Arizona, you have experienced a monsoonal climate. A long dry season during the cold months of the year transitions to a spring season with scorching temperatures and the occasional explosive thunderstorm as the wind brings more and more humidity from the sea and, eventually, summer rain.

Many monsoonal regions experience a seasonal reversal of the prevailing winds, from offshore during the dry season to onshore during the rainy season. But the most salient feature is the rainfall—a monsoon climate sees most of its annual rainfall concentrated during the summer, as shown in the seasonal comparison in figure 1.

Monsoons have been central to the

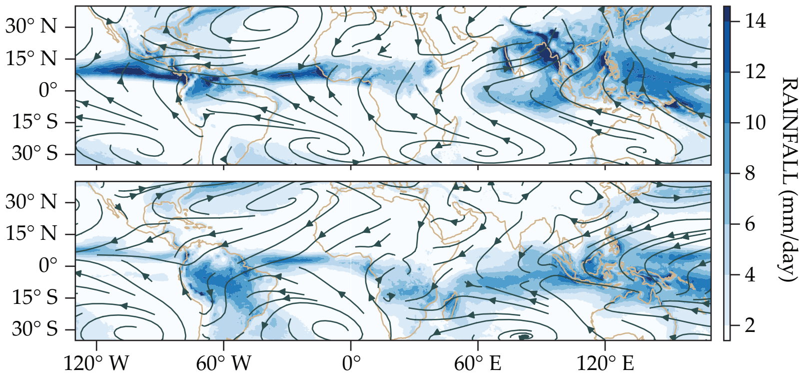

FIGURE 1. MONSOON SEASON is characterized by tropical rainfall (blue shading) and converging, near-surface wind patterns that occur in the Northern Hemisphere from June through September (top) and in the Southern Hemisphere from December through March (bottom).

identity and art of many world cultures. Their winds power sailing vessels, and their rains fulfill the water needs of billions of people in the tropics and subtropics. Monsoons have also been central to the development of climate science.

In 1686 Edmond Halley published for the Royal Society of London what scientists now think of as the first attempt to explain the atmosphere's general circulation.[1] The theory was not quite exact—Isaac Newton's *Philosophiae naturalis principia mathematica* (*Mathematical Principles of Natural Philosophy*), with its description of the laws of motion, wasn't published until the following year—but Halley got some fundamentals correct: The monsoons are not some local sea breeze but part and parcel of a planetary wind system. Somehow, that basic truth has been forgotten and remembered many times.[2]

In a lecture delivered on 16 March 1921 to the Royal Meteorological Society, George Simpson, then the director of the UK's Meteorological Office, remarked:

> I believe that very few educated people would have any difficulty in giving an answer to the question—What is the cause of the monsoon? They would refer to the high temperature over the land compared with that over the surrounding sea, and would speak of ascending currents of air causing an indraft of sea-air towards and into the interior of the country. It is only when one points out that India is much hotter in May, before the monsoon sets in, than in July, when it is at its height, or draws attention to the fact that the hottest part of India—the north-west—gets no rain during the monsoon, or even shows by statistics that the average temperature is much greater in the years of bad rains than in years of good rains, that they begin to doubt whether they do know the real cause of the monsoon.[3]

To find out the real cause of the monsoon, forget about India (or any particular locale) for now and go back to Halley's visionary perspective of a planetary-scale circulation. To make things even simpler, let's assume that Earth is a sphere that has a homogeneous surface with a gaseous atmosphere and is rotating in space, tilted on its axis, and illuminated by the Sun.

As the Northern Hemisphere tilts toward the Sun after the spring equinox, the peak of incoming solar radiation moves to the northern subtropics. Some heat is absorbed at the surface, and some is radiated back to space at the top of the atmosphere, whose cooling rate is set by the temperature of the Earth–atmosphere system, according to the blackbody approximation. The loss of heat to space, however, fails to balance the energy received from the Sun, so the atmospheric and oceanic circulations have to export the excess energy.

High in the atmosphere, the air is cold and dry, but it has high potential energy. Hence, at upper levels, that air can transfer the necessary energy out of the northern tropics and into the southern tropics. Conservation of mass requires that the upper-level air be replaced, which results in a circulation loop being formed. At low levels, air travels from the Southern Hemisphere, picking up moisture from the surface along its path. When that air rises in the Northern Hemisphere, it cools by expansion, and its water vapor condenses into clouds. Deep cumulonimbus towers extend about 10 km into the atmosphere, and heavy rainfall ensues.

So far, we have described a meridional circulation, which goes north and south in response to heat differences. But Earth is a rotating sphere, and it needs to conserve angular momentum. As air changes latitude, it changes its distance from Earth's rotating axis. Away from the surface, frictional torques are unimportant, and a parcel of air will do one of two things. It could maintain its angular momentum by acquiring eastward velocity when it moves closer to the rotation axis or westward velocity when it moves farther away. Or it could change its angular momentum in response to the effective torque of macroturbulent eddies that are formed in the sharp temperature gradients of the midlatitudes.

During the equinox seasons, the eddies penetrate into tropical latitudes and transport momentum away, slowing the circulation.[4] During the solstice seasons, the eddies in the summer hemisphere are weak, and those in the winter hemisphere don't reach the tropics. Therefore, the cross-equatorial circulation approximately conserves angular momentum and remains strong. The transition between the equinox's dynamical regime and that of the solstice season happens abruptly in late spring or early summer.[5] On the ground, it is heralded as the onset of the monsoon.

To explain Simpson's counterintuitive observation—that the hottest time of the year is not the most conducive to convective updrafts—we need to consider the phase changes of water. The water cycle is an energy cycle. When the cross-equatorial surface flow evaporates water from the ocean, the ocean cools and the energy is carried in latent form in the vapor. When water vapor condenses in clouds, the latent heat is released, which further fuels the atmospheric circulation that lifted the air in the first place. (A dry atmosphere could produce a circulation similar to what's described, but it would be much weaker.) Instead, the monsoon is strongest when and where the surface air contains the largest amount of combined heat and moisture. Known as moist energy, its distribution helps explain the localization of the planetary monsoon into each unique regional monsoon.[5]

Regional monsoons

Together, the uneven distribution of solar insolation, the conser-

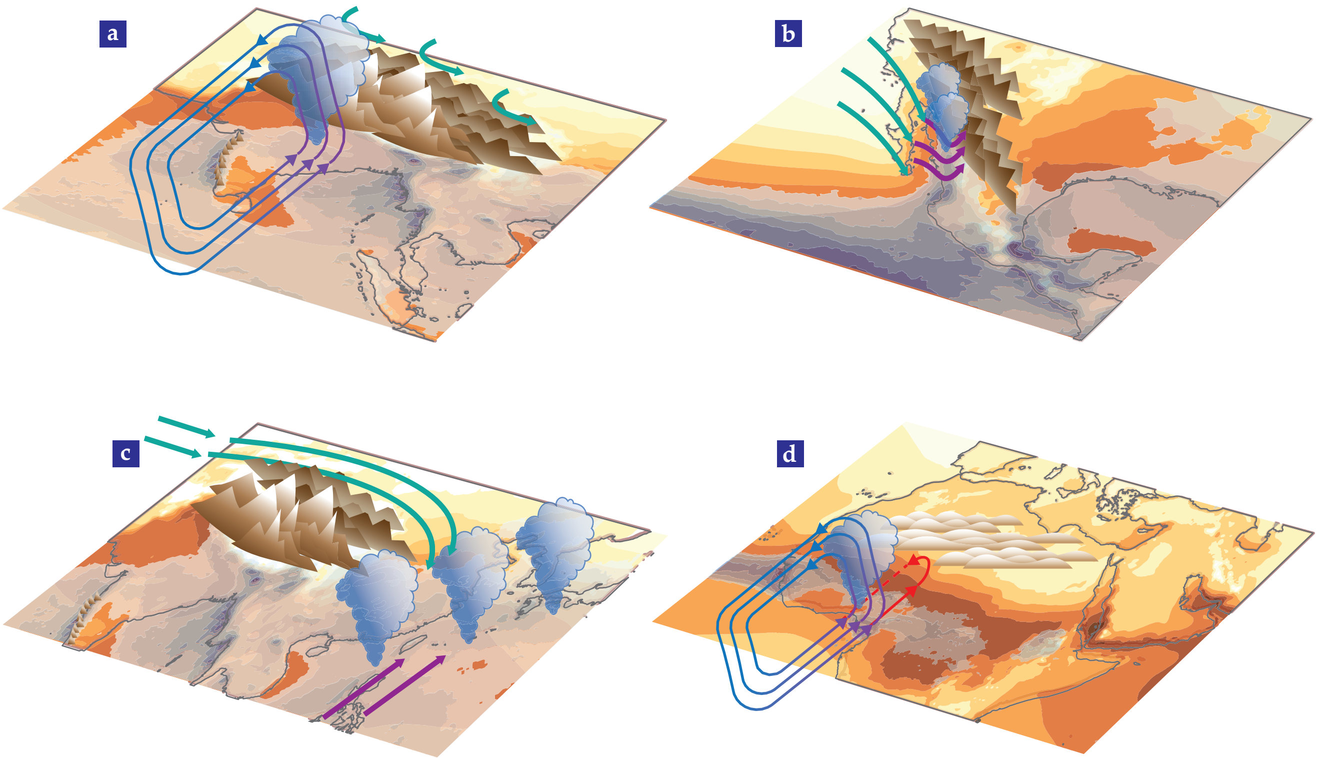

FIGURE 2. NORTHERN HEMISPHERE MONSOONS. Rainfall (blue shading) is located near regions of high, near-surface moist energy (orange) and concentrated on the windward side of mountains. **(a)** In South Asia, ascent in the regional branch of the north–south atmospheric circulation (purple vertical streamlines) stops south of the Himalayan mountains. Moist energy there becomes too low because of the effect of midlatitude winds (turquoise arrows). **(b)** In North America, the midlatitude westerly wind is deflected south by the Rocky Mountains and the Sierra Madre, picks up moist energy from the Gulf of California, and is lifted upslope to create a band of monsoonal rainfall. **(c)** Ascent in East Asia is because of warm monsoon air sliding over the colder midlatitude air flowing from the northern side of the Tibetan plateau. **(d)** In Africa, the deep monsoonal circulation stops, and moist energy becomes too low to support rainfall, once the air reaches the Sahara desert.

vation or dissipation of angular momentum, and the phase changes of water regulate the position and the strength of the planetary circulation in the tropics. But none of them explain why the African monsoon barely makes it to 18° N, whereas the Asian monsoon reaches twice as far, well into the subtropics; nor why in India, Goa receives more than 800 mm of rain during July while Bhopal sees half of that. For that level of detail, we need to abandon the homogenous sphere. Figure 2 introduces the Northern Hemisphere continents with their different geometries, locations, mountains, and deserts.

Mountains interact with the atmospheric circulation in two ways: as a source of heating at higher elevations and as barriers to the wind. Turbulent fluxes transfer heat from the mountain terrain, which is heated by the summer sun, to the high-altitude atmosphere. The transfer amplifies the pressure differential between the hot land and the cold ocean. That mechanism was long considered to be the main effect of mountain ranges on the strength of the monsoon circulation. But the exchange of dry heat from mountainous terrain remains a secondary source of energy compared with the heating of condensation released in thunderstorms. Instead, mountains affect the monsoons principally by blocking the wind and, in so doing, changing the distribution of moist energy, the location of ascent, or both.

Air can go around mountains or rise up their slopes. The effect of rising air is readily seen because it is always associated with cooling and, given enough moisture, with cloud formation and rainfall. As a result, concentrated bands of heavy seasonal rain fall along the Western Ghats of India, the Arakan range of Myanmar, the foothills of the Himalayas, and other similar places (see figure 2a). As the cross-equatorial wind that feeds the South Asian monsoon is bent by the Coriolis effect, it becomes westerly and flows into the Western Ghats. After dumping its moisture on the way upslope, the air is dry when it descends on the eastern side of the range: Summer is the dry season for southeast India.

Across from the warm Bay of Bengal, there is plenty of moisture to bring rain to the Arakan mountains. Between them and the Western Ghats, a low-pressure center develops and drives a moisture-carrying cyclonic circulation over inland India and again concentrates rainfall along the mountain range. But the Himalayas do more than just localize rainfall into a beautiful arc. They are the reason why the Indian monsoon extends so far north into latitudes that are typically much drier everywhere else in the world.[6] They stop the cold, dry midlatitude air from reaching India and lowering the moist energy; with the air's plentiful reservoir of moist energy, the Indian monsoon remains vigorous well into the subtropics.

