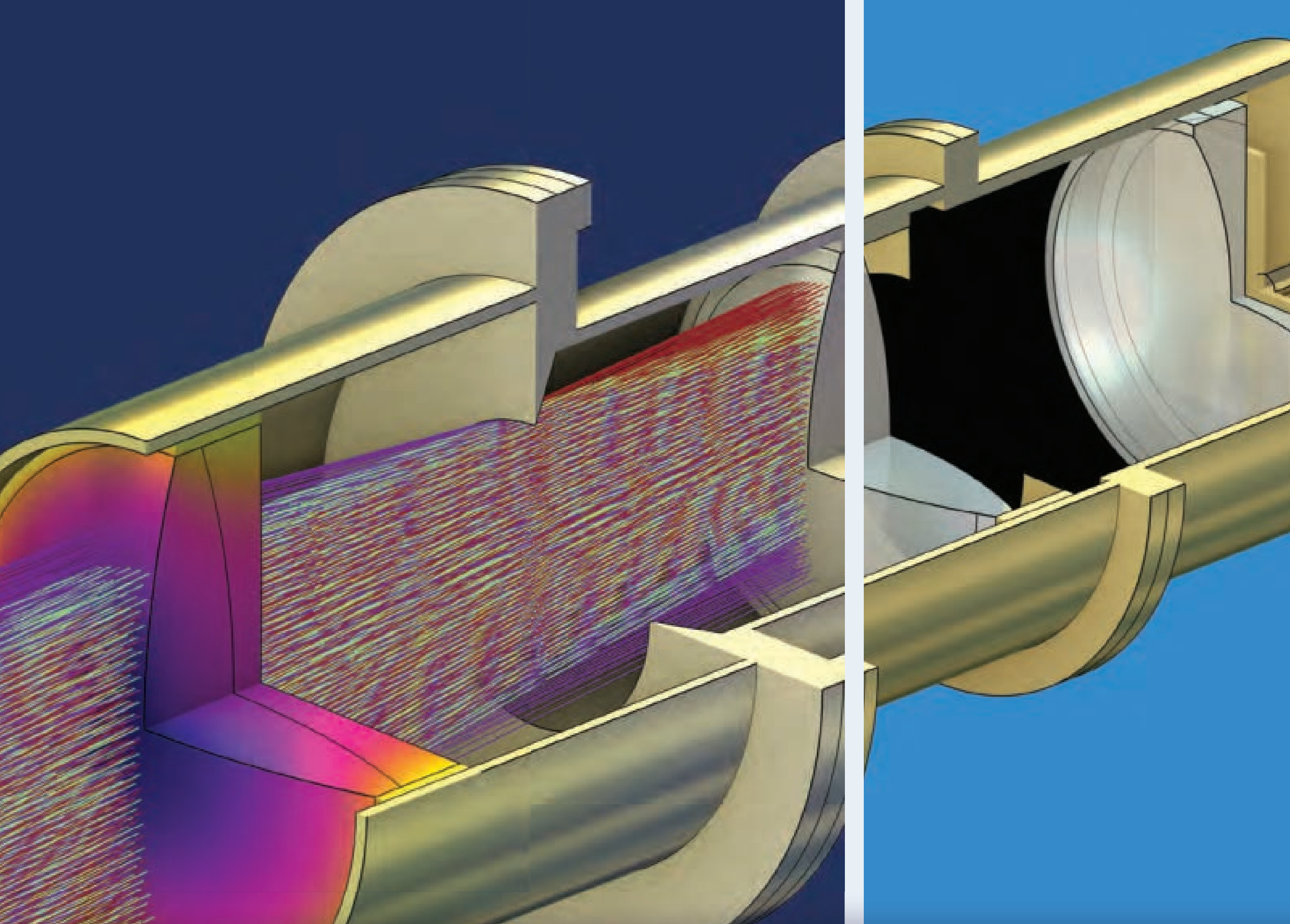


PHYSICS TODAY

January 2024 • volume 77, number 1

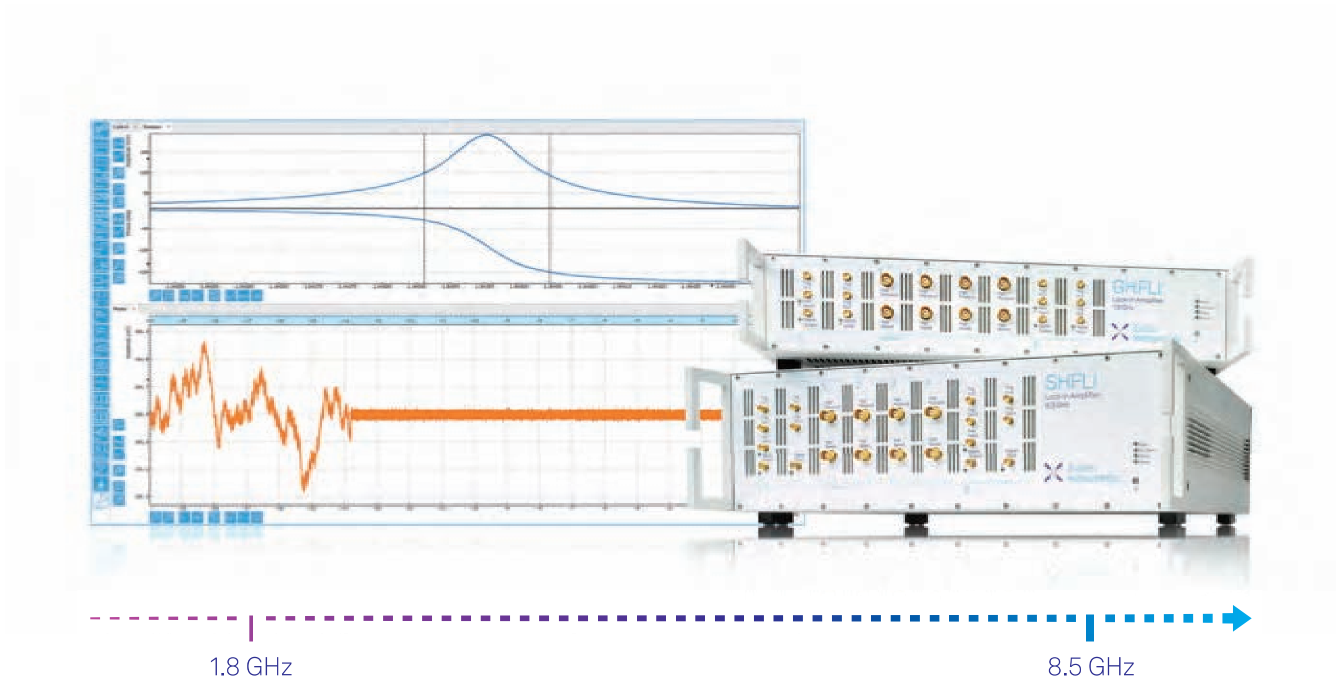
A publication of the American Institute of Physics

PECKING *without* HEADACHES

Trustworthy AI for weather prediction

Teaching physics with smartphones

LIGO's quantum noise reduction


SHFLI
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1.8 GHz
8.5 GHz

Innovation in cryogenics

Dr. John P. Davis
Founder & CTO

For more than two decades, since my grad school days at Northwestern University, I have been captivated by the beauty and elegance of low-temperature physics. Now in Canada as a professor at the University of Alberta in Edmonton and a cofounder and chief technology officer of Zero Point Cryogenics (ZPC), I continue to be amazed by the advances of quantum technology and condensed-matter physics at low temperatures. The driving force behind many of those developments is the capabilities afforded by modern cryogenics, such as dilution refrigerators.

Yet despite significant improvements, dilution refrigerators remain finicky to operate, have reliability problems, and are time consuming for academic and industry labs alike. In my lab at the university, I own dilution refrigerators from almost every provider on the market, and they all require countless hours of expert technicians to maintain.

ZPC was founded in 2017 with the mission to make the world's best and most reliable dilution refrigerators so they can be a straightforward tool to aid in quantum R&D rather than the focus of effort in the laboratory.

For example, what if the still and return lines of your dilution refrigerator were made with all-metal seals, such that you would never lose precious helium-3 from a failed O-ring? What if the joints were never exposed to soft solder flux and thus would prevent leaks from developing over time? What if you never needed to fill a liquid-nitrogen cold trap again because it was smartly integrated into the fridge? Those are the kinds of advances we have already made at ZPC, with many more on the horizon.

Our vision at ZPC is to become the premier choice for cryogenic solutions in both academia and industry. One way we are moving to fulfill that is by improving the footprint of our systems. We envision a day when thousands of dilution refrigerators will fill quantum computing data warehouses, and we are designing our systems today around that future. Similarly, we are advancing the state of the art in vibration isolation so that sensitive academic experiments can operate with ease at millikelvin temperatures.

We are constantly innovating at ZPC. We focus so heavily on innovation because cryogenic needs are constantly changing. We value innovation because a significant portion of our staff is made up of trained physicists who have used dilution fridges in their research and know what users want and need. Our staff members have a broad spectrum of in-house expertise, which covers every step of the manufacturing process—from design, to CNC (computer numerical control) machining, to polishing and gold plating, to extensive testing and system optimization.

At Zero Point Cryogenics, we believe that the future of cryogenics is rich. We will continue to strenuously push innovation in cryogenics today to unlock the full potential of quantum technologies tomorrow. Contact us to discuss your cryogenic needs.

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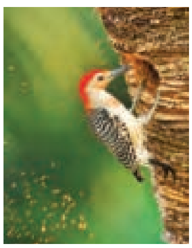
FEATURES



ON THE COVER: Wood chips fly as this red-bellied woodpecker prepares its nest in the trunk of a tree. With each peck, a woodpecker's head decelerates at up to 400 *g*, the standard acceleration due to gravity. That deceleration far exceeds what would render a concussive blow to a human brain. But with its much smaller size, a woodpecker's brain can tolerate stronger shocks. For more on how woodpeckers avoid head injuries, see the Quick Study by Sam Van Wassenbergh and Maja Mielke on **page 54**. (Image by FloridaStock/Shutterstock.com.)

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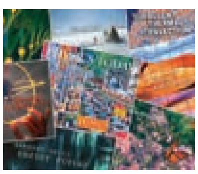

CYNTHIA CUMMINGS

Best of 2023

Take a look at Physics Today's most popular articles from last year, including several available only online. Archival PT coverage of J. Robert Oppenheimer, open educational resources in physics classrooms, and the seemingly unstoppable ITER fusion energy project in France attracted readers' attention.

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The year in books

Physics Today's books editor, Ryan Dahn, looks back at 2023 and recommends a list of books for physics and history-of-science enthusiasts. Selections include an engaging guide to science communication and an illuminating history of Mayan astronomy in the first millennium CE.

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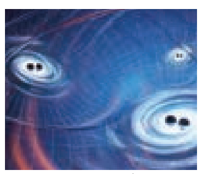

OLENA SHMAHALO/NANOGRAV

Rolling cosmos

By analyzing deviations in the arrival times of pulsar radiation, researchers have concluded that the cosmos is churning with nanohertz-frequency gravitational waves. Sarah Vigeland and Stephen Taylor describe the crucial correlation between the signals of different pulsars that enabled the discovery.

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Hong Kong University of Science and Technology: Innovating Today, Imagining Tomorrow

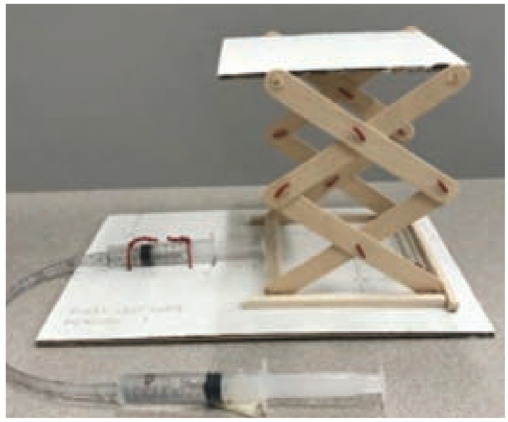
The Hong Kong University of Science and Technology (HKUST) is a dynamic, young research university with a diverse international student body and faculty who relentlessly pursue excellence in teaching and research. Situated on a hillside overlooking scenic Clear Water Bay at the eastern edge of Hong Kong and the southeastern coast of China, HKUST has rapidly established itself as a leading institution on the academic world map. Since the university's founding in 1991, the physics department has grown from 9 to 38 faculty members and now has 180 research graduate students. The department's research areas have also expanded to include condensed-matter physics; atomic, molecular, and optical systems and quantum optics; particle physics and cosmology; quantum information; scientific computation; soft-matter and biological physics; and metamaterials.

The physics department promotes the pursuit of cutting-edge research by cultivating a collaborative, supportive, and cohesive environment. For example, the Center for Fundamental Physics focuses on theoretical and experimental research about the origin, fate, and fundamental building blocks of the universe, and it has participated in several global endeavors, including the ATLAS collaboration at CERN. The emphasis of the Center for Metamaterials Research is on the design, fabrication, and characterization of different metamaterials to explore novel wave phenomena and to manipulate light and sound in ways not possible before. The IAS Center for Quantum Technologies brings together a team working across several core areas with focuses on quantum materials and devices, quantum control, and software. The newly established Center for Theoretical Condensed Matter Physics strives to foster a dynamic research atmosphere and encourage international academic collaboration in a major subfield of physics.

The physics department's research efforts are supported by critical infrastructure, specialized equipment, high-performance computer clusters, and services provided by the university's Central Research Facilities. For example, the Materials Characterization and Preparation Facility offers advanced characterization tools, sample and materials preparation apparatus, and a helium liquefier. The Nanosystem Fabrication Facility has state-of-the-art equipment for developing innovative micro/nano devices and systems. The recently acquired NVIDIA DGX SuperPOD system is a state-of-the-art AI supercomputing facility. It serves as a platform to foster an AI for Science environment and is certainly one of the best computing facilities in Hong Kong.

The department's goals for future growth are to enhance existing core strengths and build up world-class capabilities in rapidly developing areas aligned with university initiatives, such as big data and renewable energy and new energy materials. To achieve these goals, the department will strive to continuously attract outstanding new faculty members at all ranks, and it plans to fill 10 new faculty positions in the next few years. To learn about opportunities as soon as they are posted, interested candidates may visit jobs.physicstoday.org and create an alert for "HKUST."

Retired? Become a sub



IN A PRE-ENGINEERING CLASS for which the author was the substitute teacher, a student uses a drill (left) to create the holes for bearings in a hydraulic scissor jack (right). The students used the jack to lift a cup of liquid without any spilling out.

I am grateful to Don Rea for his February 2023 letter (Physics Today, page 11), which describes the American Association for the Advancement of Science's STEM Volunteer Program. That said, he gives no actual data to support his argument that "a consortium of STEM societies is the best approach for implementing a program in support of K–12 STEM education." The clearest indication of success that he provides is anecdotal: an email from a teacher to a volunteer in which she thanked him, said it was an "absolute pleasure" to work with him, and expressed that she would encourage more schools to use the program.

I have found a way to support STEM (science, technology, engineering, and mathematics) education that is quite simple and does not require the consortium that Rea describes.[1] As a retired physics professor, I have become a substitute teacher in a local high school district, in a city where 80% of the population is Hispanic or Latino, according to the US Census Bureau.[2]

To become a substitute in my district, I had to provide my university transcripts, pass a background check, and get tested for tuberculosis. I also had to take online courses that covered topics such as sexual harassment and accident protocols.

For retirees, substitute teaching is an ideal setup. In my district, vacancies are listed on a website that includes the duration of the assignment. Some are as short as an hour-long class, while the longest time I spent covering an individual teacher's classes was four consecutive days (which was a bit rough for a retiree, since it required me to wake up each day at 6:00am). I take an assignment only on a day I want to work. Sometimes I'll just work two or three classes in an afternoon. On average I work three to five times per month when I'm not traveling or doing experiments.

The website for the district names the teacher, lists the teacher's primary subject area (for example, math, pre-engineering, or construction technology), and provides the teacher's email address so the sub can ask questions.

I cannot say that substitute teaching is the "best approach" for supporting STEM education, but I can say that every class has been a fulfilling experience for me, and several students have provided feedback expressing how I have helped them in some way. I've heard from some that I'm "the best substitute they ever had." I've received thank-you letters from others, with one saying, "Listening to you talk about the cool things you were able to accomplish, where you taught, and where you got your degrees made me super hopeful and want to study physics further. It was like a spark ignited when you talked." Now and then I've even heard feedback along the lines of "I wish you were my regular teacher."

As soon as I accept a job, ordinarily I contact the teacher I'll be filling in for and ask the topic to be covered on that day. That allows me to plan accordingly. For example, in a pre-engineering class, I brought a few small acoustics demonstrations. For one math class, I was told the topic would be graphing equations, so I brought a laboratory notebook that had an average of at least one graph per page and passed it around. One student was really enthusiastic and asked me several questions about the content of my lab book, which also included schematic circuit drawings, photos, and sketches of apparatuses. Not all students will be so eager, but if you inspire even one student per class or one per day, you're still making a difference.

CONTACT PHYSICS TODAY

Letters and commentary are encouraged and should be sent by email to **ptletters@aip.org** (using your surname as the Subject line), or by standard mail to Letters, Physics Today, American Center for Physics, One Physics Ellipse, College Park, MD 20740-3842. Please include your name, work affiliation, mailing address, email address, and daytime phone number on your letter and attachments. You can also contact us online at **https://contact.physicstoday.org**. We reserve the right to edit submissions.

No matter where you retire, you will find a school district that needs substitute teachers for STEM classes. If you were a physicist for 40 years, you'll find that you have plenty of material to inject into almost any class. No larger organization is required!

Reference

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CO_2 pipelines: A way forward?

David Kramer's piece "Capture alone isn't sufficient to bottle up carbon dioxide" (Physics Today, July 2023, page 22) focuses on the need in the US to create a massive CO_2 sequestration capacity, which is indeed in need of attention. But the story was deficient in one respect and inaccurate in another.

In Oklahoma, induced earthquakes over the past decade have mainly been attributed to wastewater disposal—in particular, high injection rates—but some have been associated with hydraulic fracturing, or "fracking."[1,2] Those relationships suggest that high-rate injection of supercritical CO_2 into deep saline aquifers may lead to seismicity. Indeed, the Intergovernmental Panel on Climate Change foresaw that possibility in 2005.[3] Because the physical properties of supercritical CO_2 differ from those of wastewater, it's uncertain whether they will have identical seismogenic effects. But there is a need for regulations, guided by independent research, that ensure that CO_2 sequestration is performed in a manner that does not lead to earthquakes.

Carbon dioxide is heavier than air, and therefore its airborne dispersion characteristics are altogether different from those of natural gas, and CO_2 presents an increased danger to both land-based and aquatic life. Indeed, contrary to Kramer's assertion that no one was injured in the 2020 CO_2 pipeline rupture near Satartia, Mississippi, the event led to the hospitalization of at least 45 people in addition to the evacuation of over 200.[4]

Given that risk, the environmental hazards, and the potential for violating the rights of Indigenous communities, CO_2 pipelines have unsurprisingly been met with public opposition. The carbon capture and sequestration community should respond by building trust with the public—starting with repurposing existing natural gas pipelines to transport CO_2—and by strictly adhering to environmental protection regulations, treaties with Indigenous communities, and existing legal requirements. Rules and regulations must be changed to ensure that the characteristics of CO_2 are fully accounted for, both in its transportation and in its sequestration, and not to accelerate the laying of new pipelines.

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A fulfilling career

I admired how the obituary of Benjamin Breneman Snavely (Physics Today, October 2023, page 69) shines a light not just on his research accomplishments but also on his life of service in the private and public sectors. I did not know Snavely, but I am grateful for how my life has been touched by many scientists like him. The authors' remembrance shows how a career in physics offers us—beyond moments of breathtaking joy in a new discovery—a path toward sustained happiness while we help those around us live enriched and fulfilling lives as we engage in our pursuit of expanding the frontiers of knowledge.

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Earth's radiative balance

In the July 2022 issue of Physics Today, Martin Singh and Morgan O'Neill address the thermodynamics of Earth's climate system (page 30). Their statement that "the climate system is close to an energy balance at all times" is true, but only if energy has been redistributed by Earth's fluid systems, oceans, and atmosphere. Their following sentence, which states that "terrestrial radiation is emitted to space at approximately the same rate at which solar energy is absorbed," is ambiguous and does not apply locally or instantaneously.

The radiant heat balance of the atmosphere, oceans, and surface of the planet depends on Earth's absorption of short-wave radiation from the Sun, long-wave emissions into space, and reflections of short-wave radiation from Earth's surface and atmosphere.

The atmosphere absorbs less than 20% of incident solar beams. Reflection and scattering from the atmosphere and Earth's surface cause 30% of the solar beams to be lost to space. The remaining 50% of the Sun's energy is unequally distributed across the planet's surface. Between the latitudes of 40° N and 40° S, more energy is received annually from the Sun than is lost to space. Poleward of those latitudes, more energy is lost to space than received from the Sun. If that imbalance were not redressed by heat transported by the atmosphere and oceans, the high latitudes would turn into a block of ice and the tropical latitudes would become unsustainably hot.[1]

For the polar regions of heat deficit to be redressed, they must draw on the tropical regions of excess heat. Approximately 30% of the excess is transferred from the tropics to the polar regions by the oceans.[2] The remaining 70% must be transferred to the poles by the atmosphere to achieve the climatic equilibriums of Earth's temperatures. Surface winds in the tropical regions of excess heat, however, are directed toward the regions of excess. Heat transport from the "warm" tropics must therefore occur at altitude rather than at the surface.

In considering the vertical motion of hot, moist tropical air, a useful, adiabatically conserved quantity is the equivalent potential temperature, which can be defined as the temperature that a parcel of air would have if all water were condensed at constant pressure and the entropy released from the sample to heat the atmosphere.[3]

A midtropospheric minimum in the vertical profile of the equivalent potential temperature prevents simple mixing from transferring surface heat to the upper levels of the troposphere. To affect that transport, protected vertical transport channels, referred to as hot towers,[2] penetrate the midtropospheric temperature minimum, and the various components of the atmospheric general circulation allow energy to reach the polar region's upper troposphere.[4]

The set of thermodynamic interactions between Earth and the Sun can be explained in quantitative detail. In fact, the complex of scales of motion that governs the radiative relationships is manifested in Earth's climate. Besides climate issues, researchers have only recently begun studying those various scales for their use by birds and perhaps other animals.[5] Cause and effect of such factors challenge predictability.

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Frequency-dependent squeezing makes LIGO even more sensitive

Researchers at the gravitational-wave observatory were already using nonclassical states of light to boost their measurement precision. Now they've unveiled a still-subtler trick.

It's been called the world's most precise machine, and it's one of the most ambitious. From an audacious dream in the 1960s to the securement of funding in 1992 to the first direct detection of gravitational waves on 14 September 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) is the product of decades of theoretical and experimental work, much of it carried out with no guarantee of any reward.

But LIGO's work is never done. After the 2015 upgrade to Advanced LIGO, the observatory could detect signals a fraction the size of a proton, but that was still only barely sensitive enough to observe gravitational waves from one of the most violent events in the universe—the merging of two black holes some 30 times the mass of the Sun. (See PHYSICS TODAY, April 2016, page 14, and December 2017, page 16.) To fully realize the potential of gravitational-wave astronomy, LIGO researchers have been working tirelessly to reduce noise and boost the observatory's sensitivity even more. They quickly ran up against the limits of quantum mechanics itself.

The Heisenberg uncertainty principle can drive a hard bargain, but it's willing to make a deal: It allows lowering the quantum uncertainty in one quantity at the expense of increasing it in another. Since LIGO's third observing run began in 2019, the observatory has been taking advantage of that offer by using so-called squeezed states of light. But it soon ran into another trade-off. Beyond a certain point, squeezing light increases the sensitivity to high-frequency gravitational waves, but it makes the noise for low-frequency signals worse.

FIGURE 1. AT LIGO'S TWIN DETECTORS—this one in Livingston, Louisiana, and the other in Hanford, Washington—powerful laser light circulates in perpendicular 4-km-long arms. Through interferometry of the light from the two arms, researchers can detect changes in the arm lengths of less than 10^{-18} m. (Photo courtesy of Caltech/MIT/LIGO Lab.)

