PT
PHYSICS TODAY
APRIL 2026 VOLUME 79 NUMBER 04

Matching pipe organs to room acoustics

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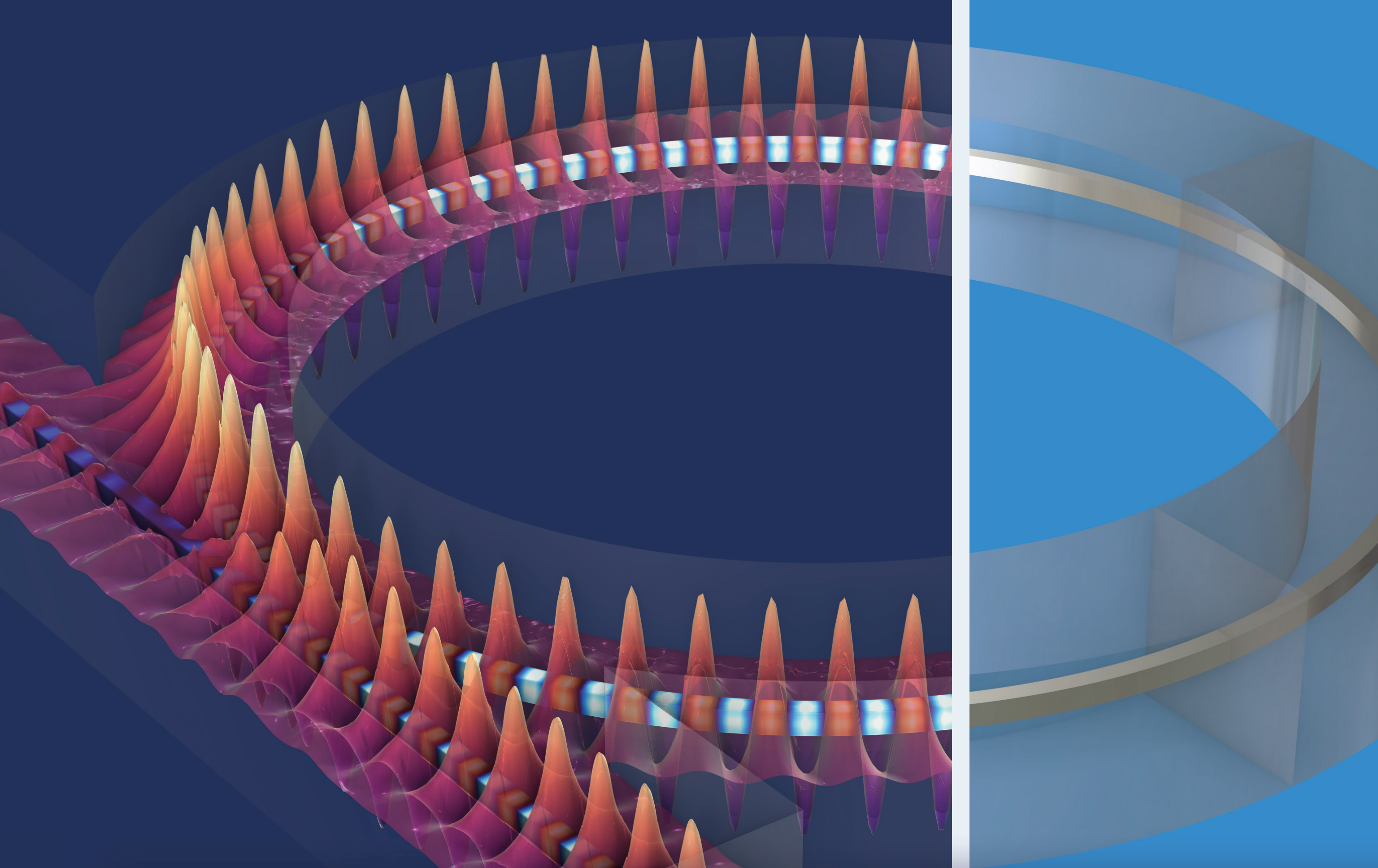

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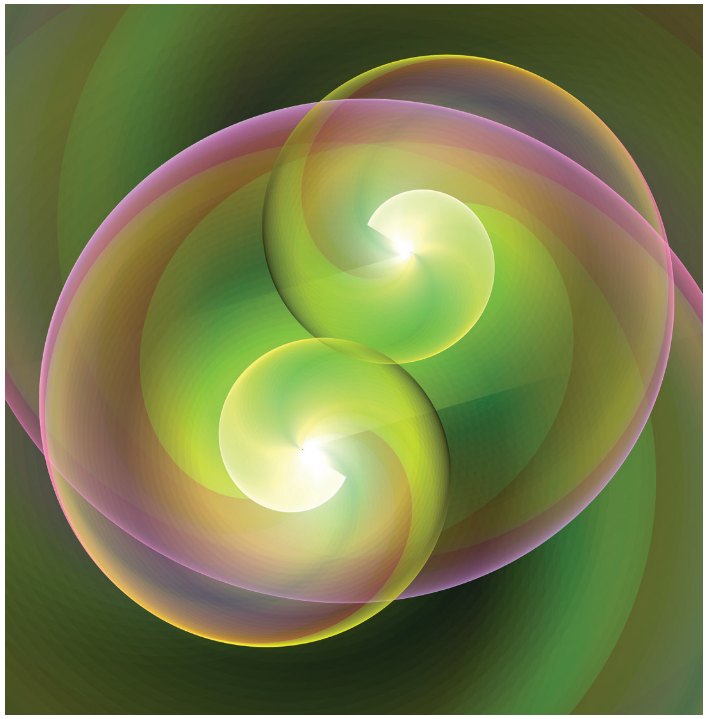

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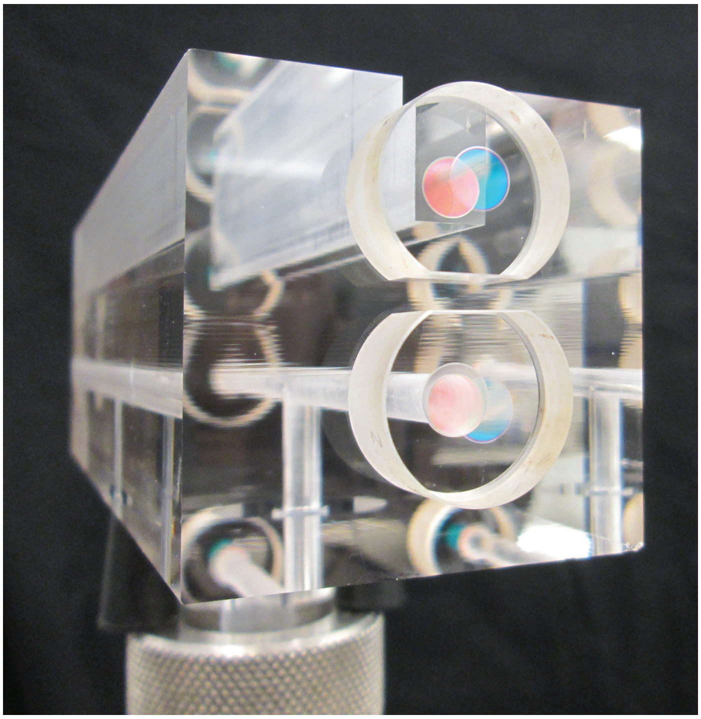

DEPARTMENTS

ON THE COVER

Built in 1968 by the Danish company Marcussen & Son, the pipe organ pictured here is located in the New Cathedral in Linz, Austria. Its 5890 pipes are divided into 70 rows, known as stops, that each have a different sound character. The pipes in an organ need to be tailored to the acoustics of the space in which the instrument will be installed. To learn more about pipe organ acoustics, turn to the Quick Study by Judit Angster, Josep Llorca-Bofí, and András Miklós on **page 52**.

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TO READ ABOUT HOW CITIES ON RIVER DELTAS ARE SINKING, TURN TO PAGE 8

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Cities built on river sediment are sinking

Using high-resolution satellite data for a global analysis of major river deltas, researchers found that 45% of those studied are sinking faster than the rate of sea-level rise.

By Laura Fattaruso

Figure 1. The city of New Orleans sits atop the Mississippi River delta. (Image from ESA/CC BY-SA 3.0 IGO.)

Where rivers meet oceans, flowing water suddenly has space to spread out. The current slows, and sediments suddenly drop out of suspension and pile up to form massive fans of sand and silt. Many of civilization's earliest cities were built on the fertile farmland of such river deltas. Today, deltas are home to an estimated 350 million to 500 million people globally. Alexandria, Egypt—the largest city on the Mediterranean coast—is built atop the western edge of the Nile River delta. Guangzhou, which sits at the mouth of the Pearl River in China, is 1 of the 10 delta-situated cities that have populations greater than 10 million.

Cities and coastlines across the globe face growing flood risk from sea-level rise caused by climate change. But for dozens of major cities that are built on river deltas, rising oceans are not the only threat. The land is sinking beneath cities including New Orleans (see figure 1); Buenos Aires, Argentina; and Bangkok, Thailand. "When we talk about climate change, people have an appreciation for sea-level rise and its effects on coastal communities, but land subsidence still appears as an underappreciated hazard," says Leonard Ohenhen at the University of California, Irvine.

Many factors contribute to land subsidence. Sediments in deltas naturally compact over time, and the process is exacerbated by the physical weight of urbanization and population growth. Pumping water out of aquifers deflates the ground surface, and the demand for water only grows with increasing populations. Physical barriers, such as dams and levees, that are used to prevent routine flooding of population centers can also keep out a supply of new sediments that typically build up the delta over time.

In a new study, Ohenhen and colleagues analyzed vertical land motion in 40 of the world's major delta systems,[1] shown in figure 2. The researchers explored not only how fast delta systems are subsiding but also how much specific human activities, such as groundwater pumping and urban expansion, contribute to their sinking. For nearly half the deltas studied, land subsidence rates exceed the rate of sea-level rise. Thus, alongside global work to curb climate change impacts, local land management strategies are crucial for reducing future flood risk.

Small movements measured from large distances

To establish the rate of vertical land motion down to the scale of millimeters, Ohenhen and colleagues used interferometric synthetic aperture radar (InSAR) data collected from 2014 to 2023 by the Sentinel-1 satellites. Launched by the European Space Agency as part of the Copernicus Earth observation program, Sentinel-1 continuously captures radar images of Earth; the satellites record each region every 6 or 12 days, depending on the region's location on the globe. A major benefit of radar imagery is that, unlike photography, it can be collected through cloud cover and is insensitive to light conditions.

The Sentinel-1 satellites send out radio waves in the C-band, which has a wavelength of about 5.6 cm, and measure the return time and phase of the reflected waves. At least two passes over a region are necessary because phase measurements from a single pass look like random noise. By subtracting a second set of measurements from the first, researchers can precisely calculate ground displacement from an orbital distance of nearly 700 km. (For more about the method, see the 2006 *PT* article "InSAR, a tool for measuring Earth's surface deformation," by Matt Pritchard.) For each delta in the study, 150–200 radar images provided snapshots of the ground motion over the full collection period.

Maps of vertical land motion for each delta system, as shown in figure 3, delineate the spatial patterns of ground motion. In the Fraser River delta in Canada, for example, hot spots of subsidence are surrounded by regions of slight uplift caused by glacial rebound. That phenomenon—the slow rise of land that had been depressed by the weight of an ice sheet—is found throughout high-latitude regions. In contrast, subsidence is widespread in the entire region of the Chao Phraya River delta around Bangkok, though sinking is most pronounced in certain coastal areas at the city's southern edge. In heavily vegetated areas or wetlands, reliable InSAR signals can't be collected, as indicated by spotty coverage in some map regions in figure 3, most notably in the Niger, Mississippi, and Paraná River deltas.

For their assessment of the human drivers of sinking, Ohenhen and colleagues gathered multiple global datasets. Published models of sediment flux and sea-level rise were used to quantify those parameters at each delta, and population data were used to quantify urban expansion. To estimate changes in groundwater storage,

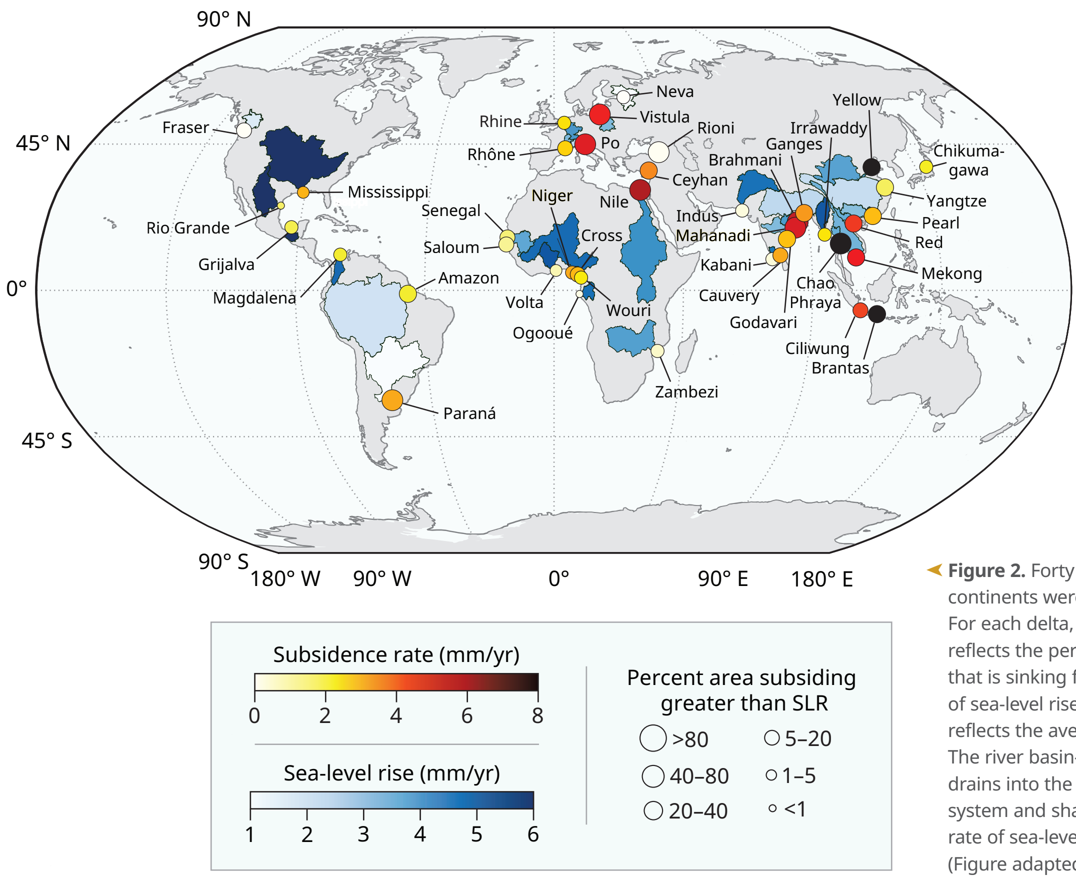

Figure 2. Forty delta systems across five continents were examined for the study. For each delta, the size of the circle reflects the percentage of the delta area that is sinking faster than the local rate of sea-level rise (SLR), and the color reflects the average rate of subsidence. The river basin—the area of land that drains into the river—is outlined for each system and shaded blue according to the rate of sea-level rise at each delta. (Figure adapted from ref. 1.)

the researchers used data from NASA's twin-satellite missions GRACE (Gravity Recovery and Climate Experiment) and its successor GRACE-FO (Follow-On). The satellites measure subtle changes in gravity across Earth's surface. Because water's mass contributes to changes in gravitational pull, the data have been used to estimate total water storage. Groundwater storage was then calculated by subtracting contributions from surface water and soil moisture and validated against independent well measurements where they were available.

