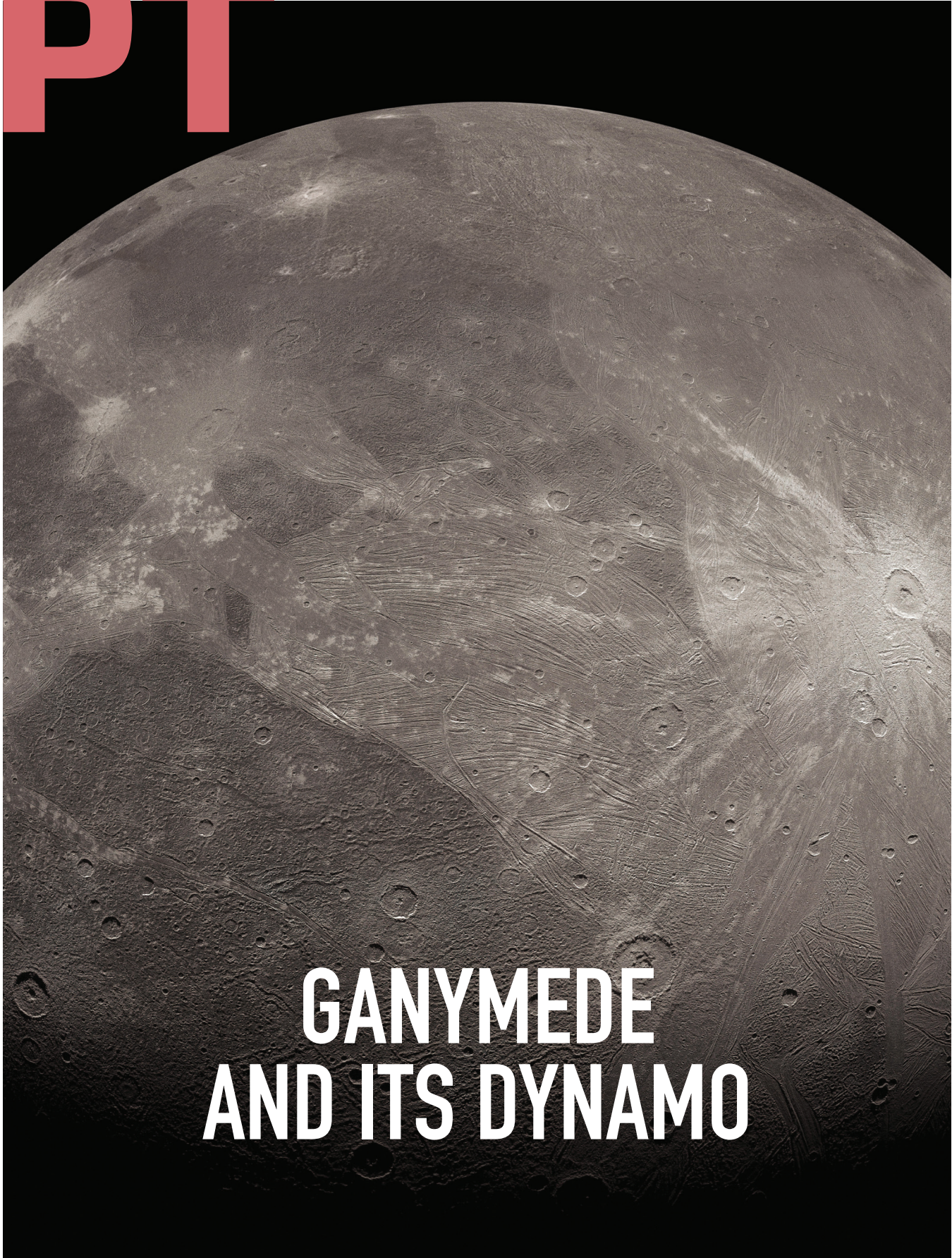


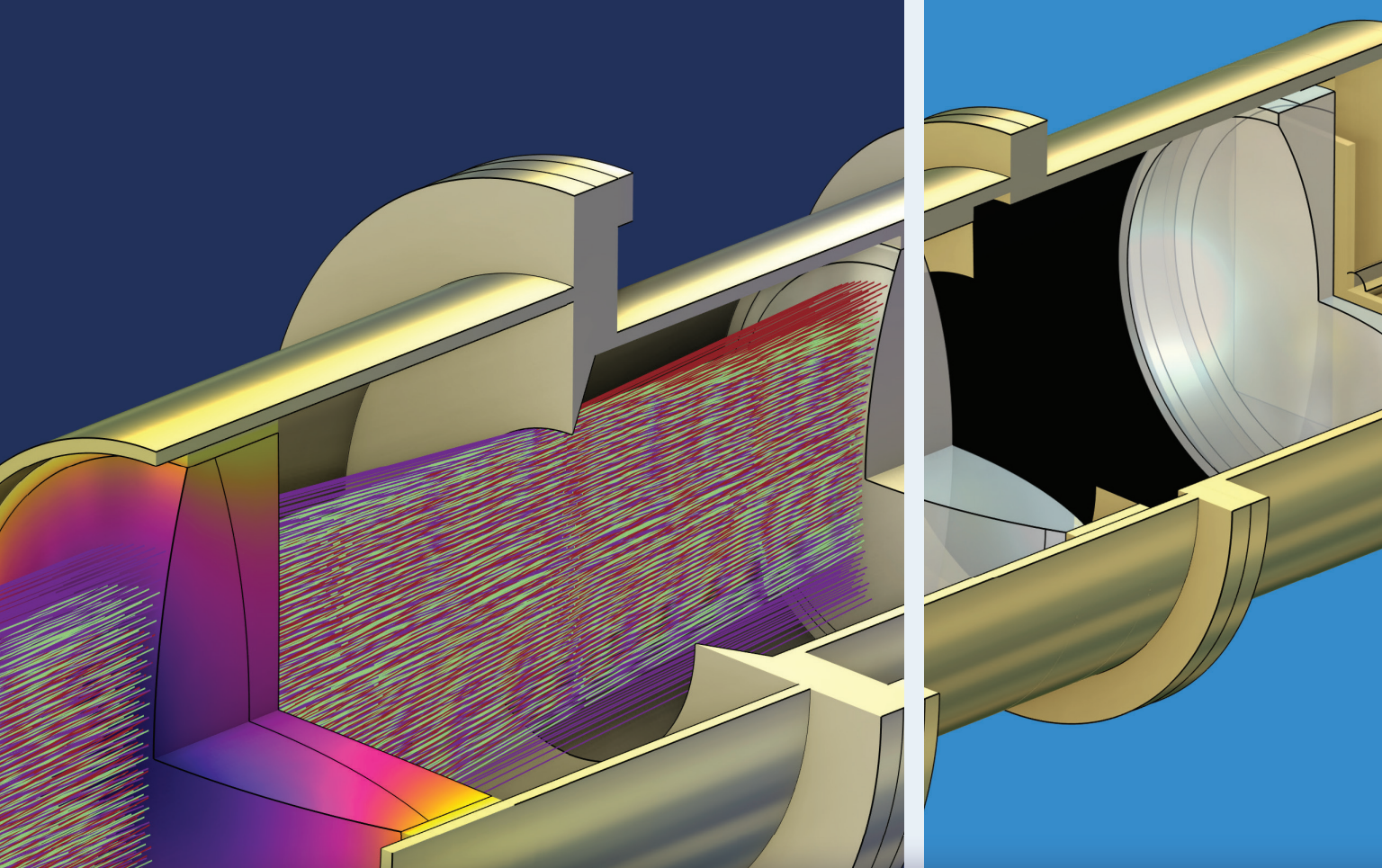


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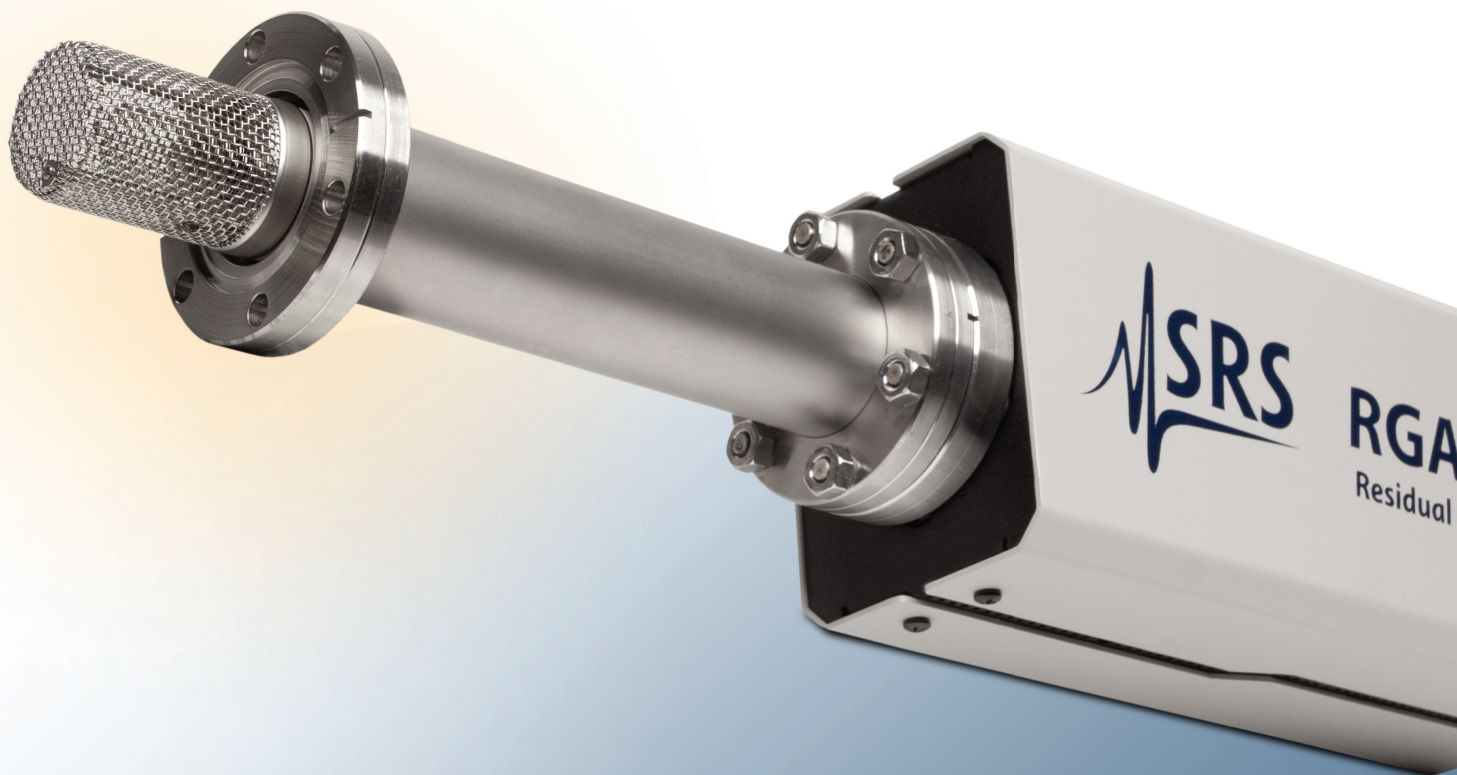
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Alan Robock, Lili Xia, and Zia Mian

Even a limited nuclear war could disrupt the climate, ecosystems, and global food supplies. Nuclear strategies and decisions should be required to factor in those potential consequences.



38 When it comes to science engagement, hire a professional

Jessa Barder

Researchers don't need to do science engagement alone. Working with professionals makes the job easier and more effective and can lead to better science.

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QUICK STUDY**A peek into the physics of squeaky sneakers****Gabriele Albertini**

When rubber-soled shoes skid on a hardwood floor, slip pulses travel between the two surfaces at high speeds to produce the familiar sound.

**ON THE COVER**

The Jovian moon Ganymede is the only moon of the hundreds in the solar system that has liquid metal flowing in its core. The resulting dynamo generates an observable magnetic field. A new model of the moon's slow-forming core shows that Ganymede's dynamo may have developed at a lower temperature than previously thought. The model also offers clues as to why moons similar to Ganymede, including neighboring Callisto and Europa, lack dynamos. To learn more, turn to **page 8**.

(Enhanced image from NASA/JPL-Caltech/SwRI/MSSS/Kalleheikki Kannisto © CC BY.)

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EDITOR-IN-CHIEF

Richard J. Fitzgerald rjf@aip.org

MANAGING EDITOR

Andrew Grant agrant@aip.org

ART AND PRODUCTION

Freddie A. Pagani, art director
Masie Chong, senior graphic designer
Nathan Cromer
Abigail Malate

EDITORS

Ryan Dahn rdahn@aip.org
Jenessa Duncombe jduncombe@aip.org
Laura Fattaruso lfattaruso@aip.org
Toni Feder tf@aip.org
Abby Hunt ahunt@aip.org
Alex Lopatka alopatka@aip.org
Gayle G. Parraway ggp@aip.org
Sarah Wells swells@aip.org

ASSISTANT EDITOR

Nashiah Ahmad nahmad@aip.org

DIGITAL OPERATIONS

Greg Stasiewicz glis@aip.org

EDITORIAL ASSISTANT

Tonya Gary

CONTRIBUTING EDITORS

Doug Mar
Lindsay McKenzie
Faith Simmons
Jacob Taylor
Clare Zhang

SALES AND MARKETING

Christina Unger Ramos, director cunger@aip.org

ADDRESS

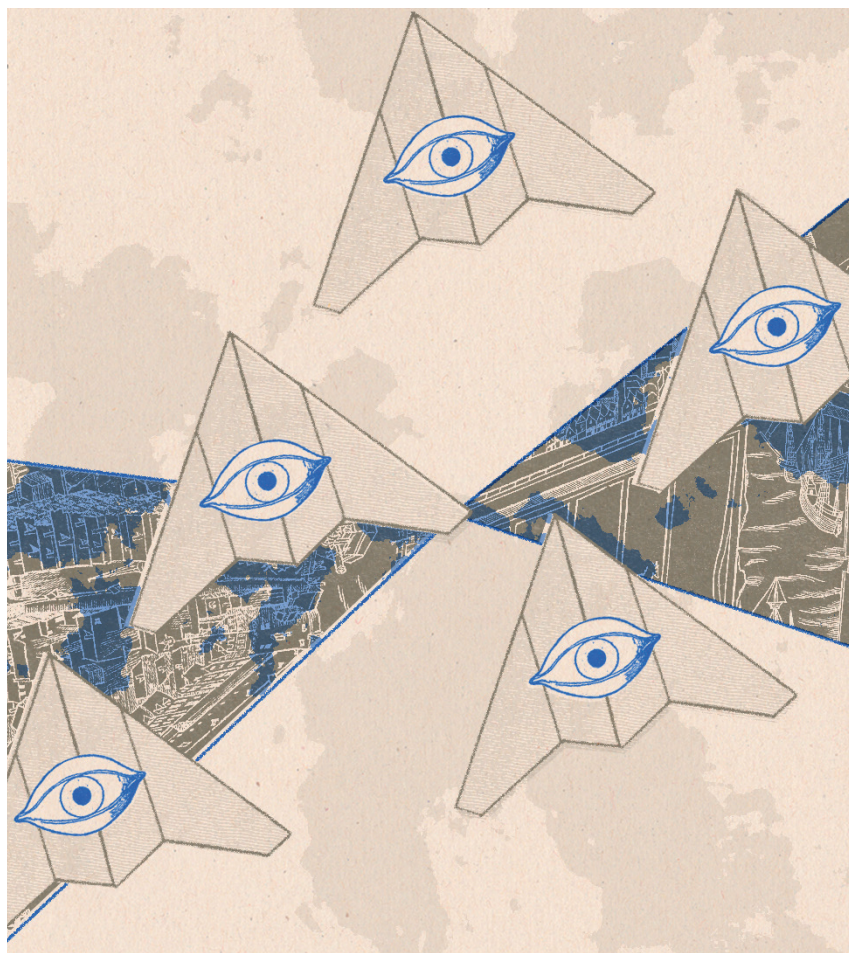
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TO READ ABOUT EXISTENTIAL-THREAT MITIGATION, TURN TO PAGE 16

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Slow-forming core could have fueled Ganymede's dynamo

Coalescing at a relatively low temperature may have helped the moon become the only one in the solar system to develop a magnetic field.

By **Alex Lopatka**

Of the hundreds of moons in the solar system, Jupiter's satellite Ganymede is the only one that's known to have an active dynamo. As liquid metal flows in the moon's core, circulating electric currents form and sustain a magnetic field. With just a handful of observations, modelers of Ganymede have conflicting assumptions about how the Jovian moon's core and dynamo formed. Now Kevin Trinh of Caltech and colleagues have reported simulations suggesting that Ganymede's dynamo began developing at a lower temperature than previously thought and, as a result, that the moon's core may be still slowly forming today.¹

Magnetic field evidence of Ganymede's dynamo was first detected in the 1990s by NASA's *Galileo* spacecraft. The detection led many modelers to assume that similarly to how Earth's dynamo was generated, Ganymede's must have been generated after a hot core had fully formed. But Ganymede and other icy moons are much smaller than Earth, so they produce less gravitational heating. The icy moons form more slowly and thus have limited amounts of aluminum-26 and other short-lived, heat-producing radioactive isotopes that are necessary to sus-



▲ Ganymede, the largest moon in the solar system, was imaged by NASA's *Galileo* spacecraft in the 1990s. *Galileo*'s magnetic field measurements revealed that the moon has an active dynamo. (Image by NASA/JPL.)

tain thermal convection and power a dynamo.

To address the contradiction, Trinh and colleagues adapted a cold-start model that Trinh and another group had developed for the neighboring moon Europa.²

The new Ganymede model starts with a mixed composition of rock, ice, and iron at 250 K. In that state, the mixture would have melted at temperatures lower than the melting point of pure iron. That would allow for Gany-

mede's core to form slowly. As the core differentiated from the rest of the mixture, the moon's interior temperature would have risen to 1250 K, and iron would then start to melt. The model shows that ongoing melting and core formation could sustain a dynamo whose properties are consistent with the *Galileo* magnetic field observations.