Now, for their fourth observing run, which began in May, LIGO researchers have broken through even that apparent barrier.[1] Using a technique called frequency-dependent squeezing, they've achieved the best of both worlds: reducing the noise across a broad range of frequencies while not increasing it anywhere. Thanks to the effort, LIGO can now detect gravitational-wave events over a larger volume of the universe than ever before—and moreover, a fundamental obstacle to pushing LIGO's quantum noise even lower has at last been removed.

Squeezed vacuum

LIGO, as the name suggests, works through laser interferometry. Light beams travel out and back along the two long arms of an L-shaped interferometer, and they recombine at their source. The system is tuned so that usually the beams interfere destructively: No gravitational wave means that (almost) no light is detected. When a gravitational wave does pass through, it alternately stretches each arm while compressing the other. The length changes disrupt the interference and create an optical signal.

The stretches and compressions are tiny. Even the powerful gravitational wave from a black hole merger, by the time it gets to Earth, creates fractional length changes on the order of just 10^{-21}. To have any hope of seeing anything at all, LIGO researchers take every opportunity to boost the signal and suppress noise. The heavy mirrors that reflect the light are hung from sophisticated pendulums to protect them from vibrational noise. The facility uses not one interferometer but two—and a growing network of partner facilities around the world—to bolster the case that any wave they simultaneously detect is not a fluke. And the interferometer arms are 4 km long, as shown in figure 1, and the circulating laser power is in the hundreds of kilowatts, so even a small

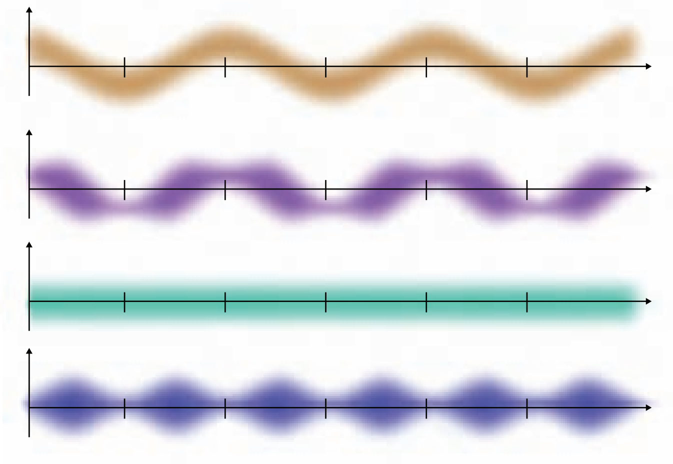

FIGURE 2. SQUEEZING LIGHT shifts the quantum uncertainty from evenly spread along the waveform (brown) to concentrated in just one part (purple). Electromagnetic vacuum states, too, can be either unsqueezed (green) or squeezed (blue). (Adapted from R. Schnabel., *Phys. Rep.* **684**, 1, 2017.)

fractional length change can leak a detectable amount of light out of the interferometer.

But measurements of a light wave's intensity, like those of any other physical quantity, are subject to quantum uncertainty—and that's true even when there's no light wave present. Even in the electromagnetic vacuum state, there's always a chance that some photons will appear. There's no way for an interferometer output to ever truly be zero, and the quantum background can easily mask the feeble signal of a gravitational wave.

So what is squeezed light, and how can it help? Left to its own devices, quantum uncertainty tends to spread out uniformly along a waveform, as shown in brown in figure 2, but that's not the only option. With nonlinear optics, you can squeeze the uncertainty out of one part of the waveform and concentrate it in another. For example, the wave shown in purple has reduced uncertainty in its amplitude and increased uncertainty in its phase. If you're looking to measure the amplitude, and you don't care about the phase, the squeezed state offers a big improvement.

Roughly speaking, the uncertainty principle treats a wave's amplitude and phase the same way it treats a particle's position and momentum: The product of the two uncertainties is constrained, but either one can be reduced at the expense of the other. For an interferometer like LIGO's, phase is the more important quantity. It's the timing of the light waves from the two arms that determines whether they interfere destructively or not.

The idea of using squeezed light for gravitational-wave detection was laid out by Carlton Caves in 1981—decades before LIGO was built and years before anyone had even observed squeezed light in a lab.[2] Caves anticipated that the way to do it was to squeeze not the state of the laser light itself but rather the state of the electromagnetic vacuum that enters the interferometer where the signal light comes out. Figure 2 shows how vacuum states can be either unsqueezed (green) or squeezed (blue). Although the vacuum lacks either amplitude or phase, those terms can be defined according to its interaction with the interferometer light.

In 2019 LIGO implemented Caves's scheme for using a phase-squeezed vacuum to substantially reduce quantum noise.[3] But there was a fly in the ointment: The increased amplitude uncertainty, which transfers to the amplitude of the light inside of the interferometer, is not harmless. When light hits the mirrors at the ends of the interferometer arms, it exerts radiation pressure on them—and because the mirrors are dangling from pendulums, fluctuations in the radiation pressure can set them swinging. The mirrors are heavy and the fluctuations are small, so they don't swing very much. But the signals LIGO seeks to detect are so extraordinarily small that it doesn't take much to obscure them.

Only the low-frequency signals are obscured: The weighty mirrors can't swing fast enough to make any difference in the detection of gravitational waves above about 300 Hz. Low-frequency signals, however, are important. The events LIGO detects—merging pairs of black holes and neutron stars—generate gravitational waves as the massive objects circle one another faster and faster for a few tenths of a second before colliding. If the observatory were to give up on detecting signals until the orbital speed had ramped up to 300 cycles per second, it wouldn't detect much at all.

Phase delay

To avoid the detrimental effect on low-frequency signals, LIGO's 2019 implementation of squeezed light limited its squeezing to three decibels, or about a factor of 2. But the researchers were already working on doing better—and once again, their work built on theoretical foundations that had been laid decades ago.

In a 2001 paper, H. Jeff Kimble and colleagues presented the idea of enhancing gravitational-wave detection by squeezing light differently at different frequencies.[4] In their analysis, "frequency" refers not to the frequency of the laser light in the interferometer (which is perfectly monochromatic) but to the frequency of the gravitational waves it's trying to detect. The state being squeezed, after all, is the electromagnetic vacuum, which doesn't have an inherent frequency itself but can be thought of as having components of all frequencies.

"Squeezing at every frequency is independent," says Lee McCuller, a LIGO scientist at Caltech, "and it just kind of works out that the way we usually make a squeezed vacuum squeezes the same at every frequency." In LIGO's case, every frequency is phase squeezed. Kimble and colleagues' idea was to instead create a state that varies from phase squeezed at the highest frequencies to amplitude squeezed at the lowest.

Luckily, a phase-squeezed vacuum and an amplitude-squeezed vacuum look exactly the same, and one can be transformed into the other simply by delaying it by a quarter of a wave cycle. So creating frequency-dependent squeezing is just a matter of introducing a frequency-dependent delay—and that can be done by bouncing the

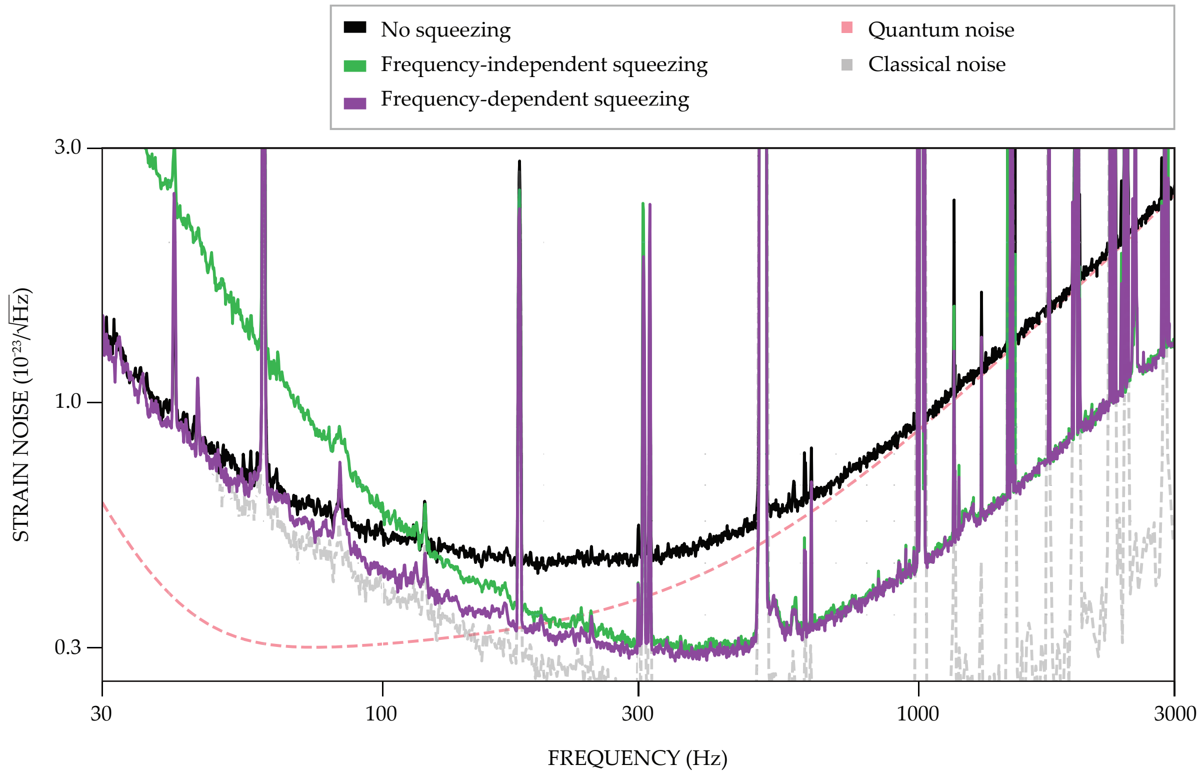

FIGURE 3. NOISE AT LIGO'S LIVINGSTON DETECTOR (black) consists of classical noise (gray) and quantum noise (pink). Using squeezed light can substantially reduce the quantum noise at high frequencies—but the initial approach, frequency-independent squeezing (green), also increases the noise at low frequencies. LIGO researchers have now implemented frequency-dependent squeezing (purple), which reduces the noise across many frequencies without increasing it anywhere. (Adapted from ref. 1.)

phase-squeezed vacuum off a long optical cavity.

"Think of it as how, when you yell into a cave, if your voice is resonant with the cave you hear an echo," says Victoria Xu, a postdoc in MIT's LIGO lab. "But if it's not resonant, you hear nothing." Similarly, the low-frequency components of the squeezed vacuum enter the cavity and ricochet around for a while before exiting, while the high frequencies ignore the cavity and are reflected straight back.

Kimble and colleagues had worked out the theory, but implementing frequency-dependent squeezing to LIGO's stringent standards posed additional challenges. "The tricky part is to think about what you're asking for," says Xu. The low frequencies that LIGO seeks to detect—from tens to a few hundreds of hertz—are extremely low by electromagnetic standards. Creating the requisite phase delay of 3 milliseconds means building a cavity 300 meters long and holding the light inside for a few thousand round trips.

And it all had to be done without losing any photons. "Squeezed light is extremely sensitive to loss," says Xu. As a nonclassical state of light, it can be thought of as made up of entangled pairs of photons. "If you lose one photon from a correlated pair, you have nothing," she says.

By 2020, LIGO researchers had tested frequency-dependent squeezing with laboratory-scale experiments, including one led by McCuller that used a 16 m cavity.[5] Satisfied that they could make it work, they decided to take the plunge and push to implement the technology for LIGO's fourth observing run.

"It was amazing that it worked so fast," says McCuller. "The 16-meter experiment took us four years—but we had just a few researchers and postdocs working on it. The real deal had to come together much faster."

"Three hundred meters is as far as I can walk in five minutes," says Xu. "To house a cavity that big, we had to build whole new buildings and new clean rooms. It's nothing that nobody's ever done before, but for LIGO it had to be done on a massive scale. And this is the kind of thing that LIGO is really good at."

A new baseline

Figure 3 shows the resulting noise reduction at LIGO's Livingston detector. (Data for the Hanford site are similar.) At high frequencies, the frequency-dependent-squeezing noise (purple) is six decibels lower than what would have been achieved with no squeezing (black), whereas at low frequencies it's unchanged. And the frequency-independent-squeezing noise (green) matches the purple curve at high frequencies, but at low frequencies it's much higher.

The black and green curves don't represent the noise that LIGO achieved during its third observing run (or at any other time), but rather they show what it would have achieved in its fourth run without frequency-dependent squeezing. "We compare the noise not to the previous run but to the best we can do now," says Lisa Barsotti, a senior research scientist at MIT's LIGO lab, "and we never make only one improvement from run to run. There's always a constant effort to keep reducing the classical, technical noise too."

With that caveat in mind, the researchers estimate that the difference between the black and purple curves means that LIGO can detect events 15–18% farther away—or over a 50–65%

larger volume of the universe—than it otherwise could. But that improvement is only the beginning.

"This is now the baseline for any future upgrade," says Barsotti. Before, LIGO had to deliberately throttle its light-squeezing efforts to avoid compromising its low-frequency sensitivity, but that's no longer the case. "The next step is to improve how much squeezing we can see," Barsotti explains. "We can squeeze the light as much as we want, and we're only limited by how well we can get it into the interferometer. This is going to be important not only for LIGO but for all future ground-based gravitational-wave detectors."

Johanna Miller

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Uncovering the molten mantle of Mars

A delay in seismic-wave arrival times reveals the presence of an additional layer in the planet's interior.

Mars is only the second celestial body, after the Moon, that humans have sent seismometers to. A desire to understand its interior, which holds clues to Mars's origin and evolution, motivated NASA to develop *InSight* (*Interior Exploration Using Seismic Investigations, Geodesy and Heat Transport*). Before that mission, astronomers' knowledge of Mars's interior came primarily from models of solar-system formation, Martian meteorites, and geophysical observations from satellites orbiting the planet. Those data provided only an incomplete glimpse of Mars's interior.

The seismometer on the *InSight* lander—known as SEIS, or the Seismic Experiment for Interior Structure—collected data from 2019 to 2022 by listening

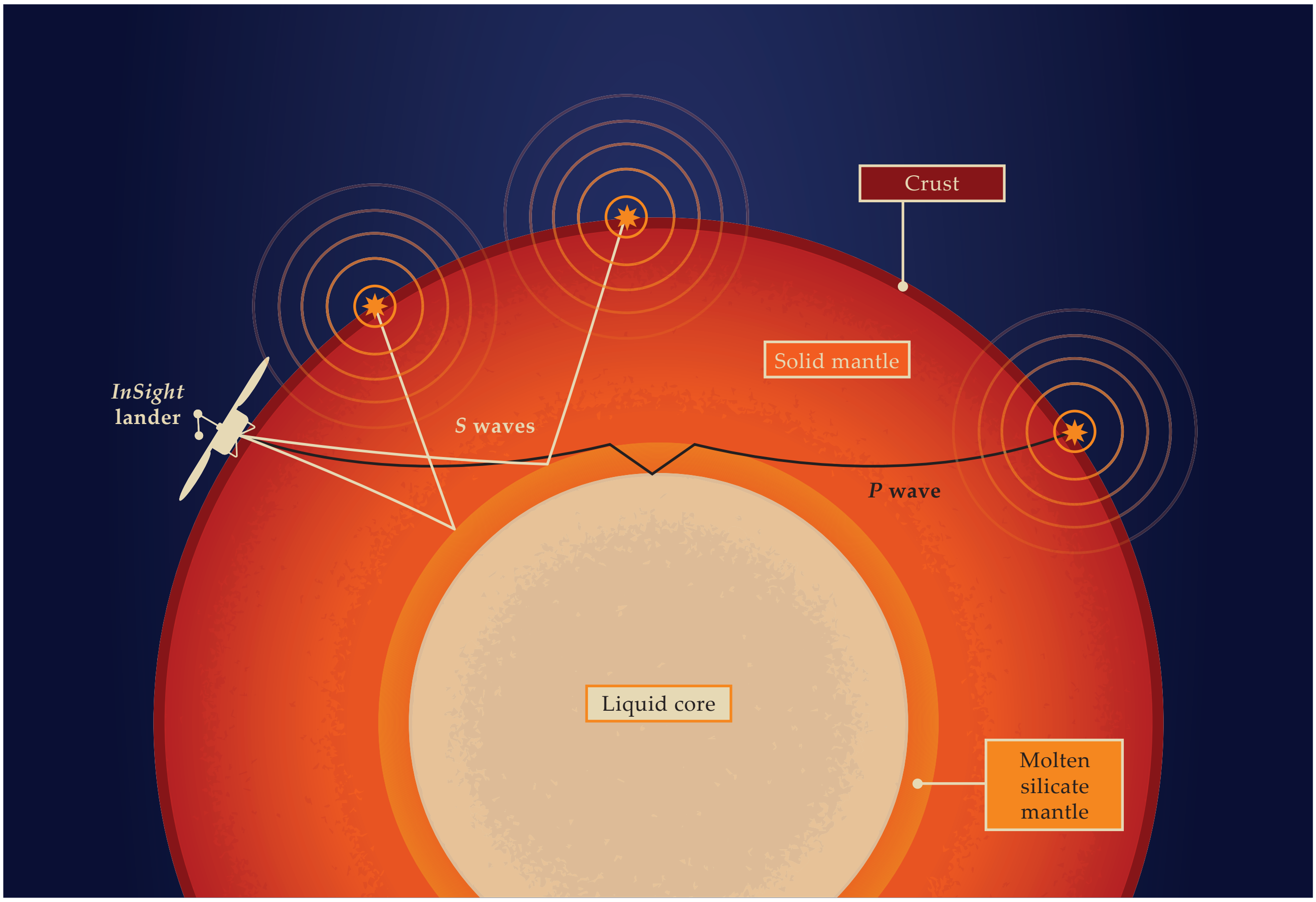

FIGURE 1. MARS'S INTERIOR STRUCTURE can be inferred from seismic waves that travel through the planet. Waves go out in all directions from the seismic events; shown here are examples of wave paths that support the existence of a deep liquid silicate mantle layer just above the core. *S* waves from events near the *InSight* lander reflect off the solid–molten boundary and can be used to determine the inner radius of the solid mantle. An event farther away allows the seismometer to detect *P* waves that penetrate to deep layers of the planet, revealing the presence of a molten silicate mantle layer. (Adapted by Jason Keisling from ref. 1.)

FIGURE 2. A METEORITE IMPACT on Mars on 5 September 2021 produced seismic waves detected by NASA's *InSight* lander on the other side of the planet. NASA's *Mars Reconnaissance Orbiter* then took this image of the impact location. The blue was added to highlight where the soil was disturbed. (Courtesy of NASA/JPL-Caltech/University of Arizona.)

to marsquakes and other tremors caused by meteorites landing on Mars's surface. (For more on *InSight*, see PHYSICS TODAY, October 2021, page 17.) Because SEIS is the only seismometer on the planet, observations can't be as precise as those from the network of seismometers on Earth, but one is better than none. Now scientists have direct data from Mars that challenge the previous two-layer (mantle and core) interior model.

In fact, the existing interior models have had to be updated following the analysis of a rare impact late in the third year of *InSight's* data collection. Seismic waves from a meteorite strike on the far side of the planet traveled deep into the mantle and reached SEIS later than expected (see figure 1). In October 2023 two independent research teams, led by Henri Samuel and Amir Khan, used the data from the event to conclude that Mars's mantle isn't homogenous: It is stratified into silicate layers with distinct compositions and states of matter—that is, the mantle is divided into solid and molten layers. Those layers create boundaries in the seismic properties—density and seismic wave speeds—that alter the path of seismic waves traveling through the planet. Each team used different methods to reach the same conclusion,[1,2] lending credibility to the existence of a molten mantle layer.

Identifying anomalies

Samuel, a CNRS research scientist at the Paris Institute of Planetary Physics and Paris Cité University, joined the *InSight* team in 2017, before the May 2018 launch. He had been looking at Mars from a geodynamics perspective. Existing models of the planet's interior structure, which assumed a homogeneous mantle in the present day, didn't match his understanding of its formation. During its early formation, Mars, like Earth, was enveloped in a magma ocean. Metals and silicates then separated, with the heavier metals sinking into the core and the lighter silicates rising to form the mantle layer. When the planet cooled, the different components in the solidifying silicate magma ocean would have stratified because they had different solubilities in solid or liquid silicate phases.

Based on that stratification of different materials, Samuel and his collaborators expected Mars to have a heterogeneous interior mantle, not a homogeneous one. But existing models assumed that present-day Mars had settled into a homogeneous mantle. "I didn't see any reason for that," Samuel says. "So I wanted to explore these other possibilities." In early 2021 Samuel and colleagues proposed that the Martian mantle had a bottom molten layer that hadn't cooled to a solid, and they made predictions about which observations would support that conclusion.[3] The researchers hoped that the *InSight* mission would allow them to investigate the interior structure and test the hypothesis.

But the early data from *InSight* weren't sufficient to test the idea. For most of the mission, the SEIS instrument was detecting only events near it, and quiet ones at that. Samuel needed seismic waves originating far from *InSight*. Only those waves would penetrate deep enough to traverse the deepest regions of the mantle, where a liquid layer would be, on their way to the seismometer.

Khan, a senior scientist at the Institute of Geochemistry and Petrology at ETH Zürich, focuses on understanding the Martian interior from a combined seismic, mineral-physics, and cosmochemical standpoint. He has been working on the *InSight* team since 2013. In 2021 he coauthored a series of papers based on the *InSight* data obtained to date.[4] Among the results was the calculated average density of the core—based on the volume of the core and the total mass of Mars—which turned out to be surprisingly low.

But the volume was derived from seismic waves that had reflected off an internal solid–liquid boundary deep within the planet. The reflected waves could provide only the radius of what the majority of the *InSight* team, at the time, assumed to be the core. "That's what limited our point of view back then," Khan says. To understand the properties of what was within the assumed core radius, he also needed data from seismic waves traveling through that region.

Existing data and models indicated that Mars's core, similar to Earth's, was primarily iron and nickel. The results for the core's average density, however, implied that it contained an unexpectedly high abundance of light elements—chiefly sulfur, carbon, oxygen, and hydrogen. That didn't make sense to Khan and his collaborators for two reasons. First, the meteorites from which the early terrestrial planets are thought to be made up didn't have the requisite elemental distribution: They didn't contain enough light elements. Second, even if those elements were present in sufficient abundance, only a fraction would sink to the core alongside the heavy metal elements; the rest would remain in the silicate mantle.

Fateful impact

Like seismometers on Earth, the SEIS instrument was used to measure two types of waves that pass through the planet's interior. *S* waves are transverse waves that travel only through solids; they reflect off a solid–liquid boundary and can be used to determine the depth of the boundary between the solid mantle and the adjacent liquid layer. *P* waves are faster longitudinal waves, which travel through both solids and liquids.

The difference in arrival times between the two wave types helps researchers pinpoint the location of a marsquake. And for the majority of the mission, the determination of the interior structure of Mars was limited because the seismic events were mostly nearby. But both teams were hoping for diffracted and core-transiting *P* waves coming from the far side of the planet, as depicted in the diagram in figure 1. Waves that traveled past the solid–liquid boundary could support Samuel's heterogeneous hypothesis and provide an answer to the density discrepancy seen by Khan.

In September 2021, on the 1000th Martian day after *InSight* landed, three fragments of a meteor struck the far side of Mars. The impact was observed in two ways. *InSight* recorded both *S* and *P* waves with SEIS, and the exact site of the impact was also detected by NASA's *Mars Reconnaissance Orbiter* (see figure 2), which provided precise location data most other seismic events lacked.

Because the location of the impact was known, the expected difference in arrival time between a *P* wave reflecting once underneath the surface of the planet and a *P* wave diffracted by the solid–liquid boundary could be determined with good accuracy. Using inversion analysis of the seismic data conducted by Mélanie Drilleau, an engineer at ISAE-SUPAÉRO, Samuel's group concluded that the *P* waves moving through or tangential to the core traveled slower than predicted by a purely homogenous model of the interior. There had to be another layer whose seismic properties differed from those of the solid mantle and created an additional boundary that altered the path of the waves and slowed them down. Moreover, at least the largest part of the additional layer had to be at least fully liquid to explain the reflected *S* waves and and to slow down the *P* waves.

Khan, meanwhile, reached out to his colleague Dongyang Huang, an experimental mineral physicist at ETH Zürich, to determine from first principles the makeup of the new layer.[5] Huang created models that simulate various seismic properties, such as the velocity of *P* waves, based on different elemental compositions of Mars's core. Those models were then compared with real SEIS data to constrain the most likely scenario. Khan and colleagues found that the *P*-wave velocity and density of core materials were consistent with *InSight* observations if Mars has a molten layer at the base of the mantle. *S* waves were reflecting off the solid–liquid boundary within the mantle, as shown in figure 1, and not off the mantle–core boundary.