A sinking feeling

With estimates for each parameter in hand, the researchers applied two machine-learning statistical analysis methods to parse the relative contributions of each human activity to subsidence rates. In an analysis of all deltas together, they found that decreased groundwater storage was the predominant driver of subsidence; sediment flux and population growth contributed to subsidence to a lesser degree and in roughly equal proportions.

Decreased groundwater storage was the dominant factor driving subsidence in most individual locations as well. In the Mississippi River delta and a handful of others, sediment loss had the greatest impact. Though population growth has contributed to subsidence in many deltas, it was not found to be the dominant driver in any of them. Ohenhen emphasizes that the human-driven processes that the researchers analyzed are not the only factors that contribute to delta sinking. Oil and gas extraction and the draining of peatland for development, for example, are also important to consider.

Of the 40 deltas that the researchers studied, 22 are sinking at average rates of 3 mm/yr or more. And for all but the ones at the Neva River in Russia and the Fraser River in Canada, more than half the delta area is sinking. The global average rate of sea-level rise is 4 mm/yr, but that rate varies significantly by region, as shown in figure 2. For three of the deltas—the ones at the Chao Phraya River in Thailand, Brantas River in Indonesia, and Yellow River in China—the average rate of sinking is at least 8 mm/yr, twice the average rate of sea-level rise. And in 18 of the 40 deltas, the rate of sinking exceeds the rate of local sea-level rise.

What can be done about it? One silver lining is that, whereas a certain amount of sea-level rise from climate change is unavoidable, human intervention can slow some of the sinking. The researchers cite regulation of groundwater pumping, managed aquifer recharge, and sediment management as avenues for reversing the course of subsidence.

For all the benefits of C-band InSAR, the 5.6 cm

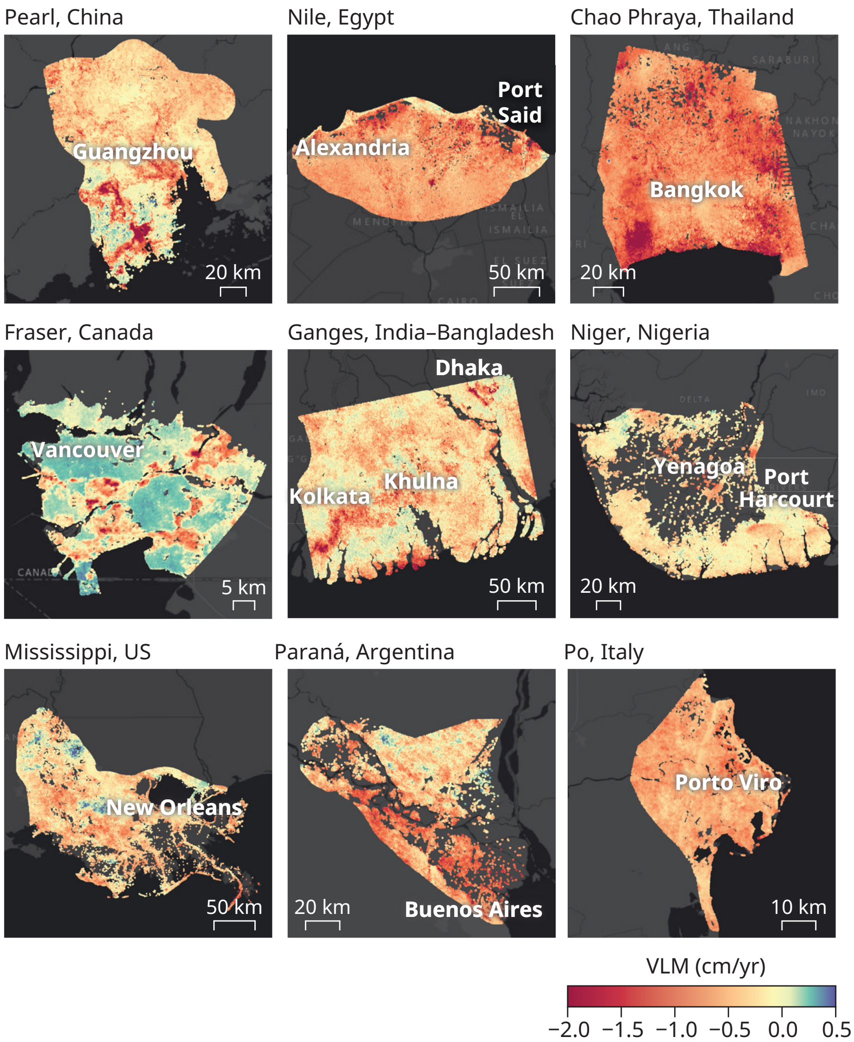

Figure 3. Maps of vertical land motion (VLM) from individual river-delta systems show areas of ground uplift (blue) and subsidence (red) for nine river deltas that are home to major cities (labeled in white). (Figure adapted from ref. 1.)

waves are affected by the presence of vegetation, which can reduce the coherence of land-surface measurements. To help bolster the dataset, NASA and the Indian Space Research Organisation (ISRO) launched in July 2025 an InSAR satellite that uses L-band radar with a wavelength of 24 cm. "The big frontier that we are focusing on is coverage and robustness in deltas, vegetation, wetlands, and seasonally flooded terrain where the C-band struggles," says Pietro Millillo, an assistant professor at the University of Houston and the collaborations lead for NASA's surface topography and vegetation incubation study. It will likely take two to five years before similar analyses can be conducted from the *NASA–ISRO Synthetic Aperture Radar* data.

Milillo says the study by Ohenhen and colleagues is "an important first step" that uses the best available data. "That kind of harmonized cross-delta comparison is something that the community has wanted for a long time." **PT**

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UPDATES

Fluid-coupled rotation demonstrates unexpected modes of motion

Two cylinders rotating in a fluid can mimic the behavior of gears and of a belt-and-pulley system.

By Sarah Wells

When a bird flaps its wings, the air pushed away creates a cascade of swirling flow patterns, which in turn assist the flight of fellow birds in its flock. Those types of fluid-mediated interactions are simultaneously well studied and still not fully understood—especially when they involve rotating bodies. To study rotational hydrodynamic interactions in a controlled setting, Leif Ristroph and colleagues at New York University turned to an idealized system consisting of two cylinders rotating in a glycerol–water solution.[1] A better understanding of the dynamics could, for example, improve the development of technologies like wind turbines and enhance physics research on the flow properties of active materials, such as bacteria swarms and microrobots.

In their tabletop experiment, the team members used a pair of six-inch-long acrylic cylinders suspended vertically in a fluid solution to see how the motorized rotation of one cylinder could drive the rotation of the other, which was able to rotate freely. The researchers varied parameters like speed and cylinder separation and recorded the rotation behavior from the passive cylinder. To visualize how the rotating cylinders affected the flow of fluid around them, the team members densely seeded the fluid with bubbles (as seen in figure 1), illuminated the fluid with a

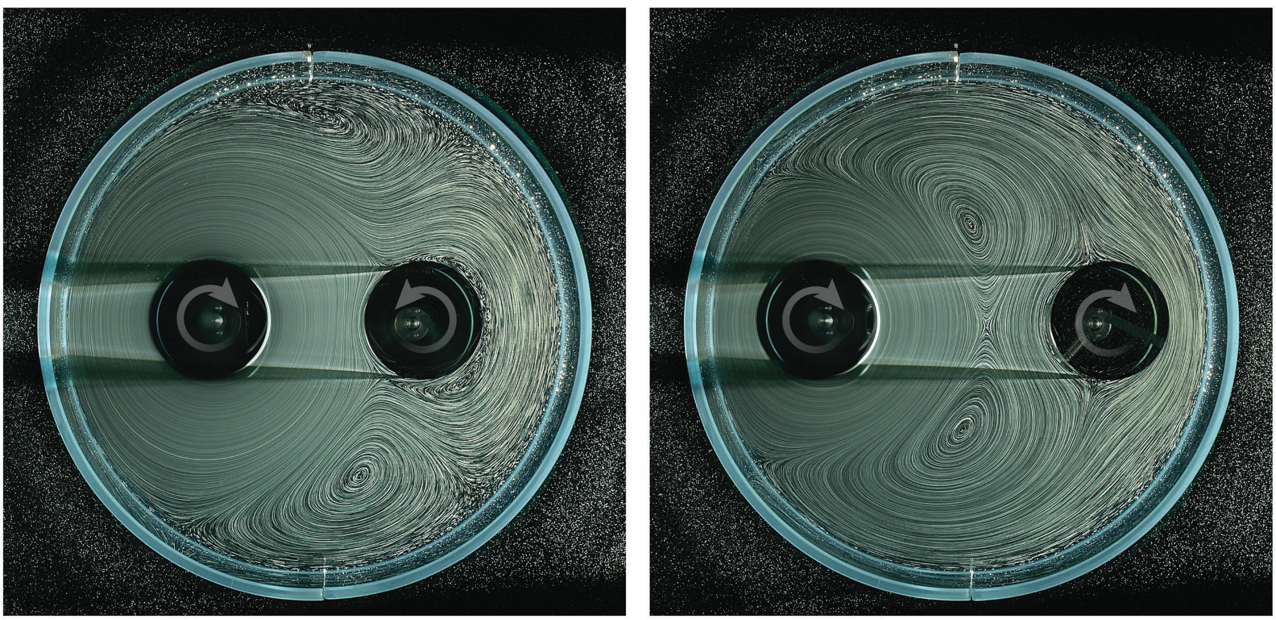

Figure 1. Researchers submerged two cylinders in a tank filled with a glycerol–water solution to observe how one cylinder would respond when the other was rotated. The image on the left demonstrates counterrotation; the one on the right demonstrates corotation. Bubbles seeded in the solution highlight the different fluid flow patterns. (Photos courtesy of NYU’s Applied Math Lab.)

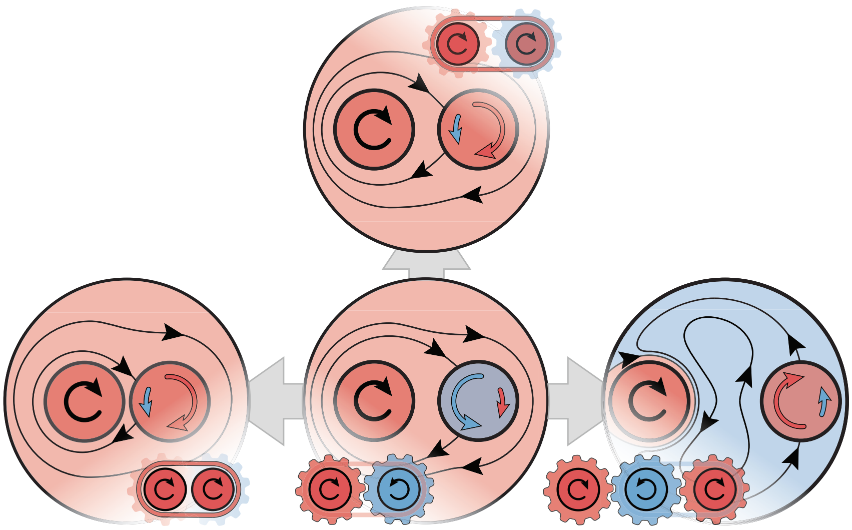

Figure 2. By making small changes to the experimental setup, such as placing the cylinders farther apart in the tank, the New York University researchers observed unexpected changes in the rotational coupling between the cylinders. In this cross-sectional schematic, the color of the cylinders, shear forces (arrows), and the surrounding fluid indicate the sense of rotation. Blue denotes counterrotation, reminiscent of interlocking gears, and red denotes corotation, which resembles belt-coupled pulleys. (Image adapted from ref. 1.)

horizontal plane of light at the cylinders' midplane, and then captured the bubble motion from below with a camera.

Based on similar interactions seen in biological contexts, the researchers expected to see counterrotation, in which the passive cylinder rotates in the opposite direction of the driven cylinder, like two adjacent, interlocking gears. Although they observed counterrotation for some drive parameters, they also observed three modes of corotation—rotation in the same direction—that were totally unexpected, says Ristroph. "What combinations of parameters led to the different outcomes turned up surprises at every corner."

Each of the four rotation modes was accompanied by distinct patterns of fluid flow around the cylinders, as sketched in figure 2. The researchers observed a transition from counterrotation to corotation when the cylinders were in close proximity or when the surrounding flow was strong; in both cases, the surrounding fluid acted like a belt that rotated the passive cylinder in the same direction as the drive cylinder. Corotation also appeared when the cylinders were sufficiently far apart to support a region of counterrotating fluid that acted like a third interlocked gear.

The team members are working on 2D simulations to better understand the underlying fluid dynamics that create the distinct modes. They are also exploring whether changing other aspects of the experimental setup, such as the fluid's viscosity or the driving torque on the active cylinder, will affect fluid flow and rotational coupling. **PT**

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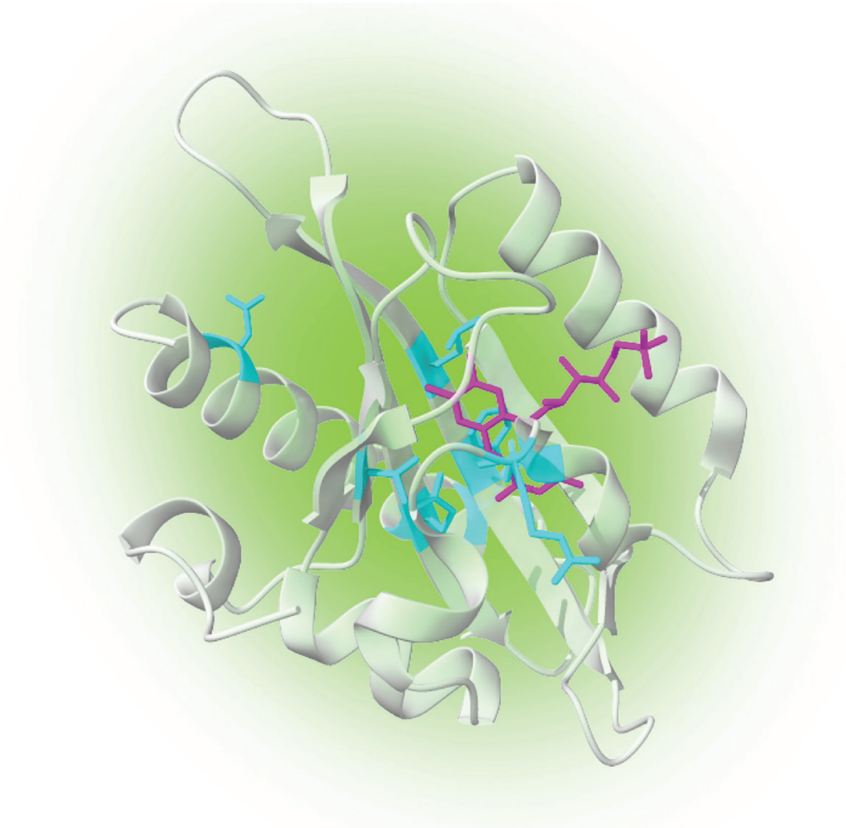
Genetically engineered protein is a versatile quantum sensor

In noisy biological environments, the fluorescent protein can pinpoint subcellular structures and detect magnetic field changes.