If Ganymede could start at a low temperature and sustain a dynamo, then why don't the neighboring Jovian moons of Callisto and Europa have dynamos? Trinh and others are still working on the answer to that question, and it may have to do with, among other factors, the moons' composition and tidal heating—the frictional heat that's dissipated when the moons expand and contract as they elliptically orbit Jupiter. Callisto, for example, has rock that's

richer in water than Ganymede's and likely experienced less tidal heating, and those factors would have inhibited ongoing core formation. Answers may be forthcoming, as the European Space Agency's *Juice* (*Jupiter Icy Moons Explorer*) spacecraft, which is scheduled to enter orbit around Ganymede in 2034, will collect more observations of Jupiter and its moons.

PT

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Wildfire emissions reverse declines in US surface ozone levels

A dataset of daily ozone concentrations with high spatial resolution enables researchers to identify the reversal.

By Sarah Wells

Created by a chemical reaction between nitrogen oxides and volatile organic compounds in the presence of sunlight, ground-level ozone can harm human health and vulnerable ecosystems. Since the establishment of regulations in the Clean Air Act, surface ozone levels in the US have declined from levels as high as 400 ppb in

some areas in the 1970s to peak values of roughly 70–90 ppb today. (Current measurements represent a daily maximum ozone level recorded in an eight-hour period.) But a new analysis by Jun Wang of the University of Iowa and colleagues has shown that the trend has reversed in the past decade because of ozone produced during wildfires.¹ The researchers estimate

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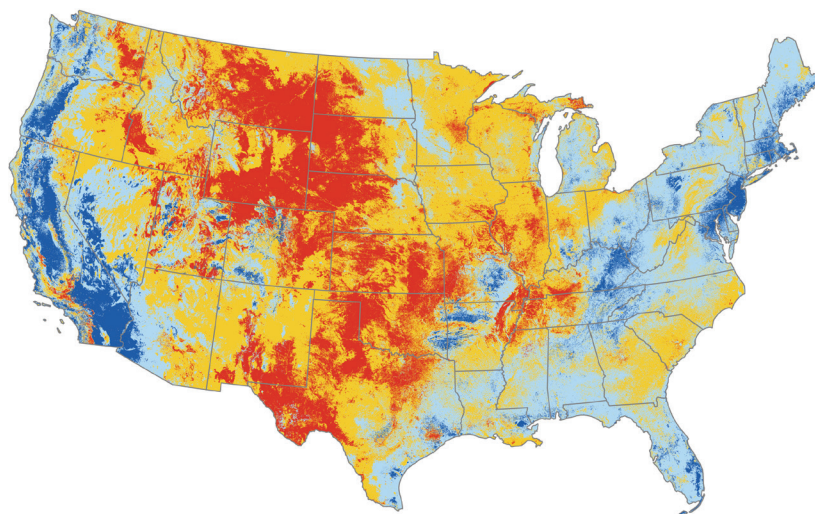
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◀ Some regions across the US have seen a decline in ozone-related air quality from 2015 to 2024 because of increased wildfire emissions, data from a deep-learning model reveal. Surface ozone (O_3) levels increased not only in the western US, where wildfires are more common, but also in the Midwest, where wildfire smoke is carried by wind. (Image courtesy of Weizhi Deng.)

■ Improving
(O_3 levels declining by > 0.50 ppb/yr)

■ Slightly declining
(O_3 levels increasing by 0 to 0.50 ppb/yr)

■ Slightly improving
(O_3 levels declining by 0.50 to 0 ppb/yr)

■ Declining
(O_3 levels increasing by > 0.50 ppb/yr)

that increasing ozone emissions from wildfires has contributed to more than 300 additional premature deaths per year from ozone-related health complications.

The Environmental Protection Agency tracks surface ozone concentrations by using more than 1000 air-quality monitoring stations across the country. Each covers approximately a 10 km radius, meaning that the stations cover only about 2% of the total US land area and 26% of the population. As a result, surface ozone data can be spatially sparse and incomplete, particularly in rural areas, and they may not fully capture nationwide trends. To create a richer dataset, Wang and colleagues used a combination of satellite and ground-station measurements and weather and air-quality models to train a deep-learning model to estimate daily surface ozone levels at 1 km resolution across the US from 2003 to 2024.

Other machine-learning models can underestimate the total number of extreme ozone events—for example, high ozone days that result from active wildfires churning out

nitrogen oxides and volatile organic compounds—because those events are underrepresented in the overall data. But high ozone days are becoming more common as a result of a warming climate, which has contributed to the increasing intensity of wildfires over the past decade and, in turn, to the growth in wildfire emissions. To address the data imbalance problem, Wang and colleagues trained their model to put additional weight on the rare but important events.

Using the new dataset, the team found that ozone levels fell at a rate of 0.65 ppb/yr from 2003 to 2015 but rose at a rate of 0.13 ppb/yr from 2015 to 2024. To isolate the impact of wildfire emissions, Wang and colleagues compared ozone-level estimates with and without those contributions and found that without the additional emissions, ozone levels would have continued to decline at a rate of 0.25 ppb/yr. And the modeling shows that wildfire emissions have affected the ozone levels not only in the western US, where the environment is more prone to fires, but also in the Midwest because of wind spread-

ing the pollutant. The figure illustrates where in the US air quality has improved or declined from 2015 to 2024 as a result of changing ozone levels. The researchers' estimate of some 300 additional premature deaths per year came from their analyzing the connections between ozone levels, wildfire emissions, and human health.

Wang says he hopes that the data can be used by public health researchers to better understand the impact of rising ozone levels on human health and to develop tools, such as high-resolution monitoring and forecast systems, to help better alert the public of their exposure to local surface ozone. Findings from the work, he says, could also potentially help in identifying sparsely monitored regions with rising ozone levels, like the Texas Panhandle, that might be included in a more robust monitoring network.

PT

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Chip-scale gyroscopes get a sensitivity boost

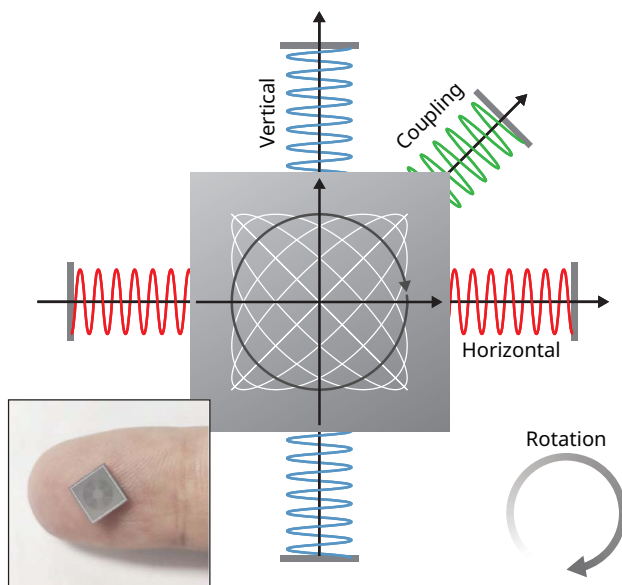
By tweaking a standard microscale gyroscope, researchers were able to significantly amplify the signals used to measure rotation.

By **Laura Fattaruso**

Gyroscopes have come a long way from some of their earliest applications in nautical navigation. Tiny versions of the devices are now used to stabilize drones, measure movement in GPS-enabled equipment, and help smartphones track users' steps throughout the day. But shrinking sizes come at a cost. Random fluctuations caused by temperature changes introduce noise that obscures the measurement of subtle rotation signals and thus limits the gyroscopes' sensitivity. Now Hui Jing of the National University of Defense Technology

and Xin Zhou of the Southern University of Science and Technology, both in China, and their colleagues have shown how small adjustments to a chip-scale gyroscope can yield a nearly 300-fold increase in its precision.¹

In a classical gyroscope, the displacement between a spinning disk and its surroundings can be used to measure rotation. The miniaturized versions in electronics, known as Coriolis vibratory gyroscopes, instead use vibrating materials that experience predictable and measurable forces when rotated. Both types of devices take advantage of



▲ **Figure 1.** A standard chip-scale Coriolis vibratory gyroscope measures rotation in a disk resonator by using two orthogonal oscillations, represented here as red and blue springs. By tuning the stiffness of the disk resonator along a third, intermediate orientation, represented by the green spring, researchers were able to increase the oscillation frequency shifts produced when the device undergoes small rotations. The chip shown in the bottom left measures 8 mm × 8 mm. (Figure adapted from ref. 1.)

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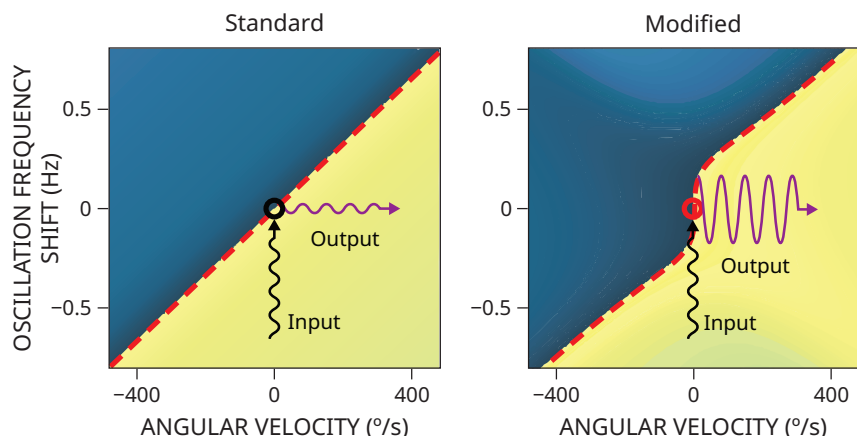
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◀ **Figure 2.** For a standard Coriolis vibratory gyroscope (**left**), the change in the oscillation frequency is linear relative to the angular velocity that produces it. By modifying the standard design (**right**), researchers were able to tune the system and produce a larger frequency shift response, particularly for small angular velocities, as shown by the dashed red line. (Figure adapted from ref.1.)

the Coriolis effect—the deflection of a moving object subject to rotation. The standard configuration for chip-scale gyroscopes involves a disk resonator made of concentric rings connected by spokes that undergoes horizontal and vertical oscillations, represented by the red and blue springs in figure 1. The Coriolis response in such devices is essentially linear: A small rotation yields a proportionate, small change in the oscillation frequency.

Research aimed at improving the precision of small-scale gyroscopes often focuses on noise reduction. Drawing inspiration from recent work on optical gyroscopes, Jing, Zhou, and colleagues wondered whether they could alter the device to instead amplify the response signal. They found that by tuning the stiffness of the system along a third orientation between

the vertical and horizontal oscillations, represented by the green spring in figure 2, they could alter the system response so that the effective Coriolis factor—the change of oscillation frequency relative to the angular velocity—increased by three orders of magnitude.

The study serves as a proof of concept for how to build chip-scale gyroscopes with higher sensitivity, but additional work is needed for such devices to be commercially viable. To tune the frequency response of the system, the researchers needed to precisely calibrate the coupled stiffness. It will be a challenge to maintain that precision under real-world operating conditions. The nonlinear signal also complicates the translation of the signal into a measurement because it requires more complex calculations and calibration, which

would need to be accounted for in a commercial design.

Many settings where gyroscopes are already used would benefit from increased sensitivity and precision, such as in vehicles and cameras for stabilization, in surgical devices for movement tracking, and in places where GPS calibration is unavailable. “The key idea,” says Zhou, “is not limited to one specific gyroscope design.” He says the principle behind the design “may be useful in other inertial sensors and possibly in other precision measurement systems where weak perturbations need to be detected.”

PT

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Fault movement may affect erosion as far as 100 km away

Land that has been damaged by the cumulative activity of faults may be more susceptible to geomorphological changes, like landslides.

By **Sarah Wells**

Crustal movement along fault lines sculpts the land by triggering earthquakes, reshaping rivers, and uplifting rocks, such as

those shown in figure 1. It’s well known that along with producing earthquakes that cause sudden damage through pulverization, active faults can gradually frac-

ture and weaken rock that is up to a kilometer away. To better understand how far the tectonic damage may reach, Boontigan Kuhasubpasin (then at UCLA) and



▲ **Figure 1.** These rocks at the Vasquez Rocks Natural Area park in Southern California are the result of uplift caused by tectonic movement along the San Andreas Fault. In new work, researchers observed signs of fractured rock and high erosion rates in areas up to roughly 10 km from that fault. (Photo by iStock.com/hmlCA.)

colleagues analyzed erosion rates at river basins worldwide.¹ They determined that erosional efficiency, a measure of how effectively eroding forces move material away, was elevated as far as 100 km from an active fault. The research team also proposed that repeated shaking from earthquakes compounded the effects over time, making rock more susceptible to geomorphological changes caused by weathering or landslides.

Unlike earthquakes, erosion takes place over millennia. To understand

how a landscape changed over time, researchers can measure the concentration of the long-lasting isotope beryllium-10. Cosmic rays interacting with quartz near Earth's surface produce *in situ* ^{10}Be , which accumulates in the upper few meters of exposed rock. High ^{10}Be concentrations indicate relatively slow erosion, whereas low concentrations suggest rapid removal of near-surface material by erosional processes. Kuhasubpasin and colleagues looked at more than 1700 ^{10}Be -derived erosion rates from

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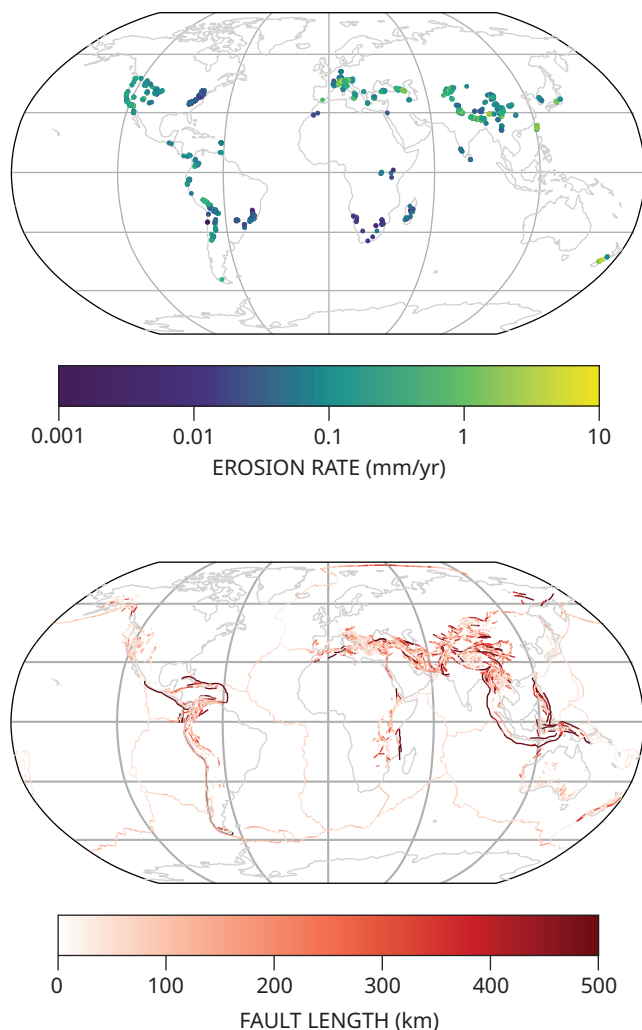
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▶ **Figure 2.** Global maps of both the erosion rates calculated from concentrations of beryllium-10 at river basins (**top**) and the distribution of active faults (**bottom**). The highest rates of erosion are shown in yellow and green, and the longest faults are shown in dark red. Using statistical modeling and machine learning, the team compared the maps and found that distance from faults had more influence on erosion than did other potential factors. (Figure adapted from ref. 1.)

across the globe and then analyzed potential sources of the erosion in those areas. The factors included mean annual precipitation, rock type, distance from active faults, and a measure of seismic shaking intensity called peak ground acceleration.

Using statistical and machine-learning models to evaluate the influence of those factors on erosion, the team found that the distance from an active fault was the primary predictor of erosional efficiency in the sampled area. Figure 2 illustrates that relationship. Erosional efficiency was at its highest up to 15 km away, and it was still elevated up to 100 km away. The team also found that the effects were strongest near large reverse faults, where rock that lies above the fault plane is forced up, and that there was a positive correlation between erosional efficiency and peak ground acceleration. To support their data analysis, the researchers analyzed previous field measurements taken near the San Andreas Fault in California. They observed signs of fractured rock

and higher erosional efficiency in areas up to roughly 10 km from the fault, though not in areas beyond that distance.

The finding suggests that repeated exposure to seismic shaking can contribute to the weakening of surrounding rock by disrupting grain boundaries and expanding fracture networks. There are still uncertainties, including how grain-to-grain disturbances propagate through rock and influence sediment dynamics, that researchers can work to better understand, says Kuhasubpasin. Altogether, the work offers a new way for researchers to understand the role of tectonic damage in geomorphological change, especially in regions where it was previously underestimated.

PT

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Multidisciplinary teams seek ways to mitigate existential threats

Nuclear winter, climate change, bioterrorism, AI. Those and other threats are growing in potential impact. What can we do?

By **Toni Feder**

What's your worst nightmare? For astrophysicist Martin Rees, it's an engineered pandemic or the breakdown of global networks for electricity and the internet—events that could produce a catastrophe on the global scale and even threaten human existence. “You can detect if someone is building a nuclear weapon,” he says, “but a lone person in a lab can create a pathogen. I worry about how to eliminate the risk without intrusive surveillance.”

Seeking ways to prepare for and prevent such global catastrophes, Rees, philosopher Huw Price, and Skype cofounder Jaan Tallinn started the Centre for the Study of Existential Risk (CSER) at the Uni-

versity of Cambridge in 2012. A few years later, physicist Daniel Holz founded the Existential Risk Laboratory (XLab) at the University of Chicago.