The interaction between mountain ranges and the midlatitude westerly wind also controls the North American[7] and East Asian[8] monsoons. Were it not for the Sierra Madre Occidental running parallel to the Pacific coast of Mexico, the westerlies would go around the Rockies at roughly 30° N, and the North American monsoon would extend across the width of Mexico at tropical latitudes before fading northward. Instead

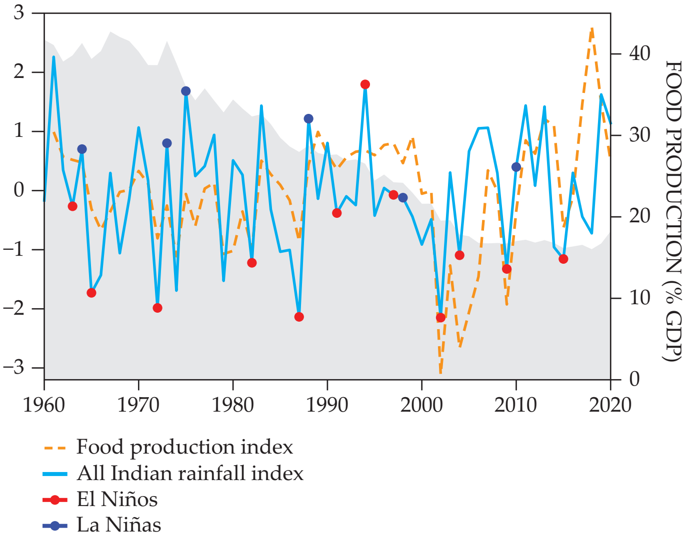

FIGURE 3. INDIA'S RAIN during the monsoon season (light blue) is modulated in part by the El Niño–Southern Oscillation. Droughts are more likely in years when the equatorial east Pacific Ocean is warm (El Niño years, marked by red circles) than in years when the region is cold (La Niña years, marked by blue circles). Food production in India has grown exponentially over time, but when anomalies are calculated from that growth curve, the relationship between anomalous food production (dashed orange line) and years of good or poor rainfall becomes apparent. The gray background shading shows the declining importance of the agricultural sector as a percentage of India's GDP.

(see figure 2b), the Sierras impose a deviation—the westerlies extend southward, rise over the ridge, and produce a concentrated band of rainfall along the slope because of the moist energy they picked up over the warm waters of the Gulf of California and the coastal region.

Shaped by the interactions of the midlatitude westerlies with the Tibetan Plateau, the East Asian monsoon is a unique mix of tropical and midlatitude characteristics. In spring, when the wind has to flow over the mountains, the circulation develops eddies, just as a stream flowing over a boulder would. The eddies create a northerly wind that collides with the monsoonal southerlies along an east–west front—known in Japan as Baiu and in China as Meiyu—where air is lifted and rain forms (see figure 2c). By midsummer, the Northern Hemisphere has heated up enough that the westerly jet moves poleward and passes the Tibetan Plateau unimpeded to its northern flank. The northerlies disappear, rainfall loses its frontal organization, and the southerly monsoon flow brings moisture and thunderstorms to northern China and the Korea Peninsula.

Over North Africa and Australia, the poleward extent of the monsoon is set not by mountains but by deserts. Because deserts are bright, highly reflective dry surfaces, less solar energy enters the system, and less moisture fuels convection. The flow, therefore, is limited: When the low-level monsoon wind penetrates inland—converging into the low-pressure center that forms over the hot desert—it has only enough energy for shallow ascent.[9] Deep, rain-bearing convection remains equatorward and is vigorous enough to sustain the African branch of the planetary monsoonal circulation, even as a layer of desert air, which forms the return flow of the shallow circulation, is entrained into it (see figure 2d).

As immense and immutable as they seem, deserts have not always been where they currently are. As Earth's eccentric orbit and angle of tilt wobble periodically over many thousands of years, the distribution of sunshine can change enough to rearrange the planetary monsoonal circulation. That rearrangement brings rainfall to otherwise dry places, sustains vegetation, and slowly transforms the bright, dry desert to a green, moist savannah. As recently as 5000 years ago, the West African monsoon reached much farther poleward, and our ancestors were seeing and painting hippos in what is now the center of the Sahara desert. (For more on how celestial mechanics affects Earth's climate, see the article by Mark Maslin, Physics Today, May 2020, page 48.)

Sources of natural variability

Although it takes the uplifting of mountains or alterations in Earth's orbit to create wholesale changes in monsoons, relatively small variations of around 10% of the seasonal rainfall happen all the time—and have profound consequences on ecosystems and human societies, as shown by the correlation between rainfall and food production in India plotted in figure 3. And that's not all: Even in years when the seasonal total is average, the rains can arrive early or late, cease for a long time in the middle of the season, or include episodes of torrential downpours. Monsoon rainfall is highly variable on all time scales, from days to decades and beyond.

The convective nature of monsoonal rainfall explains its variability at the time scale of days. In its simple form, convection happens when denser, colder air finds itself unstably on top of lighter, warmer air: Any fluctuations tend to balance the instability and return the atmospheric column to a neutral state. If those fluctuations are random, rain showers will be scattered in unpredictable ways. Otherwise, convection can get organized: in squall lines, which are lines of thunderstorms that move as a unit; around atmospheric waves that provide favorable conditions for low-level moistening or lift; and through more complex feedbacks between convection, the wind that converges into it while picking up water vapor from the surface, and the cloud droplets and ice crystals that reflect and absorb radiation. (For more on cloud convection, see the article by Caroline Muller and Sophie Abramian, Physics Today, May 2023, page 28.)

For example, most rain in West Africa is the product of highly organized mesoscale convective systems that extend for tens of to roughly a hundred kilometers and are often associated with atmospheric waves that travel along a strong easterly wind at the core of the monsoon region. In central India, the most intense rain is associated with monsoon depressions: tight low-pressure systems resembling weak tropical cyclones that typically form over the Bay of Bengal and travel inland. If the environment is sufficiently moist, those disturbances travel as far as Pakistan, as they repeatedly did in the summer of 2022, bringing floods and devastation.

Both the African easterly waves and the Asian monsoon low-pressure systems have time scales of a few days. But over weeks, those monsoons have what are known as active and break phases. An active phase can lead to floods, and a prolonged or ill-timed break can dry crops. Over the Indian Ocean and the northwestern Pacific Ocean, the modulating influence comes from the so-called boreal summer intraseasonal oscillation, which produces alternating bands of active and inactive

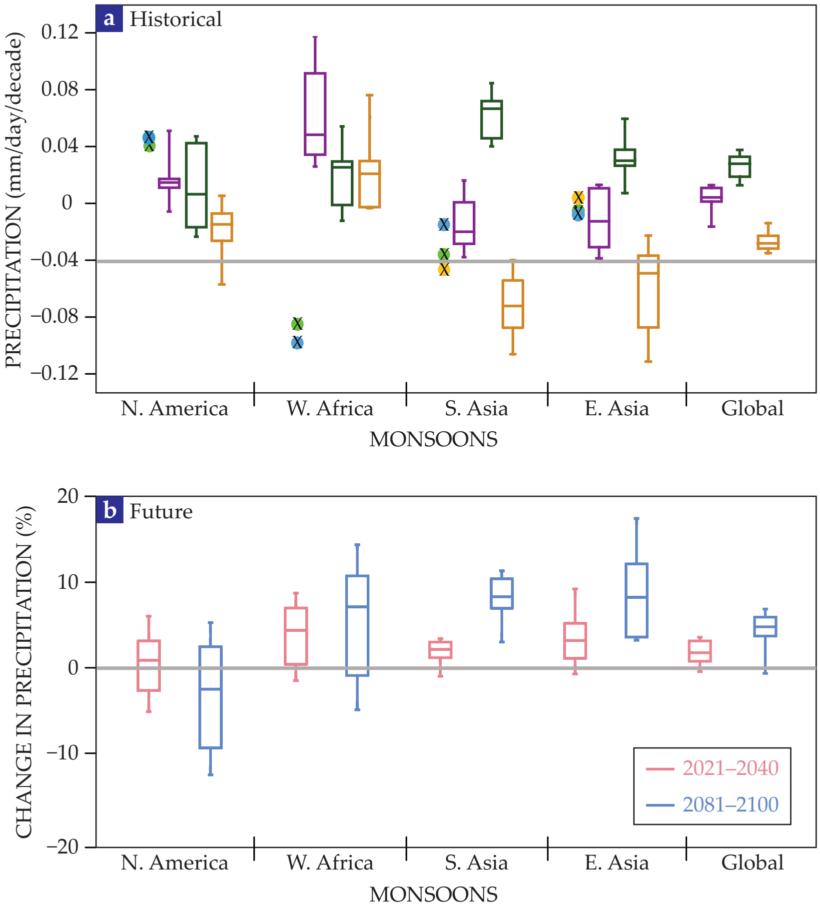

FIGURE 4. LONG-TERM CHANGES. In the Northern Hemisphere, **(a)** historical trends of regional monsoons and the global monsoon from three observational data sets (colored dots) are compared with simulations by climate models (box-and-whisker plots) forced with greenhouse gases only (green), aerosols only (orange), or all historical forcings (purple). **(b)** For each regional monsoon and the global monsoon, future rainfall changes from the historical mean are plotted for the near term and the long term. Because wind patterns are so variable under future conditions, the future change in monsoon precipitation is highly uncertain. (Adapted from figure 1 of P. A. Arias et al., in *Climate Change 2021: The Physical Science Basis—Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte et al., eds., Cambridge U. Press, 2021, p. 35.)

convection that extend in a northwest–southeast direction and propagate to the northeast. The mechanisms responsible for the intraseasonal oscillation are still debated.[10] One class of theories focuses on the effect of the strong vertical wind shear in the background monsoon flow; another focuses on the coupling between moisture and the circulation across the Indian Ocean from the relatively dry eastern equatorial region to the moist western basin.

Variations in tropical rainfall at year-to-year time scales and longer are, in large part, an atmospheric response to oceanic changes. In fact, the connection between the Indian monsoon and the state of oceans far away is at the center of another pivotal moment in the history of climate science: the discovery of the El Niño–Southern Oscillation (ENSO), the most important mode of natural climate variability. After the 1877 failure of the monsoon rains and thus of the crops in India, the British Colonial Service established meteorological observatories there and searched for monsoon predictors. The effort led to the discovery of far-flung meteorological correlations between India and Mauritius, Australia, and even farther away in Argentina.

In 1928 Gilbert Walker, an applied mathematician and director general of the Indian observatories from 1904 to 1924, collated all those associations into the concept of a "Southern Oscillation," which describes the seesaw of atmospheric pressure east and west of the date line.[11] Forty years later the meteorologist Jacob Bjerknes linked the variation in the Southern Oscillation to the variations in the temperature of the eastern equatorial Pacific, known as El Niño (if they are warm) or La Niña (if they are cold).[12] Together, the phenomenon is termed the El Niño–Southern Oscillation (see the article by David Neelin and Mojib Latif, Physics Today, December 1998, page 32).

When the equatorial eastern Pacific is anomalously warm, the whole tropical atmosphere higher than about 1.5 km warms because of the heat released in clouds. Away from the warm ocean anomalies, warmer air over a relatively cool surface boundary layer stabilizes the atmosphere, which leads to less frequent convection and less rainfall.[13] Although a warm El Niño is usually associated with drought in monsoon regions worldwide, the influence of other ocean basins and complexities in the atmospheric circulation can mask the influence of the Pacific. In India, for example, the strength of the negative correlation between ENSO and seasonal rainfall (see figure 3) has waxed and waned over many decades, which has complicated monsoon rainfall prediction.

Human effects on monsoon rainfall

Against the backdrop of natural variability, long-term trends in monsoon rainfall are emerging[14] (see figure 4a) in response to the emissions of greenhouse gases (GHGs) and fine particulate matter—also known as aerosols—that are, for the most part, the by-product of fossil-fuel burning.

Most GHGs are well mixed in the atmosphere, so the radiative forcing they impose is approximately homogeneous. Nevertheless, the atmospheric response is not homogeneous. The warming of surface temperature, for example, is enhanced over land and at high latitudes, and the response of rainfall is even more varied, being characterized by wetting in the equatorial band and at mid- to high latitudes but by drying in the subtropics. The banded structure in rainfall anomalies can be described as the enhancement of the present-day gradients between moist and dry climates. That pattern is expected when an increase in atmospheric humidity in a warmer atmosphere—itself expected from the Clausius–Clapeyron relationship between temperature and the saturation of water vapor—is combined with a planetary circulation that is not greatly changed by the GHG forcing.

On the hypothetical homogeneous planet that we took as a first approximation of Earth, an enhancement of the present-day pattern would mean a rainier rainy season during the global monsoon and a drier dry season. As it turns out, simulations with comprehensive numerical models of the climate system indicate that such an approximation is sufficient to explain the combined regional monsoons and even some of the individual ones (see figure 4b).

For example, the predicted increase in Indian rainfall of 4% per degree of global warming is, in large part, the consequence of the increase in atmospheric humidity.[15] But for any quantitative prediction of rainfall, simulations need to incorporate wind changes in response to GHG increases. Just as is the case for the year-to-year natural variability, most wind anomalies come from gradients in the surface temperature of the global oceans. Unfortunately, winds are so sensitive to the details of the warming pattern that different climate models predict different responses, which lead to a large spread in the prediction of future monsoon changes (see figure 4b). For the West African monsoon, for example, the amount of wetting predicted by a given model is related to the degree of warming simulated for the North Atlantic and Mediterranean basins in comparison with the tropical oceans.