By Alex Lopatka

When researchers study biological processes in cells, it helps if they have nanoscale sensors to take measurements. One approach is to carefully build and embed sensors into cells. (For an example with nitrogen–vacancy centers, see the 2020 *PT* story "Nanodiamonds shine as subcellular thermometers.") Another option is to exploit the biological machinery that's already there. Because of advances in genetic engineering, researchers can assemble protein sensors *in situ* by manipulating the proteins' DNA. Now Gabriel Abrahams and Harrison Steel, both at the University of Oxford, and their colleagues have engineered a fluorescent and magneto-responsive protein that has boosted magnetic-sensing capabilities.[1]



The AsLOV2 protein, illustrated here, was used as a precursor to develop the MagLOV 2 protein through directed evolution. The parts of the AsLOV2 structure that were mutated to make MagLOV 2 are highlighted in blue and purple. MagLOV 2 is more sensitive to magnetic field effects than AsLOV2 and can be used as a quantum sensor. (Image adapted from ref. 1.)

Abrahams and colleagues started with a well-known and biocompatible fluorescent protein and engineered it to have magnetic-sensing properties.[2] Then, using a technique called directed evolution, they mutated the protein, screened the resulting variants for the ones with the highest sensitivities to magnetic field strength, and then repeated the process several more times. (To read more about directed evolution, see the 2018 *PT* story "Chemistry Nobel winners harnessed evolution to teach old proteins new tricks.")

The researchers found a protein, which they named MagLOV 2, that at room temperature in living cells exhibits optically detected magnetic resonance. By shining a laser on the protein, they could excite two electrons, which develop spins that are quantum mechanically linked. The protein's fluorescence signal depends on what spin states the electrons are in. Because the spins are influenced by magnetic fields, a resonant RF field can, on demand, drive transitions between the spin states.

Abrahams and colleagues demonstrated that when the fluorescent MagLOV 2 is exposed to magnetic and RF fields, it can be used to measure the locations of proteins in cell cultures and of other structures embedded in a 3D volume. The protein sensor is less sensitive to light scattering by biological tissue than other fluorescence-based sensors, so it could outperform various localization techniques, such as fluorescence-modulated tomography.

Abrahams and colleagues also determined that in the presence of other magnetic chemical species, Mag-LOV 2 exhibits a decreased sensitivity to magnetic field effects. By quantifying the protein's response to those effects, researchers could use the new quantum sensor to identify magnetic-signal-generating molecular species, such as free radicals and metalloproteins, which are critical in physiological processes such as cell signaling, immune responses, and metabolism. PT

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Reduced pandemic emissions contributed to atmospheric methane surge

A drop in nitrogen oxide emissions led to fewer hydroxyl radicals in the atmosphere to oxidize the methane.

By Sarah Wells

During the pandemic shutdowns that began in early 2020, the anthropogenic emissions of certain pollutants, such as nitrogen oxides, dropped—which contributed to improvements in air and water quality. Nonetheless, the concentration of atmospheric methane surged. From January 2021 to January 2022, methane levels increased by 17.7 ppb, according to NOAA data,[1] the largest annual increase in the roughly 40 years that NOAA's Earth system research laboratory has measured methane (see figure 1). By 2023, the annual rate of increase had fallen back to 8.6 ppb. To put that in perspective, the total concentration of atmospheric methane was about 1950 ppb as of last fall, and every 1 ppb increase is equivalent to 2.8 million metric tons of methane entering the atmosphere.

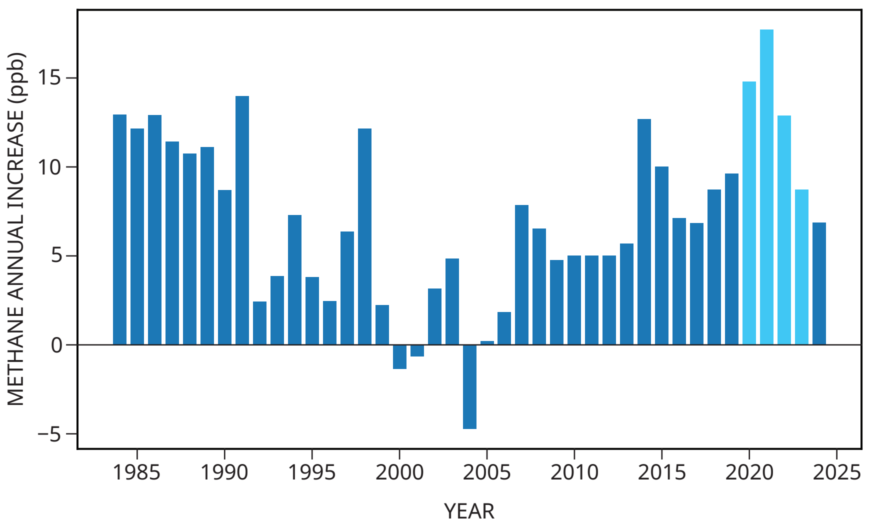

Figure 1. In 2021, the annual rate of increase in atmospheric methane concentration reached its highest level in the nearly 40 years of NOAA measurements. Methane levels change from year to year because of a variety of factors, including changes in anthropogenic and biogenic emissions levels and the capacity of methane sinks like hydroxyl radicals. (Image adapted from NOAA.)

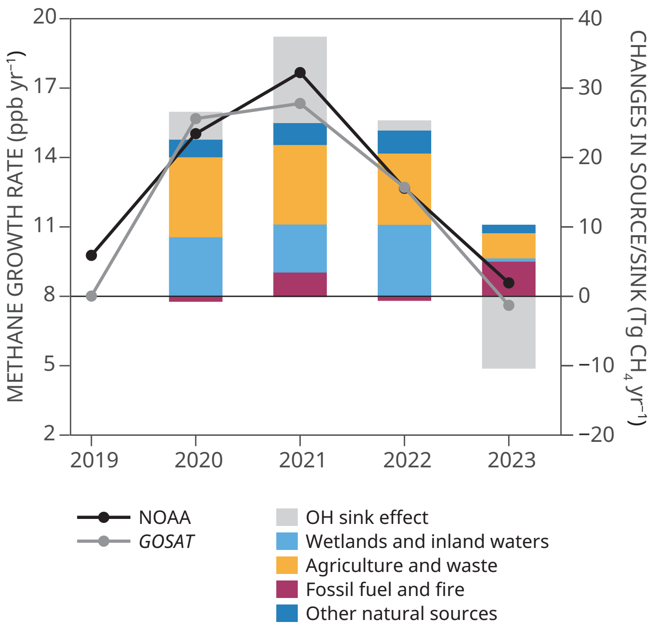

Figure 2. The lines (units on the left side of the graph) depict the annual change in atmospheric methane concentration as measured by NOAA ground observatories and the Japanese *Greenhouse Gases Observing Satellite* (*GOSAT*). The bars (units on the right) show how various methane sources and sinks contribute to the methane budget.

Tracking methane, the second most prevalent anthropogenic greenhouse gas behind carbon dioxide, is an important yet difficult task. Understanding the rises and falls in methane concentrations requires disentangling methane sources, such as emissions from human activities like burning fossil fuels and raising livestock, and biogenic sources, like wetlands, where microbes in the soil emit methane when they break down organic material. Data about those sources are not uniformly collected, and various climate models combine and weight the data differently, so estimates of the contributions that individual emission sources make to the total amount of atmospheric methane can vary drastically.

To determine how the different factors led to the methane surge, Philippe Ciais, from the Laboratory for Climate and Environmental Sciences in France, and colleagues at various institutions in different countries analyzed several data sources.[2] For top-down inventories, they looked to the Japanese *Greenhouse Gases Observing Satellite*, which measures the atmospheric concentrations of carbon dioxide and methane using spectroscopy, and NOAA's global network of ground-based atmospheric observing stations, which measure methane levels using air sampling (see figure 2). They also did a bottom-up inventory that looked at different ways of adding the contributions of various methane emitters. Comparing predictions from the different models allowed the researchers to determine which combination of sources was responsible for the surge.

The team found that the surge was primarily caused by two factors. The dominant factor, accounting for roughly 80% of the surge, was a reduced atmospheric concentration of hydroxyl radicals, which act as a methane sink by oxidizing the pollutant and breaking it down into water vapor and carbon dioxide. The drop in hydroxyl levels was caused by the drop in emissions of nitrogen oxides during the pandemic. Nitrogen oxides catalyze a photolysis reaction in ozone that produces hydroxyl radicals. The rest of the surge is explained by an increase in wetland emissions, which was caused by a particularly warm and wet La Niña season in tropical regions of Africa and Southeast Asia. The researchers quantified the impact of the wetland emissions by comparing atmospheric-inversion models, which work backward from methane concentration levels to find emission sources, and simulations of wetlands. Eventually, a shift in conditions—increased nitrogen oxides emissions as pandemic restrictions eased and a drier El Niño season starting in 2023—brought methane levels back to an expected range.

Beyond solving the mystery of the methane surge, the findings demonstrate the need for improved monitoring and climate models, Ciais and colleagues say. They highlight urgent gaps in monitoring flooded ecosystems and methane-producing microbial processes. With improved monitoring, researchers could conduct comprehensive assessments of the methane budget in months rather than years, which would help them understand changes to methane levels while they are still underway. **PT**

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PRECISION MEASUREMENT GRANT

The National Institute of Standards and Technology (NIST) anticipates awarding one new Precision Measurement Grant that would start on October 1, 2026, contingent on the availability of funding. The award would be up to $50,000 per year with a performance period of up to three years. The award will support research in the field of fundamental measurement or the determination of fundamental physical constants. The official Notice of Funding Opportunity, which includes the eligibility requirements, is posted at **www.Grants.gov**.

Application deadline is **April 9, 2026**.
For details/unofficial updates see **physics.nist.gov/pmg**.

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NIST to introduce restrictions on non-US citizens

The precision measurement and quantum communities are upset about the secretiveness of the move and its potential damage to US science.

By Toni Feder

Researchers at NIST who hail from outside the US are scrambling to find new projects, new labs, new jobs, and even new countries. They are responding to diffuse information that noncitizens are to be limited to three-year stints at NIST, and the clock is retroactive. James Kushmerick, director of NIST's Physical Measurement Laboratory, confirmed the new policy at a 4 February town hall meeting, according to several researchers at NIST's Boulder, Colorado, campus.

NIST, an agency under the Department of Commerce, is a world leader in precision and quantum measurements. Some 2800 employees plus 3200 visiting associates work at its Gaithersburg, Maryland, headquarters; another 560 employees and 940 visiting associates are based in Boulder. Of those workers, several hundred are not US citizens, according to estimates by NIST researchers. (The campus totals are from NIST's website; the institute did not respond to questions about the numbers of directly affected individuals or about the new policy.) Given that obtaining a PhD often extends to five years and beyond, graduate students will be hardest hit by the restrictions.

As this article went to press, the situation was still in flux, and NIST scientists and their colleagues say that hints of flexibility give them hope that the policy will be weakened.

Scarce communication

It's not only the new policy that has NIST researchers spinning. It's also the fact that they are hearing about it through the grapevine. Researchers from abroad are being told by their supervisors that they should start looking for other opportunities, says a graduate student at NIST who is a US citizen and who requested anonymity. (Nearly all the roughly dozen stu-

Building 1 at the NIST research hub in Boulder, Colorado, in an undated agency photo. (Photo by R. Jacobson/NIST.)

dents and scientists interviewed for this story requested anonymity: They include federal employees who don't have permission to speak publicly, researchers on visas, NIST researchers who want to protect their behind-the-scenes attempts to ameliorate the situation, and researchers at NIST or collaborating universities who fear retaliation from the government.)

Multiple sources said they had heard as early as January that the new time limits would be implemented in three steps. Reviews would begin in late March for people from "high-risk" countries: China, Cuba, Iran, North Korea, Russia, and Venezuela. "Medium-risk" countries would follow in the fall, and the review would wrap up by the end of the year with people from Australia, Canada, New Zealand, and the UK.

NIST scientists say they have yet to see anything in writing about the new policy. But termination dates of research agreements for noncitizens have been moved up in computer databases, and some graduate students and postdocs have heard from their principal investigators that their permission to work at NIST would expire on 31 March.

The NIST administration building in Gaithersburg, Maryland, in an undated agency photo. (Photo by J. Stoughton/NIST.)

Alarm and desperation

A mood of fear and outrage pervades beyond those who are directly affected. "Everyone is upset," says an outside researcher who collaborates with NIST scientists. "People are desperately seeking new positions. There are group leaders who are losing eight or more members of their teams." The anonymous graduate student says that "a lot of the research currently being done by foreign nationals simply won't get done." They point to a tabletop experiment that a noncitizen colleague had built over years; the experiment "will go unoperated for many months or even be pillaged for parts by those of us who remain."

The uncertainty and dearth of information create a chilling effect, according to many researchers associated with NIST. "People are leaving, and it will be harder to recruit even US citizens," says Maya Miklos, a graduate student at JILA who is a US citizen. "The productivity of the system will suffer."

Scientists point out that if students and postdocs leave on short notice, knowledge will be lost. A senior NIST scientist notes that they and their colleagues have been told by higher-ups "that if we have someone who is important to the lab's mission, we should bring on a US citizen, have a foreigner train them, and then get rid of the foreigner." That attitude, the scientist says, "sees people as interchangeable. It's very shortsighted."

Graduate students who do their research at NIST get their degrees from a partner university. The University of Colorado Boulder and the University of Maryland in College Park combined have 33 international students doing their research at NIST. UMD has another 20 postdocs and 11 senior scientists who would be directly affected. NIST scientists say they understand that the new policy applies even to green-card holders. A physics professor at Boulder says the campus is working to find new labs for its graduate students. It's also scrambling to find money for the students to cover rent and food. "Those are the most immediate crises," says the professor.

"We are trying to work to avoid this policy becoming reality," says a senior NIST researcher. As to exactly how they are doing that, scientists are mum. "The most senior management are getting a notion of how alarmed we are, and why," says a NIST physicist. Graduate students have run phone banks to call their representatives in Congress. And several researchers point to industry as being likely to have the most clout. The Boulder area is home to a bustling quantum industry, and many of its employees come from NIST and JILA. "Industry is appalled," says the physicist. "If industry chimes in, that could get more traction."

House letter unanswered

On 19 February, Zoe Lofgren (D-CA), the ranking member of the House Committee on Science, Space, and Technology, and fellow member April McClain Delaney (D-MD) wrote to Craig Burkhardt, acting undersecretary of Commerce for standards and technology and acting NIST director. The letter stated that the "rumored policy change . . . would severely damage NIST's ability to conduct cutting-edge research with world-class talent." And Lofgren and Delaney blasted the organization for "secretive, slapdash policy changes that pull the rug out from visiting researchers." The policy change, they wrote, would not only "be destabilizing for bright scientists who seek to bring their talents to the United States, it would have deleterious consequences on the country as a whole."