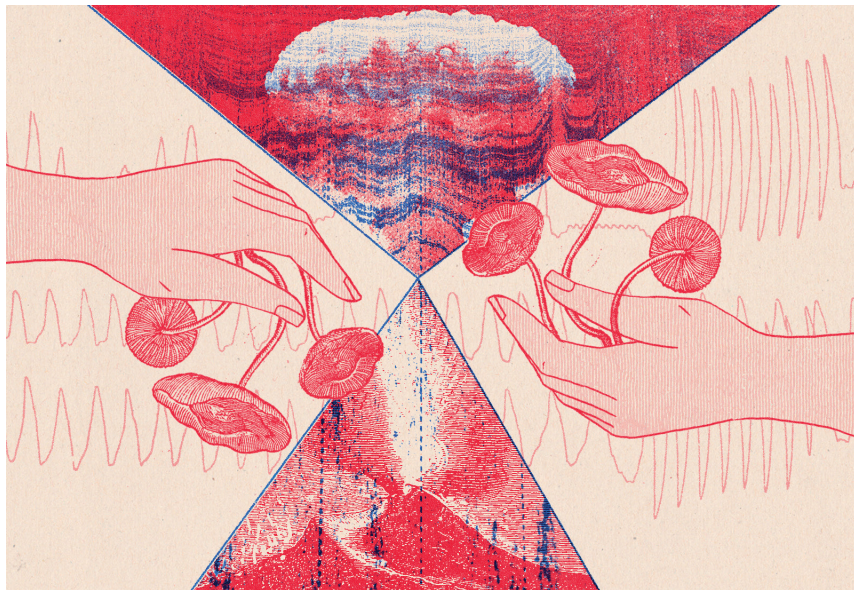
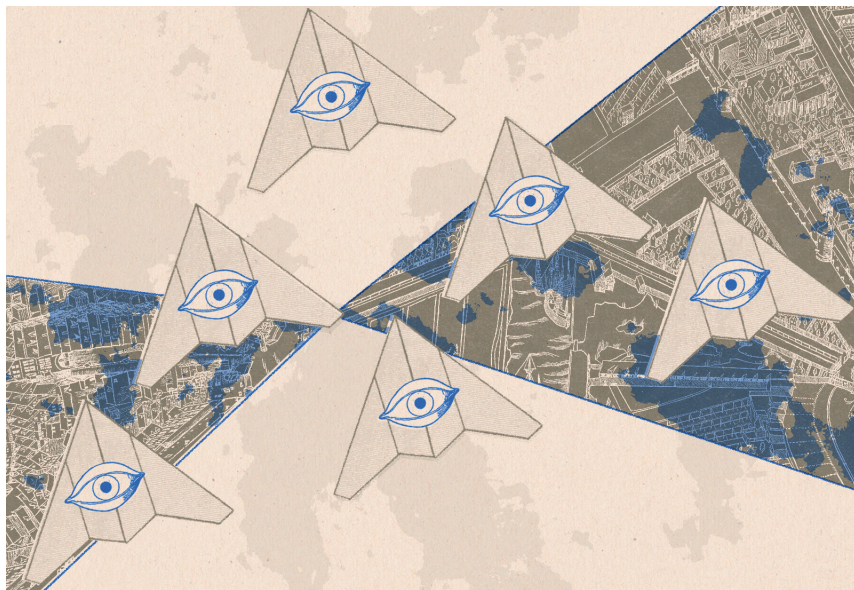
“Physicists have a moral responsibility to engage with potentially catastrophic risks associated with scientific advancement,” says Holz. “And I think that cosmologists, given their familiarity with the size and age of the universe, are predisposed to see the big picture and perhaps to have a unique perspective on humanity’s fragility.” (One of XLab’s funders is the Future of Life Institute, a nonprofit organization concerned with existential risks. The institute was started by MIT’s Max Tegmark, who, like Rees and Holz, has roots in cosmology.)

CSER and XLab are among a handful of centers that address multiple existential risks; it’s more common to focus on a single one, such as climate change or nuclear war. In addition to those topics, the centers variously take on AI, engineered biology, other new technologies, mis- and disinformation, and natural disasters. Both centers bring together multidisciplinary teams that include physicists, epidemiologists, computer scientists, political scientists, economists, and social scientists.

“The effects and implications of different risks spill over and can be intertwined,” says CSER director S. M. Amadae. As an example, she notes that a volcanic eruption, events caused by climate change, and a nuclear winter can all lead to food



▲ At the Existential Risk Laboratory at the University of Chicago, researchers consider how to prepare for and mitigate global threats. This image greets visitors to the lab’s website. (Screenshot courtesy of UChicago XLab.)



▲ Stark depictions intended to show the complexities of different existential risks were created by an illustrator and by a researcher with the Cambridge University Centre for the Study of Existential Risk. The top picture shows how defense technologies can be used for both protection and surveillance; the bottom one represents the ways humans can both respond to and create hazards. (Images courtesy of the Centre for the Study of Existential Risk.)

insecurity. Considering multiple global threats “enables a broader-minded analysis than focusing on one risk at time,” she says. “Interventions and strategies to build resilience at all levels of governance can be helpful for multiple risks.”

“When you worry about the risks of AI,” says Holz, “it’s generally AI

plus something else: AI and nuclear command and control. AI and infrastructure. AI and cyberattacks. AI and disinformation.” But if you want to truly understand the threats and how to mitigate them, he says, “you have to look at their interconnections.” What’s more, he says, students involved in XLab

want to be broadly informed. “It’s not satisfying to them to be told, ‘Pick only one threat that you’re worried about, and go work on that.’”

“We look for concrete ways to mitigate the risks,” says Amadae. One CSER researcher developed a bond-index research project to help big investors monitor where their money is going and to, for example, choose against investing in fossil fuels or AI. Other CSER researchers have embedded in government agencies to convey to civil servants and policymakers findings for mitigation approaches on arms control, online regulation, and other areas. The center also has participated in role-playing exercises with military leaders “to help them understand how easily they can make decisions that increase the risk of conflict,” says Amadae. “It was eye-opening how easy it was to convince them to buy more types of weapons.”

Future leaders

Last year, CSER launched a one-year master’s degree program in global risk and resilience with the aim of educating future leaders to play a role in the analysis and mitigation of existential risk. The first cohort consisted of about 30 students from 14 countries; their backgrounds are in math, philosophy, medicine, politics, and other areas. They graduated in July, and they are moving into jobs in finance, the civil service, think tanks, and more. Some, says Amadae, are interested in the center’s planned PhD program, which will welcome its first students in fall 2027.

XLab plans to eventually offer a degree program. “The ultimate goal is to create a new discipline that holistically addresses existential threats,” Holz says. For now, XLab offers an undergraduate class called “Are we doomed?,” runs a



▲ The inaugural class of the global risk and resilience master's degree program at Cambridge University graduated in July. (Photo courtesy of the Centre for the Study of Existential Risk.)

10-week summer research fellowship, supports undergraduate and graduate students doing research year-round, and organizes conferences (including, for example, the conference highlighted in *PT*'s 2025 story "Nobel laureates issue declaration for the prevention of nuclear war"). More than 100 students from across the globe have participated in the summer program since it began

in 2022, says Holz. Examples of past research topics include strategies for deterring a nuclear weapons-capable Iran, climate consequences of nuclear winter, wastewater-based surveillance techniques for monitoring pandemics, and situational awareness and deception in AI agents.

Jo Jiao is a University of Chicago math and philosophy double major. She co-initiated an undergraduate

XLab AI safety group that hosts speakers, runs AI strategy and research groups, and offers a fellowship for students to learn about AI governance, security, and safety research. AI presents two main areas of risk, she says: misuse ("How do you prevent malicious actors from using AI to bad ends?") and super-intelligent AI ("You would be worried about a smart system conspiring against humans"). University students are at the start of the talent pipeline, she notes: "We are trying to get students interested in AI safety and to help them orient their careers to make sure that AI is developed safely and to mitigate potential catastrophe."

Be prepared

"There are many steps we can take to reduce threats. Engagement is very important," says Stephen Luby, a public-health physician and Stanford University professor who cofounded the Stanford Existential Risks Initiative. He is involved in designing a bioreactor that captures waste methane and converts it to protein to support aquaculture. "If we can make it efficient and profitable, it would offer scalability and resilience in the face of a food supply shortage," he says.

More broadly, says Luby, "there are huge technical agendas for figuring out what humanity can do to lower risk."

CSER and other centers are "a small step," says Rees. In an ever-more interconnected world, he says, a catastrophe stemming from "error or terror" can cause devastation and societal breakdown that cascades globally. Such threats are growing in potential impact as AI and biotechnology advance. Minimizing their likelihood should be higher on the agenda of governments, he says. "We need to be more prepared."

PT

Muon detectors for the people!

The specialized devices are democratizing access to cosmic-ray experiments.

By **Jenessa Duncombe**

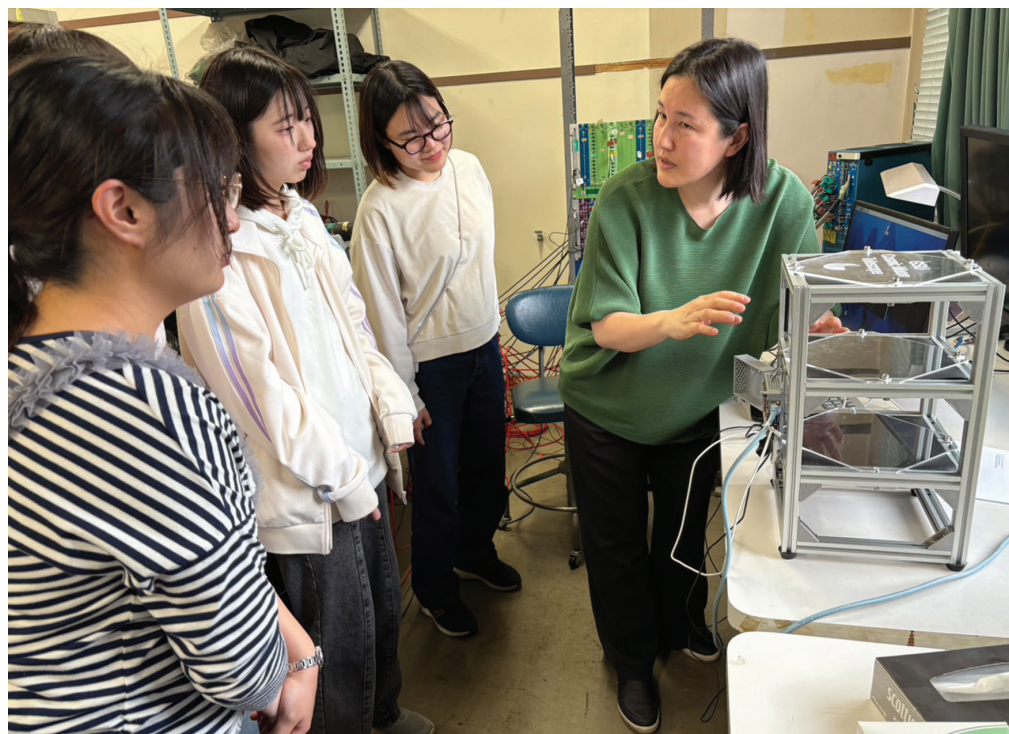
Handheld and tabletop muon detectors have proliferated in high school and college classrooms in recent decades. The instruments are safe, low cost, and durable, and they open possibilities for exploration in physics, space-weather studies, and atmospheric science. Several programs, shown in the table on page 20, have taken different approaches to supplying muon detectors to students and researchers. Together, the initiatives have resulted in the deployment of thousands of muon detectors worldwide, according to estimates by program organizers.

When a cosmic-ray proton or nucleus that comes from the Milky Way, another galaxy, or the Sun and travels near the speed of light collides with Earth's atmosphere, the clash produces a shower of particles. Those particles can decay into muons, subatomic particles that have the same charge as electrons but are 200 times as massive. Muons at rest have a lifetime of just a few microseconds, but if cosmic-ray muons are

moving fast enough, relativistic time dilation will allow them to survive long enough to reach Earth's surface. About two to three muons per second pass through an outstretched hand of someone on Earth.

Showers of muons provide ample potential for experiments with small-scale detectors. For example, people interested in physics and astrophysics can deploy muon detectors to study special relativity, radioactive decay, or gamma rays. Those interested in space or planetary weather can measure hurricanes or the onslaught of coronal mass ejections. Those scrutinizing human civilizations can study muons passing through ancient ruins. (See *PT*'s 2004 story "Muons may unlock secrets of Teotihuacan.")

The primary goals of two muon-detector programs, CosmicWatch and QuarkNet, are outreach and education. Spencer Axani, a University of Delaware physics professor who founded CosmicWatch while a graduate student at MIT, says he receives frequent emails from high school and undergraduate students who



◀ Physics professor Shimomura Maya at Nara Women's University in Japan shows students a tabletop muon detector from the gLOWCOST program in April 2025. (Photo courtesy of Xiaochun He.)

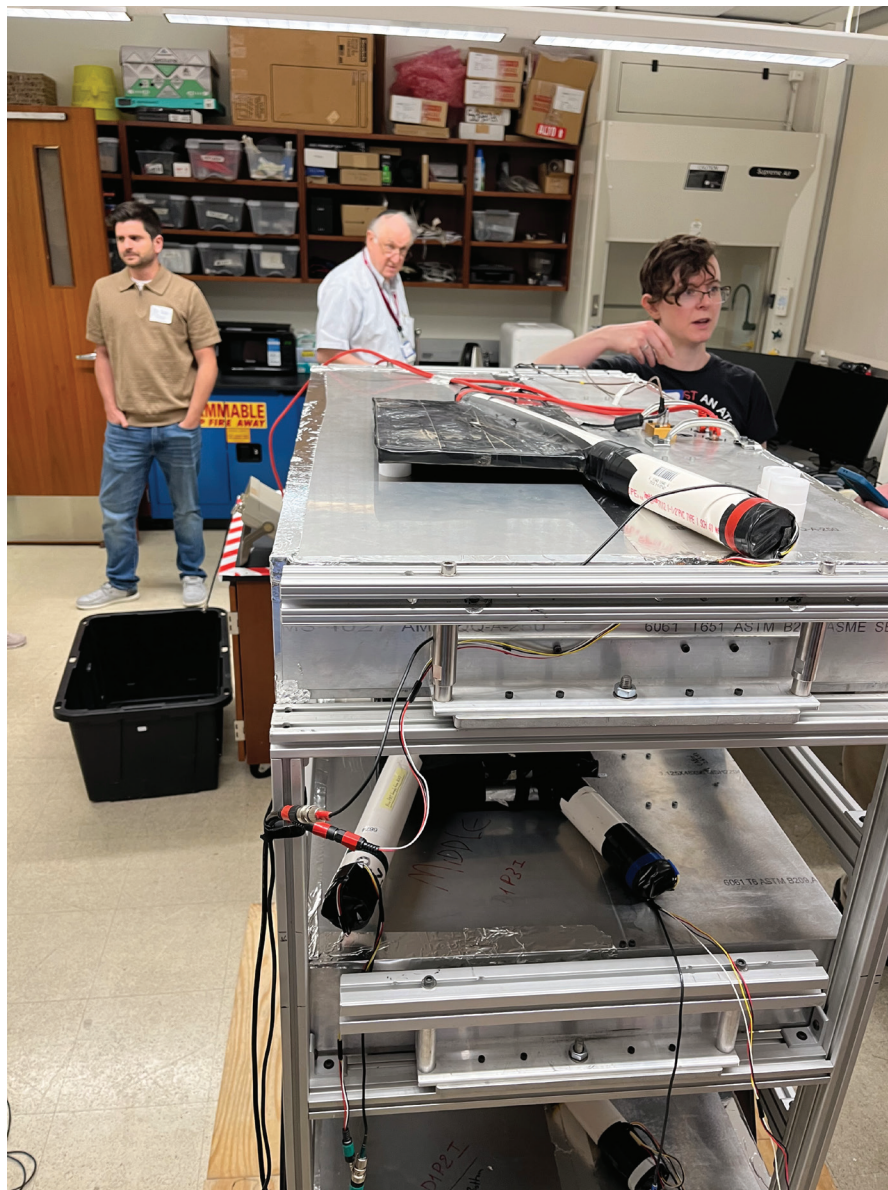
Program	QuarkNet	CosmicWatch	gLOWCOST
Founded	1998	2017	2023
Organizers	Fermilab and the University of Notre Dame	University of Delaware and MIT	Georgia State University
Muon detector	Tabletop; provided either disassembled or fully assembled	Handheld; provided either disassembled or fully assembled	Tabletop; provided fully assembled
Primary users	High school classrooms	Individuals; high school and college classrooms	Research laboratories; middle school, high school, and college classrooms
Data sharing	Online data portal	Under development	Daily plots; data available on request
Funders	DOE, NSF	NSF, MIT, SensL, Wisconsin IceCube Particle Astrophysics Center, National Centre For Nuclear Research (Poland)	Georgia State University, DOE, NSF
Distribution	Several hundred	3000–5000	28
Cost	Free for participating teachers; valued at \$3000–\$4000	Estimated cost of purchasing DIY electronics, \$100; fully assembled detector sold for \$299 or as a pair for \$499	Free for participating groups; valued at approximately \$700

are designing experiments using CosmicWatch detectors for their applications for college and graduate school. Some undergraduate physics courses now distribute CosmicWatch detectors to students for coursework. (See Axani's 2017 *PT* article “An easy-to-build desktop muon detector.”)

QuarkNet pairs particle physicists with high school teachers through 50 regional teaching hubs in the US. The program distributes muon detectors and instructs teachers on how to teach with them. Some 400–500 teachers per year are involved in the program, says Mark Adams, an emeritus physics professor at the University of Illinois Chicago and a QuarkNet master

teacher. Dozens of participating high schools have banded together over the years to monitor storms, coronal mass ejections, and eclipses with QuarkNet detectors. Teachers often hang on to their detectors until retirement, says Adams, who helps refurbish them and sends them to new teachers.

The newest of the programs is gLOWCOST (global low-cost observation of the dynamic changes in the space weather and terrestrial weather). It distributes fully assembled and calibrated tabletop muon detectors to research groups worldwide. Xiaochun He, a physics professor at Georgia State University and gLOWCOST's founder, believes that if the project is



◀ QuarkNet muon detectors stacked in a cosmic-ray experiment for a teacher training. For this activity, the paddle-like detectors are measuring the muon rate as a function of zenith angle. (Photo by Mark Adams.)

successful, it will not only provide outreach opportunities for middle and high school students but also create a global cosmic-ray muon-flux monitoring network for space and terrestrial weather. He says his goal is to deliver detectors to researchers in more than 100 countries in the next five years.

These outreach activities can inform research, says Janet Conrad, an MIT physics professor and CosmicWatch cofounder. CosmicWatch's prototype inspired the "grandchildren" of cosmic-ray detectors installed in the recent upgrade to the IceCube Neutrino Observatory, says Conrad. (See *PT*'s 2026 news story "IceCube expands neutrino search to spot fainter signals.")