The effect of atmospheric aerosols is even more complicated. Unlike carbon dioxide, aerosols absorb and scatter light, tend to concentrate close to their sources instead of spreading evenly across the globe, and can change the brightness and life span of clouds. Thus uncertainties arise in the characterization of radiative forcing induced by aerosol as well as in the simulation of the response to such forcing.

Nevertheless, evidence is accumulating that 20th-century aerosol emissions induced long-term changes in monsoonal rainfall. Increases in North American and European aerosol emissions after World War II contributed to the mid-century drying trend in West Africa,[16] which culminated with the great droughts of 1968–73 and 1983–84. The increase in emissions in Asia contributed to the decline in average seasonal rainfall over central India[15] between the 1950s and the early 2000s. Clean air initiatives have greatly reduced aerosol emissions in North America and Europe, and similar ones are expected to be implemented in Asia. When that happens, the monsoons will respond to the changing pattern of radiative forcing (see figure 4b).

Rainfall extremes

Across the globe, the chitchat about the weather, the recollections of the farmers, and the data of the climatologists all agree: Rain has been falling more erratically with heavier downpours and spells of drought—and not just in monsoon regions. Those changes are an expected consequence of warming.[17] For more on extreme climate, see the article on page 40 in this issue.

One way of explaining the observations—especially relevant for tropical regions—starts with linking convection to the environment in which it happens. Raindrops form when a plume of air is sufficiently buoyant to reach high into the atmosphere and create a deep cloud. For the most part, that buoyancy is determined by how warm and moist the plume is compared with the environment above and whether it entrains dry air during its ascent: Moisture availability is the key parameter. During a rainfall event, precipitation always dries the air column, while the circulation can either replenish its moisture or bring drier air. The tug-of-war between those processes determines the length of the event and, to a good approximation, the total accumulation of rainfall. In an environment with more moisture, the circulation can have more extreme fluctuations, which leads to a broader distribution of rainfall and more common extreme events.

A rough estimate of how extreme rainfall will change in a warming world is derived from the Clausius–Clapeyron relationship: A warmer atmosphere, without unexpectedly large changes in relative humidity, will contain more water vapor. In a convective event, low-level convergence will bring in that extra vapor, and its condensation will release extra heat, leading to a more vigorous circulation and convergence. For every 1 °C of warming, the direct increase in moisture resulting from the Clausius–Clapeyron effect will lead, at a typical tropical temperature, to a 7% increase in rainfall, and the additional feedback with the convergent circulation can more than double that increase.

The theory predicts the intensity of individual convective elements but is not sufficient to predict more complex changes, such as shifts in the tracks of tropical depressions. Thus predicting flood risk at the local level remains a research goal.

The world's monsoons are continuously monitored and anticipated in weather forecasts, seasonal outlooks, and climate projections. It is the task of meteorologists and climate scientists to deepen our understanding of the workings of the atmosphere to reduce uncertainties in all those predictions. As we make clear here, we are hard at work on that task. But societies have already been given enough information to become more resilient to the inevitable extreme weather and climate events and to prevent the worsening of such hazards.

Although food production in India, for example, is still tightly linked to the seasonal rainfall, the nation's GDP is not so tightly linked because the Indian economy has diversified, and agriculture for the past several decades has played a diminished role (see figure 3). In Bangladesh, an early warning system that combines monitoring, forecast dissemination, and savvy evacuation and sheltering plans has paid off: In 2020 a massive cyclone killed about 30 people, a far cry from the 300 000–500 000 people who died in a similar one in 1970.

Just as important, though, the world needs to prevent the ongoing exacerbation of weather and climate hazards by slowing climate change. To do so requires curtailing and eventually ending our emission of greenhouse gases—a tall order for sure, but here, too, we know enough to act.[18]

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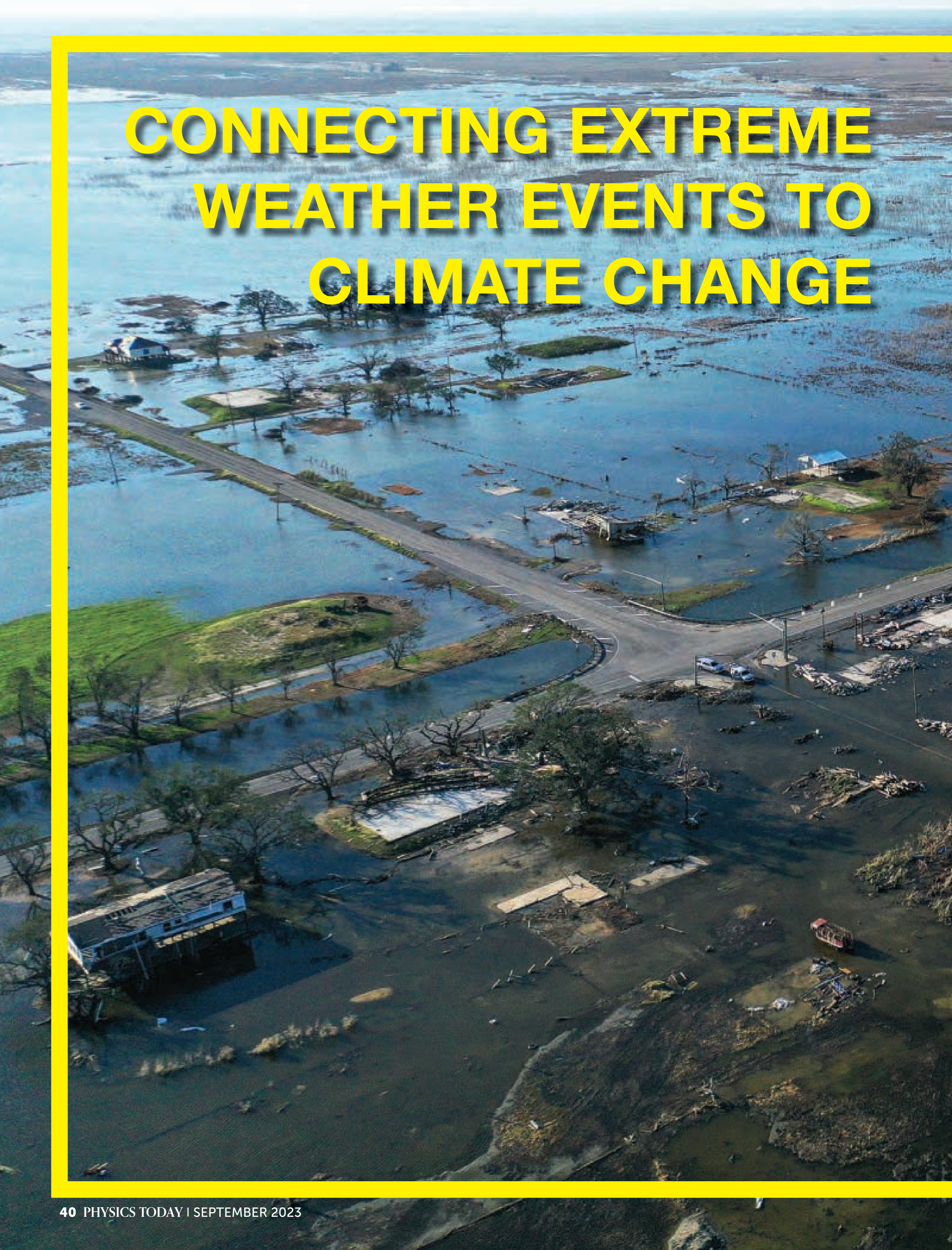
CONNECTING EXTREME WEATHER EVENTS TO CLIMATE CHANGE



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Michael Wehner is a senior staff scientist in the applied mathematics and computational research division at Lawrence Berkeley National Laboratory in Berkeley, California. His research examines extreme weather events in a changing climate.

Michael Wehner

Advances in attribution science are improving understanding of human influence on our planet.

After his house in Oxford, UK, was flooded by an exceptionally rainy storm in January 2003, Myles Allen proposed that the anthropogenic influence on severe weather events could be quantified.[1] Before that, most climate scientists avoided discussing how human activity affected individual extreme weather events. Rather, they would deflect, saying, for example, "While no individual event can be tied to climate change, whatever happened is consistent with expectations." That statement is no longer true. Using extreme-event attribution techniques, it is now possible to make quantitative statements about the human influence on many classes of individual weather and climate events.

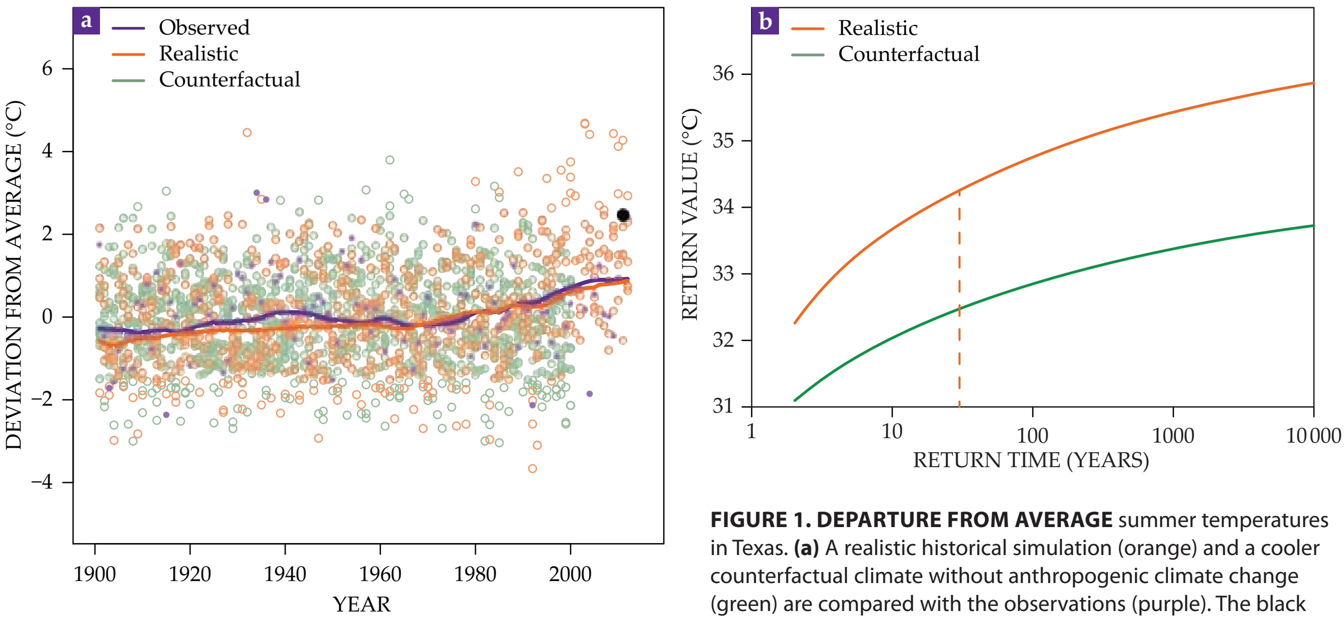


FIGURE 1. DEPARTURE FROM AVERAGE summer temperatures in Texas. **(a)** A realistic historical simulation (orange) and a cooler counterfactual climate without anthropogenic climate change (green) are compared with the observations (purple). The black dot represents the observed value of 2.467 °C for 2011. The solid lines represent the smoothed temperature anomalies. (Adapted from ref. 6.) **(b)** Simulations show the likelihood of Texas summer surface air temperature in a realistic climate (orange) and the cooler counterfactual climate (green). A return value (maximum temperature) has a 1/(return time) chance of being met or exceeded in a given year. The dashed line indicates that the observed temperature was a 1-in-30-year event in 2011, and it was 1.5 °C warmer than it would've been without climate change.

In 2003, shortly after Allen's proposal, central Europe experienced a disastrous heat wave that caused more than 70 000 excess deaths. At the time, using a high-quality record of European temperatures and a single climate model, Allen and colleagues estimated that climate change at least doubled the chances of the measured high daytime temperatures.[2] Since then, the field of extreme-weather-event attribution has expanded to include not just heat waves but also floods, droughts, heavy precipitation, and certain extreme storms, such as hurricanes (reference 3, chapter 11).

There is extensive literature on the detection and attribution of long-term changes in various climatic properties. Those studies provided the basis for the Intergovernmental Panel on Climate Change to assert in its sixth assessment report that "it is unequivocal that human influence has warmed the atmosphere, ocean, and land" (reference 3, page 4). While traditional attribution statements about climate change have focused on long-term observed changes in the climate system, extreme-event attribution statements are generally about the human influence on a single event. Although scientists are often asked if climate change caused a particular weather event, such inquiries invite a more general investigation into causality (see the box on page 43). Complex events, such as a storm or a heat wave, result from multiple complex causal factors—and not just ones related to climate change.