In the letter, Lofgren and Delaney requested responses to questions about the existence of the NIST policy, how it was developed, how it's been communicated, whether an appeals process has been established, and more. Specifically, they requested a briefing on the issue by 25 February. By the end of that day, they had heard nothing from NIST.

Still, the letters and phone calls, publicity about the situation, and other pushback may be making a difference. The NIST physicist who commented on connections to industry says that on 24 February, senior management told scientists that decisions are not final. According to the physicist, the new understanding is that deadlines and restrictions may be open for discussion. That could mean exemptions for graduate students, for people from specific countries, or for those who work in certain research areas, the physicist says. "We interpret it as, We don't have to kick people out the door," they say. "No one really knows. But I would call this an improvement of sorts." **PT**

Science inspires, but does not limit, Andy Weir's fiction

Spreadsheets littered with calculations motivate the science-fiction writer's stories, including *Project Hail Mary*.

By Jenessa Duncombe

Editor's note: This story contains minor spoilers about the plot of Project Hail Mary.

Amount of fuel required. Mass of ship. Distance, in light-years, to destination. Those are some of the values in the Excel spreadsheet Andy Weir made when writing his 2021 novel, *Project Hail Mary*. The book centers on an astronaut who wakes up in a star system 12 light-years from Earth with little memory of how he got there. A series of misadventures follows. A movie adaptation hit theaters on 20 March.

Weir says he enjoys making his novels' spreadsheets more than writing. "I set things in motion very specifically," says Weir, who also wrote *The Martian* (2011) and *Artemis* (2017).

To generate story ideas, Weir muses about what-ifs and lets the answers determine whether the story is worth telling. "I try to set up an interesting scenario and then just see where it goes," he says. *The Martian* began with the question of how an astronaut could survive alone on Mars. Weir solved the problem iteratively, posting his drafts online for readers to weigh in. He created a spreadsheet to calculate launch windows according to orbital trajectory calculations. "If you say Sol 417, I could look it up in my spreadsheet and find the calendar date [in the story]," Weir says. The book and the 2015 movie earned praise for the realistic depictions of space engineering and the Martian environment.

In *Project Hail Mary*, a light-eating space microbe dims the Sun, which cools Earth's surface by 6 to 8 degrees Celsius and throws the planet into an extinction-

Ryland Grace, played by Ryan Gosling, must save Earth in the new film *Project Hail Mary*, based on the book of the same title. The movie's backdrop features realistic readouts calculated by author Andy Weir and the movie's science advisers. (Photo by Jonathan Olley.)

level event. The protagonist, Ryland Grace, could rescue Earth if he could remember who he is and how he got into space.

Weir tinkers with the story's numbers to devise the most-thrilling scenarios. "If I haven't defined enough of those starting conditions, then that means I get to go back and retroactively decide things," says Weir. He gives the example of adjusting the amount of fuel in Grace's spaceship to keep the story exciting.

A former software engineer, Weir consults websites for educators and students as sources for his science information. "I have a really tough time reading scholarly papers," he says. Although he knows scientists he could ask, he finds that Googling is a faster way to answer his questions. Science motivates Weir's stories, but he doesn't let it get in the way of a good plot. "If I don't like a fact, I change it," Weir says.

Project Hail Mary features a mixture of realistic, plausible, and fantastical scenarios. The ship at the heart of the story is "something that we *could* do with five or ten years and a few trillion dollars to play with," Alex Howe, an astrophysicist and science communicator who reviews science-fiction books, wrote on his blog.

The habitability of Venus's clouds is another plot point in the story, and that is an active area of research. In a paper published in *Nature Astronomy* in 2020, researchers claimed they had found evidence of phosphine gas in the clouds of Venus. Phosphine comes exclusively from biotic sources on Earth, and the authors stated that there is no known abiotic source on Venus. Several subsequent analyses of Venus data failed to find phosphine. Several missions to Venus by the mid 2030s are being considered.

One fictional exoplanet, Erid, at the heart of the story, was inspired by a nearby three-star system, 40 Eridani, that is the target of exoplanet searches. Catherine Clark, an astronomer who studies multistar systems, has studied the stars of 40 Eridani. No exoplanets have been confirmed there, says Clark, "but as a nearby bright star, 40 Eridani A is a good candidate for future planet searches."

On the more outlandish end of the spectrum, Weir invented the concept of "super cross-sectionality" to explain how the space microbe stores energy. The movie summarizes the concept with a quip from Grace, played by Ryan Gosling, who says that the microbes "toot to scoot." The film skims over many of the other science plot points that come up later in the book.

Weir crunched more numbers for the film. Much of the movie takes place on a spaceship, and the directors wanted realistic readouts on the ship's screens. Weir calculated the distance of the ship to its destinations, the current velocity with respect to the target star, and other values depending on where a scene occurred. Weir says that a physicist on set would at times double-check his math and that NASA engineers reviewed cuts of the film. "They told us little things like, 'Yeah, this is wrong, but it doesn't matter.' Or 'This is wrong, and it does matter.' "

Having explicit math featured in his stories also opens it up for critique. One criticism, pointed out by readers online, is about the atmospheric pressure of the exoplanet Erid. In the book, Erid is said to have an air pressure 29 times as high as that of Grace's spaceship. That is incorrect. What Weir meant is that Erid's atmospheric pressure is 29 times as high as Earth's at sea level—the spaceship's internal air pressure is kept at 0.4 atmospheres. "It's not perfect. I make mistakes," Weir says. Changing the book in subsequent printings is harder than a simple find and replace, says Weir. "We just don't bother making those changes."

Weir acknowledges that the scientific scenarios he investigates aren't novel in and of themselves. "I'm not even the first person to strand someone on Mars in fiction. I just like to do things my own way: meticulously, nerdishly, scientifically." PT

Eiffel Tower to gain symmetry with addition of women's names

Women will join men in being honored on the Paris icon.

By Toni Feder

Women scientists' names are to be inscribed on the Eiffel Tower, as shown in this mock-up. They will be added above the names of men, who had to have made their scientific contributions in the century preceding the tower's completion. The names face outward just below the first floor of the tower. (Image courtesy of Agence Pierre-Antoine Gatier, 2025.)

The names of 72 women scientists, mathematicians, and engineers are set to be inscribed on the Eiffel Tower, Paris Mayor Anne Hidalgo announced on 26 January. They will join an equal number of men's names, which have been there since the tower was completed in 1889. Gustave Eiffel, the tower's architect and engineer, wanted the tower to be a monument to French scientific prowess.

The inspiration for the gender parity came from student and Eiffel Tower tour guide Benjamin Rigaud. In August 2021, he says, a tourist asked him whether Marie Curie's name was inscribed on the tower. In that moment, says Rigaud, he realized that there were no women represented among the inscribed names. "Everyone should know that many women have contributed to science," he says.

Rigaud was joined in his efforts to add women's names to the Eiffel Tower by student organizations and especially by Femmes & Sciences, a French association that promotes women in science, which lobbied the mayor's office. "We carried the project over the past five years and brought it to success," says Femmes & Sciences vice president Isabelle Vauglin. The mayor commissioned the association to select which scientists to honor.

The women's names are to be inscribed directly above the men's in the same 65-centimeter-tall gilded lettering, as shown in the rendering. Because of limited space, names cannot exceed 12 letters. As with the men's, that means last names only. The honorees include mathematician Sophie Germain (1776–1831), chemist Irène Joliot-Curie (1897–1956), and physicist Cécile DeWitt-Morette (1922–2017). Most are French, but a few, such as Rosalind Franklin (1920–1958), are from other countries but spent time working in France. (A brochure with information about each of the women scientists is available online.)

"It's a scandal that there are only men on the Eiffel Tower," says Françoise Combes, an astrophysicist and president of the French Academy of Sciences. "We want parity for science. And for young women, seeing that women are scientists serves as a model."

Some permissions, formalities, and the making of prototypes are still needed, says Combes. She expects the names to be added to the tower before the end of the year. **PT**

Sketches, such as these (clockwise, from top left) of Edmée Chandon, Rosalind Franklin, Henriette Faraggi, and Yvonne Choquet-Bruhat, and descriptions of the scientists whose names are to be inscribed on the Eiffel Tower are featured in a brochure that is available online. (Images © MkF éditions/Mathilde Cordelle.)

Challenges await NSF's next director

By Lindsay McKenzie and Clare Zhang

The White House formally nominated Jim O'Neill on 2 March to be the next director of NSF. Until recently, O'Neill was acting director of the Centers for Disease Control and Prevention, a position now assumed by Jay Bhattacharya, who also directs the National Institutes of Health. O'Neill worked for the Department of Health and Human Services during the George W. Bush administration and later became an investor, including for the Thiel Foundation's Breakout Labs, which funded early-stage commercialization of scientific research.

If confirmed by the Senate, O'Neill will head an agency that has undergone rapid change. NSF has been without a director since Sethuraman Panchanathan resigned in April 2025. Since then, the agency has seen staff cuts, grant terminations, grant-review process changes, a restructuring of its divisions and directorates, and a major reduction in the use of rotators—scientists, engineers, and educators who work at NSF on a temporary basis to help set funding priorities and evaluate grant proposals (see the 2022 *PT* article "Stepping into NSF" to read about working as a rotator).

At a February meeting of the National Science Board, which oversees NSF, Micah Cheatham, NSF's chief management officer, said the agency is seeking approval from the Trump administration to hire more staff because its current level of around 1300 employees is "too low." Cheatham also shared plans to reduce the number of grant solicitations the agency offers and to speed up review processes.

Some NSF projects are experiencing construction delays, according to a Government Accountability Office report published in February. Of the seven major research infrastructure projects in various stages of development, four have fallen several months behind schedule since July of last year. All the delayed projects are still within budget, but some have been reduced in scope. NSF says labor shortages and budgetary uncertainty are contributing to the delays (see the May 2025 *PT* article "Trump defunds NSF construction budget").

The agency is also operating without a headquarters. NSF vacated its former building in Arlington, Virginia, in January. But its new home, in a building a few blocks away, is not yet ready for staff. As a result, most NSF personnel are working remotely with no concrete date set for when they will return to the office. Committee meetings that usually take place in person are being held virtually.

An NSF spokesperson says that work on the agency's new headquarters began shortly after the lease was signed in December 2025. The spokesperson adds that the agency "quickly established a presence in the building" and that NSF leadership and staff who are involved in outfitting it are on-site daily. NSF "is looking forward to fully occupying the building as quickly as possible," the spokesperson says.

Layoffs hit National Laboratory of the Rockies

By Jacob Taylor and Lindsay McKenzie

At least 130 employees were laid off in February at the National Laboratory of the Rockies, previously known as the National Renewable Energy Laboratory (NREL). The dismissed staff had worked in research and operations roles, according to local news reports. The job losses follow a 10% budget cut to the Department of Energy's Office of Energy Efficiency and Renewable Energy, which is a major source of funding for the lab. They also come less than year after the lab laid off 114 employees.

According to its website, the lab employs nearly 4000 people, though it is unclear if that number accounts for the recent rounds of layoffs. Several Democratic members of Colorado's congressional delegation have spoken out against the dismissals.

DOE renamed the lab in December. In a press release, Assistant Secretary of Energy Audrey Robertson said the name change came about because "the energy crisis we face today is unlike the crisis that gave rise to NREL." She added, "Our highest priority is to invest in the scientific capabilities that will restore American manufacturing, drive down costs, and help this country meet its soaring energy demand."

The lab started as the Solar Energy Research Institute and opened in 1977 as part of the federal government's efforts to mitigate the effects of oil embargoes. The lab was renamed NREL in 1991 when it was absorbed into DOE's national lab system. **PT**

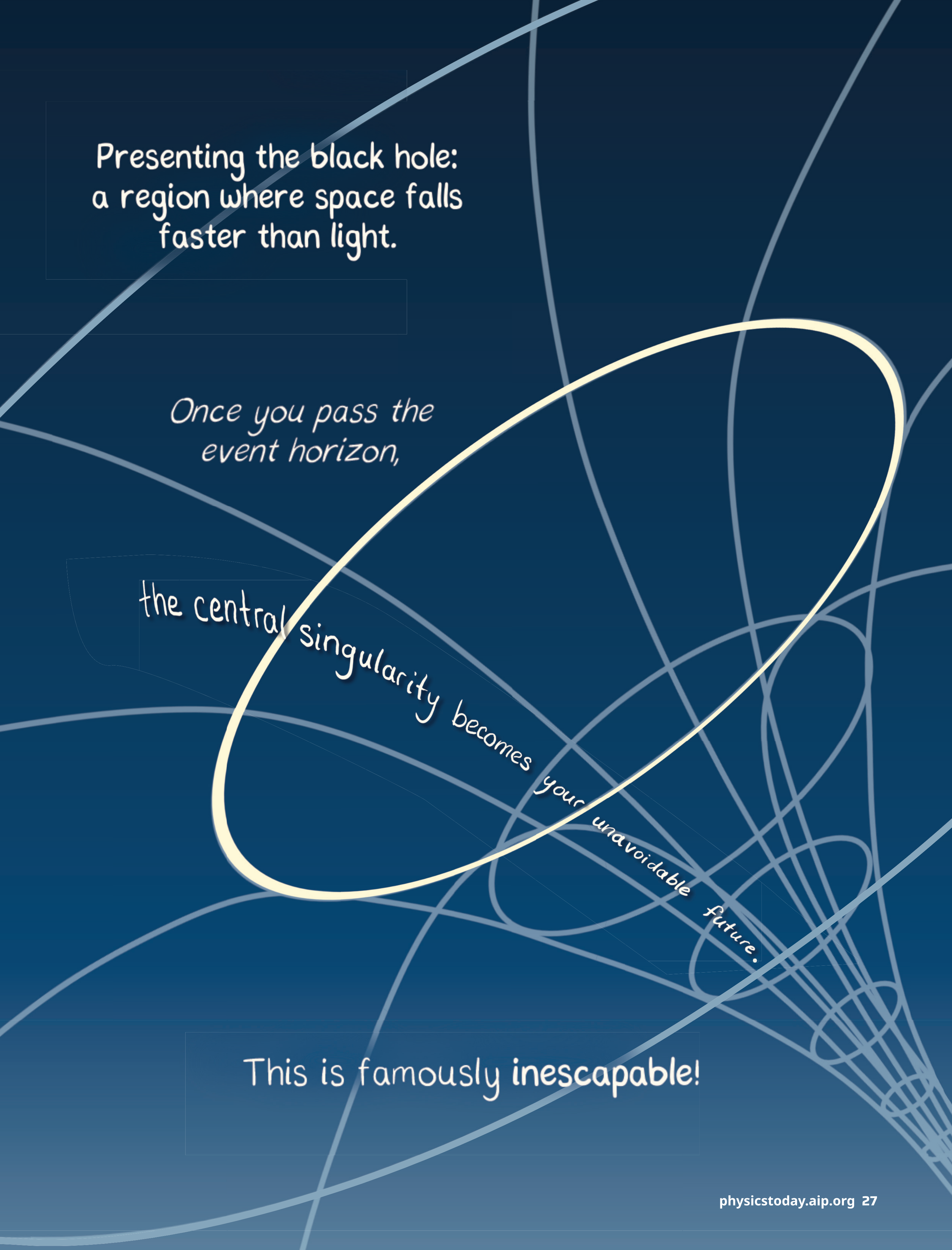
For more from *FYI*, the science policy news service at AIP, visit https://aip.org/fyi.