Physics professor David Ruffolo at Mahidol University in Thailand has advised teachers using CosmicWatch detectors in high school classrooms in the country. He is enthusiastic about the benefits for students, though he cautions teachers from expecting publishable results from individual, small muon detectors. Time-dependent atmospheric effects and the influence of the local environment on cosmic-ray muon flux at ground level makes achieving statistically significant results difficult. "For a small muon detector," he says, "it is better to stress the student experience, and not to place expectations on scientific output."

PT

If CERN can come up with the requisite billions, the Future Circular Collider is a go

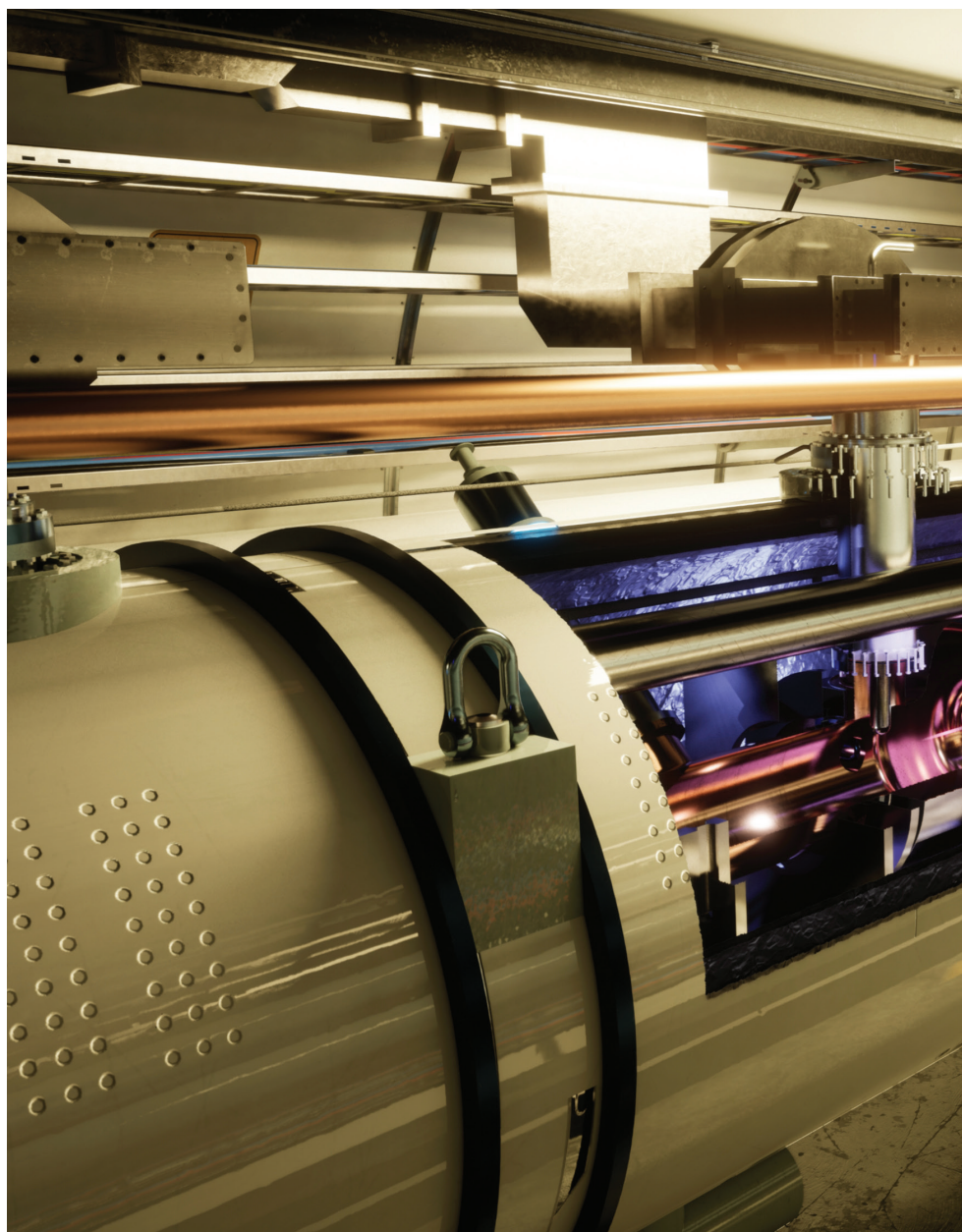
Europe's particle physicists choose a 91 km electron-positron collider as the next global flagship project.

By **Toni Feder**

The CERN Council in May agreed to move ahead with the 91-km-circumference electron-positron Future Circular Collider (FCC-ee). Now CERN has two-and-a-half years to see if it can scrape together 15.3 billion Swiss francs (about \$19 billion) to realize the project by the mid 2040s.

The number-one priority of Europe's particle-physics community is the high-luminosity upgrade of the Large Hadron Collider (HL-LHC); the vast amount of data it will produce will allow scientists to seek new particles and carry out precision studies of the Higgs boson. Next is the FCC-ee, which would study the Higgs boson, the electroweak sector, top-quark physics, flavor observables, and precision quantum chromodynamics. (See *PT*'s August 2025 story "Europe's particle-physics community weighs its next collider," by Matt von Hippel.)

The community also says that experiments and theoretical work should continue in other areas of particle physics and that particle-physics laboratories across Europe should strengthen ties with CERN. Those and other recommendations are spelled out in a European Strategy for Particle Physics 2026 update that was adopted in May by the CERN Council.



The LHC shuts down in late June for the high-luminosity upgrade. It's slated to reopen in 2030 and to run through 2041. Florencia Canelli is a professor at the University of Zurich and is the Swiss scientific delegate to the CERN Council. She notes that to stay at the frontier of science after the HL-LHC shutters for good, "the field needs ambition." It's also important, she says, for students to see

particle physics as "a thriving field with a clear vision."

With that in mind, the HL-LHC schedule determines the FCC-ee timeline: To avoid a prolonged gap in activity, CERN is giving itself through 2028 to rustle up commitments for funds and to decide whether to proceed. If approved, construction would start in the early 2030s and data collection could begin around 2045.

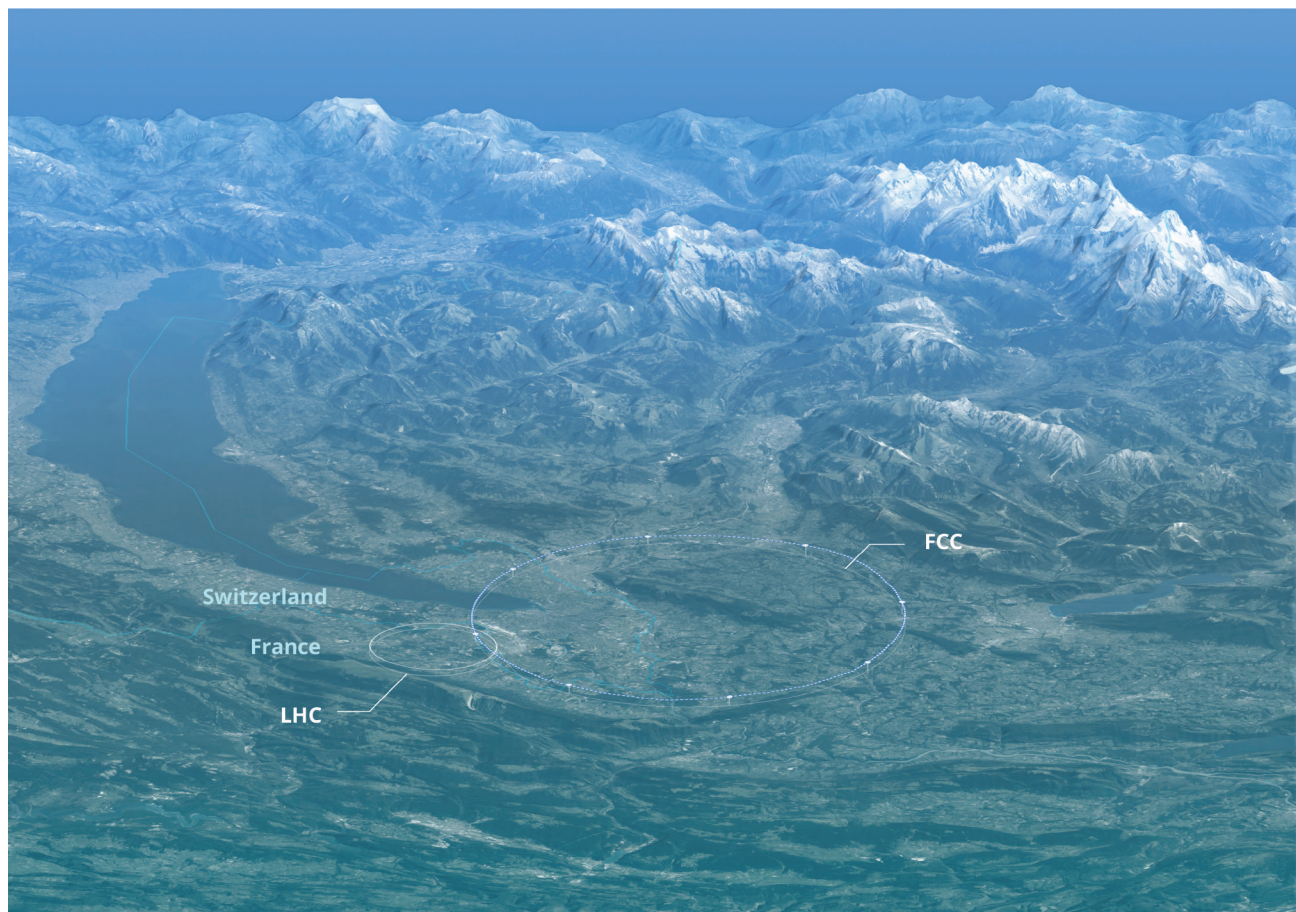
The price tag exceeds what CERN can pay out of its budget, says Karl Jakobs, strategy secretary and a professor at the University of Freiburg in Germany. To go ahead with the project, he says, additional funding to the tune of several billion Swiss francs would need to be found.

Member states may be too squeezed to contribute more than they already pay toward CERN's budget, says Jakobs, especially with many of them upping their investments into defense because of the war in Ukraine. Nonmember states are hoped-for sources of additional funds. Participation by China, Japan, the US, the European Union, and other major particle-physics communities could be crucial to realizing the FCC-ee, says Daniela Bortoletto, a professor of particle physics at Oxford University.

Notably, China's particle-physics community has expressed interest in participating in the FCC-ee. China has its own concept for a similar machine, the Circular Electron Positron Collider. (See *PT*'s 2018 story "China plans a Higgs factory.") But the CEPC is not in China's 2026–30 financial plan. Yifang Wang, who leads the CEPC project, says that for now, "we will try our best to gain support from



◀ An artistic representation of the Future Circular Collider. Some 102 cryomodules, several of which are shown, would contain a total of 408 RF cavities and accelerate the electrons and positrons to center-of-mass energies ranging from 88 GeV to 365 GeV. (Image created by the CERN audiovisual team, courtesy of CERN.)



▲ The Future Circular Collider would require digging a 200-m-deep tunnel with a 91 km circumference straddling France and Switzerland. The location of the Large Hadron Collider is also indicated. (Image adapted with permission from CERN.)

the Chinese government to join the FCC. Our community is united to support this position.” But if the FCC-ee doesn’t get the green light by 2029, he says, China’s particle-physics community will try again to get the CEPC approved.

Last year, the Breakthrough Prize Foundation, the Eric and Wendy Schmidt Fund for Strategic Innovation, and others pledged a combined \$1 billion toward the FCC-ee. The gifts are the first-ever private donations to a major CERN project.

If money for the FCC-ee can’t be raised, the European particle-physics community’s second choice would be a descope version of the machine. Savings of about 15%

could be had by building two particle interaction sites rather than four, lowering the RF system power by 40%, and scrapping the top-quark program. But there’s not a lot of room for trimming, explains Jakobs, because slightly more than a third of the total project cost is for the excavation of the 200-m-deep, 91 km tunnel that would house the collider.

Only if money falls short even for a descope FCC-ee, Jakobs says, would the community consider other collider options. The alternatives—linear colliders and circular ones that would use the existing LHC tunnel—are inferior. The FCC-ee would have a larger physics reach, be technically more advanced, and

pave the way for a transition to a 100 TeV hadron collider, the FCC-hh. A technical feasibility study completed last November found no technical barriers to building the FCC-ee.

CERN has begun engaging with local communities in Switzerland and France; the machine would straddle the border. The collider’s placement was chosen carefully to minimize dirt, noise, and traffic while the tunnel is being built, says Ursula Bassler, CERN’s director of stakeholder relations. The lab is also evaluating water and energy use to minimize the impact on the environment, she says: “We have to make a big effort to minimize nuisance to the population.” **PT**

Q&A: Alice Flarend teaches teens to think out loud

The seasoned high school physics teacher challenges students to engage in an increasingly distracted world.

By **Jenessa Duncombe**



▲ (Photo courtesy of Alice Flarend.)

“Students come to my classroom and say, ‘We’ve heard about you,’” says Alice Flarend. As a physics teacher for 26 years at Bellwood–Antis High School in rural central Pennsylvania, she has earned a reputation by asking her students to explain out loud what they’re thinking. In the classroom, she says, “the power of talk is huge.”

Flarend grew up in Chicago, where her father was an electrician at a steel mill and her mother was a secretary. Despite having no “nuclear roots,” Flarend took an interest in nuclear science in a high school chemistry class and focused on nuclear engineering for her bachelor’s and master’s studies. Midway through her doctoral program, she pivoted to teaching high school.

Unlike typical high school physics courses, Flarend’s classes include modern-day physics topics such as quantum information science. She trains other teachers in the subject and has cowritten two quantum physics books aimed at high school students. In 2023, she received the Paul W. Zitzewitz Award for Excellence in K–12 Physics Teaching from the American Association of Physics Teachers (AAPT).

The following interview has been edited for length and clarity.

Tell me about your path into teaching.

I went to the University of Michigan for my PhD in nuclear engineering

and had a great adviser, but I found out I was much more interested in why people didn't understand nuclear science. This was post-Chernobyl, and I remember Greenpeace protesting nuclear energy on campus.

A group of us nuclear engineering graduate students would visit schools. More than one teacher said, "We want to know about how things blow up." We would tell them that nuclear reactors don't blow up like a nuclear bomb. We were hearing people's ideas that nuclear energy is so inherently dangerous.

These experiences were way more interesting to me than going to my PhD lab. So, I thought I'd try teaching for a year and see if I liked it. If not, I told myself that I'd go back and get my PhD and make more money. I found an all-girls private school in Toledo, Ohio, called St Ursula Academy. They hired me.

How did it go?

Before I took the job, I had done some cursory reading on teaching. And I thought I had to explain science clearly and do hands-on problems. But the people-management aspect of teaching is something that was very unexpected to me. Working in a PhD lab, the neutrons I worked with didn't care if it was Monday or Friday afternoon. My neutrons didn't have a dog that died or a boyfriend that broke up with them. That aspect was very challenging for me and still is. But I ended up really liking it.

You've been teaching high school for more than 30 years. How has your approach changed?

Something I struggled with early in my career is the question, "Is my job to prepare kids for college physics, or is my job to help them understand physics?," which in a way are two different things. I'm on the

"Let's have them understand physics" side. I can help them be curious and to not think of physics as plugging numbers into an equation. If they can live a more interesting scientifically minded life, not be scared of it, that's worth it.

What's one way that you bring quantum physics into your high school classroom?

I anchor a quantum unit in quantum cryptography, which is needed because when quantum computers get powerful enough to break our current system of encryption, we will need a way to encrypt information that even a quantum computer can't break. The unit uses photo polarization to help students understand quantum states and superposition.

You also train other teachers on quantum science. Can you give us an example?

A majority of physics teachers do not have any colleagues teaching physics within their building, so they have no resources right down the hall. In many districts, the people teaching physics are doing so under an emergency certification and they need help with both content and classroom activities.

In a PhD lab, the neutrons I worked with didn't care if it was Monday or Friday afternoon.

One really fantastic model of professional development for teachers was Quantum For All. We hosted middle and high school teachers for a week during the summer and taught them classroom-ready quantum activities

that, at that point, we'd vetted for years. Then the next week, we hosted a quantum camp for middle and high school kids, and those teachers taught those kids. It gave teachers a reason for learning the subject, and it made it a little less scary because the teachers had lots of support around them. The camps were held 2022 through 2025.

Teachers can struggle if they haven't dealt with quantum physics. They're learning again. You remember what it's like to be uncertain and not know all the answers.

A lot of the students liked it. Of course, they're teenagers, so some of them were very apathetic.

You've cowritten two books about quantum physics for advanced high school and early-college students. How did that come about?

I got this email from Bob Hilborn, an emeritus physics professor at Amherst College, out of the blue right before COVID. Bob was looking for an "Alice" to write a quantum book with, because there is a quantum trope of Bob and Alice. The book, *Quantum Computing: From Alice to Bob*, was very conversational and accessible but still with some linear algebra with two-by-two matrices. No calculus.

Bob taught from the book for a college course, and that ended up being the inspiration for the second book, which comes out in July, called *Quantum Computing and Quantum Physics: A Linear Algebra Approach*. It's more of a standard textbook on quantum physics and quantum computing. We took a conversational, low-key approach in the writing. We tried not to write a stuffy, boring textbook.

After 15 years of teaching, you went back to school for your

PhD in science curriculum and instruction. What did you learn?

My dissertation was about language and listening. Humans use language not only to communicate but also to think, problem solve, and learn. This is what I do in my classes. Students come to my class on the first day and say, "You're going to ask why a lot. You're always going to ask us to explain what we're thinking." I say, "Exactly, which is why this class is not going to be hard for you, because you're going to figure stuff out as you're talking."

It's hard to get them to talk. And it's not a pandemic thing. Students are used to the idea of, Tell me what you want me to know, and I'll tell it back to you, and I'll remain completely unchanged and uneducated. That's too strong a statement, but I try to get them to talk.