A new molten model

The *InSight* mission has ended, so with no other seismometers on Mars, it is difficult to verify the conclusion. Yet the fact that both groups determined that there is a molten silicate layer is reassuring. The immediate next step is reviewing previous Mars data from *InSight* and other probes in light of the new picture of the interior structure.

"This layer influences the entire evolution of the planet," Samuel says. The presence of a molten layer would have reduced the core's cooling rate while allowing the upper layers to cool faster, thus leading to a thin crust. The temperature evolution of the liquid core, in particular, would influence the generation and duration of Mars's magnetic field. Understanding why the planet's magnetic field weakened to the patchy field we see today is an active research topic among planetary scientists.

Samuel's group further suggests that above the molten silicate layer is another, partly molten layer. The more complex structure would help explain other ongoing mysteries about Mars, such as how a planet with a thick, solid mantle is able to tidally deform in response to the orbit of its inner moon, Phobos.

Jennifer Sieben

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PT

More Africans are pursuing STEM graduate studies in the US

Postgraduation, they balance opportunities abroad with ways to help their home countries.

Armstrong Mbi earned his bachelor's degree in his native Cameroon where, he says, Peace Corps volunteers who had taught him college math and physics inspired him to go abroad to pursue further studies. He applied to schools within driving distance from his brother, who lived in Atlanta and helped him navigate the application process. In 2004 he went to Mississippi State University to pursue a PhD in physics.

Mbi was one of 9622 graduate students in the US from Sub-Saharan Africa that year. Nearly two decades later, there were a record 21 237. Those numbers are from the fall 2023 Open Doors report by the Institute of International Education. The data are not broken down by field, but the report says that "most international scholars" specialize in science, technology, engineering, and mathematics (STEM) fields. At the University of Arizona, according to Kirsten Limesand, vice provost for graduate education and dean of the Graduate College, the number of international students pursuing graduate degrees in STEM rose from 805 in 2014 to 891 in 2023; during that same time, the number of African graduate students in STEM programs at the university jumped from 16 to 50.

Data don't exist for the paths that degree recipients from Africa take after they complete their PhDs abroad. Anecdotally, however, few return to the continent. Still, many try to use their education to help their home country. "The Industrial Revolution left people behind, including my country," says Chibueze Amanchukwu, who is from Nigeria. He earned undergraduate and graduate degrees in the US and is on the engineering faculty at the University of Chicago. "The African continent is playing catch-up. How do we ensure that we are active in the next revolution? My resource is education."

Conduits to international studies

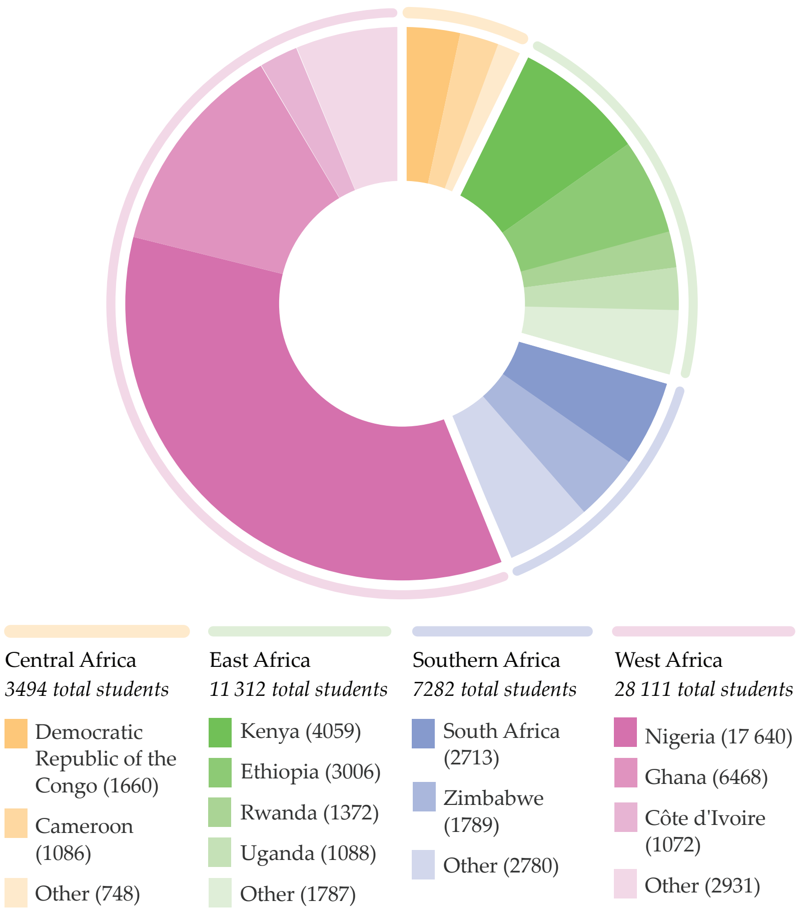
In the past few years, some US-based researchers have taken to recruiting in Africa. "Boise State needed good students," says Jodi Mead, a professor of applied mathematics at Boise State University. By her count, she has brought 15 PhD students to an interdisciplinary computing program there. "It's hard keeping US citizens in the program," she says, "because they can get jobs making more money doing less."

Brian Kyanjo of Uganda was one of Mead's first recruits. They met over Zoom during COVID-19 lockdowns when he took a course she was teaching in his master's program at the African Institute for Mathematical Sciences (AIMS) in Rwanda. "She told me about the computing PhD program at Boise State, and I was convinced," Kyanjo says. It helped that she told him not to worry about the visa

UNIVERSITY OF HOUSTON

GRADUATE STUDENTS FROM AFRICA and elsewhere come to the University of Houston thanks to its close relationship with the Abdus Salam International Centre for Theoretical Physics in Italy. Houston physicist Carlos Ordóñez (third from right) has championed the connection. The students in this 2016 photo are (from left) Emmanuel Epie (Cameroon), Wilder Daza (Colombia), Eyob Kebede Chere (Ethiopia), Ivy Ahiabu (Ghana), Erick Buko (Kenya), and Armindo Samuel Cuamba (Mozambique).

Students in the US from Sub-Saharan Africa in 2022–23
(Includes undergraduate, graduate, nondegree, and optional practical-training students)*



* Based on data from the Institute of International Education's resource Open Doors.

and service fees. "You have to pay $180 for the visa, $100 for applications, $1500 for the flight. No African student has that money," he says. Mead, says Kyanjo, "did something I never thought anyone would ever do: She sent me money just to help me get through the application process. It was from her own pocket."

For her part, Mead, who is currently on rotation as a program director in NSF's division of mathematical sciences, says she learned a lot from Kyanjo. "He said, 'You can offer me a teaching assistantship, but I can't get there. I don't have the money.'" As a result, she says, Boise State started offering international graduate students early access to funds to cover fees and flights. "That is the key," she says.

Solutions to the financial barrier for graduate students are patchwork. Some universities waive application fees. Sometimes campuses spring for a student's visa fees and flights. At the University of Chicago, the Pritzker School of Molecular Engineering provides incoming PhD students with $2500 to help them make the move. Personal loans from advisers-to-be and from mentors at African institutes are also common. Hans-Peter Marshall, a snow scientist at Boise State, has three graduate students from Nigeria. "I lent one of them money after meeting him on Zoom," says Marshall. He was confident that the student would be successful and would pay him back. "I'd done it before with neighbors in the community. They always pay back their loans."

Many of the African applicants to Boise State and other US schools come from AIMS centers. The first was founded in 2003 in South Africa, and others are now in Cameroon, Ghana, Rwanda, and Senegal. At AIMS, faculty from around the world volunteer to teach three-week-long courses for intensive master's programs. About 5% of the roughly 6000 student applicants—from all 54 African countries—are accepted to the standard AIMS program across all five centers each year, says Wilfred Ndifon, chief scientific officer of the AIMS global network and president of the AIMS Research and Innovation Centre, which opened in Rwanda last July. Some 30% of graduates leave Africa to pursue further studies, he adds. AIMS also offers smaller programs, including a master's in artificial intelligence and a PhD in data science. (For more about AIMS and related efforts to strengthen education in Africa, see Physics Today, May 2008, page 25, and January 2011, page 28.)

Micheal Kahangirwe was at Makerere University in Uganda with Kyanjo. Kahangirwe won a scholarship to the ICTP–East African Institute for Fundamental Research in Rwanda, where he earned a master's degree. (The ICTP is the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy.) He is now at the University of Houston working on his PhD in theoretical nuclear physics. "The AIMS and ICTP programs give African students a good education so they can compete to get into good universities in the US," says Kahangirwe.

Since the diploma program at the ICTP began in 1991, 35% of the 341 graduates from Africa have pursued further studies in the US; others have attended universities in Europe, the Middle East, South America, and Africa.

The pipeline of African students to the University of Houston goes back a decade and a half to connections forged between Houston theoretical physicist Carlos Ordóñez and Fernando Quevedo, the ICTP director at the time. Similarly, graduate students from Africa head to Michigan State University because of efforts by Pawel Danielewicz, a nuclear physicist. "We have had 10 in the past 10 years," he says.

Danielewicz has taught at several AIMS centers and says that the students' level of physics preparation tends to be low: "When I teach a graduate course in classical mechanics, it's often at the level of easy undergraduate." By contrast, he says, "the math level is often strong. And AIMS equips students with good coding and language skills." Studying in the US is "such an opportunity for them," says Danielewicz. "They work very hard. They are extremely determined to succeed. And they do."

Brain circulation

Brain drain is a huge problem for Africa, says Kétévi Assamagan, a high-energy


JOSH ENTERKINE

NAHEEM ADEBISI is a graduate student from Nigeria working in the cryosphere geophysics and remote-sensing group at Boise State University. He installs, tests, and—during flights—operates an airborne light detection and radar system for surveying snow depth in the mountains in Idaho.

physicist at Brookhaven National Laboratory who came to the US from Togo in the early 1990s. "The fraction of Africans that stays outside is growing." Often their home country can't provide jobs commensurate with their skills. The ones who do get science jobs in Africa may feel professionally isolated from the international community, and the salaries are small—even if they are good in comparison to other salaries in the same country, Assamagan says. Some countries are politically unstable, "and even a scientist may not be completely free to express opinions."

In Nigeria and Ghana—both among the top 25 countries of origin for international students in the US in 2023, according to the Open Doors report—good jobs for physicists exist, but the competition for them is intense, says Harriet Kumi. After earning her master's degree in physics in Spain, Kumi went home to Ghana. "For a year, I couldn't find work," she says. "The only available jobs were teaching in junior high and high school. That is not what I wanted."

Kumi taught high school for a year and applied to PhD programs. There are opportunities to study in Ghana, she says, "but mostly there is no funding. For me, it was easier to go to Europe." She received a full scholarship and is now working on her PhD in nuclear physics at the University of A Coruña in Spain. "It would be better for their countries for people to go back, she says. "But they need opportunities."

One of AIMS's goals is to raise the level of education—and the economy—in Africa. The master's program emphasizes to students that they should give back to the continent, says Ndifon. Rather than brain drain, he says, "we like to think of brain circulation."

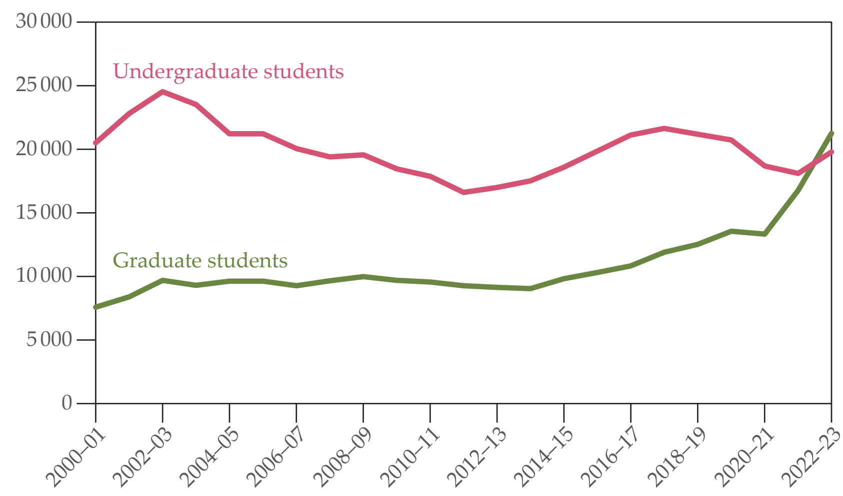
Ndifon, a theoretical biologist originally from Cameroon, earned his PhD at Princeton University; he is now based in Rwanda. "Many more Africans will return if they find jobs they see as dignified and fulfilling," he says. AIMS, with African governments and other partners, is "setting the stage for many more such jobs to be created in Africa. So many of the skill sets that Africa needs are not available here. AIMS is like a portal."

Arthur Musah has been in the US since he left Ghana in 2000 for his undergraduate studies in engineering at MIT. A lot of people from Africa don't go back right away, he says, "but some go later, after they've learned how to run companies, encountered different managerial styles, and built networks, and they can make a mark." Giving back to Africa was part of his motivation in making the film *Brief Tender Light* (see the story on page 22), which follows four African students to and through their MIT undergraduate experiences.

Last summer Amanchukwu piloted a program for senior-level undergraduates in Nigeria to do research projects with the University of Chicago. The COVID-19 pandemic had shown him that students "could do research in virtual environments," he says. "We had 100 applications for five spots." The nine-week projects were mostly computational, for which the students gained access to the university's servers. The two who joined Amanchukwu's group used artificial intelligence, machine learning, and finite-element modeling to accelerate discovery of battery materials. At the end, Amanchukwu met the students in Nigeria, where they presented their results. "The model would work for other countries and other research topics," he says.

In 2010 Assamagan cofounded the African School of Physics. The school meets in different locations across the continent for a few weeks every two years. "We tend to have a curriculum that goes from general physics to more specialized areas in nuclear high-energy physics, astrophysics, materials sciences, and applications," says Assamagan. "We try to tailor the school to what the host country needs." The next school is scheduled to take place in Morocco in July 2024.

More recently, Assamagan says, the



SUB-SAHARAN AFRICA had the highest growth of students in the US of any global region in 2022–23 compared with the year before. The plot shows the numbers of undergraduate and graduate students in the US from Sub-Saharan Africa over time. (Based on data from the Institute of International Education's resource Open Doors.)

school has expanded to host programs for high school teachers and students. In 2019 it launched a mentorship program that brings college students from Africa to Brookhaven to do research. Getting a visa to go to the US or Europe "is a formidable threshold" for Africans, Assamagan says. It seems that "visa-processing authorities at embassies assume the applicants will stay in the country and become illegal immigrants."

As for Mbi, he says that "at some point during my graduate program, I had a crisis of identity. I am going to get a PhD and go back to Cameroon. What will I do there?" Parts of Cameroon are politically unstable, he says. "I heard that one of my undergraduate professors is now in the US driving a taxi." Mbi left Mississippi State with a master's degree and moved to Georgetown University for his physics PhD. He then earned a business degree from Cornell University. He remained in the US and has held several jobs in consulting and investment banking. He is currently a vice president in JP Morgan's global research division. "When I came to the US," he says, "I could solve equations, but I didn't have a good sense of the landscape of physics. I didn't know what I wanted for my career."

"I mourn the brain drain that occurs in my home country," says Mbi. "But I think there is a balance for individual fulfillment: What do I want to do with my life? Where is the best place to do that?"

Toni Feder

Join four African students for their MIT journeys

The students share their academic and personal experiences and impressions.

The film *Brief Tender Light* follows four African students from the time they are awarded spots as undergraduates at MIT through their studies and graduation in 2015 as they learn about a new culture, confront racism and homophobia, and begin to move into careers. They all feel a responsibility toward their home countries. "I want to amass skills, amass knowledge. I want to amass leadership. I want to amass opportunities here, which are all going to be used in Zimbabwe," says Fidelis Chimombe, who is from that country (second from left in photo); the others are, from left, Sante T. Nyambo from Tanzania, Billy Ndengeyingoma from Rwanda, and Philip Abel Adama from Nigeria.

ARTHUR MUSAH

They grapple with how to balance helping their home countries with the opportunities open to them in the US. "At its core, *Brief Tender Light* is about whether youthful idealism can survive the process of growing up," says the engineer-turned-filmmaker Arthur Musah, who moved from Ghana to attend MIT in 2000. *Brief Tender Light* premieres on PBS on 15 January and will be available free for streaming at www.pbs.org and on the PBS app until 14 April 2024.

Toni Feder

Teaching physics with phones: A game changer?

Educators are creating new smartphone apps and designing new experiments for them.

Virtually every high school and college student in high-income countries has at their fingertips a powerful and versatile tool, equipped with all the sensors and visualizations needed to do experiments suitable for an introductory physics course. But most physics educators have yet to catch on to the opportunities that could arise from using smartphones in their labs.

"By far the greatest number of teachers in high school and college are still completely unaware of the potential of these devices," says David Rakestraw, who has spent the past four years at Lawrence Livermore National Laboratory developing hundreds of physics experiments for smartphones and a 3000-page guide to performing them. "It's difficult to get people to recognize new ideas and implement them, particularly because the vast majority of teachers don't know where to find information," he says.

Rakestraw's free curriculum, called Physics with Phones, provides teachers and professors with step-by-step directions plus written quizzes and other instructional material. He discovered smartphone teaching when he took a sabbatical from Lawrence Livermore to teach high school physics for a year. "I realized that the literature and the people working in this area had just scratched the surface of what is possible," he says.

Since as far back as 2012, most smartphones have been equipped with accelerometers, barometers, magnetometers, sound meters, and gyroscopes. In combination with the phones' onboard cameras and GPSs, they are ideal for teaching motion, friction and mechanics, moment of inertia, and magnetic fields, according to Rakestraw and other educators who have used them.

In the past two years, Rakestraw has relentlessly promoted his guide. He estimates he has reached several thousand students in classrooms and presented to around 700 educators at regional workshops and conferences of the American Association of Physics Teachers and the National Science Teaching Association. By the end of his teacher workshops, he says, "every one of their jaws have dropped. They say, 'My gosh, I had no idea you could do that.'"

The two most-used apps for exploiting the sensors for educational purposes are phyphox and Physics Toolbox Sensor Suite. Both are free. Physicists at RWTH Aachen University in Germany developed phyphox, which Rakestraw uses for most of his experiments. Physics Toolbox was developed by Rebecca Vieyra, a former physics teacher, and her husband Chrystian Vieyra Cortés, a software engineer. Most other smartphone sensor apps aren't tailored to education.

Roller coaster physics

Physics Toolbox began after Vieyra took 300 high schoolers on a trip to an amusement park to teach some fun physics. The motions on roller coasters and other rides illustrate phenomena such as free fall and circular motion and the forces they exert on the human body. "We didn't have enough lab instruments for them to strap to themselves, so my husband made an app for me," she says. "We started with a g-force monitor and a linear accelerator and just kept adding." With support from NSF, she and colleagues in 2019 added a feature called Magna AR, a magnetometer with augmented reality that visualizes magnetic fields in 3D (see photo on page 24). In 2022 they added a tool that uses lidar (light detection and ranging) for motion experiments. The tool is available for use only on certain models of iPhones and iPads.

"What came as a surprise to me as a designer was that we created this for high school, yet our tools have been picked up so much at the university level and are used for non-teaching-related research," says Vieyra, who is now at the Office of Academic and Learning Innovation at the University of Colorado Boulder.

No statistics are available on the numbers of teachers and professors who are using smartphones in class. Physics Toolbox has been downloaded 2 million times and averages 24 000 downloads per month. Rakestraw estimates that several hundred high schools and dozens of colleges are now using Physics with Phones experiments. Since it was released in 2020, about 35 000 users have downloaded the curriculum.

ARNESTO BOWMAN/MORGAN STATE UNIVERSITY

MORGAN STATE UNIVERSITY UNDERGRADUATES use their smartphone accelerometers to produce seismocardiograms—recordings of the body vibrations produced by heartbeats. The accuracy of the readings are comparable to traditional electrocardiograms. Using the sensors, doctors were able to detect a previously undiagnosed heart condition in David Rakestraw, the Lawrence Livermore National Laboratory scientist who developed the experiment.

VIEYRA SOFTWARE

3D VISUALIZATION of the magnetic field around a stack of ceramic magnets was produced by the Magna AR mode of Physics Toolbox. The app combines a smartphone's magnetometer with an augmented-reality framework. Each vector represents both the relative magnetic field strength at the point of data collection as the phone was moved in an arc along the side of the stack, which acts as a bar magnet, and a portion of the full field around it. The vectors pointing away from the magnet indicate that the top is the north magnetic pole.

Ann-Marie Pendrill, a retired high school physics teacher in Sweden, volunteered to survey the country's high school teachers for Physics Today. Of the 127 Swedish physics teachers who responded, 27% said they had used phyphox or Physics Toolbox in their classes, while 28% had never used smartphones in their classes at all. Others reported using single smartphone sensors and apps for such things as producing slow-motion videos or measuring audio levels.

"People tend to use what they have been using, and a lot of people don't know" about the teaching apps, Pendrill says.

Arturo Martí, a professor at the University of the Republic in Uruguay, estimates that 10–20% of secondary school students in his country are being taught physics using smartphones. He says that when he tries to educate teachers about the phones' capabilities, "they will say, 'This is very interesting and we can use the tools.' But most of the time, they don't do that." Many complain that they don't have enough phones for their classes.

Nicole Murawski, a former high school physics teacher in Michigan who more recently has worked to familiarize teachers with Physics Toolbox, surveyed US physics teachers on X, formerly Twitter, also at Physics Today's request. Of the 45 responses she received, half reported using unspecified smartphone apps once or twice a year. Another 20% said that they used them up to twice a month, and 9% reported using them one or two times a week. But 22% said they didn't use them at all.

Precision instruments

Smartphone sensors, many of which are embedded on a single microchip, weren't designed with physics teaching in mind, but they offer remarkable precision. Barometers, for example, can measure air density to three significant figures, says Rakestraw. That enables an exercise app to calculate the number of steps a user has climbed, and it also lets students see how air pressure changes during an elevator ride.

Smartphone accelerometers were sensitive enough to produce a seismocardiogram—a recording of the body vibrations produced by heartbeats—that detected Rakestraw's previously undiagnosed mitral valve prolapse. The physicians treating him were taken aback by the accuracy of the reading, he says, which was confirmed with an electrocardiogram. The Physics with Phones heartbeat experiment was particularly exciting to students in Elissa Levy's high school physics class at Thomas Jefferson High School for Science and Technology in northern Virginia; Levy says she has fallen "hook, line, and sinker" for Physics with Phones.

"If you have an accelerometer in the classroom, you have to import the data to some program, and everybody has to then analyze it," says Levy. With smartphone apps, "you just press a button, slide your phone down a ramp, and there's your graph to analyze." The data can be exported to a spreadsheet for analysis, which gives students the opportunity to brush up on their spreadsheet skills.

Using cell phones, schools and community colleges can access laboratory equipment that historically has been affordable only for wealthier schools. Many schools don't have any lab equipment at all, says Vieyra, but even well-equipped schools are unlikely to have some instruments, like gyroscopes, found on phones. Rakestraw notes that all the experiments in the Physics with Phones handbook can be done with only a handful of supporting items—string, rubber bands, golf balls, and such—none costing more than $1.

"Our students are less well-off than those going to Princeton, but everyone has a cell phone," says Douglas Singleton, who teaches physics at Fresno State, which is part of the California State University system. Lab equipment can be expensive; plastic collision cars, for example, can cost $150, he says. "If our students have a device in hand that takes better data and can be applied to a wide range of things, then let's go with that." He adds that students seem more engaged in learning with their phones. "I've come across students after labs, and they still have phyphox on their phones and are playing around with it. That's great."

The physics faculty at Fresno State is in the process of converting some of the 12 lab sections in the introductory course to Physics with Phones. "The material Rakestraw has for any given lab is enormous, so we have to pare it down to fit into the three hours we have for student labs," Singleton says.

A game changer

Those educators who are enthusiastic about smartphones say they don't plan to use them for all their labs. Rakestraw says he wouldn't expect them to. "Nobody develops a complete high school curriculum for physics, because no physics teachers want that. They are more independent; they all have different things they want to emphasize," he says.