One motivation for performing extreme-event attribution studies is to satisfy the public's curiosity about how climate change affects them. But an equally important motivation is gaining insight into the physical mechanisms behind the changes in extreme weather events. Borrowing concepts from epidemiology, scientists hope to untangle and quantify the different causal factors. The ongoing work focuses on answering two questions: "Did climate change affect the *magnitude of an event* of a given estimated rarity?" and "Did climate change cause the *chances of an event* of an observed high magnitude to change?"

Extreme heat

Those two questions are two sides of the same coin, as illustrated by the abnormally hot temperatures in Texas during the summer of 2011. Figure 1a shows observed Texas summer temperature departures (purple) from the average of the 1961–90 temperatures. Two simulations are shown, one with realistic human changes to the atmospheric composition (orange)—mainly well-mixed greenhouse gas increases, stratospheric ozone decreases, and aerosol pollution—and the other counterfactual (green), in which temperatures are cooler because it doesn't include the effect of human changes. Both the observations and the predicted data in the realistic model trend upward. The absence of such a trend in the counterfactual simulation reveals that there is an attributable human influence on Texas summer temperatures. Increasingly hot summers are expected. Yet the 2011 temperature, shown by the black dot, was about 2.5 °C warmer than the average summer and was considered a rare, 1-in-30-year event at the time.

To answer the two event-attribution questions about changes in event magnitude and frequency, one needs to turn to the climate-model data. Figure 1b shows the return values of average summer temperatures in Texas as a function of time. The return value is the highest average temperature expected to be reached once in a given period of time, known as the return time. The solid orange line, representing the realistic simulation, reveals that an average temperature of 34 °C would occur once in 30 years. In the counterfactual simulation, shown by the green line, the average temperature occurring once every 30 years would be just over 32 °C. Thus the answer to the

Causality

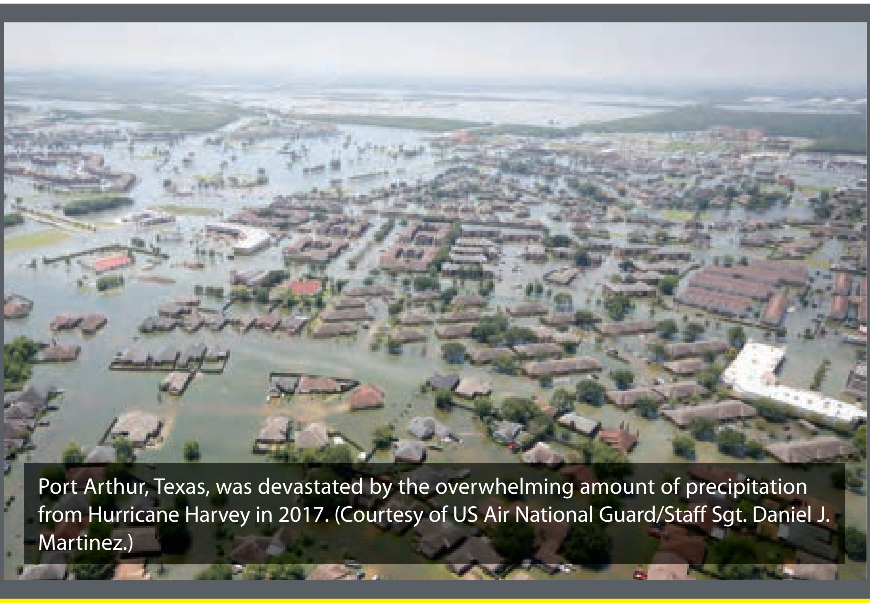
Attribution is an exercise in causal inference. Causality can be a deeply philosophical and often confusing topic. But complex events have complex causes, and statistical techniques—particularly those developed in epidemiology—can be useful to quantify the role of climate change and other causal factors in individual extreme weather events. Broadly speaking, causal-inference techniques can be divided into two classes.

The first, known as Pearl causality, after Judea Pearl, a computer scientist at UCLA, involves a direct interference in the experiment. In medicine, that familiar exercise provides one group of patients with the treatment in question and the other with a placebo. But with only one real world, scientists have to use climate models where they can control the inclusion or exclusion of the external forcing agents of interest, such as greenhouse gases or land usage.

A second technique, known as Granger causality, after the econometrician Clive Granger, can be useful when direct interference in the experiment is undesirable or impossible. In epidemiology, for instance, a study of heart disease in a selected population might consider obesity, smoking habits, family history, and other relevant causal factors. A statistical model that involves those factors as variables can provide information on their possible influence. For climate, scientists have developed extreme-value statistical models using greenhouse gas concentrations, air pollution, urbanization, El Niño, and other natural modes of variability as covariates to isolate their relative influence on extreme weather.

Both Pearl and Granger causal-inference techniques have their strengths and limitations. Granger causal inference may lead to the *post hoc, ergo propter hoc* fallacy—that correlation does not necessarily imply causality. Additionally, the influence of unspecified covariates must be considered. Because Pearl causal inference relies on models, one must first ascertain whether the model is fit for the purpose at hand. Many extreme weather events are poorly simulated when available public climate model data sets are used, and thus those data sets are unsuitable for attribution studies.

Confidence in attribution statements is increased when both Granger and Pearl causal-inference techniques can be invoked and produce similar results. Confidence is further increased when multiple independent research groups use different models, observations, and methods and arrive at similar conclusions.



Port Arthur, Texas, was devastated by the overwhelming amount of precipitation from Hurricane Harvey in 2017. (Courtesy of US Air National Guard/Staff Sgt. Daniel J. Martinez.)

first question is that climate change increased the average temperature of a 1-in-30-year event by about 2 °C.

To answer the second question about the change in rarity, one needs to estimate chances of an average temperature of 34.2 °C without any climate change. The observed temperature is near the upper bound of the counterfactual distribution, and the return time is estimated to be 66 million years. Publishing an attribution statement based on that estimate would be unwise, however, because the uncertainties from extrapolating out that far are extreme. Best practice is to put uncertainty bounds on the ratio of those return times. Using a likelihood ratio test, scientists can place a 95% confidence interval of 16 to infinity on the ratio of counterfactual to observed return times. In plain language, climate change increased the chances of the observed 2011 Texas summer temperature by at least a factor of 16.

The current global warming level of about 1.2 °C above preindustrial levels means that any rare heat wave that now occurs has an attributable human influence (reference 3, chapter 11). Most areas of the world are significantly warmer, but highly polluted urban areas may actually be cooler because of the reflective properties of aerosol pollutants. That is not to say that quantifying the human influence on heat waves is always easy. As the climatologist Geert Jan van Oldenborgh pointed out, we must do better in observational, modeling, and statistical analysis tools to increase confidence in attribution statements.[4] Indeed, summer daily high temperatures throughout the Pacific Northwest in 2021 were such far outliers that some researchers concluded that they were "virtually impossible" without climate change.[5] Confidence in that statement is limited, however, because the models used fail to adequately describe the 100-year observational record.[6]

In general, the climate change influence on the best estimate of changes in extreme-event magnitudes is relatively insensitive to estimates of event rarity. That often inspires confidence in such attribution statements even when the observational period is relatively short. Conversely, the climate change influence on best estimates of changes in an event probability—for example, the chance of exceeding 34.2 °C in Texas—is more uncertain because of both the statistical model and event characterization, although the lower bound on probability changes has been found to be independent of estimates of event magnitude.[7,8]

Precipitation

Estimating the human influence on heavy precipitation events

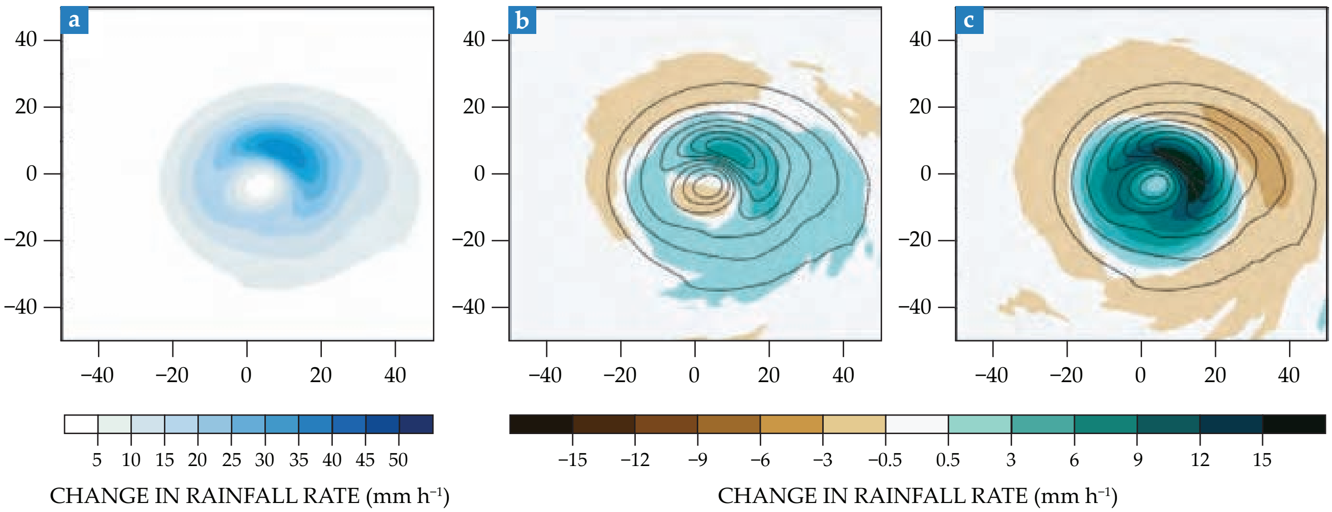


FIGURE 2. CHANGES IN PRECIPITATION during Hurricane Maria in 2017 relative to the cyclone center throughout its lifetime. **(a)** Composite simulated precipitation across multiple simulations under realistic climate conditions. **(b)** Attributable change in precipitation calculated from realistic simulations and a cooler, counterfactual simulation approximating preindustrial conditions. **(c)** Projected change in precipitation calculated from realistic simulations and counterfactual conditions at 3.5 °C warmer than preindustrial conditions, or how much worse it could've been. Contours indicate the rainfall rate from the historical simulation. The plots are in units of the grid resolution, 4.5 km. (Adapted from ref. 13.)

is more complicated than for heat waves for several reasons. The first is that precipitation is a sporadic event, and extreme precipitation even more so. (To learn about human influences on monsoons, see page 32 in this issue.) Well-established theory (the Clausius–Clapeyron relation) and traditional trend analysis reveal that saturation specific humidity increases by about 7% per 1 °C of local warming. Because extreme precipitation usually occurs in fully saturated atmospheric conditions, one might expect the likelihood of such an event to also increase at the same rate. The more likely a local area is to be fully saturated, the more likely it is to rain. Analyses that used the 100 km climate models on extreme precipitation trends confirm that rate of increase (reference 3, chapter 11). But the realism of simulated extreme storms in those coarse models is questionable. More-specialized high-resolution simulations suggest both that the Clausius–Clapeyron rate of increases in specific humidity is a lower bound for precipitation increases in certain types of extreme storms and that best estimates can exceed that lower bound by factors of two or more because of changes in localized storm dynamics.[9,10] Increases in computational resources are aiding understanding in that rapidly developing subject.

While some classes of extreme precipitation, such as wet winters, are amenable to lengthy but coarsely resolved climate model simulations because of their large spatial scales, simulations at high enough resolutions to permit tropical cyclones (less than 25 km) or convective storms (less than 4 km) are so computationally expensive that only a few data sets are available. Alternatively, one can use shorter, high-resolution hindcast or "storyline" simulations. Hindcasts simulate recent weather events for which various external factors are known or can be turned on and off. Hindcast simulations with imposed climate change permit attribution of the change in magnitude of severe storms. In many storyline event-attribution studies, two sets of hindcast simulations of the event are made: A set of the "event that was" under realistic conditions is compared with a set of the "event that might have been" had humans not interfered with the climate system. Because of their short duration, those weather-prediction-like simulations by design do not directly inform any changes in frequency. While storyline attribution studies can be made in the absence of attribution of the human influence on the local, long-term trends, confidence in an attribution is increased if multiple lines of evidence by independent research teams are available.