One example is the next-generation science standards: They are much more about having kids be scientists and gain proficiency in science practices, including designing experiments and asking research questions. Students take a more active leadership role in deciding what needs to be learned and how they can go about gathering evidence. When I use the next-generation science standards, the students are kind of shocked that scientists talk so much. The stereotype of scientists is that they work by themselves in a lab and don't talk to people.

What challenges do students face today?

Phones are definitely an issue, but they are also an opportunity. Recently, we were playing with a Tesla coil and finding out that you can play music in a square-wave format on the coil using your phone. People say that kids today don't think or do anything creative and

that they have no drive because their faces are just in their phones. These were amazing kids. We need to work on a curriculum that utilizes these digital tools to keep kids advancing and being active builders of their interests and their lives.

I try to give them opportunities to use digital tools in ways that help them learn better. I saw a speaker at an AAPT conference talk about how he has students make videos of their homework. Students would take a problem and explain how they got their solution. When someone's explaining a problem, you can tell pretty clearly whether they're faking it. I have done that a little bit with my students. The cheesy term is minds on, rather than just hands on.

I try to teach them to use AI well. I tell them to not just take the first answer but to ask the chatbot, "What do you mean by that number?" If I had to come down on a side, I am on the side of opportunity rather than AI being the end of everything.

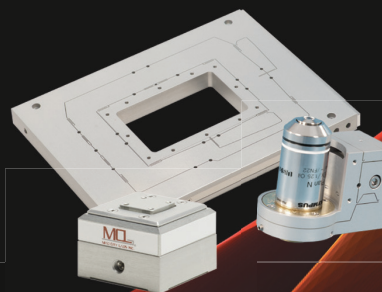
What would you say to someone interested in teaching high school science?

We are in such a teacher shortage right now that it's actually easy to get a job, especially if you're a science person. You're going to get a job, but it may be for less pay than what you're making in science. My son liked to say, "Remind me again, how much money could you be making as a nuclear engineer?" I'd say, "I'm happy with what I'm doing."

Teaching is being an engineer. I am solving problems in a particular context. If you think of it that way, it could be fun. And especially for a science person, you're still kind of doing what you were doing before. It's just in a much messier lab.

PT

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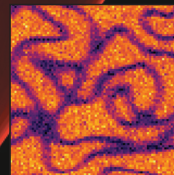


Nanopositioning Systems

Closed Loop, Piezo control
Low Noise, Picometer precision
UHV & Custom design

Micropositioning Systems

Precision motion
Intelligent control = no drift
Nanopositioner compatible



Force Microscopy

MadAFM® Multimodal AFM
Resonant Probe AFM
DIY Quantum Microscope

Single Molecule Microscopy

RM21® Microscope
Unique MicroMirror TIRF
Adaptable design



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DOE launches Quantum Genesis initiative

By **Clare Zhang**

The Department of Energy announced on 23 June a new initiative to develop and deploy “the world’s first fault-tolerant, scientifically relevant quantum computing capability” by 2028. The announcement followed a pair of executive orders signed the day before by President Trump to bolster quantum information science and technology and to direct the implementation of post-quantum cryptography standards.

The Quantum Genesis initiative, DOE says, will be a foundational element of its larger Genesis Mission, the national effort to advance scientific discovery and technological innovation by using AI. “Just as telescopes allowed us to explore the cosmos, advanced quan-

tum computers will enable us to peer into the fundamental laws of nature with unparalleled precision,” DOE Undersecretary for Science Dario Gil says in the announcement.

The initiative encompasses three priorities. DOE will create a national quantum supercomputing user facility that, when integrated with DOE’s other high-performance computing and AI systems, will form “one of the most powerful discovery platforms ever conceived,” the announcement states.

The department will also identify and implement scientific applications of quantum computing. Finally, DOE will hold a competition in 2028 to demonstrate fault-tolerant quantum systems, targeting “critical scientific applications,” including chemistry, materials science, and both plasma and high-energy physics.

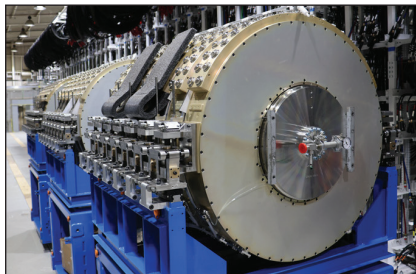
The executive order on bolstering quantum science and technology directs other agencies, including NSF, the Commerce Department, and the Department of Defense, to support the effort to build DOE’s new quantum computer.

House Science Republicans examine grant fraud

By **Clare Zhang**

During a 24 June hearing about the False Claims Act (FCA), the federal law that imposes civil penalties for misuse of government funds, Republicans on the US House Committee on Science, Space, and Technology floated several ideas to help combat grant fraud.

In the hearing, Republicans raised concerns about lost federal funds and questioned witnesses from NSF, NASA, and the Department of Justice on potential safeguards. Democrats accused Republicans of using the issue of grant fraud to justify funding cuts, and they expressed concerns about the DOJ’s recent use of the FCA to investigate federal funding recipients for engaging in diversity, equity, and inclusion practices.



The Bruno Rossi Fellowship offers a highly competitive salary and up to \$250K in startup funds for:

- Equipment
- Research consumables
- Conference travel
- The opportunity to hire a postdoc, grad student, or research associate

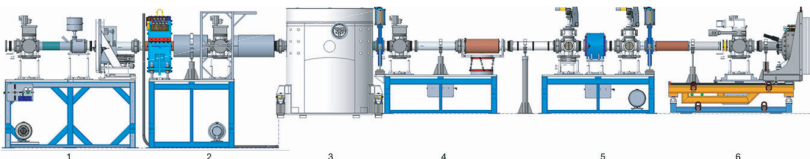
Fellows will also have access to an NNSS mentor and state-of-the-art facilities and technology.



The Nevada National Security Sites is proud to announce the Bruno Rossi Distinguished Postdoctoral Fellowship in Science and Technology, established in honor of Dr. Bruno Rossi, an experimental physicist who developed novel instrumentation to capture extremely fast physics with the limited electronics of his time. This prestigious fellowship aims to inspire the next generation of researchers to drive advancements in national security.

The Bruno Rossi Distinguished Postdoctoral Fellowship is up to a three-year program for recent PhD graduates (within five years of graduation) with expertise in accelerator physics and a passion for applying data science, artificial intelligence, and machine learning to model, control, and optimize complex systems. The Rossi Fellow will be instrumental in developing and demonstrating next-generation capabilities for the Scorpions accelerator and allied radiographic systems.

Specific initiatives include advances in the theory, computational modeling, and/or machine learning applications; strong focus will be placed on computational efforts aligning with electron-beam target interactions and/or other accelerator beam physics.



The Downstream Transport (DST) of the Scorpions accelerator handles critical safety, protection, and diagnostic functions while converting the electron beam to x-rays. Its sections perform debris mitigation (1), specialized beam transport (2), safety stops (3), transport to final focus (4), in-flight imaging and diagnostics (5), and final focusing onto the target (6).

For more information on this year’s Rossi Fellowship and to learn how to apply, scan this QR code.



Representative Rich McCormick (R-GA), chair of the investigations and oversight subcommittee, cited a 2024 Government Accountability Office report that found the government loses between \$233 billion and \$521 billion annually to fraud. He said that “federally funded research represents a meaningful share of that exposure.” Although most researchers are doing “honest work,” McCormick said, “we have an obligation to ask whether the systems meant to catch the exceptions are keeping pace with the scale of federal investment and how high the stakes have become.”

Rep. Daniel Webster (R-FL) noted that there is no government-wide framework for grant applicants to disclose their foreign ties. Brenna Jenny, the deputy assistant attorney general for the commercial litigation branch of the DOJ’s civil division, said her department would be willing to work with Congress on the issue.

Robert Steinau, a senior official who is performing the duties of inspector general at NASA, said his office is “reviewing ways to bolster our oversight capabilities,” including by initiating site visits to grantees.

Rep. Suzanne Bonamici (D-OR) said Republicans had called for a hearing on the FCA to justify slashing funding “under the auspices of combating fraud.” Subcommittee Ranking Member Emilia Sykes (D-OH) also questioned Republicans’ motives, saying Republicans were using the hearing to “talk about anything other than what the Trump administration is actually doing for American science.”

Pentagon report flags deterioration of defense research labs

By **Lindsay McKenzie** and **Aashreya Govindu**

A review of the US military’s research, development, test, and evaluation infrastructure warns that aging facilities are eroding the military’s technical advantages. Published by the Department of Defense in late

June, the report finds that money intended to support those facilities is routinely diverted to other DOD priorities.

To solve the problem, Congress should create a protected fund of nearly \$4 billion over five years for research infrastructure, the report authors say. They also recommend raising the threshold for minor construction projects from \$9 million to \$20 million to reduce administrative burden and to allow labs to complete projects more quickly. According to the report, the average DOD lab is over 45 years old and has limited funds for modernization and repair work, which leads to technical limitations and potential safety concerns for researchers. **PT**

For more from *FYI*, the science policy news service at AIP, visit <https://aip.org/fyi>.

Correction

June 2026, page 11 — The phase diagram of water inaccurately positioned two features. See the updated graph at <https://doi.org/10.1063/pt.8f1acc4af6>. **PT**

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30 PT AUGUST 2026



WILLFUL IGNORANCE OF THE GLOBAL IMPACT OF NUCLEAR WAR

By Alan Robock, Lili Xia, and Zia Mian

Even a limited nuclear war could disrupt the climate, ecosystems, and global food supplies. Nuclear strategies and decisions should be required to factor in those potential consequences.

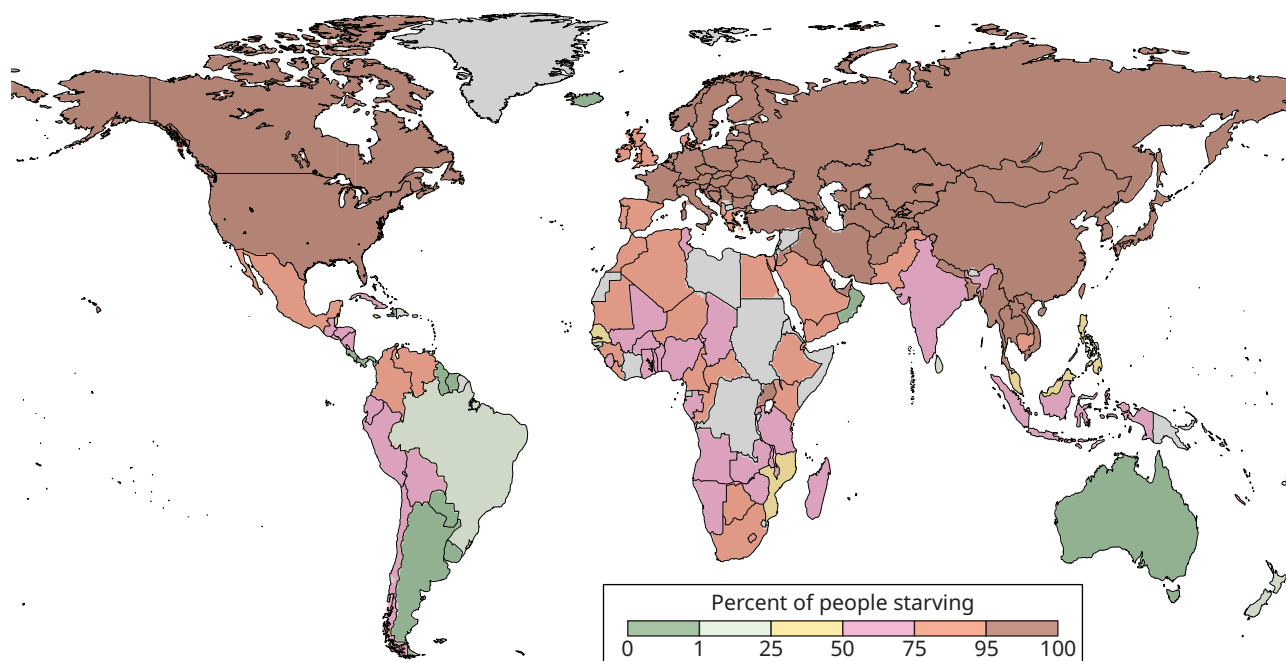
Smoke from a fire in an industrial building. In the aftermath of a nuclear attack, black smoke from widespread fires could have a long-lasting impact on climate. (Photo by iStock.com/borchee.)

Nuclear weapons were created during the 1940s and first used by the US in 1945. In the following years, more countries built weapons, existing arsenals grew in size, and city-destroying fission weapons gave way to fusion weapons, which are even more destructive. As the US, followed by the Soviet Union, began developing military strategies and plans for how to use the weapons in substantial numbers, global concern grew about the large-scale, long-term effects of nuclear war. In a 1958 memo to President Dwight D. Eisenhower that described a nuclear war exercise, Robert Cutler, his special assistant for national security affairs, observed, “The effect of any such exchange is quite incalculable.” Cutler noted that no one knew what such a war would do to “the weather; to crop cycles, to human reproduction, to the population of all areas of the world (whether or not directly exposed to the detonation). It is possible that life on the planet might be extinguished.”¹

Conducted between the mid 1940s and mid 1970s, early studies of the global consequences of nuclear war focused primarily on the long-term health impacts of radioactive fallout and the environmental effects caused by dust and nitrogen oxides produced during the explosions. In particular, studies found that dust lifted into the stratosphere by near-surface nuclear explosions force the cooling of Earth’s surface and that nitrogen oxides produced in atmospheric nu-



▲ Figure 1. Smoke from fires ignited by nuclear weapons could block sunlight for years, which would make Earth’s surface dark, dry, and cold. The disruption to agriculture and fisheries would lead to global famine. (Image adapted from ref. 7.)



clear explosions cause destruction of the ozone layer and expose Earth's surface to dangerous levels of UV radiation.² But it took until the early 1980s for Soviet and US scientists to learn that smoke from fires resulting from a nuclear blast could block out enough sunlight to plunge surface temperatures below freezing and produce what is called a nuclear winter.³ Those catastrophic outcomes helped motivate Soviet General Secretary Mikhail Gorbachev and US President Ronald Reagan to end the Cold War nuclear arms race, begin drastic cuts in arsenals, and declare in Geneva in 1985 that "a nuclear war cannot be won and must never be fought."

But the world has changed since that declaration 40 years ago. Today, nine nuclear-armed states, several of which have recently been or are currently at war, control a growing arsenal of roughly 12 000 nuclear weapons and have strategies for how to use them.⁴ At the same time, policies intended to regulate the weapons are weakening. In February 2026, New START, the last international strategic nuclear arms control treaty designed to cap the largest nuclear arsenals, expired with no prospect for a follow-on. And in May, the five-yearly Nuclear Non-Proliferation Treaty Review Conference, which evaluates the state of the 65-year-old agreement, failed for the third consecutive time since 2010 to reach a consensus about the treaty's implementation and progress, reinforcing a sense of a worsening crisis in the nuclear order.

▲ **Figure 2.** A nuclear war could result in widespread famine. The plotted calculations estimate the percentage of each country's population that would starve in the second year after a US–Russia nuclear war that injected 150 million metric tons of black smoke into the stratosphere. The estimates assume that international trade stops, food waste is eliminated, stored food is consumed in the first several months after the war, half of the livestock are consumed in the first year, and the remaining half of livestock crop feed is redirected for human consumption. Each country's available calories are assumed to be distributed to only part of the population, at the minimum intake needed to maintain normal physical activity; the remaining population fraction is counted as starving. Under those assumptions, about 6 billion people would die from famine. (Image adapted from A. Robock et al., "Opinion: How fear of nuclear winter has helped save the world, so far," *Atmos. Chem. Phys.* **23**, 6691, 2023.)

Two reports from 2024 and 2025 published by the US National Academies of Sciences, Engineering, and Medicine (NASEM) demonstrate that even in the context of increased nuclear threats and reduced regulations, the global and catastrophic impacts of nuclear war are being ignored. The 2024 report describes nuclear war consequence models developed by the Defense Threat Reduction Agency (DTRA) for the Department of Defense: "DTRA provides estimates of the impact of nuclear weapons. The consequence assessment is focused on prompt effects and military objectives. This results in a partial accounting of the consequences leading to a limited understanding of the breadth of the outcomes." The report notes that "current modeling by DoD's DTRA of the consequences of

nuclear explosions resulting from strategic deterrence failure are limited to prompt military effects, especially detonation (blast) and some fallout effects, and does not extend to broader and longer-term effects.”⁵

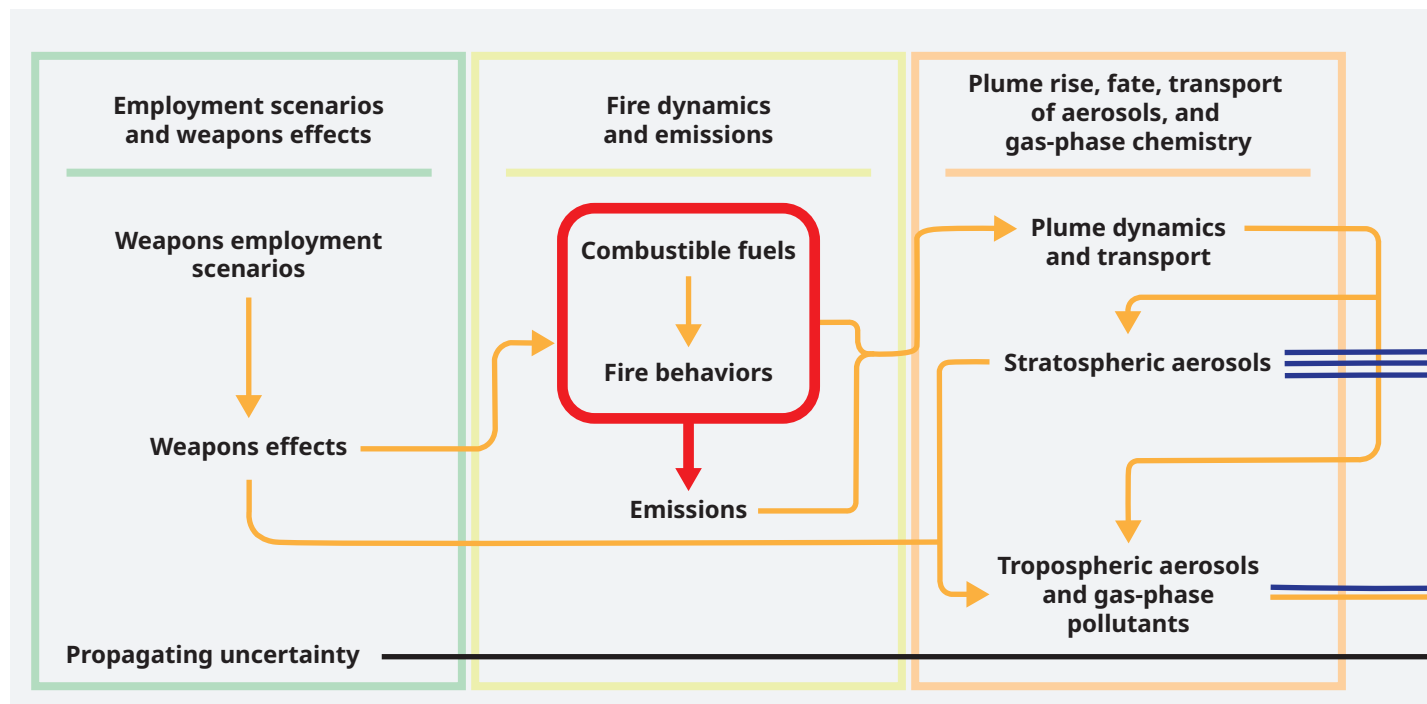
To address that gap in understanding, the 2024 report also highlights that “there is a need to better understand other physical effects of nuclear weapons (e.g., fires, damage in modern urban environments, electromagnetic pulse effects, and climatic effects, such as nuclear winter), as well as the assessment and estimation of psychological, societal, and political consequences of nuclear weapons use.”⁵ The 2025 NASEM report provides some insight into those questions by echoing the understanding from the 1980s that smoke injected into the stratosphere from a nuclear war would trigger a nuclear winter, with the potential to “alter life on Earth to a degree never seen before in human history,” including through disruptions to the “food chain and production ecosystem” (reference 6, page xiii). Given what is already known, it is clear that nuclear war threatens the security and well-being not only of nuclear-armed states but of the whole world.