Duke University professor Berndt Mueller sees Physics with Phones as a supplement to the well-equipped labs of research universities. He has adapted several of his labs to phones in his introduc-

Smartphones: Powerful sensors and interface

DAVID RAKESTRAW/LLNL

- Three-axis accelerometer
- Three-axis gyroscope
- Three-axis magnetometer
- Pressure transducer
- Light sensor
- Microphones and speakers
- GPS
- High-resolution video camera
- Lidar sensor system
- Multiple antennas for microwave detection
- High-precision timer
- Fast data processing and analysis
- High-resolution graphical interface with touch screen
- Bluetooth- and Wi-Fi-enabled data collection and data transfer

tory course. "In the spirit of new insights into pedagogy, we try to empower students to explore things on their own," he says. Rather than "following a cookie recipe" using university-provided equipment, students are able to explore on their own with phones. "This fits well into how we feel physics should be taught," he says. Still, it won't replace all the labs in his course. "Obviously, specialized equipment has advantages. And supervised experiments also have advantages. You get to the end quicker than if you do it on your own."

"There are settings in which this is a game changer," Mueller says. "It allows students in any environment to do experiments, and they have the instruments with them all the time."

Martí, a prolific author of papers on smartphone physics teaching, says he uses phones in 20–25% of his lab courses and isn't likely to increase that percentage. He says he will continue to use dedicated instruments for teaching other labs.

The available information on how high school students respond to smartphone physics teaching methods is largely anecdotal. Levy says her students "think it's awesome. They have it in the palm of their hand, and they can all take data. There's a lot of direct activity you can get when you don't have to share one device."

A 2018 study by Katrin Hochberg of the Technical University of Kaiserslautern in Germany and colleagues found that high school students who were less interested in an experiment involving pendulums at the beginning of the study profited from the implementation of cellphone teaching. A 2022 paper by E. A. Maldonado and colleagues at the Francisco de Paula Santander University in Colombia found smartphone use in high school experiments on free-fall movement led to increased student participation and motivation.

In conference proceedings published last year, Vieyras and colleagues compared the achievement and enjoyment levels of undergraduates who learned about motion using Physics Toolbox's lidar component with those of students who used commercial lab hardware. Vieyra says the results showed that students "get way more excited when they can use their own devices or some device assigned to them."

Yet Vieyra is reluctant to claim that smartphones will improve student performance. "It's not just technology; it's the pedagogical approach," Vieyra says. "Comparing a traditional lecture-based teacher and one who engages students in inquiry, you will always see better learning, whether the active learning uses technology or not."

Jay Nolt, a Duke premed junior enrolled in Mueller's class, says she thought a Physics with Phones activity on magnetic fields was one of the best labs in the course. "I thought it was a lot more engaging, and I talked with my teammates more than I did in regular labs," she says. "We were arguing about the theory, and I think I learned a lot more deeply."

But Nolt, who professes she loves physics, thinks she could be an outlier among her classmates, all of whom are taking the course as a premed requirement. Many weren't happy with the additional time the smartphone experiment required, she says. A second experiment using phones took less time, and she didn't hear similar complaints from her classmates.

David Kramer PT

ALEXEY STIOP/SHUTTERSTOCK.COM

Developing TRUSTWORTHY AI for weather and climate

Amy McGovern directs the NSF AI Institute for Research on Trustworthy AI in Weather, Climate, and Coastal Oceanography (AI2ES) and is a professor in computer science and meteorology at the University of Oklahoma in Norman. **Philippe Tissot** coleads the coastal oceanography team at AI2ES and is the chair for coastal artificial intelligence at Texas A&M University–Corpus Christi. **Ann Bostrom** coleads the risk communication team at AI2ES and is an environmental policy professor at the University of Washington in Seattle.

Amy McGovern, Philippe Tissot, and Ann Bostrom

By improving the prediction, understanding, and communication of powerful events in the atmosphere and ocean, artificial intelligence can revolutionize how communities respond to climate change.

The year is 2028 and the weather continues to produce climate-induced extremes, but something has changed. Your phone is now giving you early, accurate warnings to help you prepare.

Major heat wave hitting the SW United States in 3 weeks. Be prepared for an extended period of extreme temperatures and higher humidity than usual.

Warning: Baseball-sized hail and strong winds from the north are extremely likely to hit your house in approximately 20 minutes. Move belongings inside, and stay away from any north-facing windows.

Extreme cold temperatures are arriving in your area in 3 days and will last for at least 4 days. Prepare now to ensure your pipes do not freeze, and be ready for potentially extended periods of electrical outages.

Imagine that high-impact weather phenomena, such as those described above, are forecast with sufficiently advanced warning and precision that humankind is able to significantly mitigate the effects of such events globally. Furthermore, the predictions are known to be trustworthy, so individuals and local and state governments can act immediately to save lives and property.

Such a scenario is not just a vision: It may be a reality in a few years. As the climate changes, weather extremes are affecting species and ecosystems around the globe—and are becoming more extreme (see the article by Michael Wehner, Physics Today, September 2023, page 40). At the same time, recent developments in artificial intelligence (AI) and machine learning (ML) are showing how that vision might be realized.

AI offers multiple methods for handling large quantities of data, helping automate processes, and providing information to human decision makers.[1] Traditional AI methods have been used in environmental sciences for years.[2] Such methods include statistical techniques, such as linear regression, and basic object-grouping methods, such as clustering. Both have a history in environmental-science dating back several decades.[3] A little over a decade ago, weather and climate phenomena began to be understood with more-modern AI techniques, including decision trees—basically flowcharts created by an algorithm rather than constructed by hand—and groups of trees known as random forests.

ML, a subset of AI, focuses on methods that use data to learn and adapt so that they're

SEA TURTLES were rescued off the coast of Texas by volunteers in February 2022 **(left)** and January 2018 **(right)** after the successful prediction of a cold-stunning weather event by an artificial-intelligence-based forecasting model. After measurements of the turtles were taken, they were transported to a rehabilitation facility. (Courtesy of AI2ES.)

generalizable to novel situations. When AI is discussed in the news, it is most often referring to a specific form of ML called deep learning,[4] which has become popular lately. The key changes facilitating the explosion of deep learning have been the creation of innovative ways to handle spatial and temporal dependencies in the data and corresponding hardware improvements, which have made it possible for neural networks, a type of deep learning, to be trained with millions of parameters.

Deep learning has revolutionized the field of AI across various applications, including language translation, game theory, and image recognition (see, for example, the article by Sankar Das Sarma, Dong-Ling Deng, and Lu-Ming Duan, Physics Today, March 2019, page 48). AI methods can do the same for weather and climate predictions too (see reference 5 and Physics Today, May 2019, page 32). For example, multiple recent papers have introduced global weather-forecasting systems based entirely on AI methods. Although those systems need to be trained by traditional numerical weather-prediction models, their predictions are made solely through a deep-learning algorithm and do not depend on physics-based equations.[6]

Despite the long development history of AI methods for predicting weather and climate events, few have been implemented operationally by NOAA and private industry. Early operational AI models were based on relatively simple architectures, such as tree-based designs that can be read by humans. Several new startup companies and larger, established companies, however, are focused on applying more complex AI methods to commercial weather-prediction products. NOAA has also recently begun to deploy AI methods for targeted applications. With all the changes, it is critical that AI methods are beneficial to society, that they can be gauged by their users for their applicability, and that their predictions can be trusted.

Developing and deploying trustworthy AI requires a diverse multidisciplinary research team. The team at the NSF AI Institute for Research on Trustworthy AI in Weather, Climate, and Coastal Oceanography (AI2ES), for which the three of us work, consists of AI developers, social scientists, atmospheric and ocean scientists, and end users. AI2ES is rapidly developing new AI methods that will enable us to improve our scientific understanding and prediction of high-impact weather and climate phenomena, user trust in AI products, and our communication of AI's risks.[7]

Developing trustworthy AI

The diagram on page 29 outlines how the different pieces of AI2ES work together to create trustworthy AI. Traditional AI work is often done by only computer-science researchers, but our synergistic team is made up of researchers in AI, atmospheric science, coastal oceanography, and risk communication. Our goal is to ensure that we meet the needs of our end users—primarily forecasters and emergency managers—and that we understand what it means for AI to be trustworthy.

In any risky situation, successfully communicating and managing risk depends on the trust between those involved.[8] When applying AI methods to climate and extreme-weather forecasting, the uncertainties of AI need to be added to the uncertainties of the environmental predictions. The compounding uncertainties raise the stakes for effectively communicating the risks and make trust even more critical. When trust in AI is low, AI-based forecasts and warnings may be ignored or misconstrued. AI, therefore, needs to be both trusted and trustworthy to be used in various high-risk situations.

Trust is usually enhanced by relevant evidence of competence and reliability,[9] but trust in an AI model is also contingent on people believing that the model aligns with their own interests. Biased or poor-quality training data can lead to biased or more-uncertain AI forecasts, which have the potential to harm those whose actions depend on the forecasts.

Models in Earth sciences are used for many purposes. Some examples at AI2ES include predicting freezes for various environmental-management purposes, protecting endangered species, and forecasting and warning for severe convective storms to protect people and save lives. Risk attitudes and trust are known to vary by the nature of the decision and the decision context[10]—who controls the decision making, for example, and how catastrophic the consequences might be—and by the attributes of the modeling system and modeling context.[11] For those reasons, understanding the nature of trust and developing trustworthy AI for Earth sciences requires codeveloping it with end users. For applications where AI can affect vulnerable or large populations, it's particularly important that AI developers working with end users employ a convergence approach—that is, have experts in the environmental, decision, and AI disciplines work together closely on specific, compelling problems.

AI2ES is developing and testing explainable AI methods to help describe to end users how AI models function. Existing physics-based prediction models have the advantage of being driven by the underlying physics of the problem; one can numerically represent the Navier–Stokes equations, for example. But because AI is unconstrained by the laws of physics, it could come up with a solution that violates those laws. Providing end users with different methods to understand what the AI model has learned may improve trust, and we are interviewing end users to understand the efficacy of those methods.

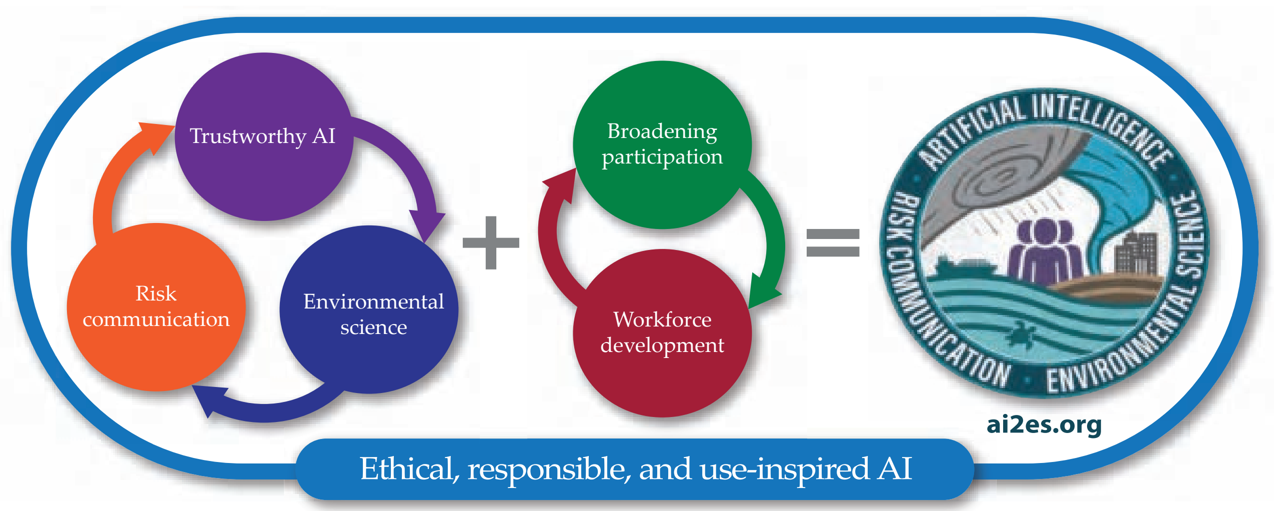
Trust, however, is contextual and subjective, and trust in AI models for weather and climate depends on a number of additional factors beyond peering inside the AI model. Those factors include having experience with the model over time, documenting performance and lack of bias across a range of extreme events for which the models are designed, and working with end users to ensure that their needs are met.

Saving sea turtles

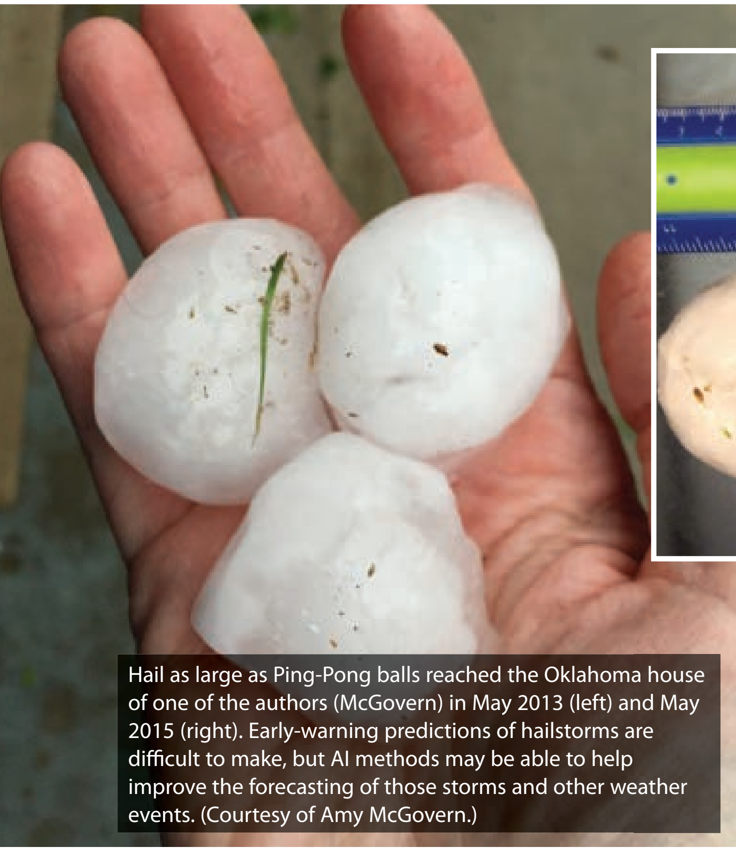
When strong cold fronts, such as the 2021 winter storm dubbed Uri, reach the southeast US, the temperatures of bays, lagunas, and other shallow bodies of water cool down rapidly. Below certain water temperature thresholds,[12] fish and endangered sea turtles become lethargic, or cold stunned, and most perish if they're not rescued. A community-wide effort for the Texas coast has grown since the mid 2000s to prepare for and mitigate the events. The program was updated following Uri, during which a record 13 000-plus sea turtles became cold stunned. Volunteers and employees of local, state, and federal agencies collect cold-stunned sea turtles along the shores or in bodies of water, and barge operators voluntarily interrupt their navigation through those waters. As climate change increases the frequency of extreme events, those types of large-scale organized human interventions will arguably need to become more frequent and more urgent if increasingly endangered species and fragile ecosystems are to be preserved.

To coordinate the rescue of cold-stunned turtles, a team needs real-time predictions of key environmental parameters, such as localized water temperature. When AI has access to time series of parameters from past extreme events, it is particularly well suited to develop targeted operational models, such as one for predicting when a cold-stunning event will happen. AI can take advantage of big, diverse data, such as gridded numerical weather predictions, satellite imagery, and ground-sensor readings.

Although the calibration of AI models can be lengthy, and care must be taken to maximize and test generalization, operational computations are fast once the information is available, particularly when done for just a few locations. The operational cold-stunning model is a type of neural network and has been used since the late 2000s. The first advisory and voluntary navigation interruption took place 8–10 January 2010 with a pre-



THE COMPREHENSIVE APPROACH created by AI2ES, the NSF AI Institute for Research on Trustworthy AI in Weather, Climate, and Coastal Oceanography. (Courtesy of AI2ES.)




Hail as large as Ping-Pong balls reached the Oklahoma house of one of the authors (McGovern) in May 2013 (left) and May 2015 (right). Early-warning predictions of hailstorms are difficult to make, but AI methods may be able to help improve the forecasting of those storms and other weather events. (Courtesy of Amy McGovern.)

diction lead time of 48 hours. The system has been used several times since, including during the past three winters, with prediction lead times extended to 120 hours. The model is an essential decision tool that local, state, and federal agency representatives use when discussing with the private sector the optimal timing of activity interruptions in Texas's Laguna Madre. The specifically designed AI model provides the long lead time critical for redirecting cargo, contacting volunteers, and carrying out other actions.

The sea-turtle program brings the possibility to test how and why the trust in its AI model came about. The research team and end users are further developing AI ensemble models to quantify uncertainties around the predicted timing of the cold stunnings. An events' end is particularly challenging to predict with a longer lead time.

As the frequency of extreme events increases, sea levels rise, and other climate-driven challenges develop, even small flooding events will have large effects. So decision makers will have to start prioritizing and preparing for a broad range of emergency events beyond the largest ones, such as hurricanes, for which state and federal resources are deployed to assist local responders. Results are demonstrating that AI is a well-suited methodology to take advantage of large, diverse data sets and model the nonlinear processes of coastal zones and other environmental systems. Other coastal environmental models developed by AI2ES researchers include predictions of coastal fog,[13] coastal inundation, harmful algal blooms, eddy loop currents in the Gulf of Mexico, and compound flooding.

Severe storms

Thunderstorms worldwide produce various dangerous hazards: strong wind, lightning, hail, and tornadoes—all of which cause significant loss of life and property. Of the billion-dollar weather and climate disasters counted by NOAA every year, thunderstorms account for the majority of the cleanup cost. AI2ES is currently creating novel AI approaches to improve the prediction and understanding of such hazards.

One such example is predicting the initiation of thunderstorms up to an hour before they begin. Even 30 minutes of trustworthy warnings will save lives and property. Airplanes could be rerouted, boats could be brought back to shore and sheltered, and event planners could safely evacuate large outdoor events to avoid disasters, such as the hailstorm that hit Red Rocks Amphitheatre in Morrison, Colorado, in June and injured 80–90 people.

AI2ES's approach to modeling convective storms is codeveloped with researchers in NOAA's National Severe Storms Laboratory. Our work builds on NOAA's warn-on-forecast system (WoFS).[14] It is a numerical weather-prediction system that is run in real time at a high resolution over areas of the US where the Storm Prediction Center expects a higher probability of severe storms. AI2ES developed an AI postprocessing system that uses numerical weather-prediction models and current observations and outputs a real-time prediction of where storms are most likely to occur in the next 30 minutes. To help ensure that the system is trustworthy, AI2ES and NOAA will continue to develop it at NOAA's Hazardous Weather Testbed, a unique facility that allows forecasters and emergency managers to try out new technologies during severe weather events and to provide feedback to the developers.

AI2ES is also working to improve the understanding and prediction of tornadoes and hail. They are small-scale phenomena that are challenging to predict, especially on a short time scale and with high spatial precision, with current operational weather models. One of our most recent methods is codeveloped with NOAA researchers working on the WoFS. Our focus is on improving the nowcasting of severe hail events, which predicts such events at high resolution spatially and within an hour of their arrival. The WoFS runs in real time, but because of the computational complexity of the model, which ingests all the current observations, there is about a 15- to 30-minute lag between the observations and the system's predictions. We developed an AI prediction system that uses deep learning to combine WoFS predictions with data from the National Light-

ning Detection Network, operated by Vaisala,[15] and we demonstrated a significant improvement in the accuracy of short-term hail prediction.

Ethical, responsible AI

An integral part of trustworthy AI is ensuring that it is developed ethically and responsibly. If not, AI for environmental sciences can go wrong in numerous ways.[16] Extreme events tend to disproportionately harm areas with fewer resources and places with histories of systematic discrimination. It is critical that society ensures that AI is not deployed in any manner that will perpetuate environmental or climate injustices. That way, society as a whole can be more resilient to climate change.

Another potential issue with AI for weather prediction is bias, which affects all aspects of the AI training process. In recent work, we have developed a categorization of bias in AI for Earth sciences by breaking it into four main categories, each of which influences the others.[17]

- **Systemic and structural biases** include institutional and historical biases that can influence the choices of data that are made available, the labels on the data used for training AI, and other aspects of AI model development and use. For example, we demonstrated that tropical-cyclone initiation prediction is more likely to occur after sunrise than before because of institutional practices around examining the visible satellite imagery.
- **Data bias** can occur because of the data selected to train the models and the processing techniques used to prepare the data for training. Those choices can result in data that are not representative of the intended populations, areas, or events being modeled. Once the data are prepared and the AI model trained, biases can be present in the validation of the model. Humans must choose which score they will use to validate the model and which cases will be used as a case study. The choices can be affected by human judgment and decision biases, such as confirmation bias.[18]
- **Statistical and model biases** can affect the actual model that is trained and can be strongly affected by human biases. For example, human programmers must choose the methods that they will use to evaluate the model.
- **Human biases** are present throughout AI methods, from data selection to the choice of model, but they are also present in the deployment and use of the model. End users, such as forecasters and emergency managers, for example, may have information overload or may need to make split-second decisions, which can bias their use of AI.

Three of the perhaps most common ethical theories are applicable to AI for the environmental sciences: consequentialism, which judges the morality of an action by its consequences, such as through a benefit–cost analysis; deontology, which judges whether an act is ethical by how the act conforms to duties or moral principles, such as the imperative to be honest; and virtue ethics, which argues that a "right" action is important to achieve human well-being. Protecting the most vulnerable might not always pass a benefit–cost rule, but deontological and virtue ethics could require it, making it imperative.

But even to understand how AI models might affect specific decisions or users in particular circumstances generally requires an insider perspective, achievable only through developing AI with the people likely to be affected. Many of those concerns and needs can be addressed, and trustworthy AI can be developed by early and continued codevelopment of AI models with direct representation; meaningful, ongoing participation of likely end-user communities; and communication throughout the development process with risk-communication experts. But such capabilities require organizational intent from the teams developing the AI models.

The future of trustworthy AI

Given the current exponential growth of AI in the sciences, society stands at the cusp of major developments in AI for science and society in general. New methods could be developed and deployed with a swiftness that was not possible even a few years ago. That gives us an unprecedented opportunity to shape the process of how AI models are developed to fully benefit society and to address environmental and climate-justice issues. The process, however, must ensure that the models are ethical, responsible, and deserving of trust if society is to realize the full benefits of AI.

To achieve such goals, and to minimize problems during the release of new technology, more comprehensive processes and development teams must be engaged. Funding from federal agencies, private-sector entities, and other places must be structured to reflect those needs. Codevelopment of AI requires funding that allows for and encourages the development of multidisciplinary teams committed to working with end users. The benefits include acting ethically, avoiding large disparities, increasing resilience to climate change, and broadening the viewpoints, knowledge, and values represented on the modeling teams.