Much progress has recently been made in understanding the human-induced increases in tropical cyclone precipitation through storyline event-attribution analyses. For instance, three independent attribution studies were performed on data from Hurricane Harvey, a stalled tropical cyclone that dumped copious amounts of precipitation on Texas's greater Houston and Gulf Coast regions in 2017.[8,11,12] A best estimate distilled from those papers is that climate change increased Harvey's rainfall by 19%, or about 2.5 times as much as what might be expected

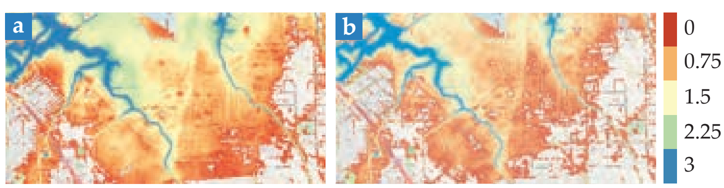


FIGURE 3. ACTUAL AND COUNTERFACTUAL FLOOD simulations in Texas's South Houston and Pasadena neighborhoods during Hurricane Harvey. **(a)** The flood that was. (Adapted from ref. 15.) **(b)** The flood that might have been in the absence of anthropogenic climate change. The difference between the models is the assumption that human activities increased Harvey storm total precipitation by 19%. Colors denote the depth of flood water in meters.

from Clausius–Clapeyron scaling of the increased available moisture from the 1 °C of attributable warming in the Gulf of Mexico. Since Harvey, numerous other tropical storms have been analyzed and have revealed similar scaling of precipitation statistics.[10,13]

The mechanism for the super Clausius–Clapeyron scaling is simple. Figure 2a shows the composite simulated precipitation from Hurricane Maria, which devastated Puerto Rico in 2017. Figure 2b shows the attributable precipitation changes at the time it occurred, and figure 2c shows the hypothetical precipitation changes in a much warmer world. The first thing to notice is that the increases, either in an absolute or relative sense, are the largest in the rainiest parts of the storm. The second is that there are decreases in the outer precipitation bands. What is happening is that warmer conditions are likely increasing the storm's wind speeds. While the changes in instantaneous maximum wind speeds are thought to be slight at present, they will become more robust in a much warmer world. That increase in tropical cyclone intensity causes the storm structure to change and become more efficient at precipitating available moisture.

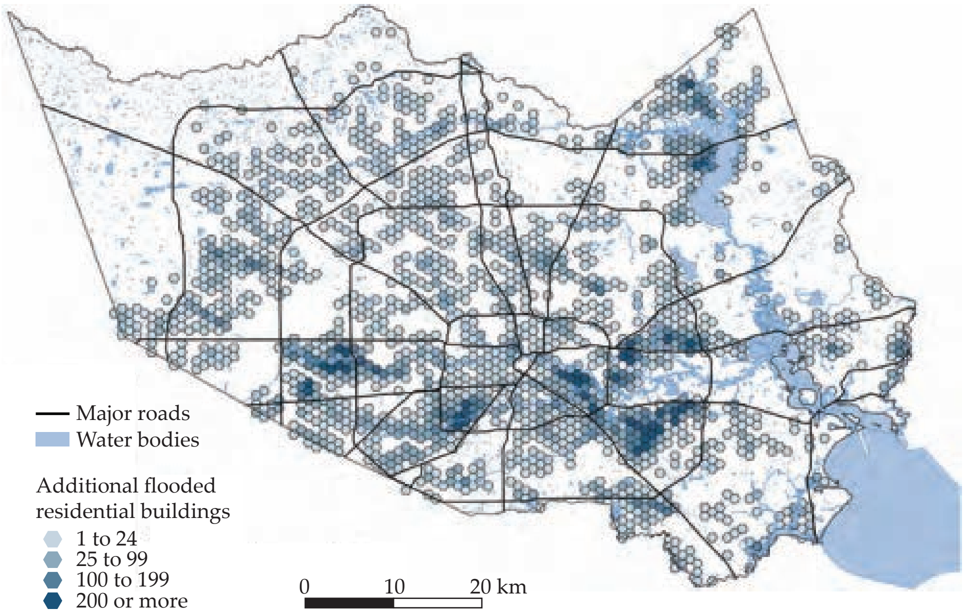


FIGURE 4. ADDITIONAL ANTHROPOGENIC FLOODING. Each hexagonal bin symbolizes the upper limit of the number of residential buildings that would not have flooded without the added impact of climate change in Harris County, Texas, during Hurricane Harvey in 2017. (Adapted from ref. 16.)

Hurricanes receive much of the attention in the attribution community, but other storm types are worth studying. A recent storyline analysis found that precipitation from a selected group of strong atmospheric-river storms affecting the San Francisco Bay Area coincidentally also increased at about twice the Clausius–Clapeyron rate.[9] Analysis suggests that those physical mechanisms of change are very different than inferred for tropical cyclones. Although few additional studies have been made of atmospheric rivers that impact coastal zones, the information has been alarming enough for decision makers to act on it.

Although interest is high, little is known with confidence about anthropogenic increases in the intense summer mesoscale convective systems that can occur in continental interiors, partly because of computational constraints. Limited studies have analyzed the human influence on environmental conditions that support tornadoes, but there is no consensus regarding how climate change has influenced tornados.[14]

Drought

Assessing the impact of climate change on drought can be complicated. One must consider the different types of droughts. NOAA classifies drought as a hierarchy of four related conditions. Meteorological drought is characterized by a deficit of precipitation; agricultural or ecological drought, of soil moisture; and hydrological drought, of water supply. Socioeconomic drought occurs when demand for water exceeds the supply.

Agricultural drought depends on both the precipitation that falls on the ground and the evapotranspiration of moisture from plants and soils. Evaporation from bare ground depends strongly on air temperature. As the temperature increases from climate change, evaporation increases lead to drier soils. Transpiration from plants depends even more strongly on air temperature. Plants cool themselves by opening their stomata and evaporating water. In hot conditions, they can draw moisture from their root system until little soil moisture is left. Decreased soil moisture may in turn limit evapotranspiration, which means the relationship between temperature and soil moisture isn't linear. Recent literature shows that human-induced climate change has contributed to increases in agricultural droughts in some regions because of evapotranspiration increases (reference 3, chapter 11).

On the other hand, consensus has not been reached on changes in meteorological drought occurrences in most regions. At this time, only studies in the Mediterranean show a consistent human influence on precipitation deficits. Still, uncertainty levels are high (reference 3, chapter 11). Likewise, meteorological drought conditions in Mexico and the Southwest US are projected to be more common as the climate warms, but a robust signal has yet to be detected.

Hurricane Harvey flooding

It should be clear from the previous sections that scientists understand the human influence on certain types of extreme weather. Methods to comprehend the connection between the anthropogenic influences on weather and the socioeconomic outcomes are just now starting to be developed. For example, consider again Hurricane Harvey, which inundated much of the greater Houston area in 2017.

A counterfactual "flood that might have been" was constructed by decreasing Harvey's observed precipitation uniformly according to published precipitation-attribution statements and using that as the input to a credible flood model.[15]

Figure 3 compares the actual flood depth and the best estimate of the counterfactual one in two Houston neighborhoods, where almost 9 000 homes were flooded. The 19% precipitation increase attributable to human-influenced climate change translated to an additional 1 m of flood waters and a 14% increase in flood area. Equivalently, as a best estimate, the probability of a $90 billion hurricane loss (the amount of estimated insured losses) in Texas was quadrupled because of climate change.

The Harvey flood model has a resolution of 30 m—about the size of a suburban property—and its results have been made publicly available at https://portal.nersc.gov/cascade/Harvey. The maps permit individuals to understand whether their home would have flooded without human-influenced climate change. Individuals can select different estimates of the human influence on precipitation and locate their home on both the realistic and counterfactual flood maps. That level of detail also permits a more refined damage estimate by combining it with socioeconomic data sets. Projecting real-estate maps onto the flood maps results in a best estimate that approximately 32% of flooded homes in Harris County, where Houston is located, would not have been flooded without climate change. Furthermore, in the actual flood, 75% of the county's flooded homes were outside the federal 100-year flood plain—likely uninsured against flood damage—adding to the $90 billion insured loss.[16] Figure 4 shows an upper bound on the distribution of homes that were flooded in Harris County because of climate change.

Census data further reveal that Hurricane Harvey's flood damages were not equally distributed across socioeconomic groups. Hispanic households are about 36% of the population of Harris County, but they owned or rented roughly 50% of the flooded homes. Additional analysis reveals that in wealthy neighborhoods, damages increased for households with more wealth. In low-income neighborhoods, the opposite trend was found: that damages increased for households with less wealth. Given the relative contribution to increases in greenhouse gases from people who are wealthy compared with people who are economically marginalized, such analyses quantify environmental and other social injustices.[16]

More than just a weather forecast

Other human impacts of extreme weather can also be quantified. Of particular interest is whether climate change increases the number of deaths from heat waves. They are among the deadliest of all extreme weather events, and epidemiology studies have developed relationships between mortality risk and temperature.[17] At high temperatures, the relationship becomes more sensitive: In already hot weather, a small increase in temperature can cause large increases in mortality. Scientists can use the relationship when estimating the attributable human temperature increase to understand the change in mortality risk during a heat wave.

Another method maps mortality and temperature curves onto temperature-change plots, like those in figure 1, to estimate the number of people who have died because of the influence of climate change on a heat wave and to determine how the probability of death has changed.[18] The models are not perfect. Incorporating adaptive measures—for example, cooling centers and other outreach that can reduce the heat wave mortality risk—into attribution statements is currently challenging. There are many additional factors to consider when extending attribution statements about the human influence on extreme weather events to attribution statements about the human influence on the events' outcomes.

The sixth assessment report of the Intergovernmental Panel on Climate Change declares that "human-induced climate change is already affecting many weather and climate extremes in every region across the globe" (reference 3, page 8). Developments in attribution science over the past two decades reinforce that statement by extending attribution statements about observed long-term climate change to encompass robust statements about the human influence on many types of individual extreme weather events. That includes heat waves, heavy precipitation events, and floods. Attribution methods for some classes of events have matured to the point where they could be operationalized to regularly inform the public about the current dangers of climate change. That would also greatly increase the number of events analyzed in that way and further understanding.

Extreme weather happens everywhere, but most event-attribution studies have focused on events in nations that have the requisite human and computational resources. Groups like World Weather Attribution (https://www.worldweatherattribution.org) have begun to apply attribution science to significant weather events in low-income countries. Such organizations' credibility is increased when they involve experts from those nations who better understand the details of local climate and associated impacts.

The extension of attribution science to connect human increases to the socioeconomic damages and inequalities of extreme weather events is now underway. That work has the potential to inform low-income nations about their loss and damages, giving them the knowledge to negotiate for more assistance from recovery funds.

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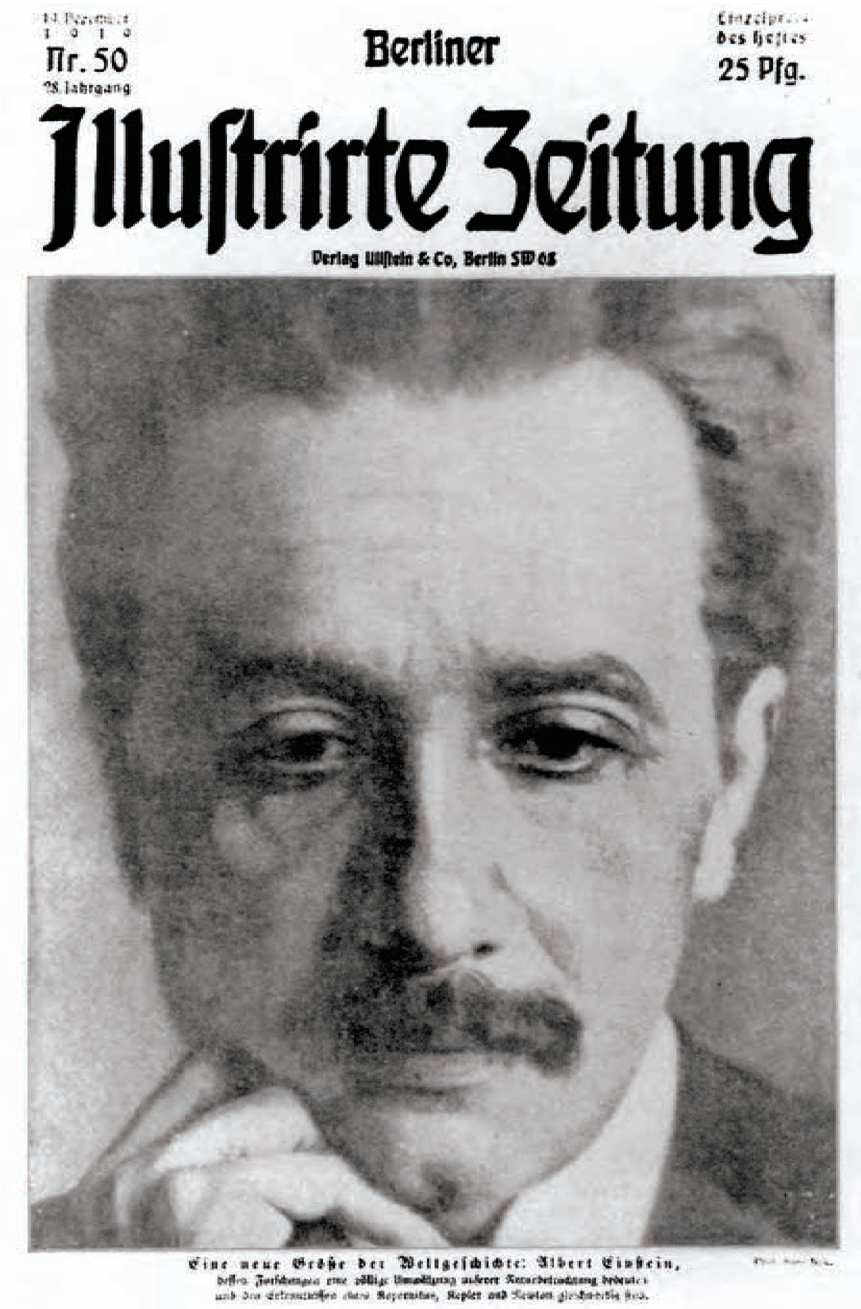
PT



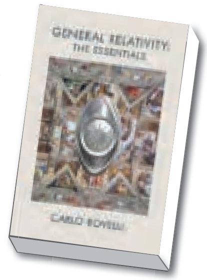
SUSE BYK/PUBLIC DOMAIN

As his celebrity began to take off, Albert Einstein graced the cover of the 14 December 1919 edition of the *Berliner Illustrirte Zeitung* (Berlin Illustrated Times).