Although there is still much to be understood about many consequences of nuclear weapons use, climate models that can render the global impacts of nuclear war have seen big advances since the 1980s. Modern

computers allow for detailed climate models that simulate global environmental processes, including the climate response to nuclear war and its effects on land, oceans, sea ice, and food security. In this article, we review what is known about nuclear winter and discuss the urgent need to incorporate current knowledge into national and international policy debates and decisions about nuclear weapons.

Global climate and food impacts

Nuclear winter is not just a drop in temperature after a war; it’s a broader Earth system response across the atmosphere, the ocean, sea ice, and ecosystems. If nuclear weapons are used on cities and industrial areas, many large fires could start at the same time, producing large amounts of black smoke that could affect climate around the world⁷ (see figure 1). Simulations of a regional nuclear war between India and Pakistan show that even a smaller-scale use of nuclear weapons that injects 5 teragrams (Tg)—equivalent to 5 million metric tons—of black smoke into the stratosphere could produce climate change effects unprecedented in recorded human history.⁸ (For more about those simulations, see the 2008 *PT* feature article “Environmental consequences of nuclear war,” by Brian Toon, Alan Robock, and Rich Turco.) Several other climate modeling groups have simulated the impact of smoke



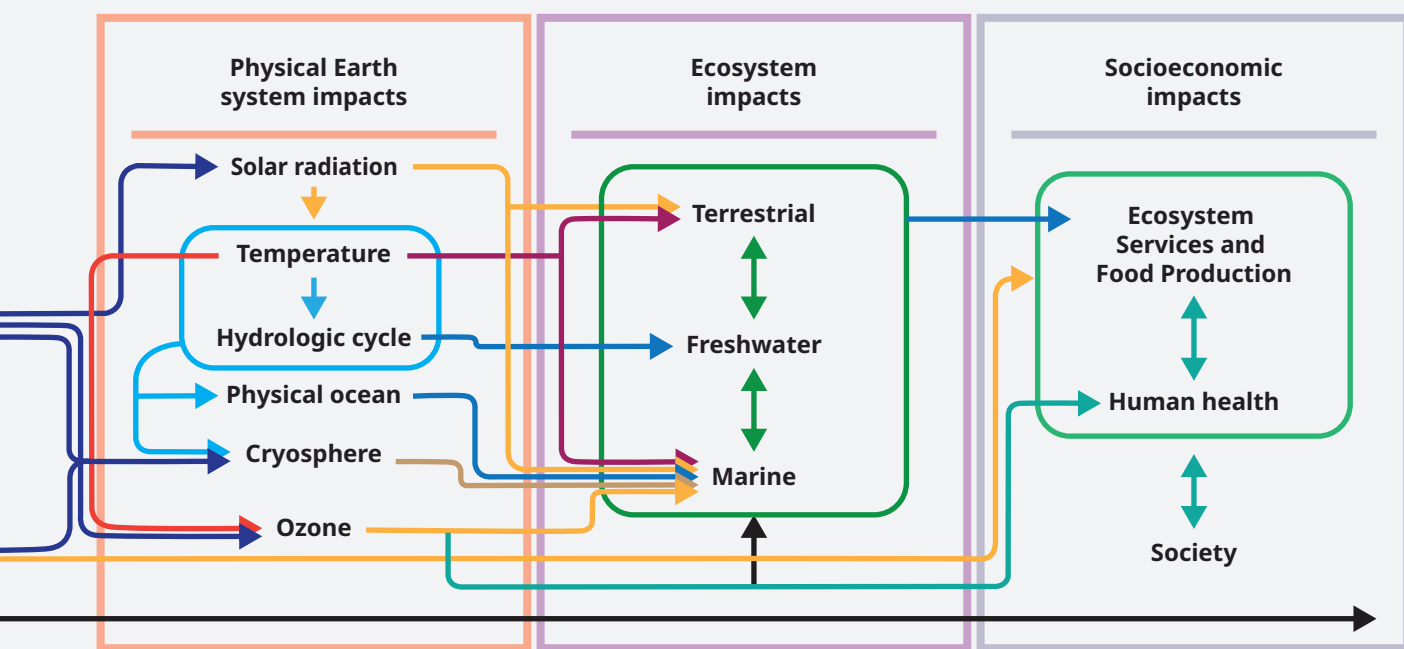
injections of comparable sizes and seen similar results.⁹ Larger scenarios, linked to wars between the US and Russia or the US and China, could produce smoke injections of 150 Tg. Smoke would reduce sunlight, drop global average temperature and precipitation, and shorten growing seasons for several years. The amplitude of the impacts would scale with the total amount injected. After a large-scale nuclear war, the ocean would respond more slowly than the atmosphere but remain changed for a longer time because of its massive thermal inertia.

For human society, the biggest effect would likely come from the food supply pipeline. Lower temperatures, less sunlight, and reduced rainfall would hurt crop production on land, while colder and darker ocean conditions would reduce marine food production. Using several crop models, Jonas Jägermeyr and colleagues found that a 5 Tg black-smoke injection would reduce global production of maize, wheat, rice, and soybeans by about 12% in the first year.¹⁰ That loss is much larger than the effects of the worst recorded natural variations in those crops. To evaluate black-smoke injections of 5–150 Tg, two of us (Xia and Robock) and colleagues combined climate simulations

with crop, fishery, and livestock models and found that the food impacts would be global and severe.¹¹ Simulations also show that the ocean would cool quickly at the surface after injected smoke reached the stratosphere; the resulting expanded sea ice would influence marine fisheries by disrupting the ocean food web.¹² In larger smoke-injection scenarios, sea ice would expand to block some ports that are now ice-free and thus could exacerbate food shortages.

In smaller nuclear war scenarios, famine could threaten 1 billion to 2 billion people. In the largest case, linked to a US–Russia war, the climate effects on food production could threaten most of Earth’s population. (To see where famine would occur, see figure 2.) The damage would not stop at production; international food trade itself could be strongly disrupted, especially if major exporting countries are also hit by large crop losses.¹³ The estimated impacts still have many uncertainties and do not yet include losses of infrastructure, transportation, fertilizer, seeds, labor, or social stability. The estimates also do not include the impacts of radiological fallout or the effects of increased UV radiation, the latter of which would be caused by nuclear war–induced ozone loss.¹⁴ For those reasons, current

▼ **Figure 3.** The issues that need to be better understood to quantify the impacts of nuclear war on humanity are often interconnected. A key unknown is the one inside the red box: How will combustible fuels respond and the resulting fires behave after nuclear attacks on cities and industrial areas? (Figure adapted from ref. 6, fig. S-1; reproduced with permission from the National Academy of Sciences, courtesy of the National Academies Press.)



models likely underestimate the full human and ecological consequences.

What we still do not know

Although modern models have greatly improved the understanding of what happens after black smoke from nuclear weapons-induced urban fires reaches the stratosphere, key uncertainties remain. The 2025 NASEM report highlights those uncertainties, beginning with the war itself. For example, where is the war fought, what kinds and how many weapons are used, and what targets are hit? Other uncertainties are related to the spread of resulting fires and the subsequent smoke. For example, how much fuel is available to burn in cities and industrial areas, how do fires spread through damaged urban areas, and how much black smoke is produced? Questions also remain about how environmental conditions, such as weather, humidity, and topography, could change the results. (See figure 3 for a flow chart that illustrates many of the uncertainties.) The 2025 report emphasizes that better urban fuel data, fire models, and emissions estimates for built environments are needed.

Another major uncertainty is the quantity and chemistry of black smoke that is injected into the stratosphere. Dynamic factors such as rain can impact the quantity of smoke that stays in the lower atmosphere, and smoke that reaches the upper troposphere or stratosphere can last much longer and spread much wider. To better understand those dynamics, the report calls for better smoke-resolving fire models and more use of observations from wildfire pyrocumulonimbus events—the fire-induced formation of cumulonimbus clouds—to test them.

In their 2025 report, the NASEM authors recommend more funding to examine the details of the different spatial and temporal scales of nuclear war effects and of the complex interconnections between smoke's aerosol properties, clouds, the ocean, ozone chemistry, food production and trade, human health, and social disruption.⁶ The question, then, is no longer whether nuclear war could produce severe environmental effects but how to better model its full catastrophic trajectory, from nuclear arsenals, war plans, and fires to the resultant impacts on climate, society, and human survival.

Policy and research implications

Physicists invented nuclear weapons 80 years ago. Today, scientists remain key to developing, maintaining, and modernizing nuclear arsenals. But they also

have a special obligation to understand and explain the full spectrum of existing and potential harms of nuclear weapons. In support of that view, the science academies of the G7 countries (Canada, France, Germany, Italy, Japan, the UK, and the US) in a 2024 joint statement declared that the scientific community has an important role in developing and communicating an “evidence base that shows the catastrophic effects of nuclear warfare on human populations and on the other species with which we share our planet.” Scientists need to engage policymakers, armed forces, and the public to consider what actions can be taken, given the fundamental threat that nuclear weapons and nuclear war pose to the populations of warring nations as well as to humanity and nature as a whole.

One practical need is coordinated national and international studies, conducted by researchers from universities, national and UN agencies, nuclear weapons laboratories, and militaries, on the effects of nuclear war.¹⁵ Among the recommendations in the 2025 NASEM report is to conduct studies on the physical effects of nuclear wars and the attendant ecological, societal, political, economic, and psychological effects over subsequent decades.⁶

In the US, however, no funding for studying the issues is available from key federal government agencies, even those that have previously supported work on the many impacts of climate change. Nuclear strategists have argued that focusing too much on the humanitarian impacts of using nuclear weapons could undermine national nuclear deterrence efforts by signaling that the US might not use its weapons out of concern for the climate.¹⁶

To advance studies on the effects of nuclear war, we recommend that Congress take up the recommendations of the Physicists Coalition for Nuclear Threat Reduction, a group that supports the reduction of nuclear threats through mobilizing advocacy across international communities of physical scientists. Congress should also require DTRA to model all nuclear weapons effects that are missing from their analyses and to include those findings in planning and decision-making at all levels.

There is room for international action as well. Work done by the Princeton University Program on Science and Global Security and the Scientific Advisory Group of the Treaty on the Prohibition of Nuclear Weapons (TPNW)¹⁷ influenced the United Nations General Assembly to vote overwhelmingly in December 2024 to establish an expert panel to study the effects of nuclear war. The new study, the first of its kind in 35 years, is examining the physical effects and societal consequences of

nuclear war on local, regional, and planetary scales. The effort includes looking at the climatic, environmental, and radiological effects and the impacts on public health, global socioeconomic systems, agriculture, and ecosystems.¹⁸ The results of the study are to be published in 2027 and will add to global awareness of the problem and the urgency to address it. The TPNW, which prohibits nations from developing, testing, stockpiling, using, or threatening to use nuclear weapons, has already been joined by 100 countries—a global majority—and provides a mechanism to take action on nuclear disarmament.

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Alan Robock is a distinguished professor and **Lili Xia** is an assistant research professor in the department of environmental sciences at Rutgers University–New Brunswick in New Jersey in New Brunswick, New Jersey. **Zia Mian** is codirector of the Program on Science and Global Security at Princeton University in New Jersey.

WHEN IT COMES TO SCIENCE ENGAGEMENT, HIRE A PROFESSIONAL

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Clockwise from top left: The author delivers a science-engagement presentation at a planetarium show. Kids participate in a kaleidoscope workshop. Actors perform during the *Quantum Voyages* theater piece. The author poses for a photo with the optics chapter at the University of Otago. (Top left photo courtesy of Solar Tsunamis research programme; top right photo courtesy of Roberta Parlavecchia; bottom right photo courtesy of James Gross; bottom left photo courtesy of Museum of Transport and Technology. Design by Masie Chong with artwork adapted from iStock.com artists RilakkuMaxx and oatawa.)

“**E**verything is so delicious. You should be a chef!” Have you been at that dinner party? The table setting is artful, the multi-course meal is beautifully prepared, and a guest offers that heartfelt compliment to the host.

Although I understand the sentiment behind the compliment, I also know from about a decade of cooking in restaurant and catering kitchens that any guest with professional kitchen experience would probably cringe at the remark. Cooking professionally bears little resemblance to hosting a dinner party. They require different, though related, expertise and experience.

Now that I have spent seven years in my second career as a professional science engagement coordinator, that dinner party scenario flashes in my head frequently. Although many articles advocate for scientists to undertake communication and engagement activities, few of those resources recommend that research groups or departments contract with science engagement professionals. That shocks me because as important as it is for scientists to undertake science engagement activities, their main area of expertise is, in fact, doing science.

Therein lies the science engagement equivalent of the dinner party scenario: Could a skilled home cook who excels at intimate dinner parties as a hobby (but has a day job) work a Saturday night dinner service at a restaurant that will feed 200 patrons? Of course. Would they enjoy it? Probably not. Having a professional cook work the line would almost definitely yield a better result. Similarly, researchers could undertake their own science engagement activities, but hiring a professional can bring valuable coordination and communications expertise to such activities.

What science engagement provides

Even though this article focuses on the role of professional science engagement coordinators, I support the treatment of science communication as an essential skill for scientists to develop and then practice regularly throughout their careers. (Scientists looking for advice can see physicist Don Lincoln’s 2025 *PT* article “A brief guide to science outreach.”) I try to avoid the term “outreach” because, for me, it suggests that the science is isolated from the communities in which the research is being done.

The value of science communication to society and to science itself is something that has been studied and written about at length, both in opinion pieces and in research literature. In 2010, for example, Research Councils UK published a report that grouped the benefits of public engagement into four categories: career inspiration, raising your profile, developing skills, and enhancing your research.¹ In a 2025 *PT* commentary, Lincoln wrote about how scientists’ “lackadaisical view of science outreach” can end up harming them because of the disconnect that develops between them and the public.

Researchers may also want to do science engagement because it helps them get funding. NSF evaluates funding proposals according to not only their “intellectual merit” but also their “broader impacts.”

Science engagement has other benefits, including opening career pathways to students from historically marginalized communities.² It can lead to increased diversity in research groups and institutions, and that brings different perspectives and approaches to problem-solving and can drive greater innovation and creativity.³

More broadly, the efforts of scientists to connect with communities of all ages



▲ The first installment in a series of graphic novels, codeveloped and cowritten by the author of this feature and Maui Studios, integrates Māori culture and knowledge with quantum physics. It's available to download for free at www.doddwalls.ac.nz/our-impact/community-engagement.

and backgrounds can build and strengthen trust and understanding in the rigorous processes by which science builds knowledge.⁴ When carried out effectively, science engagement is a powerful

tool against the spread of dis- and misinformation in communities and can even generate public support for taxpayer-funded research.⁵ Furthermore, science engagement can contribute to culture by in-

spiring works of art, music, theater, and dance.⁶

What is a science engagement coordinator?

Coordinating science engagement activities requires a lot of effort and time. When asked about the barriers to participating in or undertaking science engagement, researchers most often identify time constraints, a factor that is usually correlated with a lack of institutional support and a lack of skills.⁷ One respondent in a study by researchers from the University of Tasmania emphasized that scientists “cannot be experts in everything.”⁸

Researchers, therefore, may benefit from experts in science engagement. I am employed by the physics department at the University of Otago—Ōtākou Whakaihu Waka in Dunedin, Aotearoa New Zealand. (Aotearoa is the Māori name of the country.) In addition to supporting the department, I coordinate community engagement for Te Whai Ao—Dodd-Walls Centre, which is the country’s national center of research excellence in photonics and quantum physics. Similarly to most academic researchers, I conduct much of my work with the support of external funding, and part of my job is to help bring in more funding.

My job as a science engagement coordinator represents a superposition between a project coordinator and a science communicator.



▲ At ASB Polyfest, the largest Pasifika cultural festival for secondary schoolers in the world, a volunteer demonstrates how eddy currents will slow a magnet's drop through conductive materials.

The first part of my job is development. I specialize in hands-on, informal science engagement activities. I spend time with the academic and technical staff members of my department to develop

activities that connect to their work, including demonstrations, games, craft-based activities, engineering or design challenges, puzzles, and experiments. I've developed rocket workshops to get peo-

ple thinking about Newton's first law and about the importance of payload weight. I've built an ice variation of the game Jenga for a team that studies ice dynamics.