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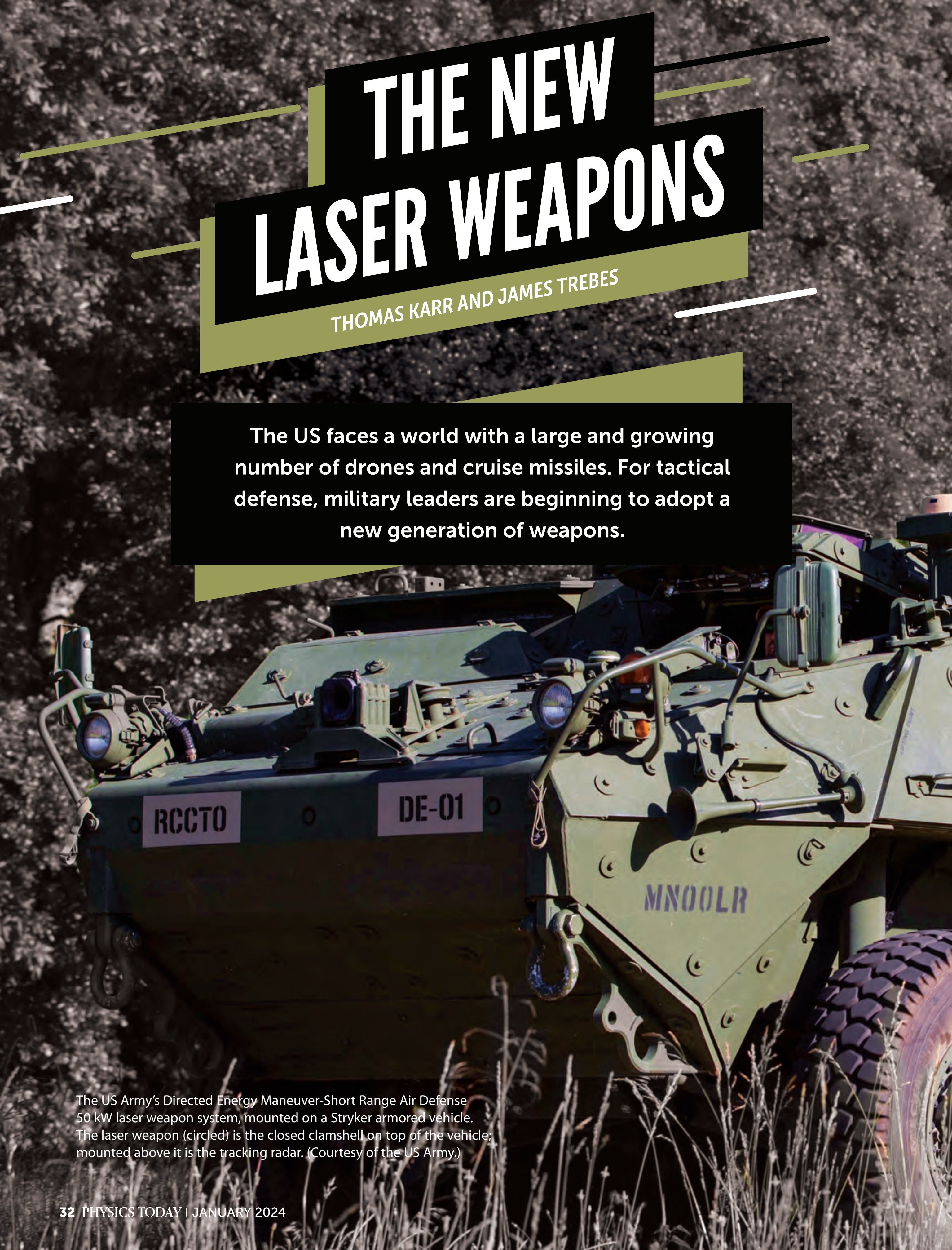
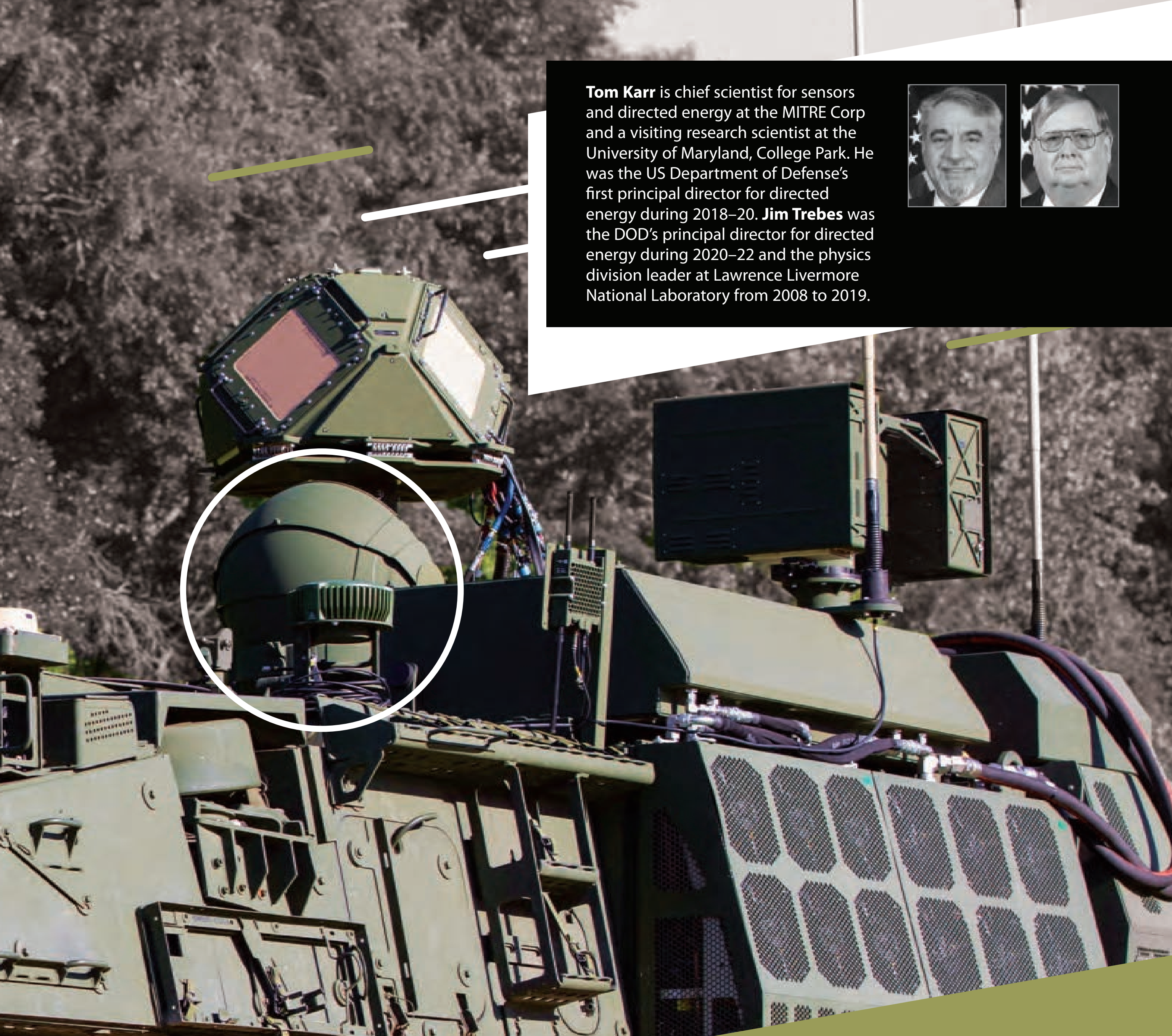
THE NEW LASER WEAPONS

THOMAS KARR AND JAMES TREBES

The US faces a world with a large and growing number of drones and cruise missiles. For tactical defense, military leaders are beginning to adopt a new generation of weapons.



The US Army's Directed Energy Maneuver-Short Range Air Defense 50 kW laser weapon system, mounted on a Stryker armored vehicle. The laser weapon (circled) is the closed clamshell on top of the vehicle; mounted above it is the tracking radar. (Courtesy of the US Army.)



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The US military defines a directed-energy weapon (DEW) as a "device that affects a target by focusing onto it a beam of electromagnetic energy or atomic particles." The focus of the military's efforts is on high-energy lasers (HELs) and high-power microwaves (HPMs). HELs include both pulsed and continuous-wave (CW) devices, and their emissions span a broad spectral range—from long-wave IR down to x rays or even gamma rays. HPM devices, by contrast, are pulsed RF beams, whose emission may extend up to the millimeter-wave or higher frequency.

DEWs recently existed only in science fiction, commonly seen in the *Star Wars* movies and in the *Star Trek* television series. Despite the excitement among developers and many billions of dollars in military funding over six decades, lasers and other directed-energy devices were not common operational weapons. Indeed, developers of traditional kinetic-energy weapons (KEWs)—guns, bombs, and missiles, for instance—have jokingly said that DEWs are "the weapons of tomorrow, and always will be." But because of recent technical advances and changes in military conditions, they are currently getting a serious reappraisal by military planners, and the US and several other nations are putting them in the field.

The technical advances have led to compact solid-state HELs that are scalable to high power, and the changes in military conditions include an exponential increase in offensive threats that cannot be fully addressed by defensive KEWs alone. Today,

Box 1. High-power microwave technology

Today's high-power microwave (HPM) systems use both vacuum-tube and solid-state microwave-generation technology and operate in single-pulse, multipulse, and continuous-wave modes. Vacuum-tube technology traces its roots back to the original vacuum tubes used for radar in World War II. Today the most mature microwave sources—relativistic magnetrons—reach 5 GW power levels. A wide range of tube types and geometries efficiently produce high power over a broad bandwidth—from ultrahigh frequencies (0.3–3 GHz) up to X-band ones (8–12 GHz).[9]

The use of solid-state phased arrays offer increased flexibility, smaller size and weight, and lower cost, compared with vacuum-tube technologies. Improvements in materials processing and manufacturing have led scientists to produce higher-breakdown-voltage semiconductor materials, such as gallium nitride. Research into microwave sources for weapons is currently quite active. Scientists focus on sources that use solid-state and vacuum-based systems capable of flexible waveforms, wide bandwidth, and high power. They also seek out novel materials that enable high-voltage and high-switching-rate operation.

A target can be attacked with HPMs using two basic methods. The so-called front-door method exploits an antenna on the target to collect the HPM signal and deliver it inside the target, typically to a low-noise amplifier. Enough signal power delivered to the amplifier can damage or destroy it. The back-door method exploits cracks, gaps, and power feeds as pathways that can leak HPM energy into the target, where it can likewise damage or destroy electronic components or subsystems for a mission kill.

An example of a vacuum-tube-based system is the Tactical High-Power Operational Responder (THOR), pictured at top and developed and tested by the US Air Force for counterdrone missions. Its mechanically steered antenna rotates 360°, allowing it to attack any target in its range. Below it is the Stryker Leonidas HPM system, an example of a solid-state system also intended for counterdrone missions and currently under development by the US Army. The flat panel is a gallium nitride transistor phased-array antenna that produces an electronically steered HPM beam. (THOR photo courtesy of the US Air Force; Leonidas photo courtesy of Epirus Inc.)

the US military fields 21 laser weapons whose average power varies from a few watts to 60 kW, and the Department of Defense's High Energy Laser Scaling Initiative (HELSI) has demonstrated three lasers with an average power of 300 kW in three distinct laser architectures.

This article focuses on laser weapons, which are receiving most of the military's DEW funding. The US and other countries are also developing and testing HPM weapons, but many details are classified, and little information is publicly available. For a summary of the technology, see box 1.

Killing the target

Against a target, a DEW can cause a hard kill—the target's physical destruction—or a soft kill, a mission kill, or a mission defeat, any of which degrades the target enough to render it unable to complete its mission. Imagine a hard kill as a wing being blown off an aircraft, for instance. To be considered a valuable tool, a DEW must also satisfy practical operational constraints, such as cost, operational feasibility, and reliability.

The standard metric of HEL-weapon quality is the fraction of power it can transmit at wavelength λ from an aperture of diameter D onto a target at range R in a "spot bucket" of diameter $3\lambda R/D$ (slightly larger than the central Airy spot of a perfect diffraction-limited beam), referred to as the power in the bucket. Its value has direct bearing on the ability to form a lethal spot on a target at range. The best HELs today produce a near-diffraction-limited beam and put roughly ⅔ of their power into the bucket.

The more direct question is, How much energy would be needed for an HEL to destroy a conventional drone or missile? Melting a large enough hole in a cruise missile to destroy whatever mechanism is inside, for instance, would result in a hard kill. Conventional missiles and aircraft are typically made of aluminum, and small drones are usually made of hard plastic, such as polyamide. Ignoring the losses from thermal diffusion, a laser can melt a target's aluminum shell by depositing about 2.8 kJ/cm^3 into the shell, or vaporize it with ~32 kJ/cm^3. The corresponding energy density to melt polyamide is 0.7 kJ/cm^3, and only slightly more to vaporize it.

But the amount of energy a weapon needs to deliver is also affected by distance. A useful HEL weapon could destroy a threat target in a few seconds at a range well outside the threat's lethal zone—what one might call a tactically interesting range. Consider a hypothetical HEL weapon whose 1 μm wavelength emission (a common one for HELs today) through a 0.5 m transmitter aperture is used to attack a threat target at a range of 20 km. The spot bucket on the target would be about 12 cm in diameter and 113 cm^2 in area. The HEL would need to generate about twice the above energy per unit volume to confidently account for losses due to target aspect and reflection, thermal diffusion, and the atmospheric path. Suppose the target's aluminum shell is 1 cm thick. To melt a 12 cm hole, the HEL would have to produce about 550 kJ.

With those weapons and engagement parameters, a 300 kW HEL, today's largest electrical laser, could deposit enough energy to kill the aluminum-shelled target in about 2.5 seconds and the plastic-shelled one in less than a second, preceded by a few seconds of slewing and tracking the target. The US military is very interested in HELs that can destroy targets so quickly. HELs with much lower energies—as little as a few millijoules per pulse—

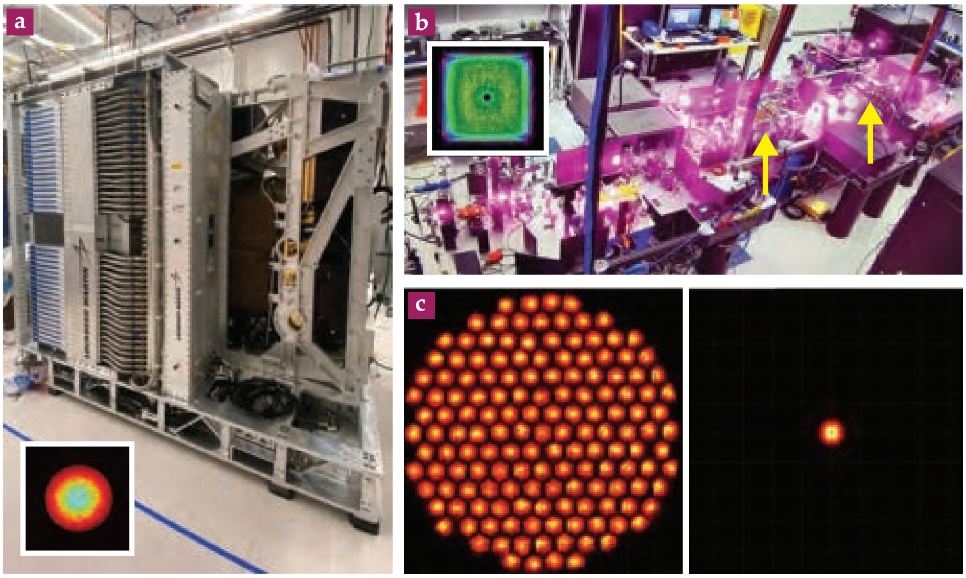


FIGURE 1. HIGH-ENERGY LASERS, produced by the scaling initiative coordinated by the Department of Defense. **(a)** This photograph of Lockheed Martin's 300 kW spectral combined fiber laser shows the edges of module boards (each of which contains a fiber laser), the pump diodes, and the control system. The inset shows the laser's far-field near-Gaussian irradiance pattern. **(b)** General Atomics' 300 kW distributed-gain laser is pictured in operation. Yellow arrows point out the compact laser-gain cells, and the inset shows the output beam's uniform near-field irradiance pattern. **(c)** The near-field (left) and far-field (right) irradiance patterns show the high quality of nLIGHT's 300 kW coherently combined fiber laser. (Photos and images courtesy of and adapted from the Naval Surface Warfare Center Dahlgren Division.)

are able to damage IR sensors, and even lower-power lasers (on the scale of 1 W) can "dazzle" (or blind) those sensors.

In the 1980s and 1990s—the Strategic Defense Initiative, or "Star Wars," era—developers were striving to make weapons capable of killing intercontinental ballistic missiles in their boost phase over thousands of kilometers. At the time, the primary HELs of interest were gas lasers: hydrogen fluoride lasers, deuterium fluoride lasers, and the chemical oxygen–iodine laser, all of which derived their power from chemical reactions. Weapons developers believed they could scale up chemical lasers in power, at least conceptually—the trick was to just use more gas in the gain cell—but they had difficulty building a gas laser that met practical military constraints, had a high average power, and had a high-quality, near-diffraction-limited beam.

During that era, US HELs were heavy, occupied large facilities, and used hazardous materials—all operational drawbacks. Searching for alternate sources, designers studied excimer and free-electron lasers as well. Although excimers never matured into weapon-level devices, the early investment in xenon fluoride, krypton fluoride, and argon fluoride lasers helped excimer lasers become the principal UV light source for semiconductor chip fabrication. In 1987 a study group on the science and technology of DEWs concluded in a report to the American Physical Society that DEW technology of the era fell short of technical requirements for boost-phase strategic missile defense and that there was no realistic prospect of meeting those requirements in any foreseeable time frame.[1]

In the 1990s and 2000s the DOD attempted to develop a megawatt-class chemical oxygen–iodine laser on a Boeing 747 for tactical ballistic-missile defense. The DOD determined its operational role highly questionable, and the program was canceled. Since then, US ballistic-missile defense has focused on kinetic interceptors, and DEW development has focused mainly on tactical military missions requiring shorter range and lower power than strategic missile defense.

The new DEW technologies

In the US, chemically pumped laser weapons are now a thing of the past. The most significant new laser technologies for DEWs in the 21st century are diode-pumped solid-state and gas lasers. Laser diodes are efficient; the best ones convert more than 50% of electrical input power into hundreds of watts of laser output power in a small package. But because they produce light in a tiny interaction region (on the scale of 10 μm^2 on a chip face), their output beams have large divergence and therefore low beam quality.

The laser diodes may interfere with sensors or blind weapons at short range, but they are not hard-kill weapons. Rather, the diode-pumped laser weapons of today are essentially beam-quality cleaners that convert the low-quality pump light into a larger high-power, low-divergence, and near-diffraction-limited laser beam.

In 2004 the Defense Advanced Research Projects Agency invested in scaling up a laser-diode-pumped solid-state crystal laser geometry called the distributed-gain laser.[2] Its geometry passes the beam through many thin crystal sheets in a gain cell pumped by diode light and cooled by liquid flowing between the sheets, and it lases at a wavelength of roughly 1 μm. To increase its power, a designer can add more crystal sheets or chain together several gain cells. In 2015, General Atomics, the contractor for the distributed-gain laser, achieved 100 kW class power—at the time the highest average power ever achieved in an electrically pumped laser.

In the 2000s the commercial laser industry developed high-power CW ytterbium-doped glass-fiber lasers pumped by laser diodes, lasing at a wavelength of about 1 μm. Today multimode fiber lasers boast powers that exceed 20 kW, and such multikilowatt varieties have become common devices for material processing. But multimode lasers are poor candidates for a laser weapon because only a small fraction of their power can be focused into the bucket. Fortunately, the commercial market also produces single-mode Yb-doped fiber lasers. And they have a nearly perfect Gaussian output beam—close to the fiber core's diffraction limit—which makes them an excellent weapon candidate. Single-mode, diode-pumped, large-mode-area fiber lasers today combine that near-diffraction-limited-beam quality with a high electrical-to-optical conversion efficiency with CW power that exceeds 1 kW.

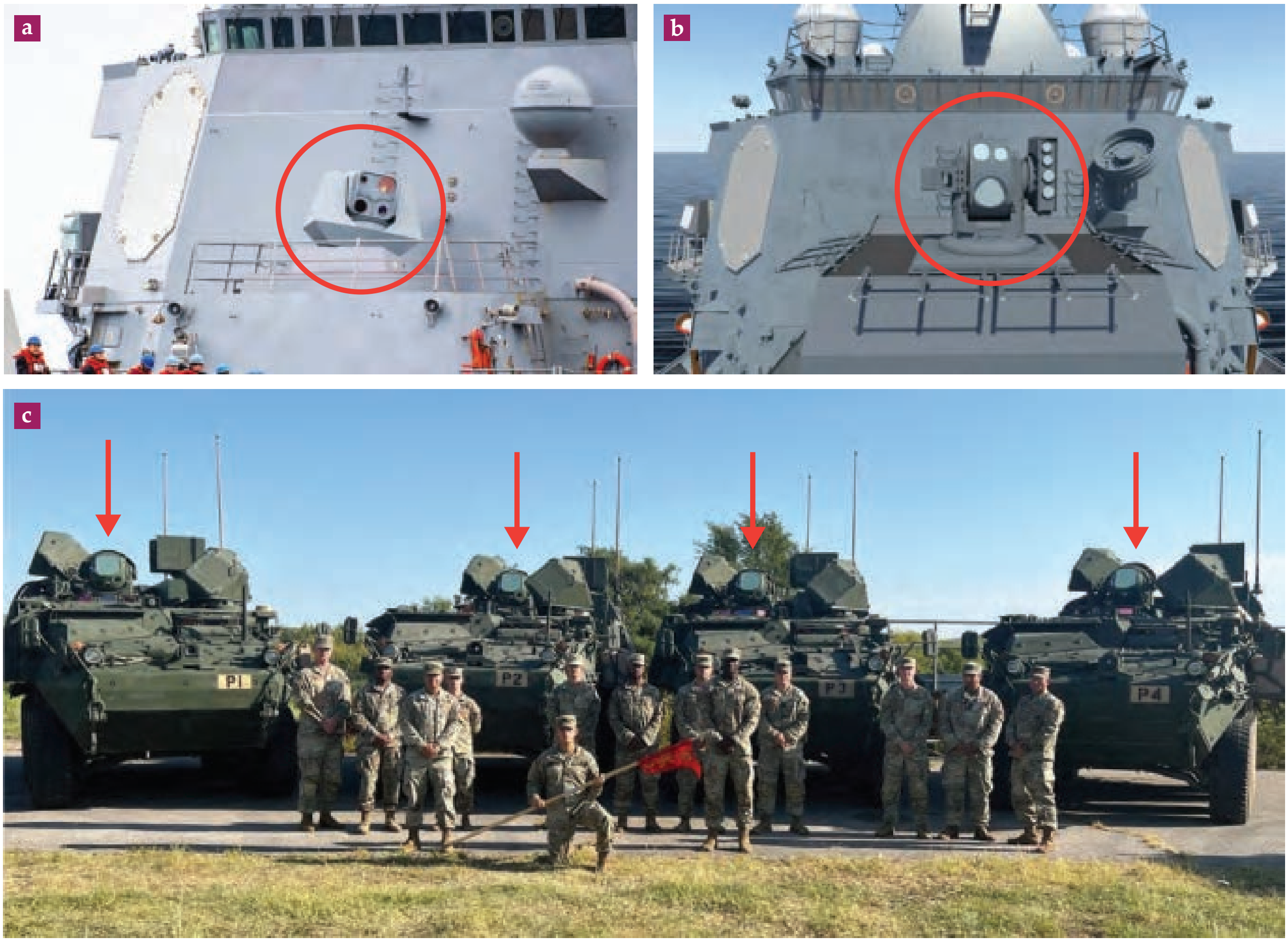


FIGURE 2. MOBILE WEAPONRY. (a) The Optical Dazzler Interdictor, Navy, on the *USS Stockdale*, is designed to blind adversarial IR sensors with a low-power laser beam. Circled are apertures for guiding the beam and tracking targets. (Courtesy of the US Navy/MCSN Elisha Smith.) **(b)** The 60 kW High Energy Laser with Integrated Optical-Dazzler and Surveillance is mounted on the *USS Preble*. Circled are the beam director (the large aperture at the bottom) and other apertures for tracking sensors and illuminating laser beams. (Courtesy of Lockheed Martin.) **(c)** The first platoon of four 50 kW US Army laser weapon systems in Fort Sill, Oklahoma. Red arrows point to each vehicle's laser. (Courtesy of the US Army.)

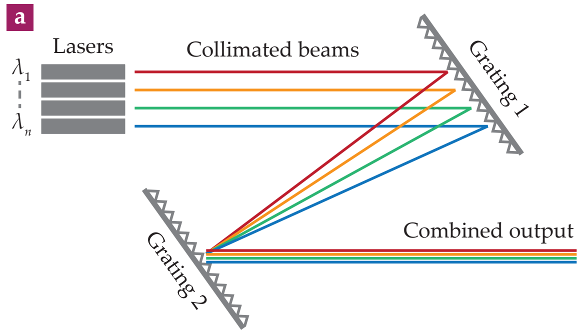
Single-mode fibers can be combined in various ways to produce higher-power CW lasers—for an explanation of various combining schemes, see box 2. Both the spectrally confined fiber and coherently combined fiber architectures are modular systems that can be scaled up with the addition of more fiber-laser units. Most of the laser's pump light is efficiently converted into the high-power signal, and the high peak power needed to drive the diodes is typically delivered by batteries that are recharged at lower power. Waste heat in the diodes and fibers is removed by conduction to water-cooled plates. The spectrally confined fiber, coherently combined fiber, and distributed-gain-laser architectures are solid-state systems, power-scalable, compact, inherently rugged, and suitable for integration into mobile platforms, including surface vehicles, ships, and aircraft.