Black holes aren't black

A half century after the discovery of Hawking radiation, we are still dealing with the quantum puzzle it exposed.

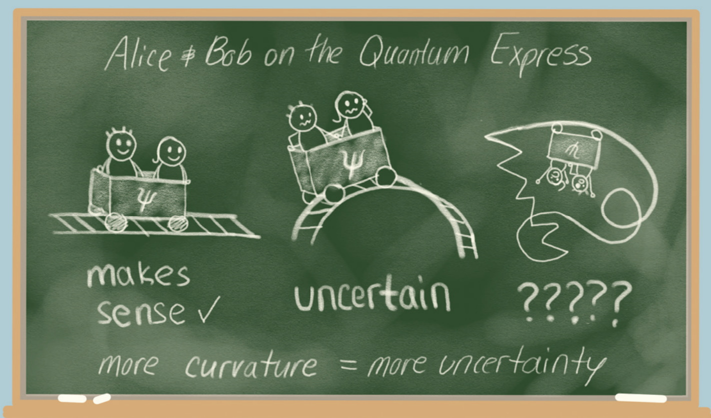
By Claire Lamman

Claire Lamman is a cosmologist, science communicator, and postdoctoral researcher at the Ohio State University in Columbus. More of her work can be found at https://cmlamman.github.io.


Presenting the black hole: a region where space falls faster than light.
Once you pass the event horizon,
the central singularity becomes your unavoidable future.
This is famously inescapable!

But quantum physics tangles the classic story.

In 1974, Stephen Hawking applied quantum field theory to the spacetime metric of the event horizon.

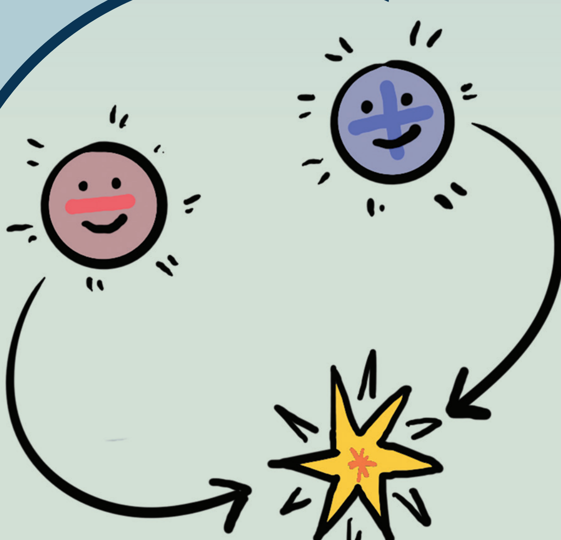


Describing a field under the quantum framework works fine in a flat spacetime.

But in very curved space, like around a **black hole**, you end up with an uncertainty in the local energy density.

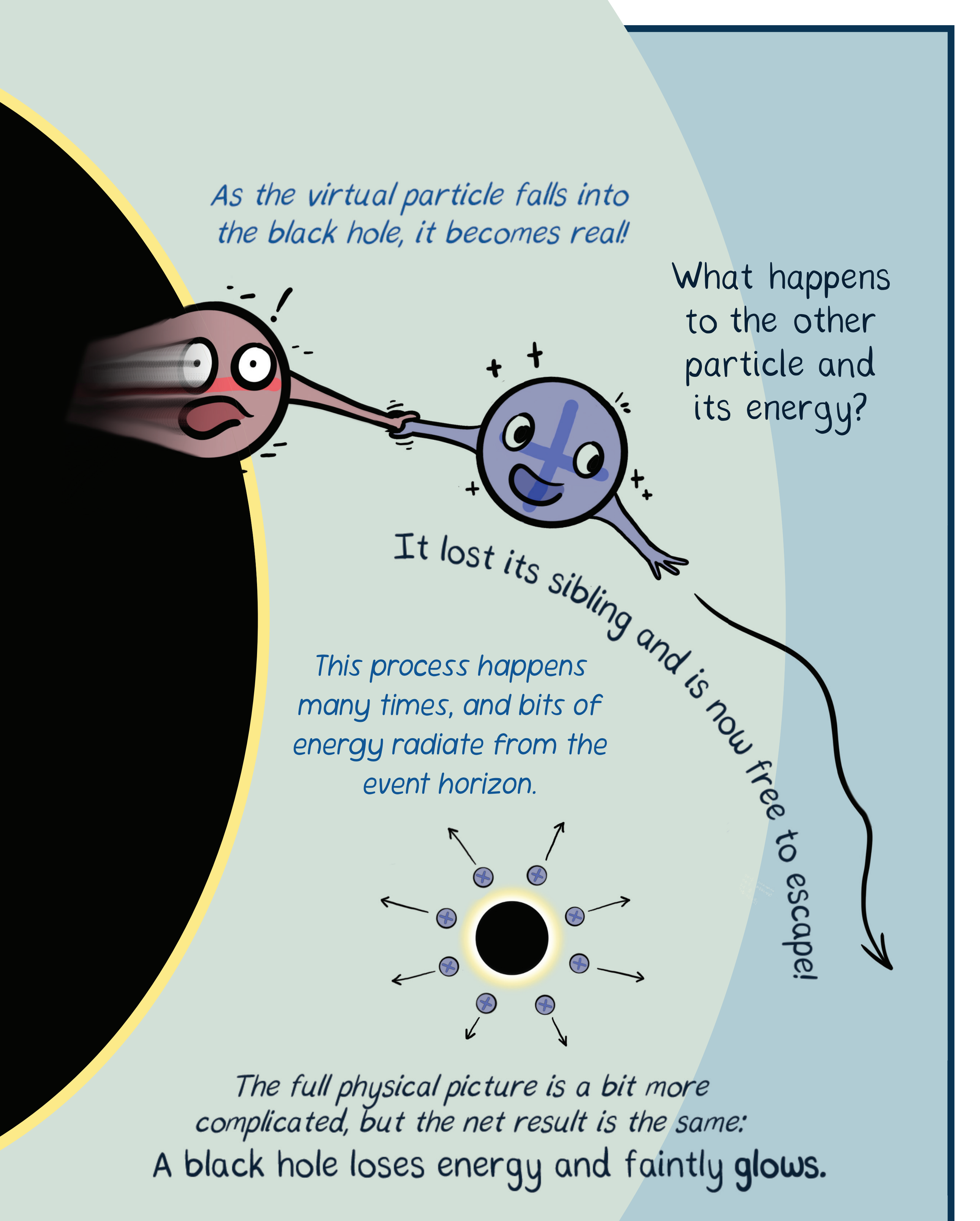
Uncertainty causes weird effects near the event horizon.

Hawking showed how quantum fluctuations allow energy to escape from a black hole, a process now known as Hawking radiation. He described this **heuristically** with virtual particle–antiparticle pairs, here represented with ⊖ and ⊕ :



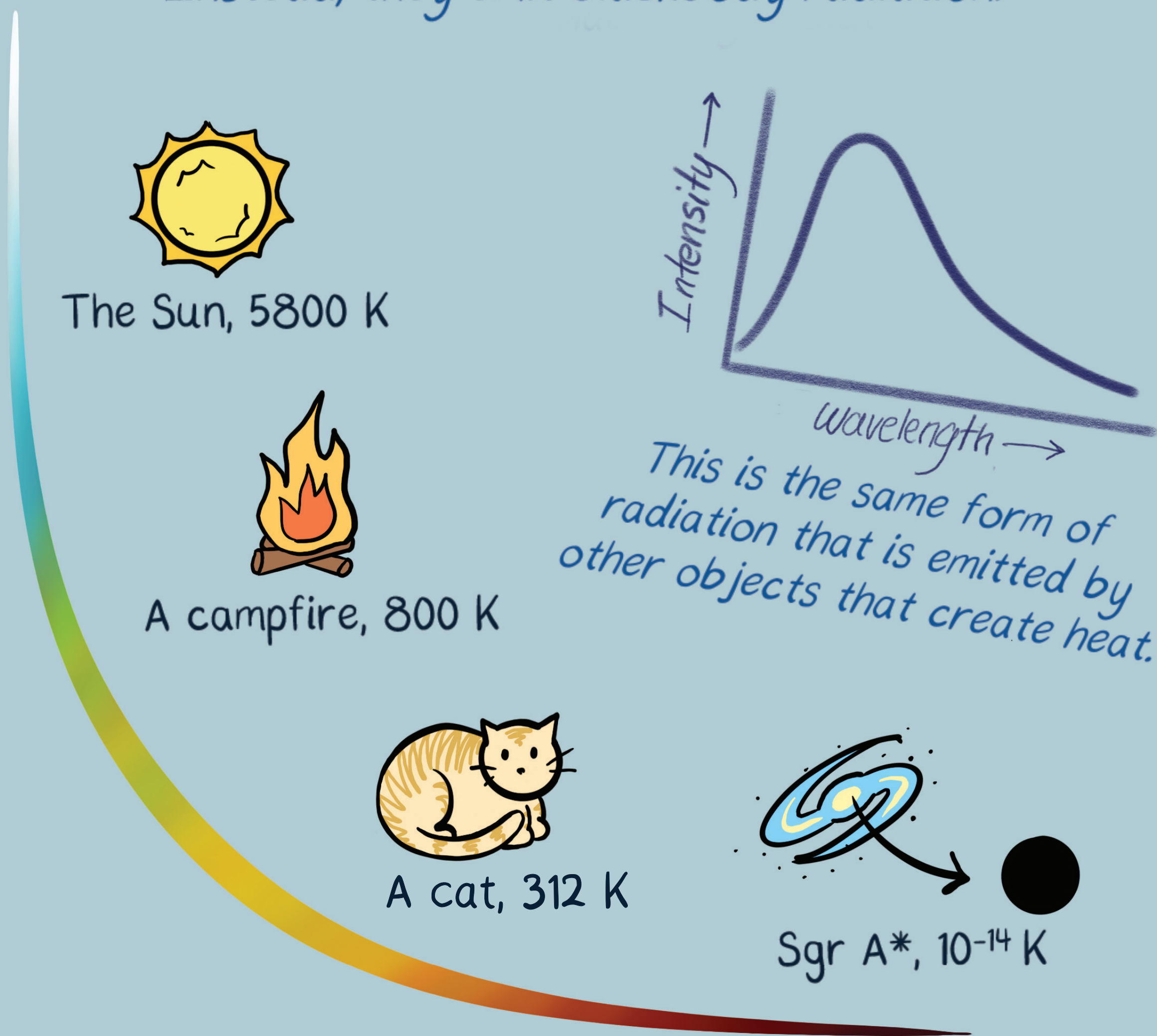
Normally, the particles annihilate each other soon after being created.

But near the event horizon, one can fall through it.


As the virtual particle falls into the black hole, it becomes real!
What happens to the other particle and its energy?
It lost its sibling and is now free to escape!
This process happens many times, and bits of energy radiate from the event horizon.
The full physical picture is a bit more complicated, but the net result is the same:
A black hole loses energy and faintly glows.

Black holes aren't black!

Instead, they emit blackbody radiation.

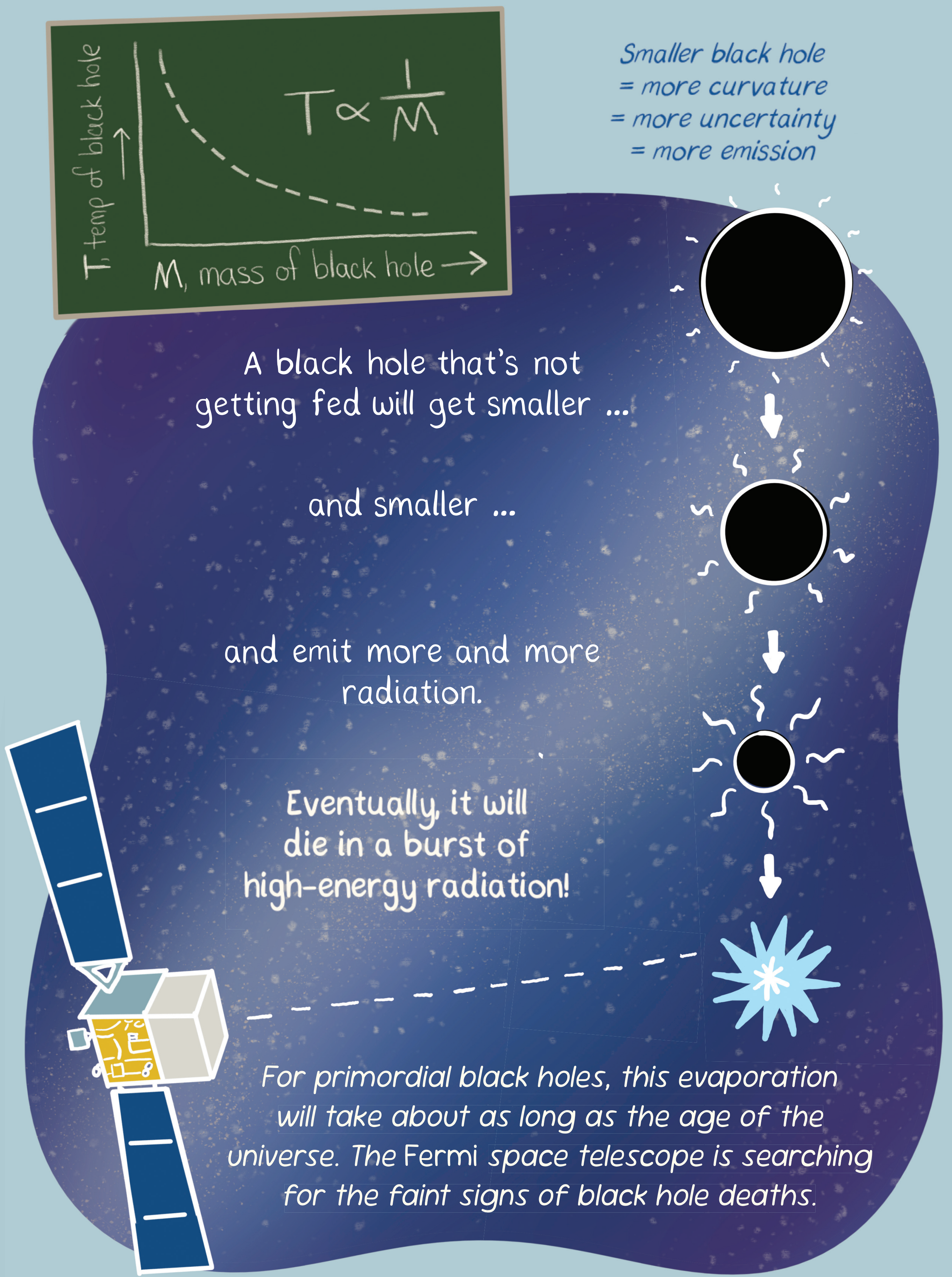


These all have a temperature, including black holes!

Could we detect the glow from a black hole?

Maybe.