I've developed a series of puzzle challenges that explores the evolution of cryptography, from ancient scytale ciphers to the modern RSA encryption that secures the internet. Accompanying resources include a basic introduction and model of quantum key distribution, a protocol that uses entangled photons as encryption keys. In the model, two people can attempt to encrypt and decrypt messages sent to each other while a third person tries to measure the key that they need for decryption. The exercise reveals that the measurement process alters the keys that the two communicating parties are working with, and so they know immediately that someone is eavesdropping.⁹

Currently, I am codeveloping storylines for a series of graphic novels with Māui Studios, a Māori creative agency based in Christchurch. Each novel's storyline features a quantum concept portrayed as accurately as possible—kind of an antithesis to *Ant-Man*, you might say. The work is possible because I have access to my university department of physicists who not only believe that the activities are valuable but also are willing to help.

After developing the engagement activities, I deliver

them with department members or research teams at community festivals, family fun days, class visits, pub talks, and school-holiday programs. I adjust content according to time frames, audiences, and locations: Is the event for 5-year-olds outside on a rugby field? A group of 70-year-olds in an auditorium? A class of 13-year-olds right after lunch? (Yes, the time of day absolutely matters.) Will teachers or caregivers be around?

I handle the back-and-forth with the event organizer and school or community contact, complete the health and safety paperwork, wrangle volunteers from my university's

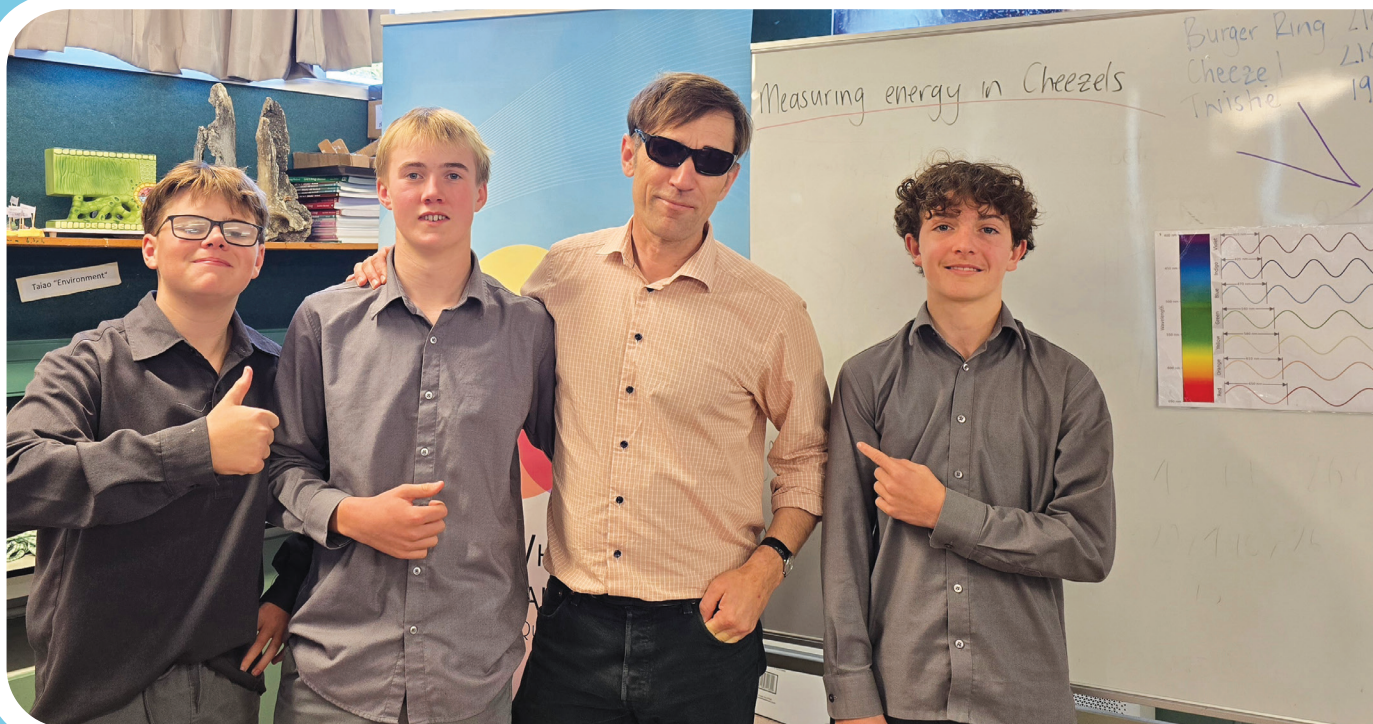
academic and technical staff, sort travel bookings, get all the equipment and gear to the site, and coordinate everything else associated with the event. My work takes me all over Aotearoa New Zealand.

Studies show it is essential not only to work with students and teachers in a formal learning setting but also to deliver informal science engagement activities that include students' wider support network, particularly their families.¹⁰

That approach extends the life of any positive impact the activities have by empowering the students' grown-ups, as I call them, to reinforce and recall the activity

at home. Incorporating the students' grown-ups into the activity also helps the grown-ups overcome any anxiety or insecurity they might be feeling about their own ability to engage with STEM subjects. The approach is particularly effective in families where the grown-ups may not have attended a university. Broadening the grown-ups' horizons helps broaden the children's.

Then I conduct a debriefing with department staff and teachers that I've been coordinating with to evaluate the programs and activities. Are they having the desired impact? What needs to change? I



▲ Niels Kjærgaard of the University of Otago and Te Whai Ao—Dodd-Walls Centre and year-nine students at a school in the Southland region of Aotearoa New Zealand participated in a 2025 science department tour. When the author returned to the school this year without Kjærgaard, the same three boys asked after him. (Photo courtesy of Kowhai Charlton.)



▲ Aotearoa New Zealand member of parliament Scott Willis (left), Transpower senior principal engineer Andrew Renton (center), and Craig Rodger of the University of Otago's physics department (right) stand by an installation explaining a plan they developed to protect the national grid from major space-weather events. The temporary installation was on display at the interactive science showcase *Solar Tsunamis–Parawhenua Kōmaru* at the Tūhura Otago Museum.

liaise and maintain connections with teachers, community organizers, artists, cultural leaders, libraries, and museums around the country. I'm always open to building new relationships to see what is going on or if there is a new community to work with. I also try to stay up-to-date on research coming out of the science communication field.

Bringing in a professional

If you're a researcher who's interested in getting you and your department involved with

science engagement activities, you should consider working with a professional. But how can you persuade your department head or principal investigator to invest even a bit in someone like me?

There are three primary areas in which science engagement professionals deliver the most value.

Time. I went into some detail about my job because I wanted to illustrate how much development, organization, and evaluation are required for effective science engage-

ment activities, especially for groups doing them for the first time.

Working with a professional reduces the amount of time that a scientist or researcher is required to do things that aren't lecturing or research. Plus the experience of science engagement professionals provides the scientist or researcher with insights to handle projects more efficiently. We know when the design of a demonstration isn't going to work because it's too easy to break or that a sugared-up preteen can unintentionally weaponize it. We know which questions will likely get asked by different demographics or, if we ask a question, which answers will likely be given. We also have a solid feel for how many activities will fill up a 45-, 60-, or 90-minute program for different demographics and venues.

We are more than happy to work independently or share our methods, whichever would be most beneficial for you. Time and effort shouldn't be a barrier to your participation in quality science engagement activities.

Impact. Achieving a desired impact sometimes requires thinking outside the box. Professional science engagement coordinators are particularly adept at that because a major part of the job is building and maintaining a diverse network of personal connections. Sometimes, people fall into the trap of thinking that only scientists can communicate science—but excellent science communicators can, and often do, come from the humanities and social sciences, precisely because so much of the communication work is about humans.¹¹

Once an activity is finished, then an engagement coordinator needs to measure or evaluate its impact. Articles recommending that scientists participate in communicating their science will often mention evaluation and assessment of the engagement activities as an important part of the process. Guidance on how to do that beyond “counting audience members” or “counting likes and shares” is harder to come by outside of science communication research.¹² That's because tracing outcomes is not a straightforward process. Being able to draw a direct line of causality from someone participating in an event to them choosing a STEM pathway is highly unlikely because that's not how humans work.

How many people participated in the activity is only one of several factors that a coordinator considers when

evaluating impact. If you want more rigorous, ongoing evaluation, outsourcing the analysis to a professional science engagement coordinator can prove immensely valuable to any informal science engagement activities your research team or department chooses to invest in.

Better science. The science engagement activities that professional coordinators organize can lead researchers to do better science. One postdoctoral fellow commented that he appreciates the new perspective he has for his research in spectroscopy after hearing me describe it to a four-year-old as “reading rainbow code.” Now, when he starts to feel frustrated, he opens the thank-you card we got from the preschool after our visit and remembers some of the magic and wonder that science can bring.

Another research fellow I've worked closely with for over a year learned communication skills from public events that I facilitated. She's now taking those skills and designing her own interactive demonstration to add to her overseas invited guest lecture to undergraduates at a summer school.

Two PhD students in the physics department at the University of Otago shared their appreciation for two engagement programs I developed for them that required travel to different cities. They reflected not only that they appreciated the value of engaging the communities we visited but also that the trips presented opportunities to build new collaborations across universities in Aotearoa New Zealand. One of them emailed the director of Te Whai Ao—Dodd-Walls Centre to say, “I have found outreach to be more than just community engagement, but also a great opportunity to visit other places and meet others in the field.”

Where can I get a coordinator?

We're probably a lot closer than you think. I, along with a lot of other professional science coordinators who I know, came from jobs at museum engagement programs and often with a postgraduate degree in social science. Partnering with museums and science centers can provide access to great venues for talks, and those places will often already have networks in the community.

I have also met some incredible science communicators who have backgrounds in theater. Actor Alan Alda, for example, started a second career in science engagement and founded a science communication

center. Programs that offer degrees in science communication can point you toward their alums—who may well be working in a nearby museum.

As the professional practice of science engagement continues to grow, researchers are starting to see that working with a professional has significant value.¹³ That's not to say that scientists can just check out because we've got this handled. You're not escaping my shoulder tapping that easily—my work depends on a close relationship with experts. But the responsibility doesn't need to rest exclusively on your shoulders, and you don't need to be experts in everything, including engagement.

PT

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▲ The author ran an after-school science engagement program at Aotearoa New Zealand's Tūhura Otago Museum in 2022. (Photo courtesy of Tūhura Otago Museum.)

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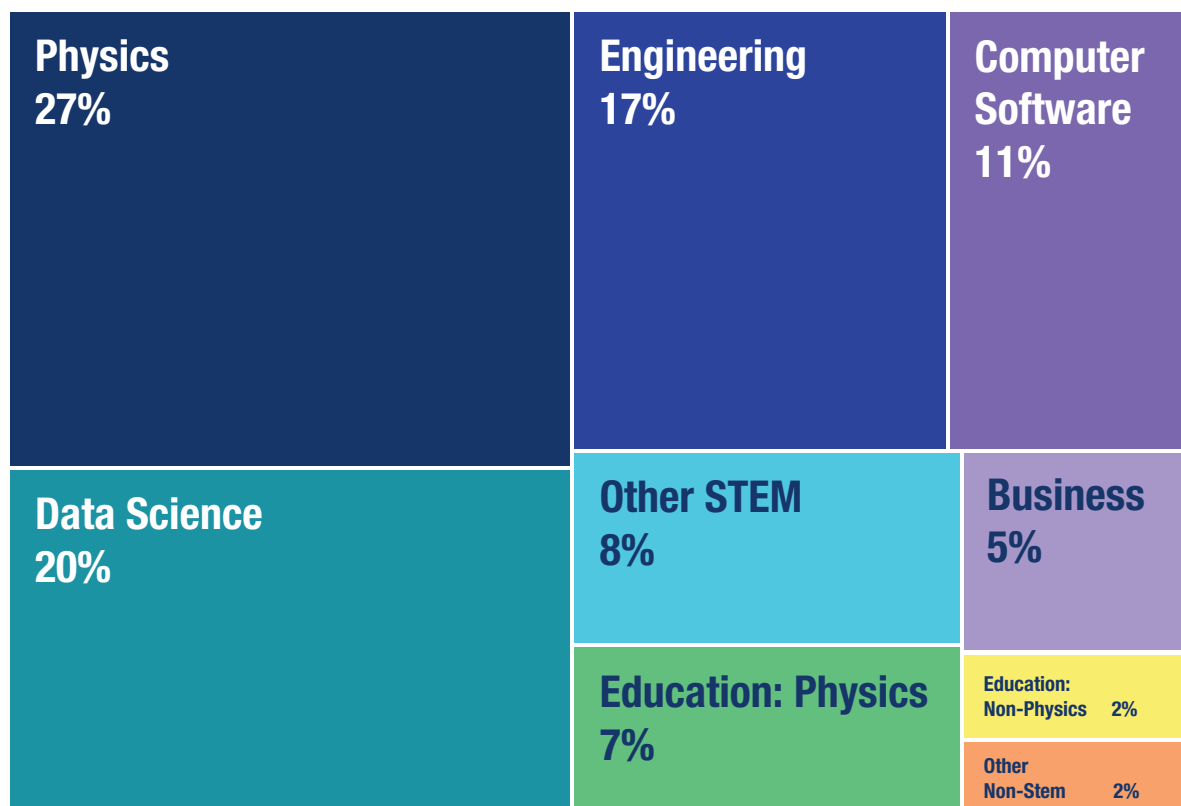
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Jessica (Jessa) Barder is a science engagement coordinator at the University of Otago-Ōtākou Whakaihu Waka in Dunedin, Aotearoa New Zealand. She develops and delivers activities for, among other programs, New Zealand's five-year research program to develop cutting-edge photonics to improve global space-based climate monitoring.

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WHAT CAN PHYSICISTS DO?

An interview series that profiles scientists who opted for careers outside of academia.

Dwayne Bryant works with cancer patients

By Toni Feder

Senior health physicist, Columbia University

BS, physics, Rowan University, 2020

MS, medical physics, Columbia University, 2026

How did you figure out what you wanted to do?

I knew that I wasn't interested in becoming a professor. My physics undergraduate program offered a certificate in health physics, for which I took a couple of extra classes and did an internship. I got experience and connections with people in the field.

(Photo courtesy of Columbia University Environmental Health and Safety.)



What were you looking for in a job?

I had shadowed health physicists and learned about radiation safety. That was a positive experience. I applied to a bunch of jobs in radiation safety. I knew that I wanted to make a difference by directly helping people.

How do you spend your time?

I provide patients with information about radiopharmaceutical treatments and give them patient-specific instructions on topics like how long to keep their distance from other people or when it is safe to hold children for extended periods of time. I facilitate the administration of radioactive materials. And I make sure the dose is correct. I continue as a liaison to the patient after the treatment.

One of the nice things about this job is that your day-to-day isn't the same. Some days, I do regulatory paperwork or test equipment. I make sure the clinical health physics team's radioactive waste is safely stored or disposed of. And I perform shielding evaluations for the hospital.

What do you like about your job?

I love what I do. You form a connection with the patients. It gives a sense of fulfillment when they are going through a difficult time in life. Being able to have that impact and help someone is really fulfilling.

How do you use your physics?

I do calculations related to patient therapy treatment and shielding evaluations. Physics is also important for understanding how radiation interacts with the human body. Photons interact differently than electrons or neutrons. I also provide supplementary training for nurses and new staff.

What new skills did you need to learn?

It's really important to have the ability to communicate. And to learn to work on a team.

What is the salary range?

Straight out of college, you can make anywhere from \$60 000 to \$80 000 a year as a health physicist.

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A peek into the physics of squeaky sneakers

When rubber-soled shoes skid on a hardwood floor, slip pulses travel between the two surfaces at high speeds to produce the familiar sound.

By **Gabriele Albertini**

The squeaking of sneakers is the unofficial soundtrack of a basketball game. Squeaks also arise in a range of mechanical systems, including hip and knee replacements, where polymer liners slide against metal or ceramic heads, and bicycle brakes in need of a tune-up. Until recently, the processes responsible for producing squeaks were poorly understood: How does slip occur at a frictional interface? What governs the interfaces' stability? Could there be a way to suppress the sound? As part of a team of applied physicists and engineers, I have been probing some of the fundamental questions about friction at interfaces between soft and rigid materials.

Generally, the sound created when two materials slide over each other is the result of a macroscopic stick-slip: The surfaces momentarily stick together, the system stores elastic energy up to the point where equilibrium is lost, and then the surfaces slip, which releases that energy. If the frictional force drops with increasing slip velocity, that can give rise to self-excited oscillation. A small increase in velocity leads to reduced friction, which causes a further increase in velocity. Many earthquakes are generated via the same stick-slip process.

Such a description, however, fails to capture the rich dynamics of extended frictional interfaces, where instead of slipping all at once, surfaces slip by means of the propagation of crack-like slip fronts and slip pulses.

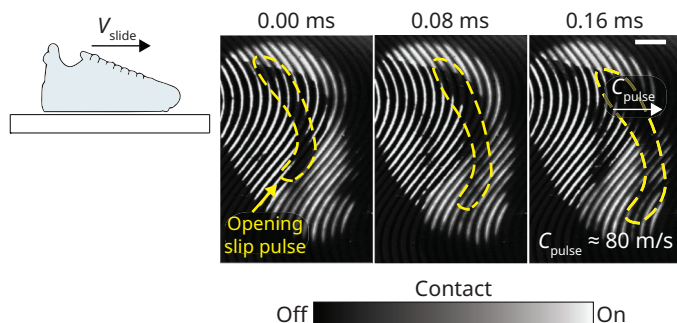


▲ (Image cropped from a photo by Thomas Ronveaux/Pexels.)

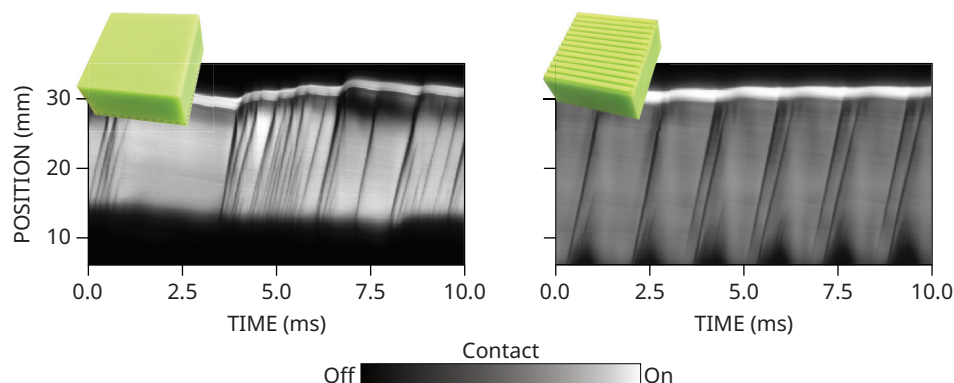
Localized slip distribution is particularly pronounced when the sliding involves a rigid surface and a soft solid—in our study, a squeaking shoe.