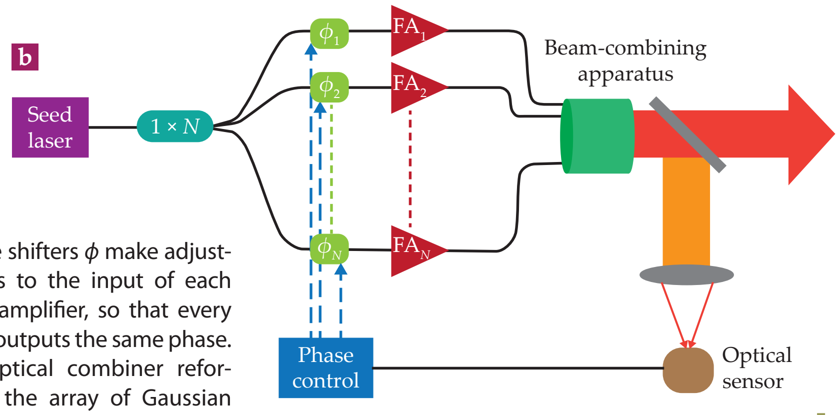
The higher the average power of a DEW, the greater the number of targets it can engage in a given time and the longer the range over which it can engage them. In 2019 that capability prompted the DOD to begin HELSI, which scales up the power of diode-pumped solid-state lasers, reduces their size and weight, and increases their efficiency.

HELSI's first objective was a 300 kW laser with good beam quality and the highest efficiency, lowest size, and lowest weight achievable in the short term. Three contractors—Lockheed Martin, nLIGHT, and General Atomics—proposed three different laser architectures to achieve those milestones, and they did so in 2022. Two representatives, shown in figure 1, are the highest-average-power electrically pumped lasers in the world today. This past year the DOD began the next phase of HELSI, with the goal of extending laser power above 1000 kW to enable DEWs to engage targets more quickly and over a longer range and to reduce laser size and weight to make it fits into a greater variety of military platforms. The DOD plans to demonstrate those lasers in 2026.

Another diode-pumped laser may also scale up as a DEW: the diode-pumped alkali laser.[3] A three-level laser of alkali atoms in a buffer gas, the device uses diode lasers to pump the alkali atoms from the ground to an excited state, the buffer gas moves them to a slightly lower excited state, and they lase on the transition back to the ground state. Researchers can scale the laser up in power by enlarging the gain volume and increasing diode brightness. Maintaining good beam quality and efficiency with increasing power comes with practical challenges. Even so, since

Box 2. Fiber lasers, creatively combined





The spectrally combined fiber laser can be thought of as a prism run backward.[10] Imagine a few fiber lasers, as shown in panel a, each emitting a different wavelength λ. The beams are arrayed in space and directed at diffraction grating 1. They all diffract from the grating at different angles, such that they strike grating 2 at the same point and are diffracted at the same departing angle—the different wavelengths combine, forming a single, collimated beam. As long as the wavelength spread of the fiber lasers is small, all wavelengths focus at the same point on the target.

The coherently combined fiber laser,[11] by contrast, is a phased array of beams, all with the same wavelength from a seed laser, as shown in panel b. For the beams to focus at the same point on the target, they must all have the same phase. But the phase of each fiber output changes with thermal and mechanical fluctuations. The array's coherence is maintained by electronic closed-loop control of the fiber beams. A small amount of power from the array is diverted to a wavefront sensor, which measures the phase of each beam. Phase shifters ϕ make adjustments to the input of each fiber amplifier, so that every fiber outputs the same phase. An optical combiner reformats the array of Gaussian beams into a more uniform irradiance across the output aperture.

The advantage of lasers made by combining fibers is that they can be scaled up in power by increasing the power of each fiber-laser amplifier and by increasing the number of spectral or spatial fiber channels. (panel a courtesy of and adapted from the Air Force Research Laboratory; panel b adapted from C. L. Linslal et al., *ISSS J. Micro Smart Syst.* **11**, 277, 2022.)

2001, various universities, the Air Force Research Laboratory, and Lawrence Livermore National Laboratory have been conducting research that strives to do just that.

The military's evolving role

The US military no longer overmatches its potential adversaries in conventional weapons. It now faces a world with large and growing numbers of sophisticated unmanned air systems, known as drones,[4] and precision-strike cruise and ballistic missiles[5] supported by networks of intelligence, surveillance, and reconnaissance sensors and soon to be enhanced with artificial intelligence. An adversary could attack with conventional weapons in swarms so large that a conventional kinetic defense against them would be prohibitively expensive. DEWs offer military planners a potentially affordable layer of tactical defense against the growing threats.

Electric DEWs are particularly appealing. They can operate for as long as they have electrical power and cooling—that is, they have a "deep magazine" that does not run out of shots. Indeed, their cost per shot is low, needing little more than fuel

FIGURE 3. NON-US SYSTEMS. (a) China's Silent Hunter laser weapon is housed in a transportable container. Apertures contain the high-energy laser, tracking sensors, and illuminating lasers. (Courtesy of the Defense Systems information Analysis Center.) **(b)** Russia's Peresvet "dazzler" weapon is mounted atop a transportable military container. The white beam director rotates about two axes to track a target in space. (Courtesy of the Russian Ministry of Defense, CC BY 4.0 DEED.) **(c)** The Dragonfire laser[8] is the UK's demonstration of a high-energy laser weapon. The larger aperture houses the weapon's beam director, and the smaller aperture houses a tracking sensor. (Courtesy of MBDA.)

to generate electricity, and their effects are scalable, running from reversible interference to catastrophic destruction.

But they have weaknesses as well. A DEW kill is less obvious than one from a KEW, which generally produces flaming wreckage. Also, most DEWs must be guided much more accurately than most KEWs. To produce an effect, the beam from an HEL often must be put within a fraction of a meter of a vulnerable target spot. What's more, the use of DEWs in combat is immature; commanders and troops have little experience with such weapons in the field.

Because the performance of a DEW deteriorates in the presence of bad weather and turbulence, HELs require a relatively clear line of sight to their targets. HPM weapons are less affected by weather because RF beams can propagate (albeit with some loss) through clouds and rain. Nevertheless, their environmental sensitivity does not make DEWs inferior to KEWs. Direct-fire KEWs similarly require a clear line of sight, and most modern indirect-fire KEWs, such as rockets, artillery, missiles, and glide bombs, must be precisely aimed and targeted by sensors. All targeting sensors, including those used to guide KEWs, can be degraded by turbulence, smoke, clouds, and rain, as can the command and control links between sensors and weapons.

US and foreign developments

For decades DEW programs have been limited to demonstration units that operate at sites such as White Sands Missile Range in New Mexico. Today the potential military value of DEWs has motivated several nations to cautiously move them beyond demonstrations and into limited operational deployment. Easy missions that can be done today against soft and slow targets at short range include interfering with intelligence, surveillance, and reconnaissance sensors; destroying drones, artillery and mortar shells, and short-range rockets; and attacking ground vehicles and infrastructure from the air.

The US is currently deploying multiple HEL-weapon systems, some of which are shown in figure 2. The US Navy operates two. The first is the Optical Dazzler Interdictor, Navy—a laser used to dazzle sensors on drones and small boats and interfere with adversaries' intelligence, surveillance, reconnaissance, and targeting systems. Seven such lasers have already been installed on destroyers, and one more is planned. The second is the HEL with Integrated Optical-Dazzler and Surveillance, a 60 kW fiber laser made by Lockheed Martin and mounted on the *USS Preble* in 2023.

Meanwhile, the US Army is moving forward with its Directed Energy Maneuver-Short Range Air Defense systems. With a 50 kW laser mounted on a Stryker armored vehicle, the weapon is intended to defend mobile forces against rockets, artillery, mortars, drones, and helicopters. The army took delivery in 2023 of the first platoon of four systems.[6]

The size and weight of the new 300 kW lasers is appropriate for large platforms, such as ships or trucks and fixed installations. Two development programs use those lasers as part of HELSI: the army's trailer-transportable Indirect Fire Protection Capability-High Energy Laser and the navy's High Energy Laser Counter Anti-Ship Cruise Missile Project.

The US is not alone in its DEW ambitions. Other countries pursuing them include Australia, China, France, Germany, India, Iran, Israel, Japan, Russia, Turkey, and the UK.[7] Little information is available on the efforts of those countries, but a few weapons are shown in figure 3.

Challenges

A DEW is much more than just the directed-energy source. It requires pointing, tracking, beam control, and fire control. Beam control is the technology that delivers the HEL's power to a target. Atmospheric turbulence and thermal blooming can broaden the beam and reduce flux on the target. Adaptive optics is critical to ameliorating those effects.

The DOD in 1991 declassified much of its groundbreaking work on atmospheric optical propagation and adaptive optics (see Physics Today, February 1992, page 17). Leveraging that DOD work, astronomers introduced many innovative adaptive-optics approaches and technologies. The beam directors in future HEL-weapon systems will probably use wavefront sensors and deformable mirrors to guide the laser beam and partially correct for turbulence on its way to a target.

Military services want highly efficient DEWs that can be mounted on mobile platforms with light and small power and cooling units. Chemical bonds are an excellent way to compactly store energy, and chemical lasers efficiently transform that energy into laser light (though with hazardous chemicals and infrastructure too large for military platforms). Although the new electrical lasers have a form well suited for military platforms, they are less efficient, need a separate source of electrical power, and convert at least ⅔ of that into waste heat. As electrical HELs grow in power, they will need higher efficiency and more compact sources of power and methods of cooling.

If the new DEWs realize their potential—a deep magazine, little cost per shot, and simplified logistics—and if designers can overcome DEWs' current weaknesses, they may help fill the growing gap between kinetic offense and defense. That's a big "if." But military planners need new tools to deal with the new threats, and increasingly they are turning to DEWs.

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Tatiana Afanassjewa in Vienna in 1906.
(Courtesy of the Ehrenfest-Afanassjewa family.)

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More is known about him than about her:

Tatiana Ehrenfest-Afanassjewa

Margriet van der Heijden

Tatiana Afanassjewa and Paul Ehrenfest, her husband, shared their love for physics and mathematics, but their ideal of studying and working together went against the zeitgeist.

Albert Einstein sat down at his home in Princeton, New Jersey, in January 1939 to write a letter to Tatiana Afanassjewa, the widow of his close friend Paul Ehrenfest. The roughly six years that had passed since the two had last seen each other—Afanassjewa was in Leiden, the Netherlands—had been hard on Einstein. He had escaped from a Europe that was teetering on the brink of a devastating war, and his stepdaughter Ilse and his wife Elsa had both since passed away. More recently, one of his two grandsons had died as well.

The events had been painful, Einstein wrote, adding that "words like these would normally not cross my lips." He made an exception in his letter to Afanassjewa: "You are especially close to me because of some sort of inner kinship. It is a certain outsider mindset about one's personal life and a sense of being fulfilled with objective matters, here too, away from our contemporaries—that is how we both are."[1]

The words must have comforted Afanassjewa, who had her own losses to bear. In 1933, shortly after Einstein's departure from Germany, her husband died by suicide in the waiting room of Professor Waterink's Institute for Afflicted Children in Amsterdam, where their youngest son Wassik, who had Down syndrome, was cared for. In a desperate act, he had shot the 15-year-old boy first. In January 1939 Afanassjewa's eldest son, Pawlik, died in an avalanche in the French Alps.

How melancholy must have been the memory for both Einstein and Afanassjewa of the years when Einstein was a regular guest in the spacious Ehrenfest house, which then was filled with music, laughter, and debates about physics. In addition to their two sons, Afanassjewa and Ehrenfest had two daughters, Tatiana and Galinka. "I have never experienced such a happy life in any other home," Einstein wrote in a letter to the couple in the autumn of 1919, after having spent two weeks in Leiden.

Vienna and Saint Petersburg

Who were Paul Ehrenfest and Tatiana Afanassjewa? As is so often the case with couples, more is known about him than about her. The first 40 years of Ehrenfest's life and work have been documented in a scientific biography,[2] and memoirs have been written by Ehrenfest's students—among them the mathematician Dirk Struik, the physicist Johannes Burgers, and Jan Tinbergen, one of the 1969 Nobel laureates in economics. Their writings recall the vibrant and intellectually inspiring atmosphere that Ehrenfest and Afanassjewa created in their home in Leiden.

By contrast, Afanassjewa's work and her contributions to the lively scientific debates have long gone unnoticed, even in the Netherlands. Only recently did her innovative work and contributions in the fields of thermodynamics, statistical mechanics, and mathematics education draw broader attention.[3] Yet an unwavering love for physics and the natural sciences was what brought Ehrenfest and Afanassjewa together in 1903, and it was what cemented their relationship thereafter.

A deep pleasure of the natural sciences guided the steady, more introverted Afanassjewa. Born in Kiev, then part of Russia, and raised as a single child in the wealthy Saint Petersburg household of her aunt and uncle, Afanassjewa had a love for science that led her to study at the Bestuzhev Courses, an institute of higher education for women. It also took her from Saint Petersburg to Göttingen, Germany, where she studied mathematics and physics in 1903 and 1904 and where she met Ehrenfest.

To Ehrenfest, the rational beauty of the natural sciences, particularly of physics, served as a lifeline for him, too, in a world that he frequently found overwhelming and sometimes downright hostile. His parents, who successfully ran a store selling groceries and household supplies in a Catholic neighborhood of Vienna, provided him and his four older brothers with a solid education. In a short memoir in 1932, he uses rosy terms to describe the busy household of their assimilated Jewish family. At the same time, however, the venomous antisemitism of many of his neighbors, peers, and teachers deeply hurt him. As a teenager, he was also deeply shaken when over the course of a few years, the shop was sold, his elder brothers left the house, and his parents died, one soon after the other. His love for mathematics and physics kept him afloat.[4]

Science became the guiding principle in their lives in Vienna, where they lived in 1905 and 1906; in Saint Petersburg, where they lived between 1907 and 1912; and in Leiden, where they moved in 1912. It motivated them to surround themselves with a large circle of friends, many of them physicists and mathematicians. And more than two decades after the move to Leiden, it was what kept Afanassjewa going after the loss of Ehrenfest and their two sons, Wassik and Pawlik.

Subtle contributions

Despite the key role that science played in the lives of the couple, it is difficult to briefly explain the scope of Afanassjewa's and Ehrenfest's work because of the subtlety of their contributions to solving often delicate problems in complex fields. The most important paper they wrote together stems from work during their second stay in Göttingen. Toward the end of 1906, they had returned to that mecca of mathematics and physics, after spending their first two years as a married couple in Vienna, where their eldest daughter, Tatiana Pavlovna, was born. At the time, neither Ehrenfest nor Afanassjewa had a job, but they had both inherited enough money—from his parents and from her uncle—to write and study without worries, at least for a few years.

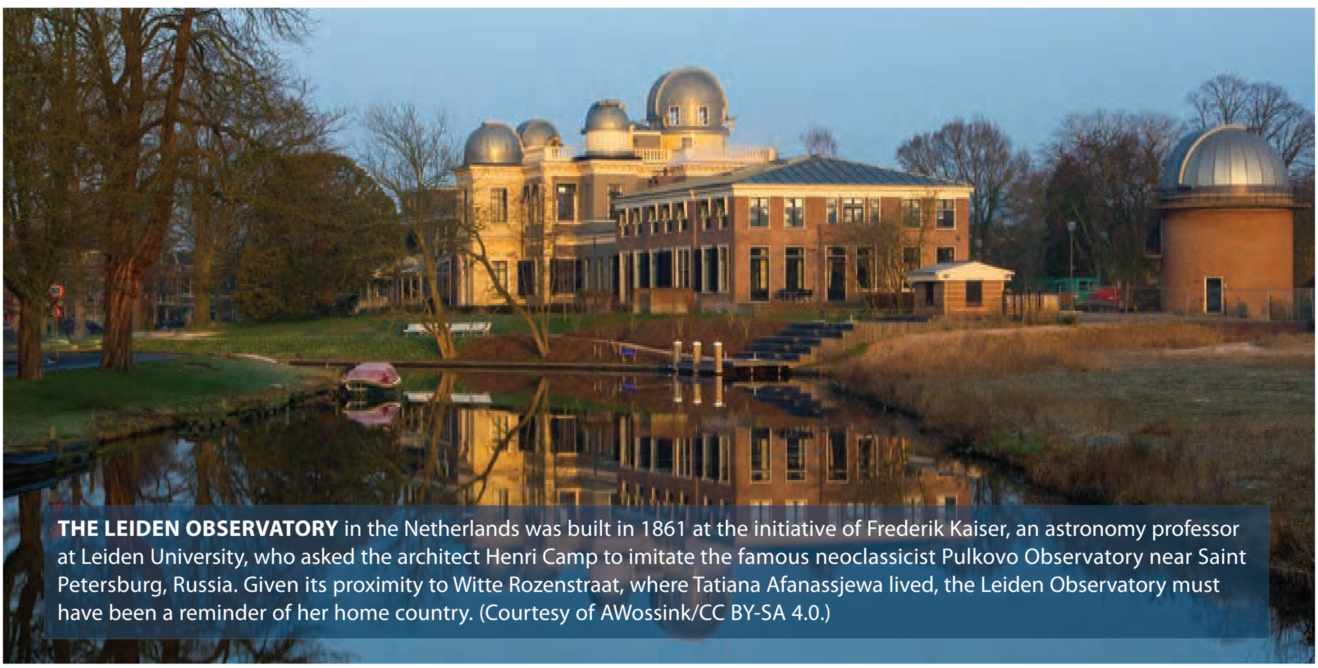
Afanassjewa had little hope of establishing a career in academia. The Bestuzhev Courses, which she had completed in Saint Petersburg, were well known in Russia and were supported by renowned scientists, including Dmitry Mendeleyev. Elsewhere in Europe, though, professors did not know what to make of that type of education and found it difficult to gauge the value of her diploma. That Afanassjewa had not been able to obtain any additional diplomas or write a dissertation during her first stay in Göttingen did not help matters.

Ehrenfest, who had studied with Ludwig Boltzmann in Vienna and who had obtained his doctorate at the end of 1904, also struggled to find a position. His misfortune was that Boltzmann, whose earlier comments on his thesis had been sparse, was no longer able to write a recommendation for him; Boltzmann died by suicide in the late summer of 1906.

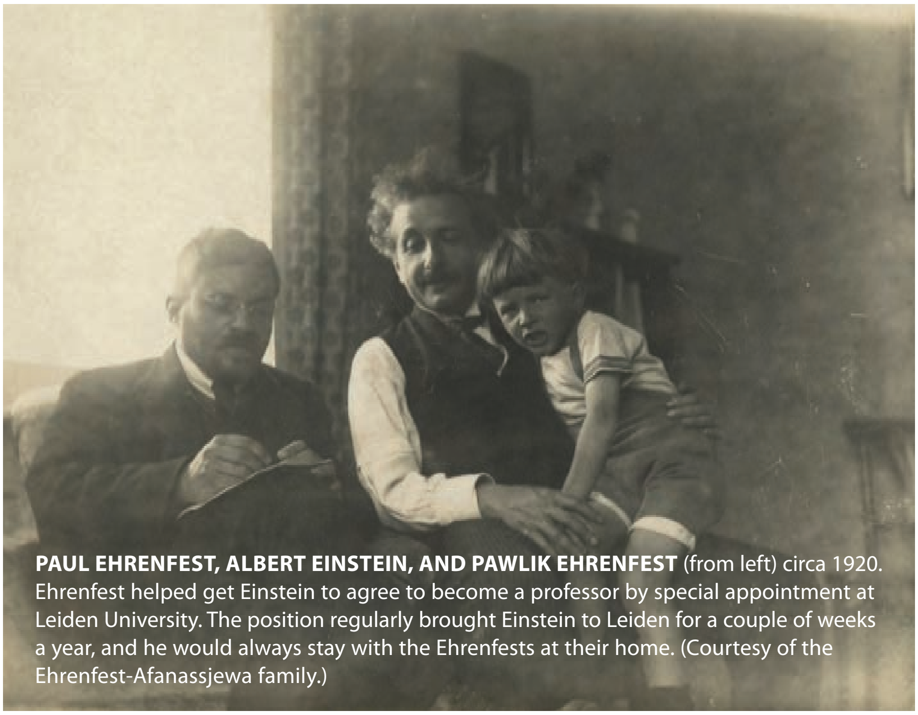
In Göttingen, the couple's luck turned when they published their so-called urn model, the topic of their first joint paper.[5] Later Ehrenfest would simplify it further to the "dog–flea model": It illustrates entropy by imagining how two dogs lying next to each other will each end up covered in an equal number of fleas, even if initially one dog was free of fleas and even if a single flea jumps just as easily in one direction as in the other.

The mathematician Felix Klein was so impressed by the original urn model that in 1906 he asked both Ehrenfest and Afanassjewa—whom he explicitly included in his invitation—to write an overview of the field of statistical mechanics and of Boltzmann's work. It was to appear in the prestigious *Encyklopädie der mathematischen Wissenschaften* (Encyclopedia of mathematical sciences), in which Klein intended to present all branches of mathematics and their applications.

Undoubtedly, Ehrenfest and Afanassjewa only got the assign-



THE LEIDEN OBSERVATORY in the Netherlands was built in 1861 at the initiative of Frederik Kaiser, an astronomy professor at Leiden University, who asked the architect Henri Camp to imitate the famous neoclassicist Pulkovo Observatory near Saint Petersburg, Russia. Given its proximity to Witte Rozenstraat, where Tatiana Afanassjewa lived, the Leiden Observatory must have been a reminder of her home country. (Courtesy of AWossink/CC BY-SA 4.0.)



PAUL EHRENFEST, ALBERT EINSTEIN, AND PAWLIK EHRENFEST (from left) circa 1920. Ehrenfest helped get Einstein to agree to become a professor by special appointment at Leiden University. The position regularly brought Einstein to Leiden for a couple of weeks a year, and he would always stay with the Ehrenfests at their home. (Courtesy of the Ehrenfest-Afanassjewa family.)

ment because Boltzmann was no longer available, but they did make the most of the chance to establish a name for themselves. Letters from Hendrik Lorentz reveal that he was impressed by their joint publication in Klein's *Encyklopädie*[6]—although it will probably always remain something of a mystery why Lorentz asked the relatively unknown Ehrenfest in 1912 to succeed him as a professor at Leiden University.

Strengths and weaknesses

The urn model and its more playful flea variant also highlight the couple's individual strengths. The urn model aligns with Afanassjewa's inclination for mathematics, her fondness for logical reasoning, and her lifelong interest in probability. The flea model is clearly a product of Ehrenfest, who blended his charismatic personality, his sharp tongue, a Socratic line of questioning, and ingenious metaphors to brilliantly lead an audience toward a profound understanding of the essential points of a theory or publication. Such qualities also made him an excellent sparring partner for colleagues, and he became close friends with Einstein and other well-known physicists, including Niels Bohr, James Franck, Wolfgang Pauli, and Erwin Schrödinger.

Ehrenfest's tragedy was that his qualities and scientific contributions were simply not enough for him. He regretted his own "lack of creativity," and his sense of inadequacy deepened over the years. It began to culminate when a new generation of young physicists developed quantum mechanics by using mathematical tools that many older physicists found difficult to grasp. In letters to colleagues and to Afanassjewa, Ehrenfest complained almost incessantly about how family and financial matters were keeping him from working, studying, and thinking seriously and profoundly.

Surely, their circumstances obliged Ehrenfest to take on occasional jobs as an examiner and a public lecturer. Their large house in Leiden had become a burden after the Russian Revolution of 1917 had reduced Afanassjewa's Russian railway stock to worthless pieces of paper. They needed to support not only their immediate family but also Afanassjewa's aunt and mother, who had escaped from Russia. On top of that, they needed to pay the substantial monthly bills from the Trüper Institute in Jena, Germany, where their youngest son, Wassik, was being cared for.