Spacetime, essentially

In a June 2012 Physics Today article, Nelson Christensen and Thomas Moore divided textbooks on general relativity into three broad classes. Their first category was books with a math-first approach, which tend to focus on the mathematical tools of the theory before applying them to the physics of spacetime. Second was authors who take a physics-first approach, who describe the geometry of several spacetimes and explain how particles and light move through them before demonstrating how those spacetimes are derived. Finally, they described the active-learning approach, which emphasizes intertwining mathematics with example spacetimes so that students can learn tensor calculus through example.

General Relativity
The Essentials
Carlo Rovelli
Cambridge U. Press, 2021. $64.99



In his recent textbook, *General Relativity: The Essentials*, Carlo Rovelli pioneers a new approach—which I'll call "concepts first"—that places physical motivations and reasoning front and center. Rovelli relentlessly limits the mathematical exposition and gives copious room to the conceptual and physical insights of the theory. The pithiness of the book complements that approach and gives the reader a global view of general relativity. That is a major advantage for someone who wants to learn what the theory is about and is studying to become one of its craftspeople.

Physics-first textbooks weave Albert Einstein's ideas throughout their narrative as they build up to the full mathematics of his equations. Rovelli reverses that and follows a path more like the one Einstein took: He lays out all the conceptual principles of relativity as clearly as possible and only after they are assembled works to express them in mathematical language.

At times Rovelli's treatment of the mathematical content is so terse that it is a bit opaque. That pithiness, while often a pleasure, can also lead to jumps in sophistication. For example, he presumes that the reader is familiar with action principles, the calculus of variations, and the ways those result in physical equations of motion; he quickly introduces differential forms and some aspects of tensors; and he expects that readers know how vector and tensor wave polarizations transform. Those jumps are probably essential to keep the text brief, but when new readers cannot fully reconstruct an argument, they should know that they may be missing some context.

That said, the overall result is a wonderful display of the physics of general relativity. Rovelli unabashedly serves up his perspective on the theory and paints beautiful vistas of the physics. The book brims with surprising physical intuitions: I was delighted, for example, to come away from page 5 with a perspective on Galilean relativity, new to me, that is much more closely tied to how I think about special relativity.

General Relativity will delight many readers. Not only does Rovelli meticulously motivate the ideas that lead to the theory, but he also presents many technical, mathematical topics in their simplest possible form and then builds on them. For example, he gradually develops the discussion of curvature through its history. Similarly, he examines frame fields and their relation to the gravitational field within the easily visualized context of a two-dimensional sphere. The book's thorough grounding in examples and simple cases is somewhat rare among general-relativity textbooks. It should be essential to those who want to understand where general relativity comes from and its conceptual core. It will also help serious students prepare for more mathematically difficult literature.

Rovelli ends his book in a novel and risky way by using the tools he has built up throughout the book to discuss the cutting edge of research in quantum gravity. Among others, he presents the thrilling idea that quantization of the gravitational field can lead to granularity in the fabric of space and time and discusses how quantum spacetimes are likely to be subject to the same quantum superposition that enriches and complicates the foundations of all quantum systems.

Of course, the risk is that the ideas mentioned in that part of the book may turn out to be empirically wrong. But the reward is great too. Rovelli's excitement about doing research at the edge of what is known is palpable. It provides students with a rare look into researchers' ideas as they create them. That gambit continues the book's theme: It offers an accomplished scientist's carefully thought-through and distilled perspective on general relativity and engenders a sense of delight at the panoramic view that the theory provides on the geometry of spacetime.

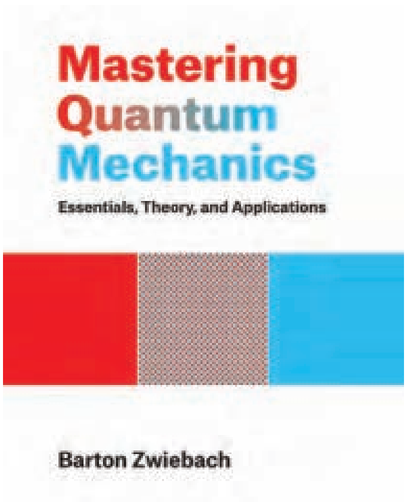
Hal M. Haggard
Bard College
Annandale-on-Hudson, New York

NEW BOOKS & MEDIA

Mastering Quantum Mechanics

Essentials, Theory, and Applications

Barton Zwiebach
MIT Press, 2022. $110.00



After many years of teaching quantum mechanics at MIT, theorist Barton Zwiebach has decided to produce a textbook based on his experience. The result, *Mastering Quantum Mechanics*, is encyclopedic: It clocks in at over 1000 pages long and is intended to accompany a three-semester-long course—although Zwiebach does include ideas on how to use the text for a one- or two-semester sequence. Although the book's length may overwhelm some readers, it allows Zwiebach ample room to provide clear and in-depth expositions of fundamental concepts like the Schrödinger equation, the harmonic oscillator, and the hydrogen atom. —RD

Lost Women of Science

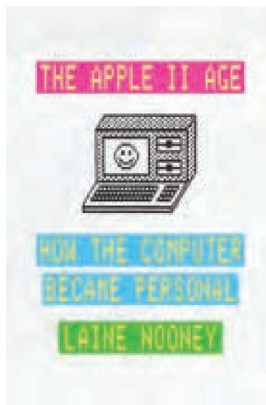
Katie Hafner and Carol Sutton Lewis, hosts
PRX and *Scientific American*, 2023 (Season 6)

Inspired by Christopher Nolan's recent biopic *Oppenheimer*, the latest season of the *Lost Women of Science* podcast focuses on the women of the Manhattan Project. Indeed, hundreds of female scientists made substantial contributions both to the design and fabrication of the nuclear weapons themselves and to the debate about whether they should be used against Japan. The first episode of the season focuses on Leona Woods, the only woman scientist on the team led by Enrico Fermi that built the first sustaining nuclear reactor, Chicago Pile-1. Later episodes focus on Frances Dunne, Carolyn Parker, Lilli Hornig, and Melba Phillips, among others. The bite-size episodes are each about 10 minutes in length. —RD

The Apple II Age

How the Computer Became Personal

Laine Nooney
U. Chicago Press, 2023. $28.00



Nostalgic computer hobbyists, beware! Laine Nooney is out to "rob" you of your "much-cherished faith in computing's primordial innocence" by deconstructing the mythology surrounding the Apple II, the first personal computer to gain widespread market appeal. To do so, they look at five pieces of software—VisiCalc, the first spreadsheet program; Mystery House, the first graphical adventure game; Locksmith, a disk-copy utility; the Print Shop, a layout program that allowed users to create printed material; and Snooper Troops, an educational game intended to teach students deductive reasoning. Using contemporary hobbyist and trade magazines as a source base, Nooney demonstrates that the personal-computing revolution of the 1970s and 1980s was more a product of the "financial interests of an elite investor class" than the stereotypical Silicon Valley hacker. —RD PT

NEW PRODUCTS

Focus on lasers, imaging, microscopy, and photonics

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

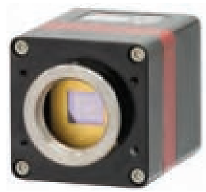
Backscattered-electron and x-ray imaging detector

The Unity detector from Oxford Instruments enables a new imaging technique called BEX in scanning electron microscopes. According to the company, Unity is the first detector that features backscattered-electron (BSE) and x-ray imaging sensors within one detector head located under the microscope pole piece. Topographic, crystallographic, atomic number, and elemental information are combined in an immediate full-color, high-resolution visual output. Accurate chemical mapping of whole samples is provided in minutes; users can quickly identify features and regions that warrant further investigation. The novel operating position for the x-ray sensors allows consistent chemical data to be acquired across a wide range of working distances. The BSE sensors are custom shaped to maximize signal collection and Peltier cooled for enhanced sensitivity. The company says the Unity detector can increase microscope productivity by up to 100-fold. ***Oxford Instruments Nanoanalysis**, Halifax Rd, High Wycombe HP12 3SE, UK, https://nano.oxinst.com*

Optical filters

Newport, a brand in the MKS Instruments Photonics Solutions division, now manufactures ODiate optical filter coatings on its next-generation thin-film-coating platform. The filters are designed to deliver high precision, high productivity, and consistent spectral performance and to provide a high signal-to-noise ratio, low cross talk between channels, and repeatable spectral-feature placement for optical systems in scientific and medical applications. The filters offer a wavelength range of 340–1800 nm, a transmission peak of greater than 98%, a central wavelength accuracy of ±0.25%, scattering and absorption of less than 1%, and a typical scratch–dig specification of 60-40. Substrate materials include Borofloat, fused silica, and silicon; the substrate is at most 200 mm in diameter and 6 mm thick. ODiate optical filters can be used in analytical instruments, fluorescence imaging, spectroscopy, microscopy, and laser systems. ***Newport Corporation**, 1791 Deere Ave, Irvine, CA 92606, www.newport.com*

Fast, digital short-wave IR camera



Raptor Photonics' Owl 640 S features faster frame rates than the standard Owl 640 model. It can run at 300 Hz in full-frame resolution and up to 30.2 kHz with a region of interest of 32 × 4 binning, enabling high-speed digital video. The rugged digital camera uses a 640 × 512 pixel indium gallium arsenide sensor, which enables high-resolution imaging in the short-wave IR region from 0.9 μm to 1.7 μm. It has a readout noise (rms reading) of less than 50 e^-, which allows for an ultrahigh intra-scene dynamic range that permits the simultaneous capture of bright and dark portions of a scene. Intelligent Automated Gain Control enables clear video in all light conditions. Applications for the Owl 640 S include beam profiling, hyperspectral imaging, semiconductor and solar-cell inspection, thermography, astronomy, and surveillance, such as vision enhancement. ***Raptor Photonics Ltd**, Willowbank Business Park, Larne, Co Antrim BT40 2SF, Northern Ireland, UK, www.raptorphotonics.com* PT

OBITUARIES

George William Crabtree

George William Crabtree, a pioneering scientist and esteemed researcher at the US Department of Energy's Argonne National Laboratory, passed away on 23 January 2023 in Chicago. He leaves behind a remarkable legacy that profoundly influenced the fields of superconductivity, magnetism, and energy-storage research.

Born on 28 November 1944 in Little Rock, Arkansas, George had a curious mind and a passion for science. He began his journey at Argonne in 1964 as an intern from Northwestern University. After receiving a bachelor's degree in engineering in 1967, he earned his master's degree in physics the following year from the University of Washington in Seattle. George then went back to Argonne, where he focused his research on condensed-matter physics. In 1974 he earned his PhD in the subject from the University of Illinois Chicago and also became a staff physicist at Argonne.

George first set out to understand Fermi surfaces. He employed de Haas–van Alphen measurements to map the Fermi surface of transition metals, including platinum, palladium, niobium, and gold, and such mixed valence materials as $LaSn_3$ and $CeSn_3$. His characterization of niobium's complete Fermi surface is still considered foundational to condensed-matter physics.

George turned to studying magnetic superconductors in the 1980s. He homed in on their electronic properties, especially whether ternary rare-earth compounds exhibited both superconductivity and magnetism. Among the other important work that cemented George's stature in the field was his research into organic superconductors and itinerant *f*-electron behavior in heavy-fermion superconductors.

After Georg Bednorz and Alex Müller discovered high-temperature superconductors in 1986, George began research into vortex matter, and his work contributed greatly to the study of superconductivity. His analyses of the properties of vortices, which control type II superconductors' electromagnetic behavior, proved instrumental in future applications. George and a devoted team of experimentalists and theorists looked extensively at the magnetic field and temperature phase diagram of the 90 K superconductor $YBa_2Cu_3O_{7-\delta}$ with various types of induced defects, and they were able to show the melting of the vortex lattice and the ubiquity of the vortex liquid state.