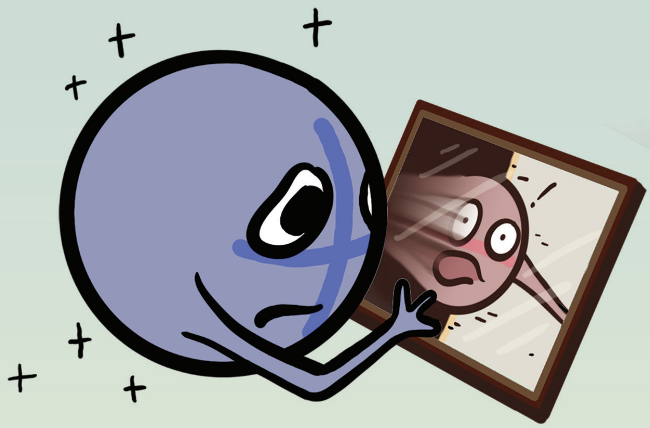
The uncertainty in energy density at the event horizon, and thus emission, is related to the curvature of spacetime.


T, temp of black hole
M, mass of black hole
$T \propto \frac{1}{M}$
Smaller black hole
= more curvature
= more uncertainty
= more emission
A black hole that's not getting fed will get smaller …
and smaller …
and emit more and more radiation.
Eventually, it will die in a burst of high-energy radiation!
For primordial black holes, this evaporation will take about as long as the age of the universe. The Fermi space telescope is searching for the faint signs of black hole deaths.

But if black holes die,
we have a problem.

What happens to everything inside them??

Let's revisit the particle lost to the singularity. Its sibling has not forgotten about it, as they are entangled!



The lost particle has information about the state of the particle pair. Hawking believed that black holes destroy this information, which violates a core principle of quantum mechanics.

*It contradicts **unitarity:** The initial state of a system can be determined from its final state. This is impossible if information about an initial state is destroyed.*


This is known as the **information paradox.**
All three things, as we currently understand them, cannot be true at once:
1) General relativity
2) How black holes work
3) Quantum mechanics
What's the solution?
This is very robust.
Maybe black holes don't actually destroy information. (But this is hard to show!)
Maybe unitarity is wrong. Maybe quantum theory must be revised.
Why might a human, safely away from any black holes, care?
It can help us understand why you're even around to wonder this!
Our universe began in an extremely dense state in which quantum mechanics dominated. We can't replicate this on Earth, but black holes give us present-day laboratories to explore similar conditions.
Hawking radiation is a clear example of a clash between general relativity and quantum theory, but it is also a process that can be explained only through the application of both. The solution to the black hole information paradox could be the key to describe our universe under a unified framework.
PT

(Opening image by Cyan Images/Shutterstock.com; spiral design by Freddie Pagani with artwork adapted from iStock.com/Ihor Reshetniak.)

HOW THE TWIST OF A MOLECULE AFFECTS ELECTRON SPIN

By David Waldeck, Ron Naaman, and Joseph Subotnik

Since the discovery was first reported in 1999, researchers have uncovered many aspects of the chiral-induced spin selectivity effect, but its underlying mechanisms remain unclear.

From time to time, a phenomenon is uncovered that eludes the commonly accepted theoretical frameworks. Such was the case for the chiral-induced spin selectivity (CISS) effect, which challenges widely used simplified molecular models for electron transport and transfer. The CISS effect reflects the innate ability of chiral materials to orient electron spins. It reveals a fundamental connection between chiral structure and electron spin in molecules and materials, and its implications for chemistry, biology, materials science, and other disciplines remain to be fully explored and mapped.

Chiral materials are those whose structure lacks mirror symmetry. A common example of chirality is hands: Your left and right hands cannot be superimposed, but they are mirror images of each other. In chemistry, molecules with that symmetry feature are called enantiomers. Many biological compounds, such as certain amino acids and components of RNA and DNA, are not only chiral but homochiral, meaning that they exist as only one or the other form—either left- or right-handed. The origins of homochirality in biology remain unclear. Research that uncovers the mechanisms underlying CISS might also shed light on the homochirality of biomolecules.[1] (To learn about chiral spin structures known as skyrmions, see the recent *PT* article "Magnetic skyrmions: A new frontier for quantum computing," by Christina Psaroudaki and Christos Panagopoulos.)

Spin selectivity in chiral matter manifests across a wide range of materials and conditions, and more than 50 research groups around the world are exploring the phenomenon. The first report of the CISS effect came in 1999 from experiments in which it was found that the ratio of spin-up to spin-down electrons, transmitted through a film of chiral material, depended on the material's handedness.[2] (For more details about that initial experiment, see the box on page 39.)

Although many of the early studies of CISS were performed with organic molecules and biomolecules, the effect has subsequently been reported for chiral quantum dots, hybrid organic–inorganic perovskites, metal oxides, metals, semiconductors, polymers, and supramolecular assemblies. In using different mechanisms and measurement methods, researchers report spin-selective transmission over sample lengths ranging from nanometers to millimeters. A variety of methods, including time-resolved electron paramagnetic resonance spectroscopy and scanning tunneling microscope measurements of single molecules, have been used to observe CISS.[3]

Describing observations of CISS requires a more sophisticated treatment of electron and nuclear dynamics than what is conventionally used when modeling electron transfer and transport. The standard theoretical framework is to start with the Born–Oppenheimer approximation, which separates the treatment of atomic nuclei and electrons, and a single-electron model, in which the motion of one electron is considered in the mean field that is created by the other electrons and the nuclei. That approach to the electronic structure has been useful for describing charge-transfer reactions and the conduction of electrons through molecules.[4] Historically, however, most experiments have not probed the electron's spin degree of freedom, and recent work examining such a spin aspect shows that chiral matter distinguishes between the electron spin orientations.

The CISS effect challenges conventional wisdom about electron transport. For example, chiral organic molecules display high spin selectivity at room temperature, despite their weak spin–orbit coupling. Research on the CISS effect stands at an unusual cross-

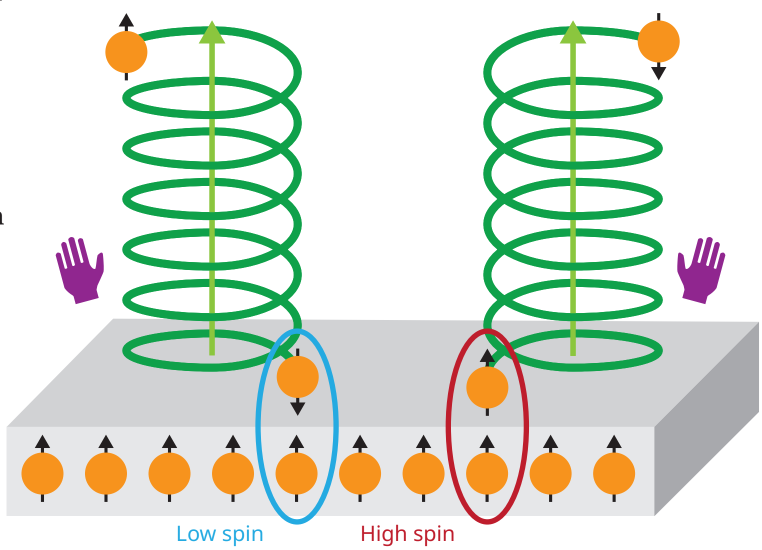
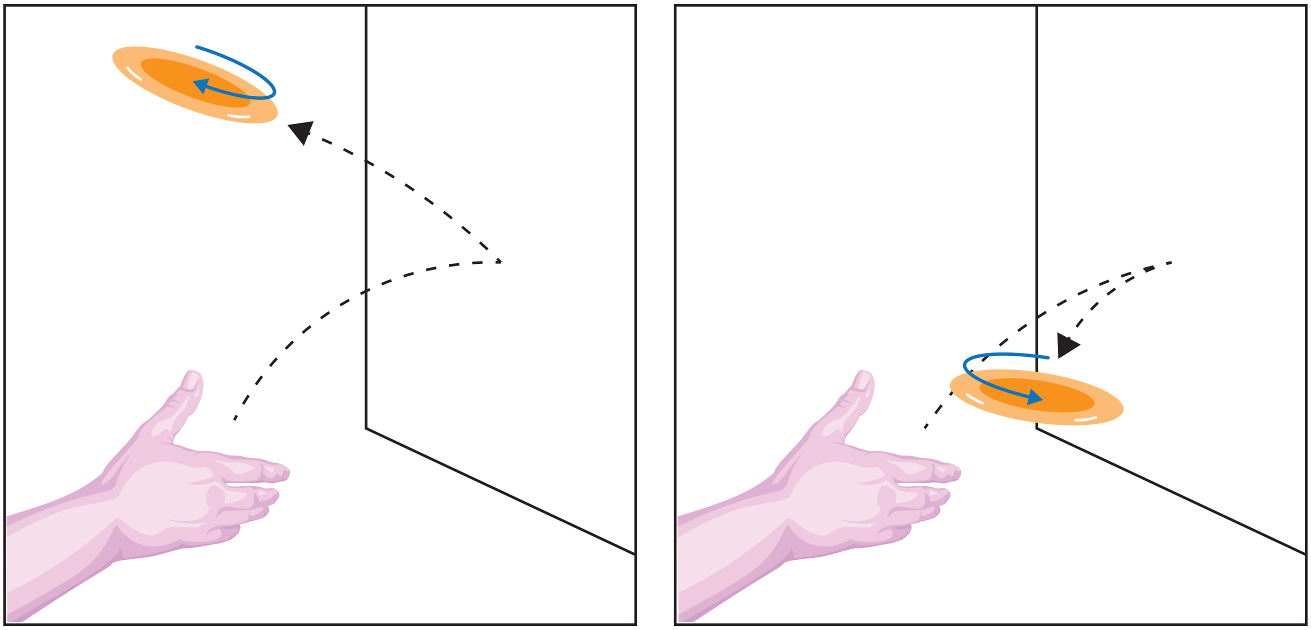


Figure 1. The connection between charge polarization and spin polarization in a chiral molecule. The electrical polarization (green arrow) of a molecule, here represented by a spring, creates a spin polarization that depends on the molecule's handedness. Interaction between a magnetized ferromagnetic surface and chiral molecules yields either a low- or high-spin potential depending on the direction of magnetization of the ferromagnetic substrate and the handedness of the molecule. (Illustration adapted from ref. 15.)



▲ **Figure 2.** A frisbee bouncing off a wall provides a useful analogy to chiral-induced spin selectivity. **(left)** If a frisbee is rotating clockwise and hits a wall on the right of the thrower, it is scattered forward and upward in a stable trajectory. **(right)** If a frisbee is rotating counterclockwise and hits a wall on the right of the thrower, it loses momentum and scatters backward and downward into a less stable trajectory. The opposite is true for a wall located on the left. (Illustration by Freddie Pagani with artwork adapted from iStock.com/jameslee1.)

roads for 21st-century physical sciences: Experiments measure signals that are quite large, and many results have been reproduced in different laboratories, yet theory has not converged on a mechanism. Given the range of molecules and materials displaying the CISS effect, it may be that beyond a basic mechanism, there are multiple manifestations of the effect, with each one being appropriate for the type of system—for example, metals versus insulators—and each linking to underlying features of chirality and how it breaks the simplifying symmetries of achiral matter.

What makes CISS special

When researchers consider electron conduction through a molecule or material, they usually model electron motion in a straight line. In such a case, interactions with vibrations—that is, phonons—or with other electrons decrease the transmission; experiments are often performed at low temperatures to avoid scattering events. Because the motion is assumed to be in a straight line between collisions, the issue of angular momentum conservation is often neglected.

In contrast, electron transmission through a chiral system follows a curved path, and the electron must exchange momentum with the system. For solids with a high density of electronic states, one electron can exchange momentum with another passing electron. In the case of insulators or organic molecules, however, the electrons of the system are localized; changing their momentum requires a large amount of energy that is rarely available. Nevertheless, chiral systems can possess low-frequency chiral phonons, which carry angular momentum, and electrons can exchange momentum with them. Many researchers in the field believe that angular momentum considerations will be important for any CISS mechanism.

What makes the electron–vibration interaction efficient? As a simplification, consider a chiral molecule to be a helical chain of atoms. As a passing electron interacts with the helical potential, it polarizes the electron clouds on the atoms. The amount of charge displacement during such collisions depends on the kinetic energy of the electron (typically 3–5 eV for conduction electrons injected from an external electrode) and on the system's polarizability. That charge redistribution affects the charge density on the chemical bonds and causes vibrational excitation.

In addition, backscattering of electrons to directions that do not lead to transmission can occur, and any change in energy must be dissipated. That picture implies that dissipation and nuclear motion are important to include when describing electron transport in chiral matter.

From experiments to a mechanism

The early photoemission experiments on CISS, described in the box on page 39, imply that the electron spin is locked either parallel or antiparallel to

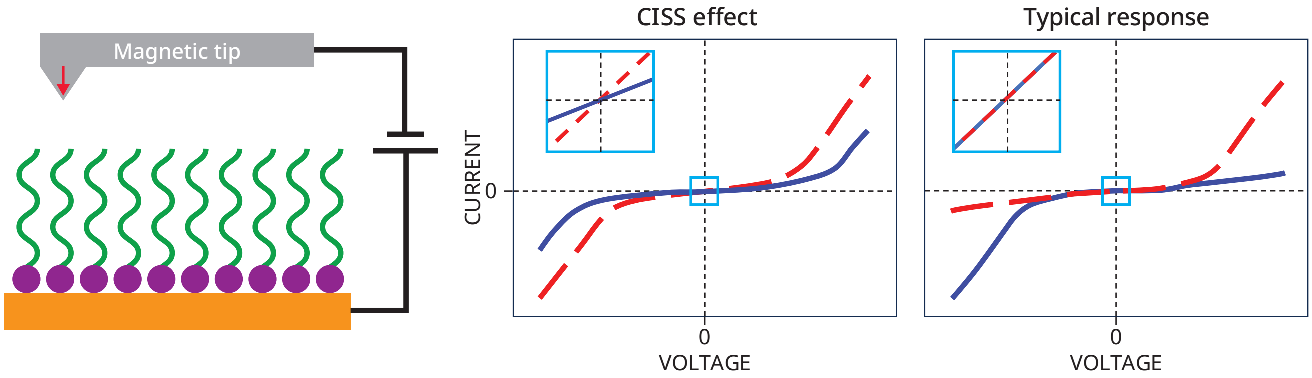


Figure 3. An experimental setup **(left)** for taking magnetoresistance measurements of a chiral material film in electrical contact with a metal substrate, such as gold. Current–voltage curves are collected for both north- (blue curves) and south- (red curves) magnetized tips, as shown in the middle and right panels. Common achiral magnetoresistive devices **(right)** exhibit time-reversal symmetry: The measured curves look the same if the magnetization direction and applied voltage are both reversed, and near the origin the curves overlap, as shown in the inset. But in chiral molecules **(middle)**, the north and south curves cross but do not overlap, and reversing the voltage just flips the current. Such behavior reflects the violation of time-reversal symmetry by chiral materials. (Figure adapted from ref. 17.)

the electron's velocity. That supposition is consistent with a wide range of experiments.[3] Recent measurements of pure spin currents show a strong dependence of transmission on material chirality. A robust theory should capture that feature.