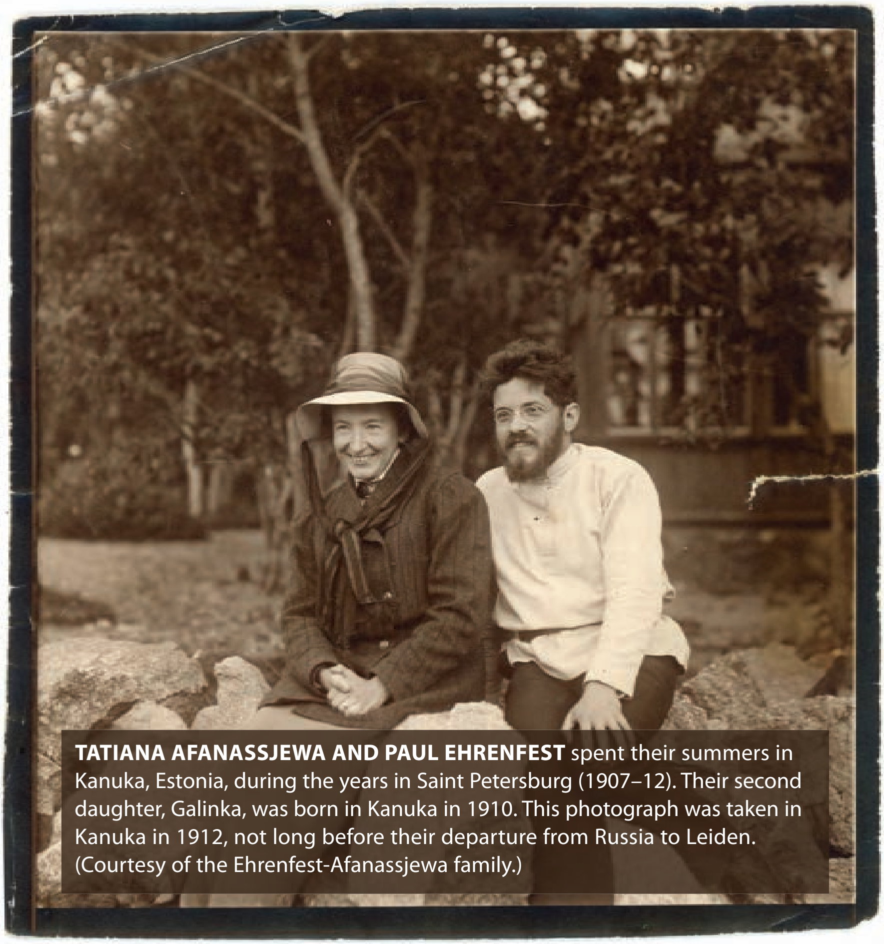
Debating circles and a working group

Yet the person whose wings were truly clipped was Afanassjewa. Time and again, whenever opportunities might have presented themselves, she seemed forced by her circumstances to instead become someone she was not: an elementary school teacher, a devoted housewife, a woman happy to live a quiet and secluded life in a provincial Dutch town, as opposed to a woman longing to write, debate, travel, and—most of all—think for herself. In fact, she already had to overcome adversity as a young girl. She was just a toddler when her father collapsed and was taken to a "mental asylum." Her mother had to earn a living while Afanassjewa was fostered by her wealthy aunt and uncle. And since her conservative uncle was opposed to her plans to enter the Bestuzhev Courses, she could begin her studies there only after his death.

After marrying Ehrenfest in Vienna in December 1904, Afanassjewa audited lectures at the University of Vienna, but being pregnant and then a young mother, she felt out of place. In Saint Petersburg, where the university had just opened its doors to women, she finally did manage to complete an internationally recognized degree in mathematics and physics. The bureaucratic procedures, however, were so lengthy that she ended up missing an opportunity to write a dissertation. Less than a year later, in July 1910, she gave birth to daughter Galinka. Ehrenfest, meanwhile, had come to realize that he would probably never obtain a formal position in Russia, so he decided to spend the rest of the summer at the German resort Bad Kissingen.

Still, and in spite of the stress of a young family, Afanassjewa and Ehrenfest managed to gather a lively circle of physicists and mathematicians around them while living in Saint Petersburg. Their *kruzhoks*, or debating circles, became popular among many young scientists, and Ehrenfest, with the extensive knowledge of recent developments in theoretical physics that he had gathered in Vienna and Göttingen, became a leading figure among them.

Afanassjewa, meanwhile, went quietly about her own business. She organized her own kruzhok on probability, wrote a paper on the role of probability in physics, and found employment at the Russian pedagogical museum of one of the military academies. Its task was to educate military recruits, most of them illiterate or with only limited skills in reading, writing, and arithmetic, from all over the vast Russian empire. At the turn of the century, however, when the benefits of proper schooling became increasingly clear, the museum broadened its scope. A working group of mathematicians, among them the applied mathematician and naval officer Aleksey Krylov, had begun to debate the didactics of mathematics and organized a lecture series for secondary school teachers and for anyone else interested in education. Soon after delivering one of the lectures, Afanassjewa was invited



TATIANA AFANASSJEWA AND PAUL EHRENFEST spent their summers in Kanuka, Estonia, during the years in Saint Petersburg (1907–12). Their second daughter, Galinka, was born in Kanuka in 1910. This photograph was taken in Kanuka in 1912, not long before their departure from Russia to Leiden. (Courtesy of the Ehrenfest-Afanassjewa family.)

to participate in the working group in Saint Petersburg. It was there that she began to develop her ideas on didactics, inspired also by lectures by David Hilbert and Felix Klein.

A woman's place

Once Ehrenfest and Afanassjewa were in the Netherlands, after Ehrenfest's appointment at Leiden, their roles shifted to a more traditional pattern. Now it was Ehrenfest who held the formal position and Afanassjewa who had to manage on her own. She would soon discover that the Netherlands offered far fewer possibilities than Saint Petersburg had. Leiden was a provincial town, and according to unwritten but strictly applied rules, the wives of professors in the Netherlands stayed at home and devoted themselves to good causes and children. In 1924 a royal decree even formalized such habits by stipulating that women must be honorably discharged from public-service positions as soon as they married. It left Afanassjewa no choice but to work from home, independently, without the encouragement of daily encounters with colleagues, without the benefits of a salary and an office, and without a job title that would lend her prestige and a place in the historical record.

A testament to Afanassjewa's perseverance is that, despite all the setbacks, she almost immediately seized an opportunity to organize another kruzhok, this time with Dutch mathematics teachers. It was Lorentz—whose wife was cautiously supporting feminist causes—who had put her in touch with a group of teachers who worked with the Dutch educational reformer Rommert Casimir. Ehrenfest had his doubts about the enterprise. "Nothing will come of the reform of mathematics education," he grumbled after one such session. "Just look how they can never agree on anything." Afanassjewa, however, was happy that the teachers debated at all; that in itself meant progress, she said.[7] Yet even she had to admit that professionally things developed slowly in the Netherlands, especially for herself.

By contrast, her private life was busy. In 1914 the family had moved into a large house on Witte Rozenstraat ("White Roses Street"). Afanassjewa herself had designed the house in the neoclassicist style that was so popular in Saint Petersburg. Their son Pawlik was born there in 1915, followed in 1918 by son Wassik. The two young boys required care, and Ehrenfest and especially Afanassjewa supervised the homeschooling of their daughters. Afanassjewa shared Ehrenfest's objections to the traditional school system, and she wrote in the family diary that "little good was to be expected" from the Dutch schools where children had to memorize the names of "Dutch canals" and read "saccharine little stories devoid of any poetry."

A novel way of teaching geometry

In short, Afanassjewa was kept occupied with a multitude of duties as a wife, a mother, and a host to the many visitors and guests they received in their home. In addition, she worried about Wassik and was anxious about the Russian Revolution and the horrors of World War I, which, although it spared the neutral Netherlands, brought violence and uncertainty across Europe. All those events would distract anyone more than enough from working hard and thinking deep. It once more illustrates Afanassjewa's steadfastness that she still managed to write three papers that were read to the Royal Academy of Sciences by Lorentz and the Leiden professor Johannes Kuenen. Yet it is not surprising that it took her until 1924 to publish work with which she truly made her mark in the two fields that had been at the core of her interests for many years: thermodynamics and the didactics of mathematics.

Afanassjewa published a pamphlet in 1924 on the didactics of geometry.[8] The refreshing methods she proposed began with an intuitive learning stage that allowed children to explore space and its concepts. Almost immediately, her proposal led to a debate with the established mathematics educator Eduard Dijksterhuis, who fiercely defended traditional teaching methods in a lengthy rebuttal.[9] Soon afterward, the Dutch Inspectorate of Education assigned a national committee to investigate the secondary school science curriculum, while a new journal about teaching methods in mathematics was established as well.

In the following year, Afanassjewa's paper on thermodynamics similarly offered innovative ideas. Building on the earlier axiomatic treatment of thermodynamics by the Greek mathematician Constantin Carathéodory, the paper suggests that the laws of thermodynamics, as formulated by Lord Kelvin and Rudolf Clausius, do not exclude negative temperatures on the kelvin scale, which was a novel suggestion at the time. In addition, Afanassjewa's subtle and profound discussion of thermodynamic equilibrium and nonequilibrium states still is part of current debates about the topic among philosophers of science.[10]

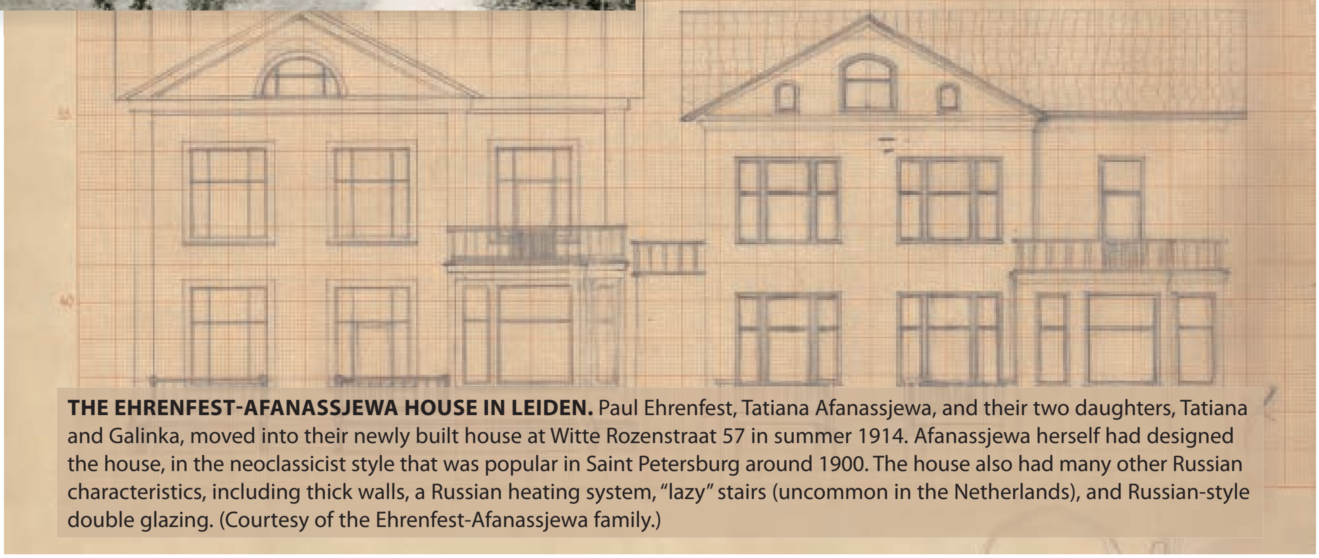
Escape to Russia

Afanassjewa must have been disappointed, however, because she was not invited to be a member of the Dutch committee on education or an editor of the new journal on teaching methods in mathematics—even though her pamphlet had been the trigger for both initiatives. She must have been equally disappointed that her paper on thermodynamics found a similarly lukewarm reception because her observations got lost in the tsunami of publications on the revolutionary theory of quantum mechanics. "It would be entertaining if all publications by my wife and myself could at one point all be [. . .] printed together in chronological order," Ehrenfest wrote in 1926 in a document expressing "a couple of wishes" in case of his own death. Their ideal had always been to work and study together. Yet society's expectations and their disappointments about their careers began to burden the once so unreservedly happy relationship between Afanassjewa and Ehrenfest.

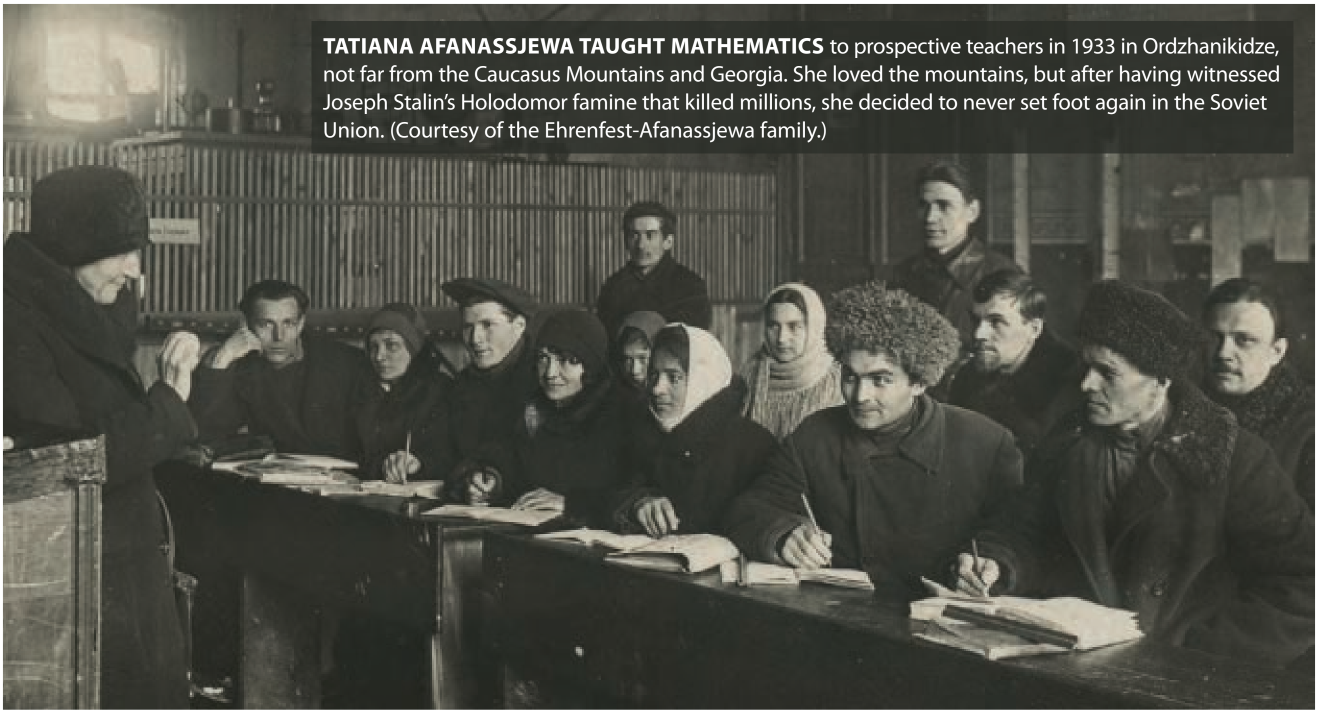
Without hope of a formal position, with her daughters growing into adults, and with her husband becoming increasingly nervous and grumpy, Afanassjewa often felt lost in Leiden. In 1926 she could no longer resist the call from the Soviet Union, where her expertise was appreciated and where friends and former colleagues were happy to welcome her. It marked the beginning of a period during which she would travel to the Soviet Union twice a year for three to five months. She worked as a university professor in Simferopol in Crimea, taught prospective mathematics teachers in Ordzhanikidze, and lectured in Moscow and Leningrad. On her way back and forth to Leiden, she would always make a stop in Jena to visit Wassik.

Recovering in Spa

Ehrenfest, who had increasingly been growing tired of Afanassjewa's sober and intellectual lifestyle and her endless willingness to help friends in the Soviet Union, was now missing her presence in the Leiden house. Their two grown-up daughters regularly traveled abroad too. Often alone in the house, with only his young son Pawlik and old baba Katja—Afanassjewa's mother—for company, Ehrenfest



THE EHRENFEST-AFANASSJEWA HOUSE IN LEIDEN. Paul Ehrenfest, Tatiana Afanassjewa, and their two daughters, Tatiana and Galinka, moved into their newly built house at Witte Rozenstraat 57 in summer 1914. Afanassjewa herself had designed the house, in the neoclassicist style that was popular in Saint Petersburg around 1900. The house also had many other Russian characteristics, including thick walls, a Russian heating system, "lazy" stairs (uncommon in the Netherlands), and Russian-style double glazing. (Courtesy of the Ehrenfest-Afanassjewa family.)



TATIANA AFANASSJEWA TAUGHT MATHEMATICS to prospective teachers in 1933 in Ordzhanikidze, not far from the Caucasus Mountains and Georgia. She loved the mountains, but after having witnessed Joseph Stalin's Holodomor famine that killed millions, she decided to never set foot again in the Soviet Union. (Courtesy of the Ehrenfest-Afanassjewa family.)

found that his mood swings were becoming more severe. He frantically typed long letters to Afanassjewa, to almost 100 colleagues, and, in some cases, to their wives. He began to travel through Europe in an almost compulsory manner and increasingly used his sharp tongue for sarcasm rather than playful wit. In 1931 he fell in love with Nelly Posthumus Meyjes, an art critic eight years younger than him.

Once Afanassjewa heard about the affair, she tried to take it lightly. But Ehrenfest's desire to share all sorts of intimate details of his two lives with both women, and even with the children, soon created tensions. When Afanassjewa asked for a divorce, Ehrenfest plunged into a depression. Einstein visited him in September 1932 and was so concerned that he wrote a letter to the curators of the university to ask them to relieve Ehrenfest of some of his duties.

A few days later, Einstein traveled to the Belgian town and health resort of Spa, where Afanassjewa, completely exhausted for the first time in her life, had withdrawn herself. During his two-week stay, they went for long walks together, discussing marital problems and other topics. One was Afanassjewa's recently published *Übungensammlung*, a collection of simple exercises to acquaint children with geometry.[11] When Ehrenfest arrived, with the booklet in hand, at the end of Einstein's two-week visit and joined them for walks, Einstein must have hoped for the best.

In hindsight, such a happy outcome in such dark times seemed unlikely. In the Soviet Union, Joseph Stalin had strengthened his iron grip on the hungry and exhausted population. After the Holodomor famine of 1932–33 that killed millions of Ukrainians, Afanassjewa would never set foot in her native country again. In Germany at that time, Adolf Hitler was rising to power. Ehrenfest traveled to Berlin in May 1933, where he met Schrödinger and Max Born and drew up an extensive list of Jewish colleagues whom he hoped to bring to the attention of academic aid organizations elsewhere in the world. In a desperate move, he also went to visit the Nobel laureate Johannes Stark, who had written papers that had once inspired him to go to Göttingen for further studies but who had now become a staunch Nazi. Would Stark "dare to ignore me disdainfully, while I am still the same Jew as before," Ehrenfest asked rhetorically.[12]

Back in Leiden, spiteful young men greeted Ehrenfest at the train station shouting: *Isak! Isak! Was heb Du o Hast?* ("Isaac, Isaac, why are you hurrying?"). He wrote to his former student Samuel Goudsmit, "And these kinds of *Strassenbelastungen*—stressful events on the streets—"are rapidly increasing here!"[13] A few months later, after breaking up with Posthumus Meyjes, Ehrenfest spent three days with his family. He then went to the Waterink's Institute in Amsterdam where they had moved Wassik to safety from the Trüper Institute in Nazi Germany, and he ended both his son's and his own life.

Enduring love for science

"I was so very pleased with your letter," Einstein wrote on 22 October 1945 to Afanassjewa. "Such a sturdy and steadfast personality one seldom encounters. Also, an interest in the foundations of physics has remained alive in you as if you had not experienced these harsh and threatening years."[14] Einstein had been happy to learn that Afanassjewa, her daughters, and her grandchildren had all survived the horrors of World War II.

Soon a food parcel arrived in Leiden from a company in New York, followed by another and yet another. Afanassjewa wrote to Einstein, "Now we have received nice goods from you again."[15] It was not until the end of 1947 that Einstein reluctantly agreed to Afanassjewa's request to send the food parcels to their colleague Edmund Bauer in Paris instead, since she had asked, "Are you planning to feed me until my death?"[16]

Their correspondence continued until shortly before Einstein's death in 1955. The letters must have been a comfort to

Afanassjewa, alone in her huge house in Leiden, and to Einstein, equally alone in his small house in Princeton. Writing after the death of Afanassjewa's son Pawlik in 1939, in a letter that has been carefully preserved by the Ehrenfest family, Einstein reflected on Shakespeare's plays: "Human fate is extraordinary when it is described by such a wonderful man, but one should not have to live through it oneself and be permitted to just be eyes." To the sad reflections he added words of consolation, writing about what they both shared, an enduring love for physics and mathematics that continued to give their lives meaning. "Only objective matters have retained their radiant shine for me. They appear in the same glory as the first geometry book that I received as a child. It surely is the same for you as well."

I thank Anne Kox, Henriette Schatz, and the article reviewers for their comments and suggestions.

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Early Science Service contributor Emma Reh sits atop a horse in Oaxaca, Mexico, where she reported on archaeological excavations. (Courtesy of Smithsonian Institution Archives, Accession 90-105, Science Service Records, Image No. SIA2009-2150.)

Lost voices of science journalism

"Blonde Girl Explorer Mystifies Natives of 'Forbidden City.'" In eight words, the progressive and the problematic collided in a 1933 *Science News Letter* headline. The blonde girl in question was science journalist Emma Reh, writing at a time when most journalists were men. She had moved to Mexico to escape a failing marriage. While there, she conducted research in anthropology, immersed herself in Indigenous culture and language, and reported on archaeological research sites in places like Oaxaca and Quintana Roo. But Reh's article—as its title made clear—centered the reporter and sensationalized the culture she had come to study.

In her newest book, *Writing for Their Lives: America's Pioneering Female Science Journalists*, Marcel Chotkowski LaFollette has undertaken an ambitious task. She introduces nearly 60 reporters—mostly women, including Reh, but also a small handful of men—who served as some of the earliest science writers in the US. The resulting work spans several decades in quick succession. LaFollette describes a cohort of journalists who wrote about medicine, nutrition, psychology, chemistry, the social sciences, and more. She draws their histories from the records of the Washington, DC–based Science Service, a news service and nonprofit organization created in 1921, known today as the Society for Science.

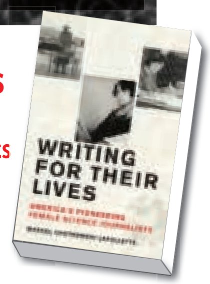
According to LaFollette, women were the majority of the editorial staff writers for the first 40 years of the organization's operations. At the time, she says, "no newspaper in the United States employed a woman to write about science." Most of Science Service's syndicated content, however, appeared without attribution to individual authors, effectively masking the gender of the contributing writers.

LaFollette counterbalances that erasure by uncovering the identities of 58 women who wrote for the news service during the first half of the 20th century. Summarizing the contributions of so many journalists in a relatively short space, though, means that each individual receives only a few moments of attention. Quick biographical sketches reveal the writers' travels, genealogies, parents' employment, and relationships with siblings, in addition to the subjects on which they reported. What the reader hungers for most, perhaps, is more analysis of the perplexing blend of inclusion and inequity that emerges in this history.

The strongest sections of the book are its middle chapters. Here, LaFollette slows down, introducing the reader to

Writing for Their Lives
America's Pioneering Female Science Journalists

Marcel Chotkowski LaFollette
MIT Press, 2023. $26.95 (paper)



Reh, Jane Stafford, and Marjorie Van de Water and the topics that they covered: archaeology, medicine, and psychology, respectively. The intersection between professional and personal motivations, the impact of chronic underpayment, and the profound commitment that contributing writers demonstrated under difficult circumstances begin to come into focus. Reh, for example, sent dispatches to Science Service from Mexico while she waited for her divorce to be finalized, but editors typically declined to pay her an advance. When Science Service fell short of meeting her needs, Reh sent her work to other publishers, including *Scientific American* and the *New York Times*, reaching new audiences.

At its heart, *Writing for Their Lives* is an homage to archivists. Photographs are at once intimate and professional, beautifully evoking the lives and personalities of LaFollette's subjects at work. An independent historian and a research associate at the Smithsonian Institution Archives, LaFollette draws most heavily from the Smithsonian's collections, including Science Service employment records and professional correspondence. The result is a cabinet of curiosities, filled with details that other authors might have passed over. In presenting, for example, the managing editor's personal stationery that highlighted his wife's chemistry degree, or the cost of travel for a freelancer—$45.93 for a trip to Saint Louis, including "railroad fare and Pullman charge . . . 'hotel, meals, tips, taxis . . . and the pressing of a frock'"—LaFollette invites the reader to explore the records alongside her.