ARGONNE NATIONAL LABORATORY

George William Crabtree

George's passion for energy research was equally profound. He took a broad approach to energy challenges and advocated for sustainable solutions to combat climate change. His tireless efforts in strategic planning for energy-related programs and research were highly regarded and influential. The reports he produced were the basis over the past decade for the DOE Office of Science's basic-energy-sciences portfolio.

As director of DOE's Joint Center for Energy Storage Research from 2012 until his death, George led groundbreaking experiments in battery science and technology. His vision and dedication to fighting climate change were evident in his pursuit of beyond-lithium-ion battery chemistries that are important for the transition from fossil fuels to carbon-free technologies. For George, combating climate change was personal, and that mission became a main focus of his work.

In 2010 George became a professor at the University of Illinois Chicago. The following year he started the university's Summer Institute on Sustainability and Energy. A distinguished professor of physics and of electrical and mechanical engineering, he also served as director of the school's Energy Initiative.

George received numerous awards over the years. For his decades-long studies on superconductivity, he was recognized in 1982 and 1998 with the University of Chicago Distinguished Performance Award at Argonne National Laboratory, and DOE honored him four times—in 1982, 1985, 1995, and 1997—with its Award for Outstanding Scientific Accomplishment in Solid State Physics. For his profound understanding of vortex matter, he earned the Kamerlingh Onnes Prize with Eli Zeldov in 2003. The American Institute of Aeronautics and Astronautics presented him with the 2022 Energy Systems Award for advancing next-generation energy systems that transition from fossil fuels to carbon-free technologies.

Beyond his scientific prowess, George will be remembered for his warm and steady demeanor, which guided important and challenging discussions to productive outcomes. He was always willing to lend a helping hand, and his leadership inspired those around him. Whether working in the lab, organizing camping events for colleagues, or enjoying cherished moments with his wife Barbara and close friends, George expressed a humility and curiosity that were truly inspiring.

Paul Kearns
Argonne National Laboratory
Lemont, Illinois

John Edward Harries

Determining how water interacts with the long-wave radiation emitted from Earth's atmosphere was John Harries's research mission. He set out to explore that question through observations. His instruments flew on all the platforms available to an atmospheric physicist: aircraft, balloons, and, ultimately, satellites. His many outstanding contributions included the first detection of the greenhouse effect from the additional anthropogenic carbon dioxide. The spectroscopy of Earth's radiation budget was his great passion, and he developed the first airborne spectrometer to measure the far-IR. He was healthily critical of models and rightly emphasized the need for measurements to test them.

I first came across John's work in 1987, when I started my PhD. My supervisor put in front of me a 1982 paper by John showing how the approach pursued by many researchers was unlikely to be a real test of ozone chemistry. The paper was insightful and technical, and it challenged the atmospheric-sciences community. Little did I know John would have a hugely positive influence on my research path and career.

John was born in Sedgefield, UK, on 26 March 1946. His parents were from south Wales, and he was proud of his Welsh roots. Talking rugby was a sure way to get his attention. He studied physics at the University of Birmingham. After graduating in 1967, he joined the National Physical Laboratory. He was awarded his doctorate in physics from King's College London in 1971.

At the National Physical Laboratory, John worked on a lab spectrometer to measure the far-IR properties of greenhouse gases. He then further developed the instrument for balloon flight and for trips on the Concorde when concern grew about high-altitude planes' impact on stratospheric ozone.

In 1980 John moved to the Rutherford Appleton Laboratory as an associate director. John's team and colleagues from NASA made important contributions to understanding the Antarctic ozone hole. Their satellite data improved the understanding of stratospheric water vapor and circulations involving the ozone hole and enabling the transport of trace gases throughout the stratosphere.

HARRIES FAMILY COLLECTION

John Edward Harries

Imperial College London appointed John to a chair in Earth observation in 1994. I joined him as a lecturer and had the immense pleasure of seeing him at work. Working with European partners, John developed the Geostationary Earth Radiation Budget instrument (GERB), whose objective was to examine the balance of the solar and outgoing longwave radiation budget in an orbit. GERB achieved high spatial and temporal resolution of the radiation budget for the first time. John led the project, including overseeing the building of a calibration facility at Imperial. GERB was deployed on four spacecraft in the Meteosat program, run by the European Organisation for the Exploitation of Meteorological Satellites. The four launches, between 2002 and 2015, have created a unique data set to test our understanding of climate science.

Not satisfied with that alone, John also led the development of an airborne spectrometer that allowed the first far-IR measurements from an airplane. That part of the spectrum fascinated John for good reason: Much of Earth's radiation balance is achieved by radiation emitted at those wavelengths. The European Space Agency is now pursuing a satellite version.

John was always clear about the need not just to collect data but to test theory. He was imaginative in his analysis, including a report in *Nature* in 2001 on the anthropogenic greenhouse effect of CO_2 in which he and his colleagues combined the first satellite observations of Earth's radiation with more recent observations. He wasn't satisfied to rely on what the models were saying should have happened.

Between 2010 and 2013, John provided counsel to the Welsh government as its first chief scientific adviser. In that role he developed a national strategy for science—the first of its kind in Wales. He also served as president of the Royal Meteorological Society from 1994 to 1996, and he was presented with its Mason Gold Medal in 2014. John served as chair of the European Space Agency's Earth observation program board. In 2011 he received NASA's Distinguished Public Service Medal.

John died on 21 December 2022 in Llanbadarn Fawr, Wales. He was one of the kindest colleagues. He had time for everybody, and he had such a genuine warmth toward his students and fellow researchers.

Ralf Toumi
Imperial College London PT

RECENTLY POSTED NOTICES AT
www.physicstoday.org/obituaries

Russell K. Hobbie
3 November 1934 – 16 December 2021

Joseph F. Dillon
25 May 1924 – 5 December 2021

Anatoly Grinberg
17 February 1932 – 22 October 2021

Claud Marvin Kellett
5 September 1928 – 18 October 2021

Gary Earl Mitchell
5 July 1935 – 15 October 2021

Thomas Brennock Day
7 March 1932 – 15 June 2021

Paul Van Campen Hough
21 May 1925 – 11 January 2021

Amy Lang is a professor of aerospace engineering and mechanics and directs the Bio-inspired Flow Control Laboratory at the University of Alabama in Tuscaloosa.

Microscopic scales enhance a butterfly's flying efficiency

Amy W. Lang

Ever catch a butterfly and noticed what looks like dust coating your fingers? They're the scales covering the insect's wings, and they allow it to slip through the air.

Monarch butterflies follow a migration pattern unlike any other known species of their kind—they can travel more than 4000 km from the northern US or Canada down to central Mexico to hibernate. At first glance, such a long trek is unexpected: With short, broad, and large wings relative to their body, butterflies look like no other flying animal. But that achievement may be the result of more than just soaring high to catch the right wind currents.

Classified scientifically with moths as Lepidoptera (Greek for "scaled wing"), butterflies can have more than a million microscopic scales covering both sides of their wings. The scales vary in shape, but they typically measure about 0.1 mm and are arranged like shingles on a roof, as shown for a monarch in figure 1. In addition to repelling water, the scales give the insects their unique color pattern, which helps them avoid predation, regulate temperature, and attract mates. And their microgeometry reduces skin-friction drag by as much as 45%. This Quick Study explains how.

Butterfly scales

Flying efficiency drives the diversity of wing shapes in insects, and size is an important factor. Higher flapping frequencies are used by smaller winged insects, such as flies (200 Hz), and lower frequencies by larger insects, such as monarchs (10 Hz). Most butterflies, including monarchs, fly within a few meters of the ground, though monarchs have been observed during migration to reach altitudes of more than 1 km, where they can glide for miles in the wind currents. When cruising near the ground and flapping their wings, they can reach speeds of up to 5 m/s—about half the speed of Usain Bolt, the fastest human on record.

In 2017 Nathan Slegers and I worked with colleagues to analyze the flapping motion and trajectory of monarch butterflies, first with their scales intact and then with the scales removed. For one thing, the experiment disproved the myth that scales are essential for the insect to fly. More importantly, gently removing the scales, which are anchored to the wing much as bird feathers, decreased a butterfly's weight by an average of just 9.5%.

Yet in a study of more than 200 flights by 11 specimens, the removal decreased a monarch's mean climbing efficiency—defined as the total change in kinetic and potential energy achieved by the butterfly per flap—on average by 32%. The scales impart a unique, advantageous geometry: They are angled upward and form microscopic cavities that improve the wing's aerodynamics.

Aerodynamics of flight

As shown in figure 1, the four fundamental forces on a butterfly in flapping flight are the lift (**L**), which counters the weight (**W**),

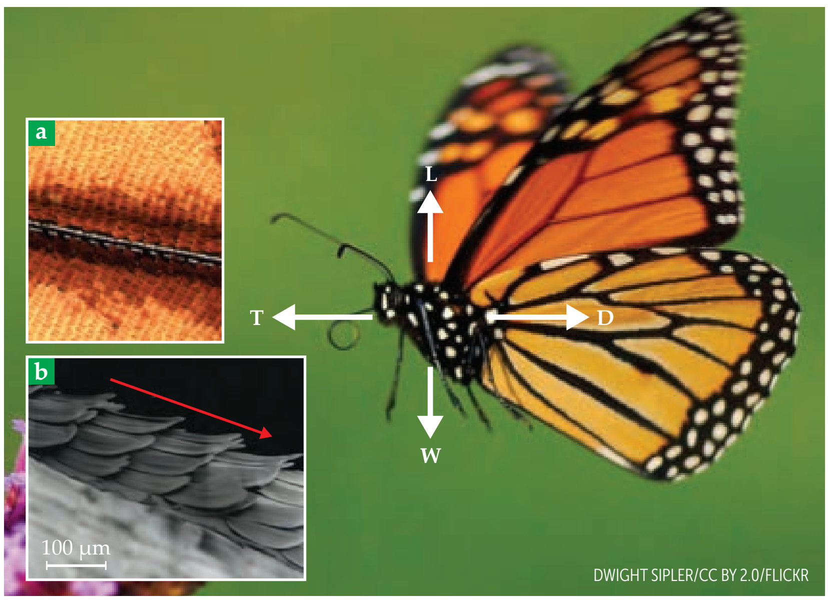


FIGURE 1. A MONARCH BUTTERFLY experiences the forces of lift (**L**), which counters its weight (**W**), and of thrust (**T**), which counters its drag (**D**). **(a)** A microscope image of a wing reveals discrete scales, each about 0.1 mm long, that form rows perpendicular to wing veins (black). **(b)** Microcavities are created on the wing's surface as the scales' tips curve upward. The orientation of airflow (red arrow) transverse to the cavities decreases the skin friction. (Insets adapted from N. Slegers et al., *Bioinsp. Biomim.* **12**, 016013, 2017.)

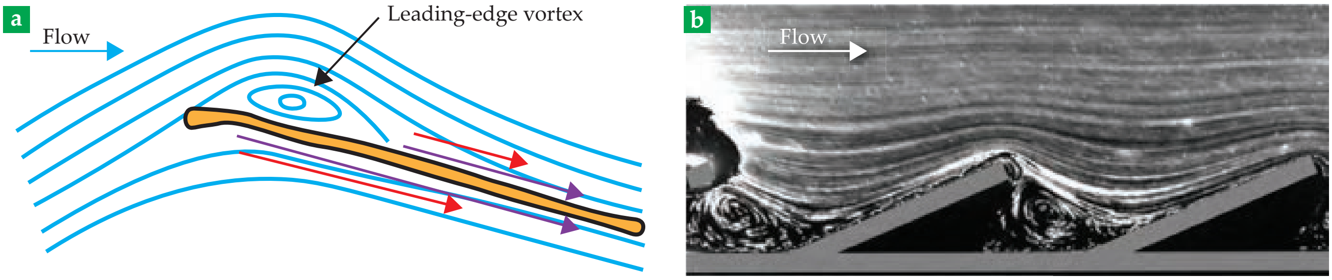


FIGURE 2. STREAMLINE PATTERNS. (a) As air flows over a butterfly's wing during flight, a leading-edge vortex forms on the upper surface. As the viscous air travels across the wing, it generates skin friction, which creates drag (red arrows) on both sides of the wing. Without the so-called roller-bearing effect created by the wing's scales, the drag would be greater (purple arrows). **(b)** In a fluid visualization experiment employing mineral oil, the tiny cavities between scales (gray bars) trap fluid, which then rotates in small vortices. As if sliding across roller bearings, the outer air flows over the surface with less skin friction. (Adapted from S. Gautam, PhD thesis, U. Alabama, 2021.)

and the thrust (**T**), which counters the drag (**D**). Three of them—lift, thrust, and drag—are generated on the wings. To climb, the insect's lift and thrust must be greater than its weight and drag. Furthermore, the only ways by which net lift, thrust, and drag are imparted to the wings are through the pressure (normal force per unit area) and shear stress (tangential viscous force per unit area) of air in contact with the wings.