An alternative route to unveiling the CISS mechanism (or mechanisms) is through the exploration of structure–function relations that serve as predictors for spin selectivity. Although chiral structure is often considered a binary quantity—left-handed versus right-handed—the chiro-optical properties of chiral matter vary in strength, and that behavior also applies to the CISS effect. In fact, numerous experiments have shown that the CISS response correlates with the strength of a molecule's differential absorption of circularly polarized light. Such a correlation implies that the transmission probability for electrons through a chiral molecule and the anisotropic polarizability of that molecule are related. The length of a chiral molecule has also been shown to correlate with its spin selectivity, but those correlations cannot be easily disentangled from the dependence of rotatory strength on molecular size.

The hypothesis that chiral phonons play a role in the CISS mechanism has spawned numerous studies into the temperature dependence of the CISS effect because the density of phonons depends on temperature. Several studies confirm that CISS increases with temperature, from tens of kelvin up to room temperature. Other studies, however, show different behaviors that may be a result of a different underlying mechanism—for example, electron–electron interaction rather than electron–phonon interaction—or other effects in the samples.

Temperature-jump experiments, which use a laser pulse to locally heat chiral materials and create a nonequilibrium population of chiral phonons, have demonstrated strong spin-dependent electromotive forces in the heated material.[5] In a more incisive study relayed to the three of us in personal communication, Renee Frontiera at the University of Minnesota Twin Cities has found that chiral phonons are generated when charge transport occurs through chiral materials. Thus, the role of chiral phonons for CISS is strongly implicated, and there are grounds to be optimistic that this role may be fully revealed over the next few years.

Hall effect measurements[6] and studies of magnetic imprinting by chiral molecules on soft ferromagnets[7] imply that charge redistribution in a chiral molecule is accompanied by a spin polarization, as illustrated in figure 1. That induced spin polarization is transient unless it is stabilized by an interaction with another spin of a reaction partner or of a surface. When chiral molecules are adsorbed on a ferromagnetic substrate, the magnetization of the substrate can flip to orient its spins in antiparallel alignment with the excess spin density of the adsorbed molecules. That creates a metastable magnetization in the substrate. Hence the direction of the substrate's magnetization can depend on the handedness of a chiral molecule. That aspect of the CISS effect has implications for enantioselective chemistry and the origins of homochirality in biology.[1]

Challenges for creating a CISS model

The weak spin–orbit coupling, which is expected for chiral organic molecules, raises the question of how such molecules can impose strong spin selectivity. Because many experiments are performed with molecules adsorbed on surfaces, several researchers have proposed a proximity effect—the borrowing or spillover of spin–orbit coupling from a metallic substrate—that improves the spin selectivity. Other approaches invoke orbital angular momentum selection by helical molecules and orbital-to-spin angular momentum conversion to describe the spin selectivity. But many of the systems demonstrating spin selectivity lack secondary helical structure, and in many cases, the system contains significant parts that are not chiral.[8] More recent studies that probe pure spin currents imply that spin selection takes place within the chiral materials themselves.[9,10]

Ascertaining the relative importance of spin versus orbital angular momentum in CISS is not simple. As an electron passes through a chiral system with an effective spin–orbit coupling, the spin couples to the orbital angular momentum. By way of analogy, consider a frisbee bouncing off a wall, as depicted in figure 2. When a clockwise-spinning frisbee is thrown at a wall located on the right of the thrower, it is reflected forward. A counterclockwise-spinning frisbee, however, is reflected backward and loses momentum, and its trajectory is destabilized. The opposite is true for reflection from a wall located on the left of the thrower.

The coupling of the frisbee's spin and its momentum by the friction with the wall is qualitatively analogous to the situation in CISS, where the right- and left-side walls relate to the different handedness of a chiral molecule. When measuring the spin of frisbees bounced off the wall, one would observe a higher probability of clockwise spins for bounces off the right wall. Correspondingly in the CISS effect, there is a higher probability of transiting electrons having one spin direction over the other, with the preferred orientation changing with the system's handedness.

Another way that CISS challenges the conventional theoretical description for electron transport and transfer is the apparent breaking of time-reversal symmetry in magnetoresistance experiments on

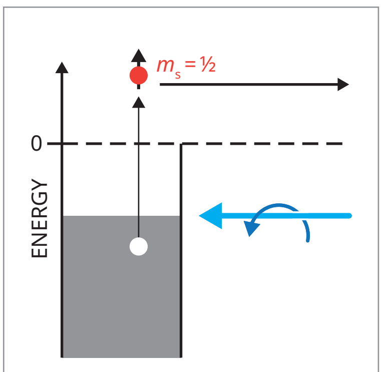
Key experiments in the history of CISS

The first report of chiral-induced spin selectivity (CISS) came from measurements of low-energy photoemission from gold surfaces coated with films of chiral fatty acids.[2] The diagram illustrates the principle of the measurement.

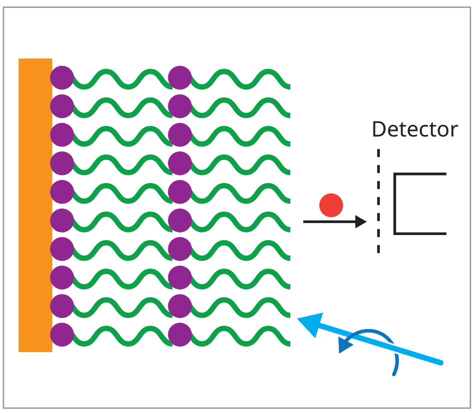
A circularly polarized photon excites an electron above the vacuum level (left panel). The electron's spin orientation is governed by the optical selection rules and the metal's spin–orbit coupling. Escape competes with electron recombination in the metal, and the probability for the spin-oriented electron to escape through the chiral layers (middle panel) depends on the handedness of the chiral molecules.

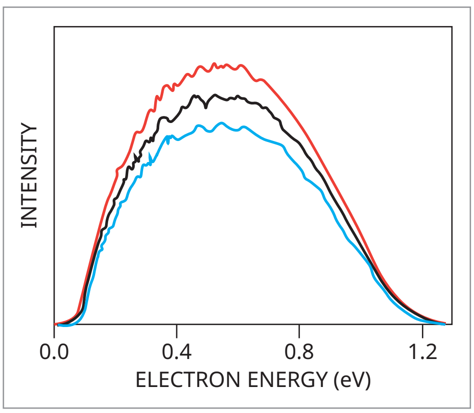
The intensity of detected electrons (right panel) depends on their light polarization (blue is for left-circularly polarized light; black, linearly polarized; and red, right-circularly polarized) for a chiral film made of five monolayers of the right-handed enantiomer of a fatty acid. Subsequent experiments measuring the spin polarization of ejected electrons found that, when chiral molecules are on the surface, the spin distribution depends only on the molecules' handedness and does not depend on the circular polarization of the light.

Although the first measurements of CISS for electron tunneling used a similar approach to that just described, it is now more common to magnetize a ferromagnetic electrode in a tunnel junction to sense the spin-dependent transmission, as shown in figure 3. Another breakthrough occurred in 2017 when researchers found that chiral molecular films generate a Hall voltage when they are charge polarized.[18] The finding demonstrates that charge polarization of a chiral molecule is accompanied by spin polarization, as sketched in figure 1.



(Right panel adapted from ref. 2.)





chiral materials. For typical systems near equilibrium, such as spintronic devices, time-reversal symmetry applies and magnetoresistance curves are antisymmetric: They overlap near the origin and exhibit distinct responses to positive and negative voltages, as shown in the right panel of figure 3. In the case of CISS, however, the magnetoresistance curves, shown in the middle panel, are symmetric: They exhibit equal but opposite responses to negative and positive voltages and have distinct and nonoverlapping curves for north and south magnetizations. The implication that the CISS effect breaks time-reversal symmetry has generated considerable discussion among researchers.

One proposed origin of that experimental behavior is nonlinearities that arise from electron tunneling. Another is that measurements are performed on open systems, which allow energy and electron dissipation. For example, the generation of chiral phonons, which would create a temperature gradient, could explain the breaking of time-reversal symmetry. Thus, dissipation could be an important or even necessary component of CISS.

How can scientists rigorously include energy dissipation, some form of time-reversal symmetry breaking, and chiral phonons in an *ab initio* model? One idea is to replace the standard Born–Oppenheimer electron Hamiltonian, which is parameterized by nuclear position, with a phase-space electron Hamiltonian that is parameterized by nuclear position and momentum.[11] If researchers parameterize electronic states in that fashion, they can readily incorporate momentum exchange between electrons and nuclei while conserving total momentum. Within that framework, CISS may be a new phenomenon that appears when chemical physics is analyzed with a more accurate treatment of electronic–vibrational coupling (in other words, without the Born–Oppenheimer approximation), and other phenomena will appear as well.

More than a curiosity?

CISS requires that scientists change their view of how electrons move in chiral molecules and materials. Its importance for applications is not as well explored.

Spintronics. The ability to manipulate spin with nonmagnetic, chiral materials rather than with magnetic materials has engendered interest in the development of new types of spintronic and spin-optoelectronic devices. For example, efforts to use chiral materials for spin valves—devices whose spin-dependent electrical resistance preferentially permits spins of one direction to pass through them—have proceeded broadly. Although many such studies report charge currents with extremely high spin polarization, approaching 100% in atomic force microscopy measurements, only in the past few years have researchers shown nearly 100% spin polarization in a device structure consisting of layered metal and chiral oxide films.[12] In addition, long-range spin transport in chiral systems, and especially chiral metals,[13] suggests the possibility of applying them as spin interconnects.

Along separate lines, the parallel or antiparallel locking of the charge carrier's angular momentum to its velocity direction has been exploited to realize a spin-polarized LED at room temperature and to electrically drive LEDs that emit circularly polarized light with opposite handedness (right versus left) in the forward or reverse direction with respect to the current direction. Emission of opposite-handed light in the two directions allows for the constructive interference of circularly polarized light in devices with simpler structures and improved efficiency.[14]

Although chiral transport layers, a few nanometers in width, can display nearly 100% spin polarization at room temperature, they have not been implemented in real spintronics devices. At present, efforts are aimed at developing device designs and demonstrating their operation rather than developing processes that incorporate such structures into commercial devices.

Chemistry. CISS offers important opportunities in chemistry, including improved selectivity in chemical reactions, enantioseparations, and a new approach to asymmetric reactions. Numerous researchers around the world have demonstrated the importance of spin considerations in water splitting and the use of chiral electrocatalysts. Such materials can immobilize reaction intermediates with defined spin-orientation relationships and can thus restrict the possible reaction pathways in a multistep chemical reaction sequence and improve reaction selectivity. Enhancing the spin selectivity of electrocatalysts promises to strengthen both efficiency and selectivity of numerous important chemical reactions, such as nitrogen fixation, carbon dioxide reduction, and urea oxidation. Those ideas are starting to appear in the engineering literature and to be implemented by startup companies.

Another important application in chemistry relates to enantioselectivity, the distinction between a chiral molecule and its mirror image. CISS provides a strategy for using oriented electron spins to initiate redox chemistry that transforms achiral reactant molecules to a particular enantiomer of a chiral product. Several groups have demonstrated the concept, but enantioselectivity has not yet reached a level of enantiopurity that makes it useful in practical chemical synthesis.

In a related approach, the interaction of chiral molecules with a magnetic surface is enantiospecific, as illustrated in figure 3. When a chiral molecule approaches a ferromagnet, it becomes charge polarized and hence spin polarized. If the spins in the magnet are aligned antiparallel to the spin of the molecule approaching the surface, then the interaction will be different from the case when the spins are parallel. The spin direction in the polarized chiral molecule depends on its handedness, so interaction with a ferromagnet can select for a particular enantiomer.[15] Enantioselectivity in chemical reactions and binding of molecules can thus involve a spin-exchange interaction, in addition to the steric geometric interactions that are commonly assumed to control enantiospecificity in molecular interactions.

Biology. Chiral biological molecules are homochiral, which raises the question, Does CISS have implications for biology? Numerous studies have shown spin-selective electron transfer through or within biomolecules, including nucleic acids, oligopeptides, and proteins,[16] and more recent work points to CISS effects manifesting in protein and enzyme interactions, proton-coupled electron-transfer processes, and cell respiration. Research on spin effects on biochemical reactions is still in its infancy, but it could offer a new perspective on biochemical processes and biological metabolism, with provocative implications for the origins of homochirality and the role of magnetic fields in life processes.

The breadth of molecules and materials in which CISS manifests suggests a fundamental connection between chiral structure and electron spin. While the importance of electron spin for describing chemical bonding and electronic structure is widely appreciated, too often researchers focus on the relatively weak magnetic interactions when considering electron dynamics and neglect full consideration of Pauli exclusion and the role of spin-exchange interactions. The CISS effect presents a challenge for theoreticians and experimentalists alike. For the first, it requires that they leave the comfort zone of the common approximations, and for the second, it opens a wide spectrum of applications that have yet to be explored.

Our cherished friend, colleague, and coauthor David Waldeck passed shortly before this article was published. He was a pioneer in CISS, and we dedicate this article to his memory.