The book unveils early and important, yet incomplete, steps toward including women's voices in science journalism. Science Service editors made space for women writers but also urged them to revise their copy for greater splash and home-economics appeal, supporting stories that resonated with traditional Western attitudes—like that of the "blonde girl explorer." The organization's first director, Edwin Slosson, advised one aspiring contributor to trim her stories by saying, "You put too much meat into your preparations. Remember that a housewife's skill is based upon her ability to make a tasty dish out of a scrap of leftover." Unsurprising for the era, but nonetheless disheartening, LaFollette notes only one woman of color who worked for the service during its first five decades. Some staff writers also hinted at the social impact of gender discrepancies in the fields they covered. "The test atomic explosions have been peculiarly man's work," wrote Helen Augusta Miles Davis about nuclear tests in Nevada and at Bikini Atoll after World War II. Despite being married to the managing editor at Science Service, Davis often wrote without compensation and without recognition on the masthead.

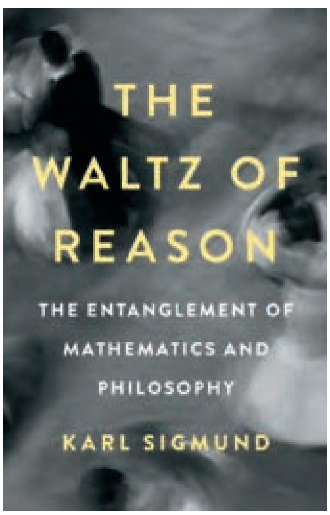
Writing for Their Lives pulls back the curtain on a complex mix of progress and disparity but often refrains from critique. It celebrates women in science journalism who challenged the early-20th-century social norms that had excluded them. It also reveals, indirectly, the considerable cultural distance between 1933 and 2023. The book is a reminder not only of how far society has come but also of how much road still lies ahead in working toward full equity and inclusion.

Michelle Frank
Leon Levy Center for Biography

NEW BOOKS & MEDIA

The Waltz of Reason

The Entanglement of Mathematics and Philosophy



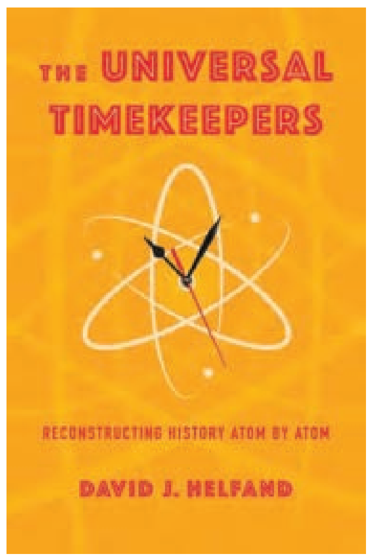
Karl Sigmund
Basic Books, 2023. $32.50

In this book, the mathematician Karl Sigmund delves into the relationship between philosophy and his own field. Chapters cover such topics as logic, infinity, limits, randomness, voting, language, fairness, and the social contract. Physicists may be interested in learning that many mathematicians also take a "shut up and calculate"–style attitude toward the foundations of their field. But as Sigmund notes, many compelling questions remain. For example, does the imaginary number *i* actually exist, or did we invent it? Could an alien civilization develop an alternate form of mathematics, or would they inevitably develop the same one we have? Sigmund's witty tone inspires readers to delve into those questions and others. —RD

The Universal Timekeepers

Reconstructing History Atom by Atom

David J. Helfand
Columbia U. Press, 2023. $24.95



How can atoms, which are predominately empty space, be used to study human history as well as that of Earth, the solar system, and the universe itself? In *The Universal Timekeepers*, the physicist David Helfand discusses the discovery and structure of atoms, subatomic particles, nuclei, and molecules before moving on to how their radioactive decay has proved to be an accurate clock with which to explore the past. In his "tales of atomic detective work," Helfand explains the diverse and wide-ranging applications of radioactive dating, including detecting art forgeries and investigating Earth's paleoclimate, the death of the dinosaurs, evolution, the Sun's birth, and the Big Bang. —CC

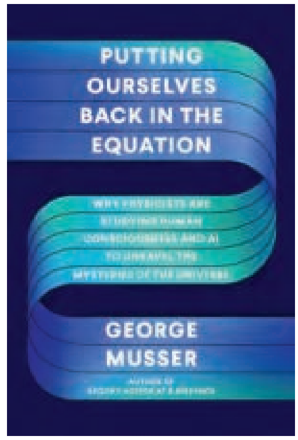
Putting Ourselves Back in the Equation

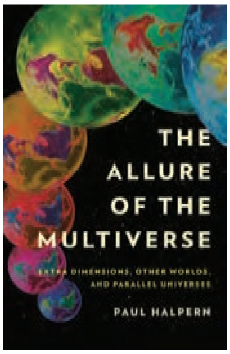
Why Physicists Are Studying Human Consciousness and AI to Unravel the Mysteries of the Universe

George Musser

Farrar, Straus and Giroux, 2023. $30.00

To develop a true theory of everything, physicists must understand the nature of human consciousness, argues the science writer George Musser in *Putting Ourselves Back in the Equation*. The book addresses what Musser defines as the "inside/outside problem"—namely, what happens when physical theories that represent the world from a third-person perspective conflict with the way we perceive the world from our first-person vantage point. After all, quantum mechanics implies that the very act of observation affects measurement. To solve the inside/outside problem, physicists are starting to delve into neuroscience and investigate artificial intelligence (AI). Based on interviews with physicists, neuroscientists, philosophers, and AI researchers, Musser's book is engaging and provocative. —RD





The Allure of the Multiverse

Extra Dimensions, Other Worlds, and Parallel Universes

Paul Halpern

Basic Books, 2024. $30.00

Popularized in the public's mind by numerous Marvel films, the concept of the multiverse is increasingly in vogue in physics as well. But if we live in a multiverse, asks the physicist and science writer Paul Halpern, how would we ever know? Moreover, if we can't detect possible other universes, is it even worth our time to ponder their existence? Halpern suggests that it is. He describes how physicists frustrated by the lack of experimental evidence for physical postulates that aim to explain phenomena beyond the standard model, such as string theory and M-theory, are increasingly turning to multiverse theories. Whether or not you agree that the multiverse concept will prove fruitful, his book is a fascinating read. —RD

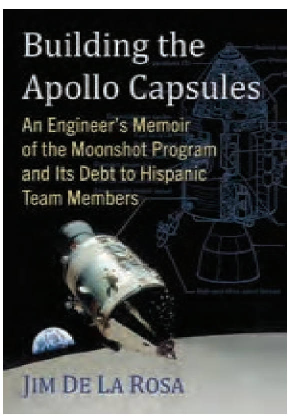
Her Space, Her Time

How Trailblazing Women Scientists Decoded the Hidden Universe

Shohini Ghose

MIT Press, 2023. $29.95

Over the past 150 years, women have made significant contributions to important scientific discoveries in a range of fields, including astronomy, space exploration, radioactivity, and subatomic photography. Those achievements, however, have often been downplayed or simply ignored. In *Her Space, Her Time*, the physicist Shohini Ghose tries to set the record straight by highlighting some of the most important women of the modern scientific age, providing biographical background and recognizing their innovative work. Interweaving those stories with anecdotes about her own childhood and educational and professional experiences over the past several decades, Ghose shows how much has—and hasn't—changed for women pursuing careers in science, technology, engineering, and mathematics. —CC



Building the Apollo Capsules

An Engineer's Memoir of the Moonshot Program and Its Debt to Hispanic Team Members

Jim De La Rosa

McFarland, 2023. $39.95 (paper)

In *Building the Apollo Capsules*, the aerospace engineer Jim De La Rosa provides an in-depth, behind-the-scenes look at NASA's Apollo program, which landed the first humans on the Moon in 1969—one of the greatest achievements of the 20th century. Part history and part memoir, the book begins in 1964 when De La Rosa joined the team working on AFRM 009, the first major test of an Apollo spacecraft, and continues through 1969, when he left the Apollo program to work on the space shuttle. Throughout, he not only highlights the many engineers and technicians who contributed to the Apollo program but also pays particular tribute to his fellow Hispanic team members, who he believes have not received the recognition that they deserve. —CC PT

NEW PRODUCTS

Focus on lasers, imaging, microscopy, and nanoscience

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

Andreas Mandelis

Short-wavelength lasers

To expand the possibilities in high-resolution Raman spectroscopy, microlithography, multiwavelength digital holography, and interferometry, Toptica now offers wavelengths at 445 nm and 447 nm in its TopMode diode laser series. The compact, reliable lasers allow for easy OEM integration and enable repeatable, high-resolution measurements. According to the company, the TopMode lasers operate as easily as helium–neon lasers but offer higher power and a choice of wavelength. The proprietary CHARM (coherence-advanced regulation method) technology stabilizes the lasers' coherence and ensures continuous single-frequency operation. Other applications for the short-wavelength lasers include scatterometry, precision metrology, and quantum cryptography. ***Toptica Photonics Inc****, 1120 Pittsford Victor Rd, Pittsford, NY 14534, www.toptica.com*

High-power, ultrafast, handheld 515 nm laser

Calmar has unveiled the latest addition to its Carmel X-series. According to the company, its Carmel X-515 is the first high-power, handheld green femtosecond fiber laser. It delivers over 0.4 W of power at 515 nm, ultrashort pulse widths of less than 100 fs, and excellent beam quality with M^2 of less than 1.2. No chiller is required because it is air cooled. The Carmel X-515 is available in a scientific version with front-panel control knobs and an OEM version operated through an RS-232 interface. The latter offers full remote access with the capability for logging data, monitoring power, running system diagnostics, and making automated adjustments to prolong its lifetime. Each version features a small 2U rackmount controller connected via a robust armored cable to an ultracompact laser head. The Carmel X-515 is suitable for various applications, including multiphoton microscopy, 3D photopolymerization, optical metrology, and ophthalmology. ***Calmar Laser****, 951 Commercial St, Palo Alto, CA 94303, www.calmarlaser.com*

High-power 561 nm CW laser

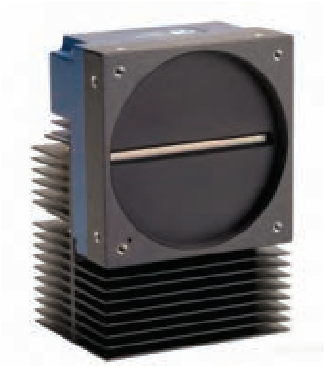
Hübner Photonics has released a higher-power model of the Cobolt Jive 561 nm laser from the 05-01 series platform. Because it delivers up to 1 W of CW output power, the Cobolt Jive is suitable for demanding applications in fluorescence microscopy. It is especially appropriate for superresolution microscopy, such as DNA-PAINT (DNA point accumulation in nanoscale topology), and for interferometric-based techniques, such as particle-flow analysis. The Cobolt Jive is a single-frequency, diode-pumped laser operating at 561.2 nm in a pure TEM_{00} beam with an M^2 factor of less than 1.1. The proprietary laser-cavity design ensures ultralow noise—typically less than 0.1% rms over a frequency range of 20 Hz to 20 MHz and a temperature range of 10–40 °C. It provides high power stability of less than 2% over a temperature range of ±2 °C and a time frame of up to eight hours. All Cobolt lasers are manufactured using the company's HTCure technology; the resulting compact, hermetically sealed package provides high reliability and high immunity to varying environmental conditions. ***Hübner Photonics Inc****, 2635 N 1st St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com*

Raman microscope

The fully automated and remotely controllable LabRAM Odyssey system has replaced Horiba Scientific's LabRAM HR Evolution microscope. In addition to the company's DuoScan and ultrafast SWIFT Raman imaging technologies, the LabRAM Odyssey integrates two new calibration tools: video Raman matching (VRM) and objective adjustment (OA). VRM ensures a perfect match between the video image and the Raman map locations; OA lets users keep their region of interest in the field of view with whichever objective they use. The LabRAM Odyssey can be configured to enable semiconductor process users to qualify the different steps quickly and confidently. With its 300 mm × 300 mm automated sample stage and automated objective turret, the LabRAM Odyssey Semiconductor can perform photoluminescence and Raman imaging on wafers with a diameter of up to 300 mm. A high-spatial-resolution mode can detect and identify defects and submicron inhomogeneities. The DuoScan imaging function permits laser macrospots of variable size for full wafer maps and high-spatial submicron step scanning for small area maps. ***Horiba Scientific****, 20 Knightsbridge Rd, Piscataway, NJ 08854, www.horiba.com*

Nano- and biomaterials characterization

The NanoSight Pro nanoparticle tracking analysis system now available from Malvern Panalytical offers smart features and upgraded NS Xplorer software that enables automated measurements. According to the company, it delivers ultrahigh-resolution size and concentration measurements for nanomaterials at up to three times the speed previously possible. Optimized for use with drug-delivery systems and samples that include exosomes, viruses, and vaccines, NanoSight Pro overcomes limitations linked to small biological particles and other low scatterers. It is powered by machine learning coupled with state-of-the-art technology, including an upgraded temperature controller that permits stress and aggregation studies to be performed at up to 70 °C. Interchangeable lasers enable application flexibility. A dedicated fluorescence mode facilitates confident detection of fluorescent subpopulations and their discrimination from the total population. ***Malvern Panalytical Ltd***, *Enigma Business Park, Grovewood Rd, Malvern WR14 1XZ, UK, www.malvernpanalytical.com*



Camera for near-UV and visible imaging

Teledyne DALSA has announced its Linea HS 16k backside-illuminated (BSI) time-delay-integration (TDI) camera. Compared with front-side illumination (FSI), the BSI model raises quantum efficiency in the near-UV and visible wavelengths and improves the signal-to-noise ratio for imaging applications in light-starved conditions, according to the company. Its enhanced near-UV and visible sensitivity makes the camera suitable for such applications as photoluminescence and life-sciences imaging and wafer, flat-panel-display, and electronic-packaging inspection. The Linea HS 16k BSI camera uses the company's charge-domain CMOS TDI 16k sensor with a pixel size of 5 μm × 5 μm and delivers a maximum line rate of 400 kHz aggregate. The Camera Link HS data interface delivers a data throughput of 6.5 GPx/s in a single cable. An active optical cable enables a longer cable length and eliminates the need for a repeater, which thus improves data reliability and reduces system costs. ***Teledyne DALSA***, *605 McMurray Rd, Waterloo, ON N2V 2E9, Canada, www.teledynedalsa.com* PT

Sam Van Wassenbergh is a professor of animal mechanics and **Maja Mielke** is a doctoral candidate in the functional morphology laboratory at the University of Antwerp in Belgium.

Why woodpeckers don't get concussions

Sam Van Wassenbergh and Maja Mielke

Contrary to popular belief, the birds don't have shock absorbers in their heads.

When knocking away pieces of hard woody bark to find food, digging nesting holes into tree stems, or making drumming sounds to lure mates or announce their territories, woodpeckers generally strike trees with their beaks at speeds of 20 kilometers per hour and can reach rates up to 30 times per second during drumming. So a sudden deceleration would exceed the threshold that would render a concussive blow—at least to a human brain. But to judge from many popular accounts, internet blogs, information panels in zoos, and educational television programs, the birds' brains emerge unharmed thanks to shock-absorption structures in the skull.

Bird enthusiasts may be comforted by the idea that a shock wave traveling backward from the impacting beak becomes cushioned before it reaches the brain. And the idea gained strength in the past decade when computed tomography reconstructions revealed a zone of spongy bone at the front of a woodpecker's brain, as shown in figure 1.

That porous zone consists of interconnected bony rods and plates, which could theoretically be compressed on impact to reduce the shock to the brain. But although it inspired the design of new shock-absorbing materials and helmets, the hypothesis had not been tested. What's more, several scientists strongly doubted it even earlier. In the 1970s psychiatrist Philip May and coworkers saw the potential of learning from anatomical adaptations in woodpeckers to withstand repeated blows. Yet in their 1976 *Lancet* article, they questioned whether the cranial absorption of shocks was part of those adaptations. "If the beak absorbed much of its own impact, the unfortunate bird would have to pound even harder," the authors wrote.

FIGURE 1. A BLACK WOODPECKER and an x-ray computed tomography reconstruction of the left half of the skull. The enlarged circle shows the spongy bone, located at the interface between the beak and the cranium, that had been hypothesized to serve as a shock absorber.

It would be maladaptive for a bird to first build up sufficient kinetic energy to deliver a strong hit to a tree by accelerating its head forward, only to lose part of that energy into its own built-in skull–beak shock absorber. (With ophthalmologist Ivan Schwab, May was posthumously awarded the 2006 Ig Nobel Prize in Ornithology for his work.)

Video evidence

As part of an international research team two years ago, we looked at three species of woodpeckers to see whether shock absorption was really taking place between the beak and the brain. We recorded high-speed videos of the birds during pecking. In Europe, those videos were made in four zoo aviaries with a black woodpecker (*Dryocopus martius*) and great spotted woodpecker (*Dendrocopos major*). In Canada, recordings were made of two pileated woodpeckers (*Dryocopus pileatus*) kept in the laboratory. Akin to how video is used in automobile crash tests, we used consecutive video frames to track the movement of landmarks on the birds' heads and then calculated their peak deceleration with impact.

The landmarks for all of them were two spots on the beak and one on the eye, which we

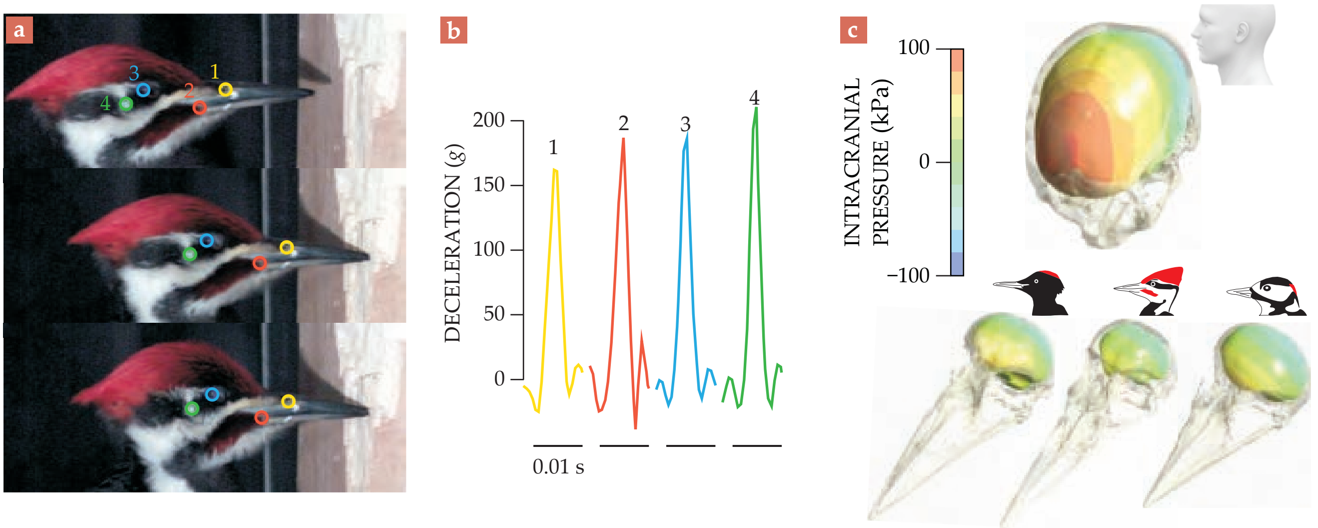


FIGURE 2. IMPACT ANALYSIS. The four tracked landmarks **(a)** on the beak and near the braincase of a pileated woodpecker. **(b)** This representative example shows the deceleration of those landmarks. **(c)** The results of a brain-cavity pressure simulation show that even the strongest decelerations analyzed in three species of woodpecker—(left to right) black, pileated, and great spotted—yield pressures that are lower than those in a human brain with the mildest concussion.

assumed moves along with the front of the braincase. The pileated woodpecker had an additional landmark, a small white dot painted on the skin covering the braincase, as shown in figure 2a. We then compared the average deceleration profiles between the landmarks on the beak and the braincase for more than 100 pecks.

We consistently found no reduced deceleration of the braincase compared with that of the beak, as seen in the results in figure 2b. Hence, between those sites no cushioning occurs by means of spongy bone compression or any other method. The woodpecker's head functions as a stiff hammer—not as a shock absorber. Furthermore, our biomechanical-model calculations prove that potential shock absorption within the skull would have reduced the penetration depth in wood by the beak for a given head-impact speed. Although such a built-in damper would slightly reduce the brain's acceleration, it would nevertheless be a waste of energy: The same work done on the wood with equally reduced brain accelerations can be achieved if the bird hits the tree more gently. Consequently, those data prompted us to conclude that the observed minimization of cranial shock absorption is a logical, adaptive outcome in birds that have evolved a wood-pecking lifestyle.

Avoiding injury

But without shock absorption in the skull, how do woodpeckers protect their brains from injury? Our data show that woodpecker brains are subjected to decelerations of up to 400 g, where g is the acceleration due to gravity. That far exceeds the estimated threshold of 135 g to cause concussions in humans. As pointed out in 2006 by MIT's Lorna Gibson, the answer lies in the mass difference between the brains of woodpeckers and those of humans. She found that the keys to the birds' ability to withstand high decelerations include their small size, which reduces stress on the brain for a given deceleration; the short duration of the impact, which increases their toleration of it; and the orientation of the brain in the skull. The pressure in the woodpecker's brain under its own deceleration is proportional to the product of the bird's deceleration, the mass density of its brain tissue, and the brain length, or volume/area.

The relevant length is that of the brain in the direction of impact. The brain of a woodpecker has roughly one seventh the length of a human's. And thus the woodpecker's deceleration threshold for concussions equivalent to the human's threshold would be $7 \times 135\ g$, or about 1000 g. The upshot is that even the hardest hits from our data set—roughly 400 g—are not as violent as they appear. The birds maintain a considerable margin of safety and still suffer no brain injury, even if they were to accidentally hit a material stiffer than wood; for a comparison between human- and woodpecker-brain pressures in response to the strongest decelerations, see figure 2c. On the other hand, the relationship between brain pressure and length can explain why no giant woodpeckers exist that can drill holes much deeper than those drilled by currently living species.

Shock absorption in woodpeckers is a good example of how hypotheses can spread to become common beliefs even with no scientific evidence supporting them. The combination of spectacular behavior receiving plenty of popular-media coverage and humans focusing on brain-protection adaptations when it comes to head impacts can be misguiding. The two factors may be responsible for the mythologizing of how woodpeckers avoid injury. We hope that our biomechanical evidence can help change that belief.

We would like to thank our collaborators Erica Ortlieb, Christine Böhmer, Robert Shadwick, and Anick Abourachid.

Additional resources

► S. Van Wassenbergh et al., "Woodpeckers minimize cranial absorption of shocks," *Curr. Biol.* **32**, 3189 (2022).
► A. A. Biewener, "Physiology: Woodpecker skulls are not shock absorbers," *Curr. Biol.* **32**, R767 (2022).
► L. J. Gibson, "Woodpecker pecking: How woodpeckers avoid brain injury," *J. Zool.* **270**, 462 (2006).
► E. R. Schuppe et al., "Evolutionary and biomechanical basis of drumming behavior in woodpeckers," *Front. Ecol. Evol.* **9**, 649146 (2021).

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Nature's defenses against erosion

The Great Wall of China still stands 2700 years after its first sections were built. But wind, rain, salt, and freeze–thaw cycles have severely deteriorated the World Heritage site, so much so that only about 6% of the nearly 9000 km structure remains well preserved. To better study the erosion, a research team surveyed numerous areas for new observations. Here Yousong Cao samples one of the sites. For many years conservators thought that the roots of mosses, lichens, and other vegetation exacerbated weathering and erosion of the wall. That thinking, however, has now been overturned.

The Great Wall was built predominantly with rammed earth: damp soil, sand, gravel, and other natural materials that are mixed with a stabilizer and compacted in a frame. Rammed earth is also a habitat for vegetation, and numerous sections of the wall are covered by biocrust—a community of microorganisms and plants. Cao and colleagues found that the sections with biocrust better protect the wall than the sections with none. They note that the biocrust sections have less porosity, water-holding capacity, and salinity than the bare sections. The biocrust also increases the wall's compressive strength and shear strength. (Y. Cao et al., *Sci. Adv.* **9**, eadk5892, 2023; photo courtesy of Bo Xiao.) —AL

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