As the insect flies, air passing over each wing—either during its downward stroke or while gliding motionless—produces a leading-edge vortex, shown in figure 2a. The swirling flow generates low pressure inside the vortex, and the resulting pressure difference across the wing generates both lift and thrust. The drag primarily arises from the shear stress.

In 2020 Christoffer Johansson and Per Henningsson used slow-motion cameras and flow measurements to discern a butterfly's distinct flight patterns. They found that the thrust is largely produced at the end of the upstroke, when the flexible wings clap together and press out the air trapped between them. The airflow can become complex, unsteady, and three-dimensional. The shear stress, or skin friction, of viscous air passing over the wing makes up about half the total drag force during gliding flight. The other major contributor comes from the swirling energy, known as induced drag, left behind in wake vortices.

A conservative estimate of the monarchs' glide ratio—the ratio of lift to drag force—is 4:1. A modest estimate for the skin friction during gliding flight could be around 10% of the lift. With their wings' low aspect ratio, butterflies are inefficient flyers, at least compared with a Boeing 747, whose glide ratio is around 17:1. A mechanism to reduce the skin friction would allow monarchs to move their lightweight bodies and large wings through the air with significantly less resistance.

Controlling skin friction

The skin friction on a butterfly's wing comes from the formation of a laminar boundary layer, a region of smooth viscous flow with a velocity difference between that of the wing and the surrounding air. Along the wing, the velocity of the air must match that of its surface—the so-called no-slip condition in fluid mechanics. But the presence of microcavities formed by the scales alters how the air interacts with the wing surface.

Because the scales are so small and the airflow over them is viscous, the Reynolds number—the ratio of inertial forces to viscous forces—is less than 10 in the cavities under the scales. At such a low Reynolds number, the flow is steady and smooth. Were the Reynolds number to increase, instabilities in the flow would emerge. My group replicated that low Reynolds number flow in the lab by replacing air with high-viscosity mineral oil and scales with manufactured plates, which increased the size of the scales 300-fold. We tested bioinspired models of the scale surface using cavity wall angles between 22°and 45°.

When the fluid passes over the scales' cavities transverse to the rows of scales, small vortices become trapped, as shown in figure 2b. Those minuscule wheels of air essentially become part of the wing surface and are independent of the outer flow. The outer flow can then skip over the surface—the so-called roller-bearing effect—thereby negating to some extent the no-slip condition. For the low Reynolds number flow experienced by a butterfly's scales during flight, lab results revealed a reduction in skin-friction drag of at least 26% and as high as 45%, compared with that over a smooth surface. (See figure 2a.)

Our latest results show that when the cavity Reynolds number is increased well above 10 (to 80 or more), that beneficial effect disappears—the skin friction drag increases—because flow in the small vortices becomes unsteady and mixes with the outer flow above it. A butterfly's tiny scales thus function precisely for the flight speeds that the insect usually experiences. Were the scales much larger, they would generate a higher cavity Reynolds number, and the flow-control mechanism that boosts flight efficiency would be lost.

Additional resources

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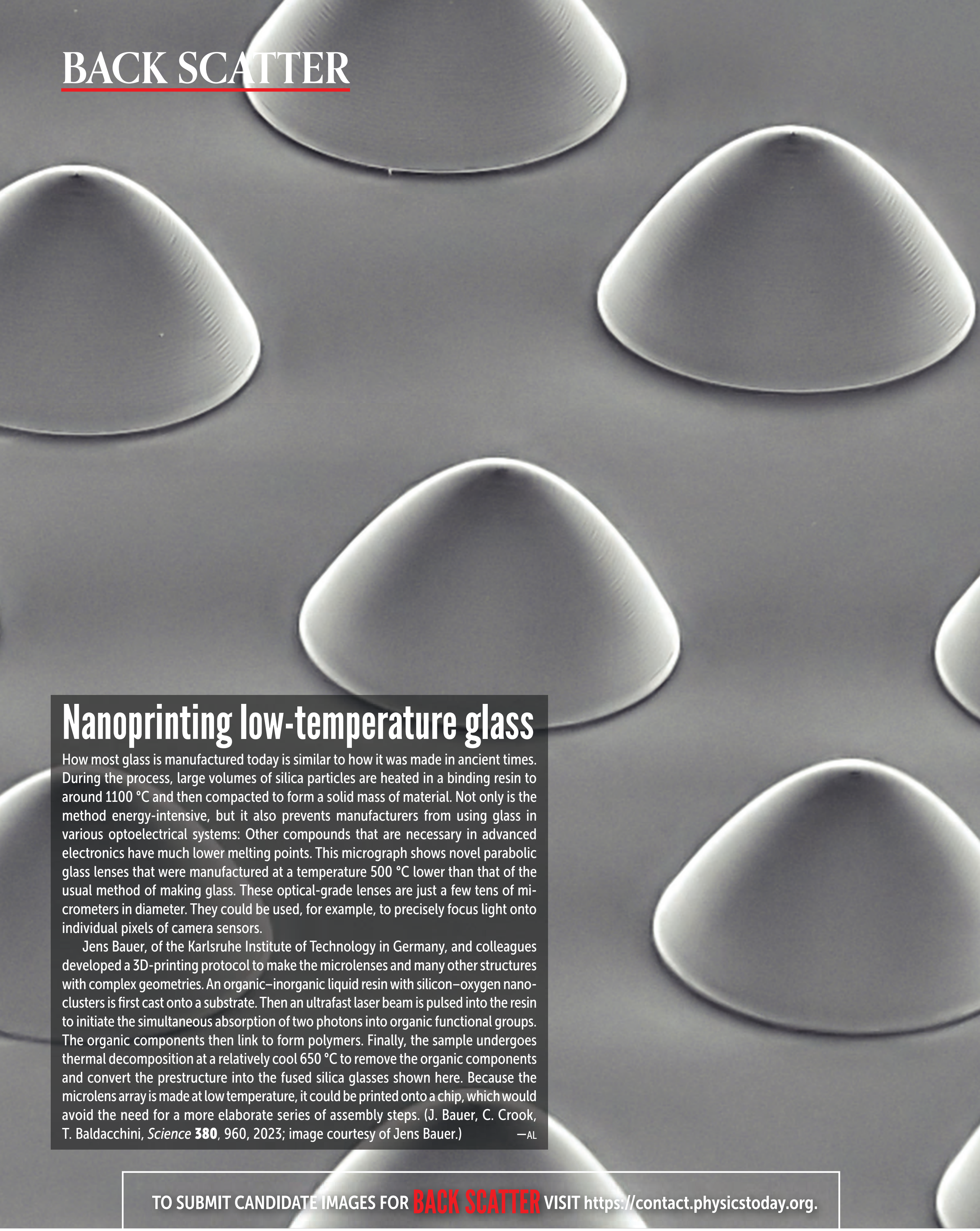
- L. Johansson, P. Henningsson, "Butterflies fly using efficient propulsive clap mechanism owing to flexible wings," *J. R. Soc. Interface* **18**, 20200854 (2021).
- D. Gibo, "Altitudes attained by migrating monarch butterflies, *Danaus p. plexippus* (Lepidoptera: Danaidae), as reported by glider pilots," *Can. J. Zool.* **59**, 571 (1981).
- A. Lang et al., "Sharks, dolphins and butterflies: Micro-sized surfaces have macro effects," *Proceedings of the ASME Fluids Engineering Division Summer Meeting*, paper no. FEDSM2017-69221 (2017).
- S. Gautam, "An experimental study of drag reduction due to the roller bearing effect over grooved surfaces inspired by butterfly scales," PhD thesis, U. Alabama (2021). PT



Nanoprinting low-temperature glass

How most glass is manufactured today is similar to how it was made in ancient times. During the process, large volumes of silica particles are heated in a binding resin to around 1100 °C and then compacted to form a solid mass of material. Not only is the method energy-intensive, but it also prevents manufacturers from using glass in various optoelectrical systems: Other compounds that are necessary in advanced electronics have much lower melting points. This micrograph shows novel parabolic glass lenses that were manufactured at a temperature 500 °C lower than that of the usual method of making glass. These optical-grade lenses are just a few tens of micrometers in diameter. They could be used, for example, to precisely focus light onto individual pixels of camera sensors.

Jens Bauer, of the Karlsruhe Institute of Technology in Germany, and colleagues developed a 3D-printing protocol to make the microlenses and many other structures with complex geometries. An organic–inorganic liquid resin with silicon–oxygen nanoclusters is first cast onto a substrate. Then an ultrafast laser beam is pulsed into the resin to initiate the simultaneous absorption of two photons into organic functional groups. The organic components then link to form polymers. Finally, the sample undergoes thermal decomposition at a relatively cool 650 °C to remove the organic components and convert the prestructure into the fused silica glasses shown here. Because the microlens array is made at low temperature, it could be printed onto a chip, which would avoid the need for a more elaborate series of assembly steps. (J. Bauer, C. Crook, T. Baldacchini, *Science* **380**, 960, 2023; image courtesy of Jens Bauer.) —AL

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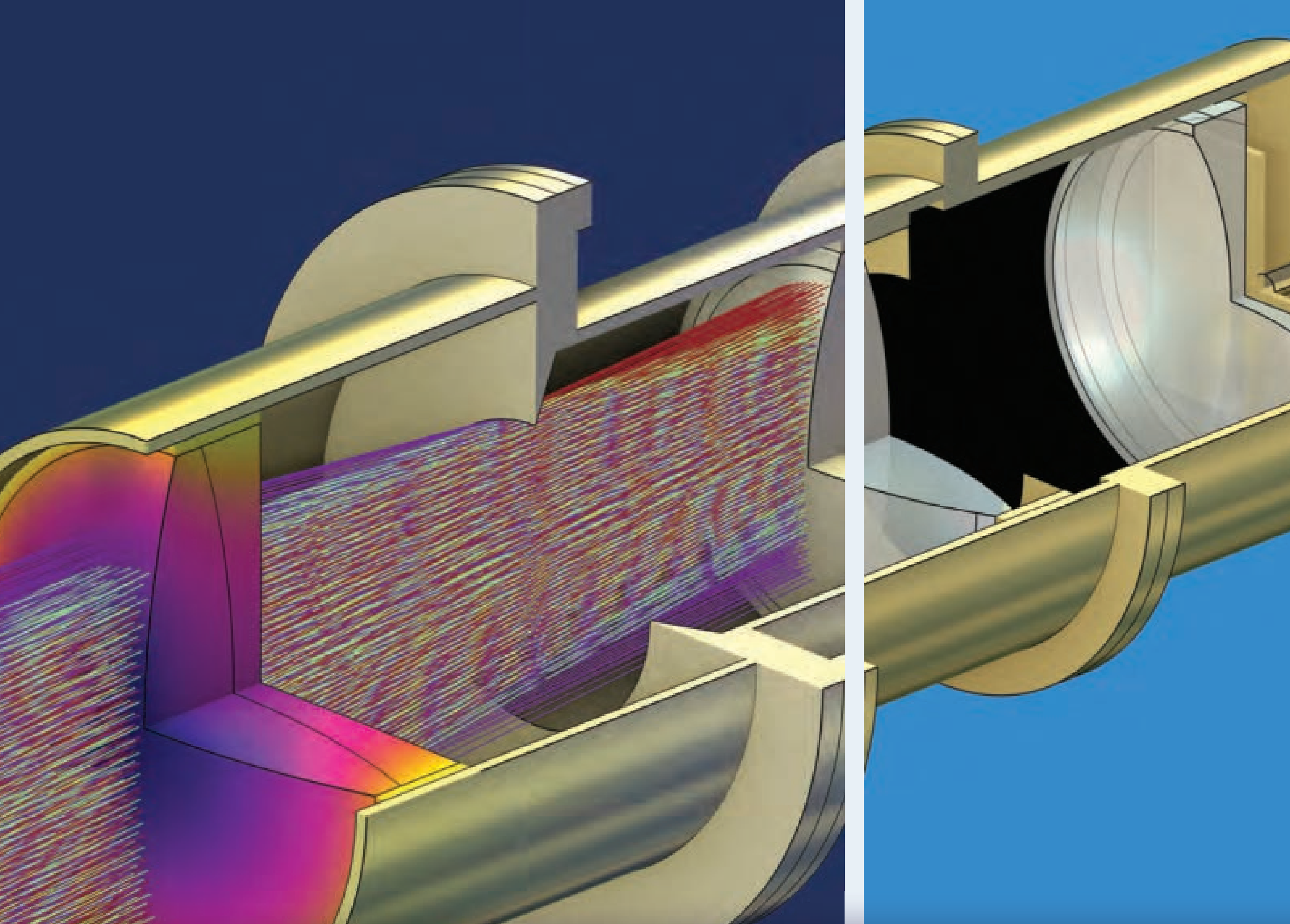

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