The shoe problem

We start our assessment of the origin of squeaking by sliding a basketball shoe on a rigid plate. To gain a direct view of the contact at the frictional interface, we take a transparent acrylic plate and mount LEDs on its sides. The light's angle of incidence is large enough that the light is totally reflected and remains trapped within the plate. Where the shoe sole makes contact,



◀ **Figure 1.** Snapshots of the frictional interface between an acrylic plate and a basketball shoe, sliding to the right at velocity V_{slide} , show an opening slip pulse traveling left to right at a speed C_{pulse} of 80 m/s—much faster than, and independent of, the sliding speed. The white scale bar in the top right corner is 10 mm. (Figure adapted from A. Djellouli et al., “Squeaking at soft-rigid frictional interfaces,” *Nature* **650**, 891, 2026.)



◀ **Figure 2.** Spatiotemporal contact maps show how opening slip pulses travel along a transect of a rubber block with a smooth surface (**left**) and one with ridges (**right**). A smooth block produces unpredictable, irregular slip pulses, whereas a ridged block produces slip pulses at a consistent frequency that results in a predictable, characteristic squeaking sound. (Figure adapted from A. Djellouli et al., “Squeaking at soft-rigid frictional interfaces,” *Nature* **650**, 891, 2026.)

the light transmits onto the rubber, and the contacting locations on the plate appear bright. We visualize the contact evolution in space and time with a 100 000 frames-per-second camera and measure the sound with a microphone.

We observe that sliding does not occur along the interface all at once. In some localized regions, contact between the sole and plate is momentarily lost, while the surrounding interface is under high pressure and stuck. The detached regions are called opening slip pulses, one of which is shown in figure 1, and they race along the interface at speeds exceeding the shear-wave speed of the rubber. The pulses are generated at constant time intervals of 0.2 ms, which corresponds to a frequency of about 5 kHz. At the moments when pulses appear, we hear squeaking sounds with the same frequency. The coincidence of both the sound- and pulse-generation frequencies is strong evidence for the causal relationship between opening slip pulses and the squeaking sound.

Nucleation and propagation

Theoretical analyses and simulations show that uniform sliding along an interface between solids of different elastic properties is unstable, particularly when, as it is in our shoe scenario, the friction coefficient is high. The instability arises from a combination of factors. First, frictional strength is coupled to contact pressure—local pressure fluctuations cause fluctuations in slip. Additionally, the mismatch between the two materials means that local slip causes pressure changes.

That two-way causal relationship between slip and pressure makes small perturbations grow indefinitely: A semistable initial state of uniform sliding will transition to a state where most of the interface remains stuck, and slip localizes into pulses that travel along the interfaces at the speed of sound. The pressure fluctuations that kick-start pulse nucleation can result from macroscopic vibrations of the system. When pressure across the interface is particularly high, tran-

sient pressure bursts may also be triggered by electrostatic discharge at the surface, similar to the discharge produced when rubbing a balloon on your hair.

To further understand what governs the dynamics of slip pulses, we cast rubber blocks on 3D-printed molds, shown in figure 2, with either flat frictional surfaces or ridges similar to the ones found on basketball shoes. Opening slip pulses are observed when both flat and ridged surfaces slide. The shape and periodicity of the pulses, however, differ significantly between the two.

On flat surfaces, pulses can travel in multiple directions—and can tilt, merge, and separate—which gives rise to messy dynamics and a scratch-like sound that contains a broad spectrum of frequencies. Conversely, on the sole-like surfaces, pulses are confined within a single ridge. Each ridge acts as a waveguide that suppresses complex interactions between pulses and tames the messy dynamics into an ordered one. Consequently, pulses are generated at a constant frequency, as shown in figure 2, and the resulting sound is a clean squeak.

We were surprised to see that such small changes in surface geometry have profound effects on the propagation dynamics of pulses. We had expected that coupling between individual ridges would cause them to behave as an equivalent continuum 2D surface. To understand why that was not the case, we made samples with a single ridge and gradually increased the ridge’s width. For small ridge widths, we found that pulses become confined, making the interface essentially 1D, and the dynamics are ordered. When a ridge is at least four times as wide as the typical pulse, the interface behaves as a 2D surface, and the dynamics become chaotic.

Setting the tone

For a given rubber-block geometry, the squeak frequency is remarkably robust. Variations in pressure or sliding velocity have negligible effects. The frequency

is, however, sensitive to the block height. The two have an inverse relationship: Taller blocks produce lower frequencies. With that knowledge, we designed a series of blocks with carefully controlled heights such that each block produces a well-defined note, and we used them to play a familiar melody—"The Imperial March (Darth Vader's Theme)" from the *Star Wars* franchise. (For a video of the song, visit <https://doi.org/10.1063/pt.b429f6ec24>.)

Why are slip pulses initiated at specific frequencies? We observe oscillations at the trailing edge of the block that gradually increase in amplitude. Each oscillation temporarily lifts the contact at the trailing edge, which sets favorable conditions for the nucleation of pulses that are locked into the first shear natural frequency of the system.

Our findings could give rise to new musical instruments or to a new era of squeakless sneakers. The latter could perhaps be achieved either with a design that harnesses the chaotic regime in which pulses are not synchronized and thus generate a "shhh" sound instead of a squeak or with a system in which pulses occur only at such high sliding velocities or pressures that they would never be generated in a given application.

On a more fundamental note, our study sheds light on the interplay between geometry and the way slip pulses propagate, a topic of interest in not only me-

chanics but also earthquake physics. Most theoretical foundations that describe slip pulses come from the geophysics community, and experimental approaches similar to ours serve as tabletop models for studying earthquakes.

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Additional resources

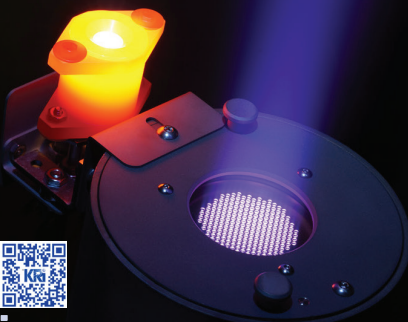
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Gabriele Albertini is an assistant professor of structural engineering at the University of Nottingham in the UK. His research focuses on nonlinear processes that govern failure of materials and systems.



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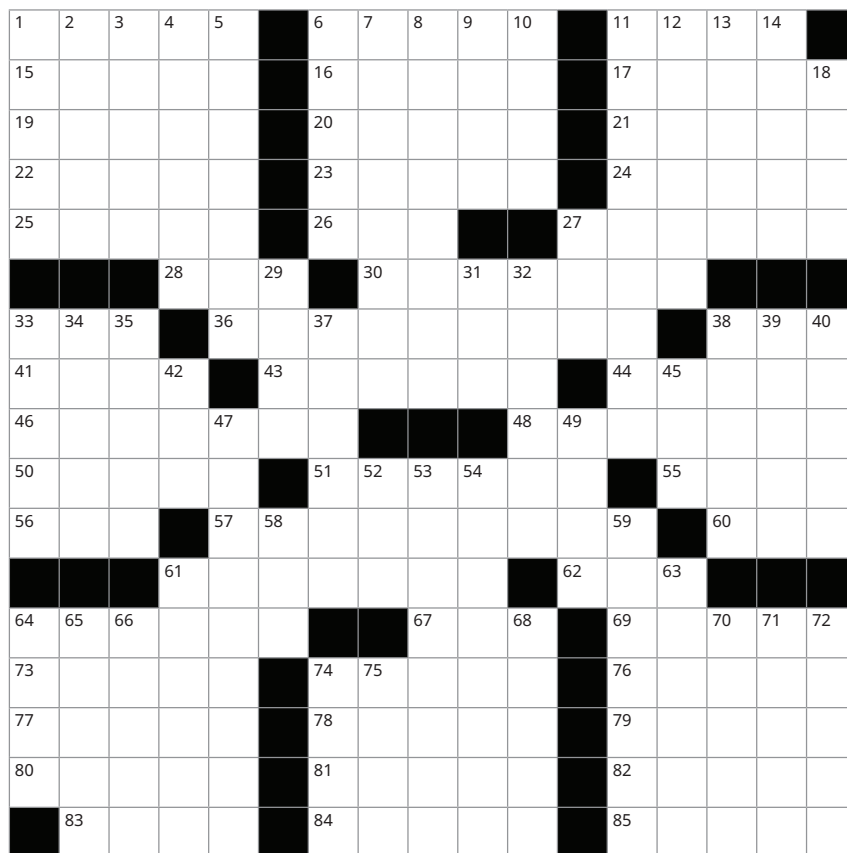
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Plot twist

By Doug Mar

ACROSS

- 1 Atomic clock timekeeper
- 6 Smacks, as a fly
- 11 Bagpiper's wear
- 15 Earthy pigment (var.)
- 16 ____-wave theory, a hidden-variable theory postulated by Louis de Broglie
- 17 Firefighter Red
- 19 Discover
- 20 Inner self in Jungian psychology
- 21 Cut into tiny pieces
- 22 Facing the pitcher
- 23 Scornful look
- 24 Tilts to one side
- 25 Way to go
- 26 60 secs.
- 27 Part of a water quality analysis
- 28 Noah's boat
- 30 DJ bribes
- 33 Used to be
- 36 Point on a golf club face at which the impact is optimized
- 38 Online segue (abbr.)
- 41 Length unit that when combined with a liquid metal forms a pressure unit
- 43 Former German Chancellor Merkel with a PhD in the type of chemistry in 48-Across
- 44 Northernmost of the major Hawaiian Islands
- 46 Brno is its principal city
- 48 Lead-in to mechanics or computing
- 50 What the Devil wears?
- 51 With 81-Across, a nonorientable surface that is formed by stretching this puzzle's grid left to right and joining its vertical edges while matching the corresponding entries
- 55 Kennel cry
- 56 Drain energy
- 57 Events of scientific interest
- 60 Aliens, for short
- 61 Puts away, as a hose
- 62 Lawyers' org.
- 64 What shape-memory materials do (hyph.)
- 67 New Deal agcy.
- 69 His razor is used to justify special relativity
- 73 Former Chinese Premier Zhou ____
- 74 Supermodel Gigi or Bella
- 76 Slow and stately, in music
- 77 Pay-TV network with *Outlander*
- 78 The ____ (a Texas landmark)
- 79 Gas law that is written $PV = nRT$
- 80 Succinct

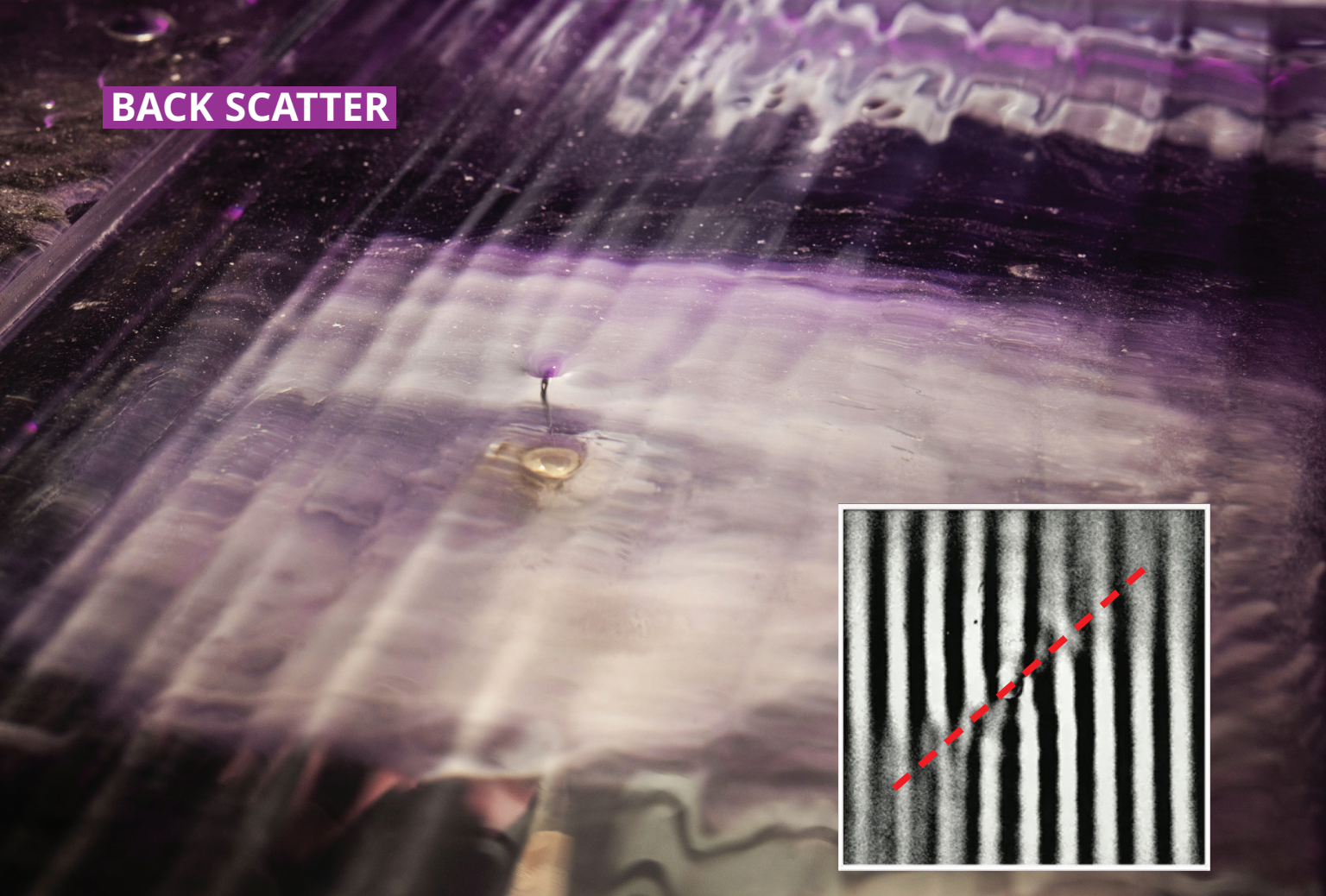


- 81 See 51-Across
- 82 Queen Latifah album *Nature of a ____*
- 83 Liberal arts college in Portland, Oregon
- 84 Speak, as thou might (var.)
- 85 Fan's opposite

DOWN

- 1 Grinding tooth
- 2 Combining form (var.) that relates to vinegar
- 3 When doubled, Japanese hot pot
- 4 Printing mistakes
- 5 Patrons of Hertz
- 6 Muscle twitch
- 7 First city in North America to designate a specific telephone number for emergencies (it was 999, not 911)
- 8 Estrange
- 9 Jackson's *Classical Electrodynamics* might be considered one
- 10 Superscript symbol that often indicates complex conjugation
- 11 Volcanic Russian peninsula
- 12 ____ *Guides*: how-to series
- 13 Jousting weapon that sits on a 64-Down (but not 18-Down)
- 14 Sounds of a metronome
- 18 Reference frame in which an object has zero velocity
- 27 Mideast political grp. founded in 1964
- 29 *The Bridge on the River ____*
- 31 French fashion monogram
- 32 Not transparent
- 33 Weaklings

- 34 2025 Best Picture winner
- 35 Leftover bit, such as the kind of paper used by Lise Meitner and Otto Frisch in their discovery of nuclear fission
- 37 Hard layer on a 1-Down (but not 72-Down)
- 38 Private pupil
- 39 Stacking ____ (crystalline defect that may affect fracture)
- 40 Certain dark-matter candidates
- 42 Word that precedes "a little lamb"
- 45 Whichever
- 47 Sublimated
- 49 Sch. whose motto is *Ex scientia tridens*
- 52 Carry-____ (things that need stowing)
- 53 Edge of a physical system where conditions may be imposed
- 54 In the first place
- 58 He/____ pronouns
- 59 Do away with
- 61 The big adjustment knob on a microscope
- 63 National park in Maine
- 64 Take a load off, or a place to do so
- 65 Keypad key
- 66 Solar ____
- 68 Take as one's own
- 70 It may cancel a trough
- 71 Banded gemstone
- 72 Term that refers to a particular type of concentration measure, namely n/V
- 74 Avocado variety
- 75 Utah ski hill that bans boarders



A classical analogue for quantum effects

By Laura Fattaruso

When researchers used a custom wave tank at the Okinawa Institute of Science and Technology to watch how standing surface waves are scattered by a vortex, what they saw was unexpected. The interaction produced the nonlocal topological effect seen here: a flat line (highlighted by the dashed red line in the inset, which has the vortex at its center) that extended across the surface of the water and rotated opposite the direction of the vortex flow. When the vortex flow was sped up, multiple counterrotating lines appeared.

The experiments were inspired by similar ones performed almost five decades ago; they were described by Michael Berry in a 2010 letter to *Physics Today*, “Aptly named Aharonov–Bohm effect has classical analogue, long history.” Those earlier experiments documented the interaction of a vortex with traveling waves, not standing ones. They managed to replicate in water waves an effect mathematically analogous to the Aharonov–

Bohm effect—a quantum mechanical phenomenon in which an electron can be affected by an electromagnetic potential despite remaining in a region that is free of electric and magnetic fields. In the Okinawa experiments, as in the earlier ones, the wave tank’s vortex, standing in for a magnetic field–generating solenoid, caused a phase shift in the water waves that’s analogous to the phase shifts experienced by passing electrons.

The Okinawa experiments demonstrate once again that classical systems can serve as laboratories for visualizing quantum effects that may be much harder to observe in quantum systems. (A. Singh et al., “Topology made visible through standing waves in a spinning fluid,” *Commun. Phys.* **9**, 123, 2026; photo courtesy of Andrew Scott, Okinawa Institute of Science and Technology, and inset adapted from the reference.) **PT**

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