—Ron Naaman and Joseph Subotnik PT

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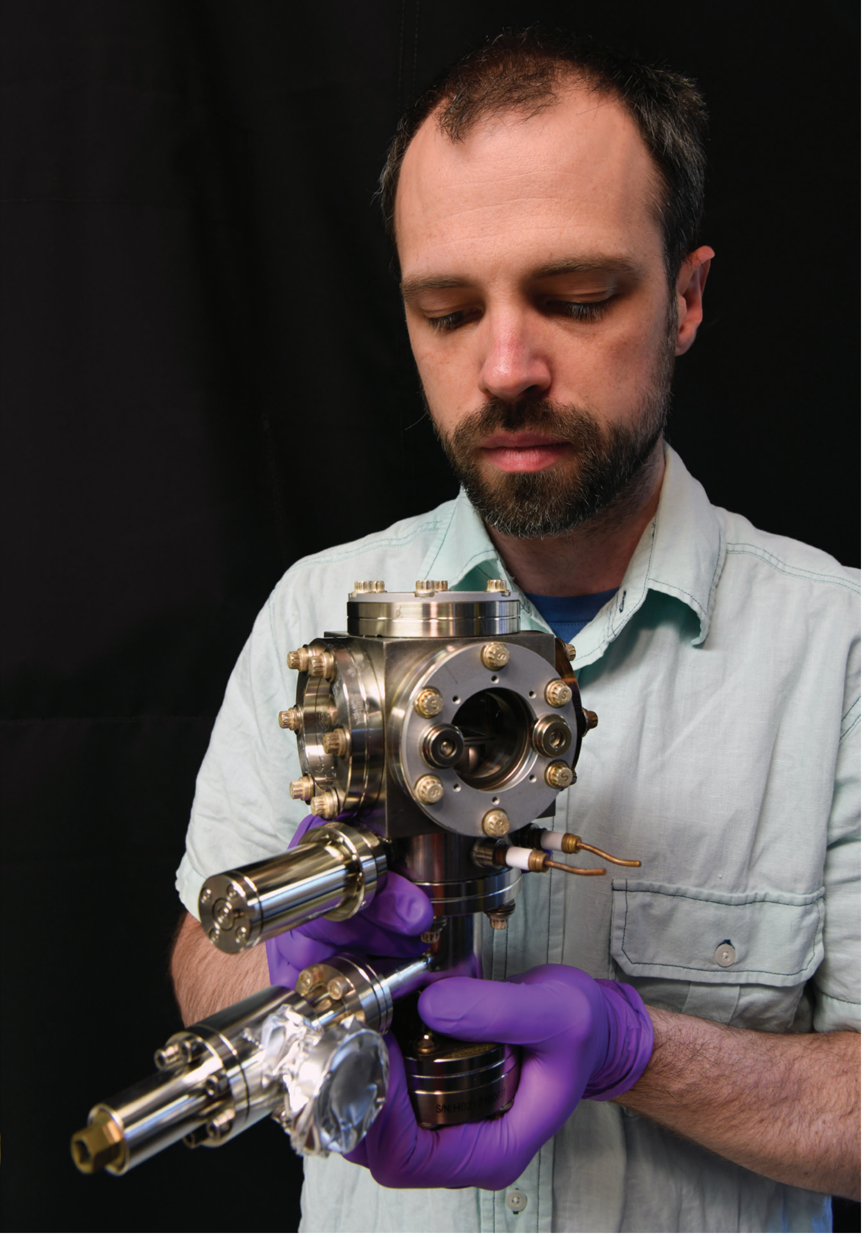

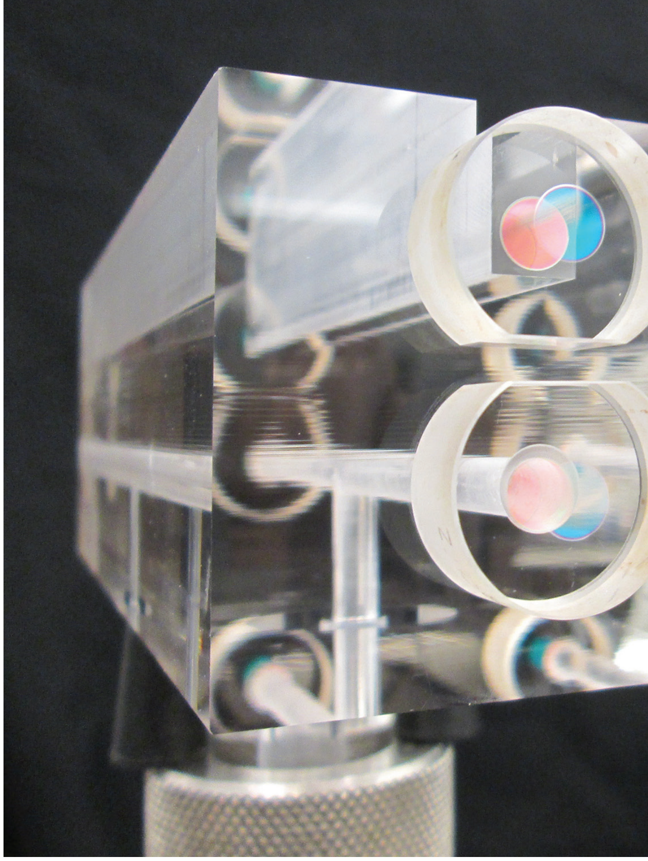

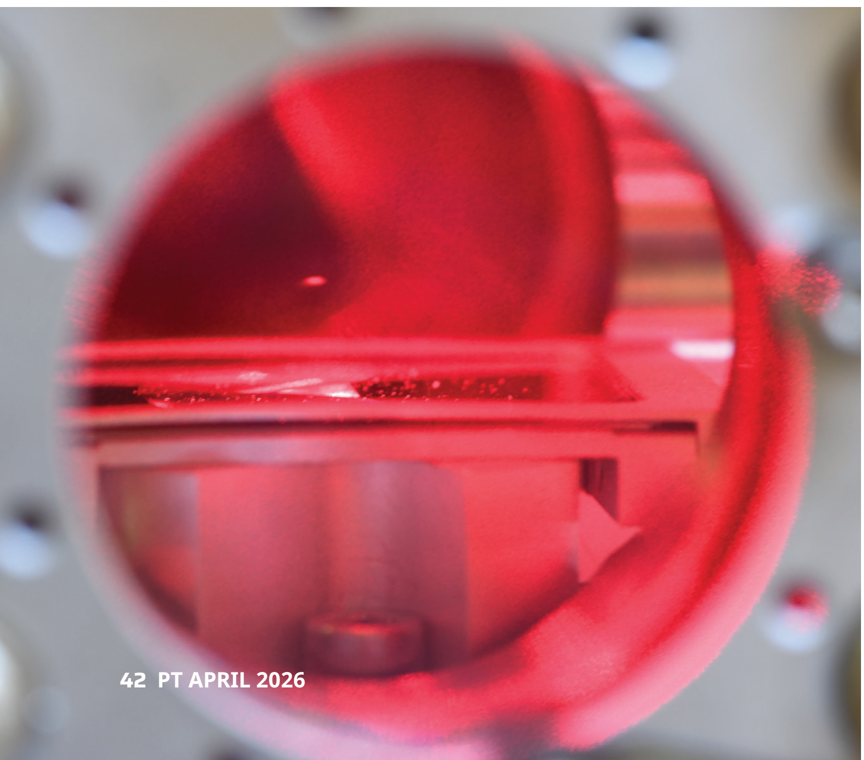

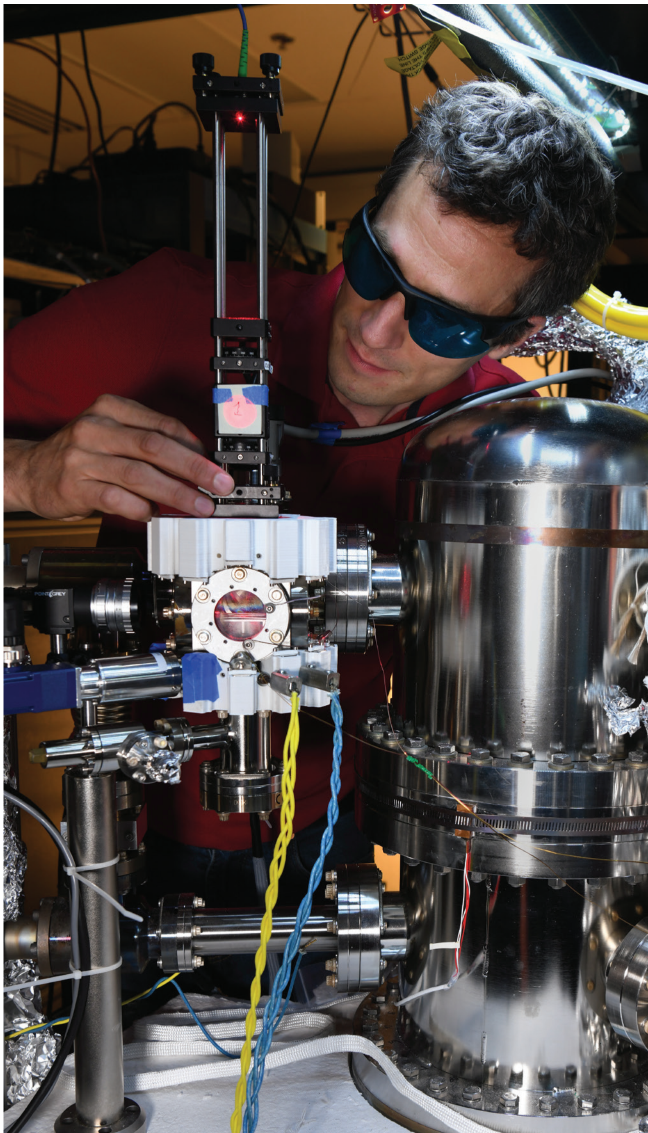

QUANTUM-BASED STANDARDS FOR PRESSURE MEASUREMENTS

Julia Scherschligt

Metrologists are using fundamental physics to define units of measure. Now NIST has developed new quantum sensors to measure and realize the pascal.

Clockwise from top left: Daniel Barker holding a prototype portable cold-atom vacuum standard (pCAVS); an optical pressure standard; Stephen Eckel adjusting pCAVS optics; and a cloud of cold, trapped lithium atoms that forms the basis of the pCAVS. (Top right photo courtesy of Jacob Ricker; all other photos by Curt Suplee/NIST.)

Units of measure have to be guaranteed in some way. Metrologists could declare a particular object as the ultimate embodiment of a unit. A single chunk of metal, for example, could be pronounced as the defining unit of mass. Or two marks could be carved in a particular stone, and the distance between them could be the defining unit of length.

Such objects are called realizations, and experiments can be realizations too. To be a primary realization, the object or experiment must not be reliant on a measurement of like kind. A primary pressure realization, for example, can't rely on a pressure gauge.

For units of measure to work globally, an international consensus system had to be developed, widely adopted, and maintained. Today, that system is the International System of Units (SI, from the French *Système International d'Unités*), also known as the metric system. The definition and methods of realization for SI units are established by policymakers at the International Bureau of Weights and Measures (BIPM), near Paris.

Any primary realization must be consistent with the established definition, so artifact-based definitions severely limit the potential for the development of new primary realizations. Previously, a meter and a kilogram were defined by a particular bar and cylinder, respectively, stored in France. Under those definitions, each artifact was the only possible primary realization of its corresponding unit.

For someone to compare an instrument or apparatus with a primary realization—for example, to determine which tape measure in figure 1 is most accurate—a trip to France was required. The unit definitions, therefore, prevented many researchers from directly accessing those primary SI realizations. Indeed, the queue at the BIPM would have grown unreasonably long if every researcher wanted to compare their measuring

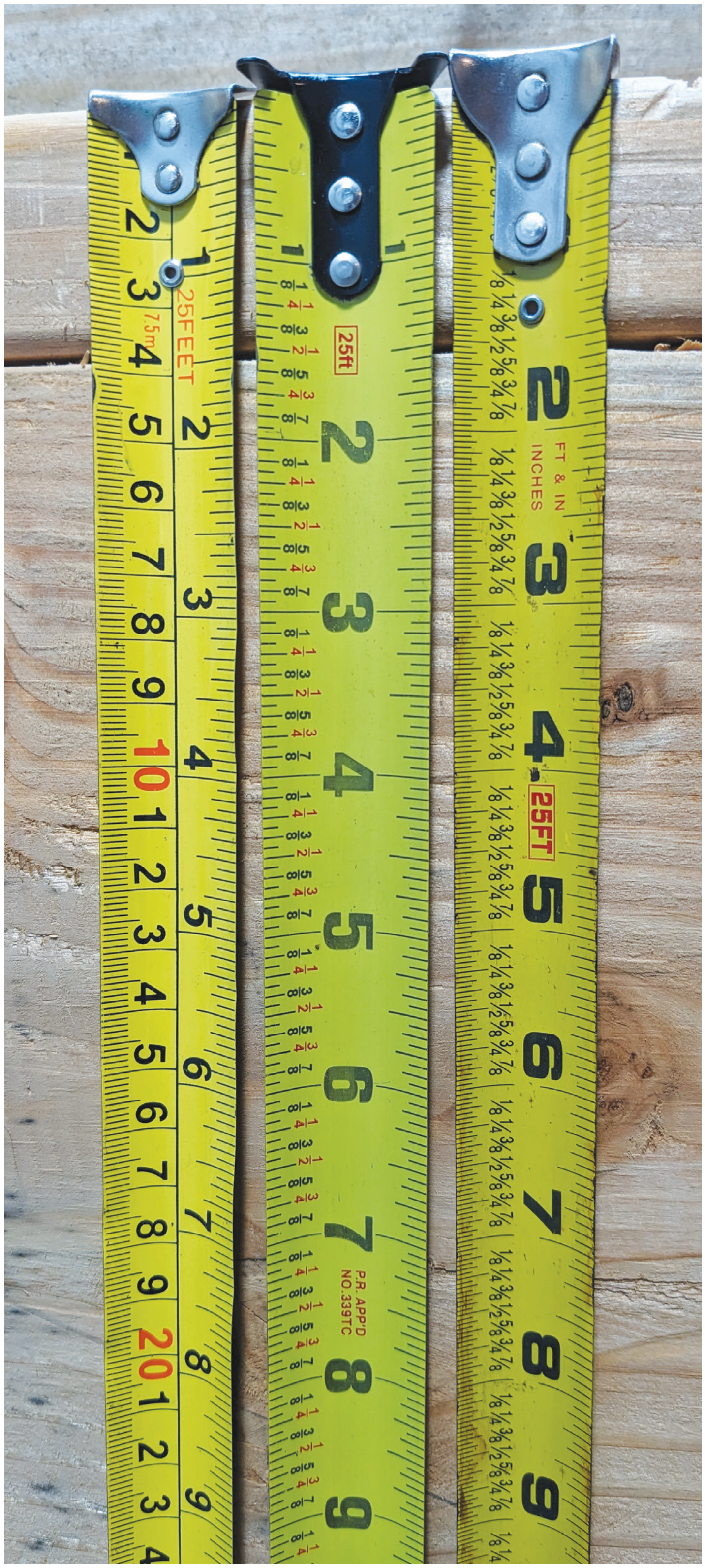

Figure 1. Which tape measure is most accurate? Prior to 1960, the ultimate way to check would be to take a trip to France and compare the length-measuring devices with the meter-defining artifact. (Photo courtesy of Alex Lopatka.)

instrument with a unique, defining artifact.

Because of those access limitations, people developed secondary standards, tertiary standards, and even standards many times removed from the primary realization. High-quality measuring devices are often calibrated to one of those standards rather than the primary realization, and the path from the device to the primary realization is the traceability chain. Each link in the traceability chain adds uncertainty, no matter how high the quality of the instrumentation is or how carefully a scientist performs a measurement. The box discusses the traceability chain further.

In 2019, the SI was redefined so that all units would be based on universal constants, such as the electron charge and the speed of light. By consensus, the fundamental constants are now fixed values with no uncertainty. If students in a lab class are re-creating the oil-drop experiment, for example, they would measure not the fundamental electric charge but the value of a coulomb. The new paradigm has been called the quantum SI because it refers to atomic-scale phenomena as the new basis to define units.[1,2] (For more on the SI redefinition, see the 2014 *PT* feature “A more fundamental International System of Units,” by David Newell.)

The redefinition has been celebrated by metrologists, but in trade and manufacturing, most metrology carries on as it always has. For example, instead of using the quantum SI, thermometry relies on the freezing points of various substances and the triple point of water, and mass metrology relies on comparisons of chunks of metal. Realizations based on the new SI are expensive and largely impractical, and they don’t necessarily offer better accuracy than realizations made with traditional technologies—not yet, anyway. But in the future, the quantum SI could result in realizations that are practical and deployable in the factory, the field, and the lab.

The optical pascal at NIST

NIST is exploring opportunities to develop quantum-SI technologies for several quantities and units, including ones pertaining to mass, pressure, temperature, and voltage. This article focuses on the effort to create quantum-SI pressure realizations. Pressure measurements are ubiquitous and span 18 orders of magnitude across various applications and processes. Some examples include advanced manufacturing, aviation, semiconductor development, and weather forecasting. Ultrahigh vacuum environments are critical in quantum information science and fusion technology, and they are required in many large-scale experiments, including the Large Hadron Collider and the Laser

The traceability chain

Verifying a measuring device with a standard is such an ingrained scientific procedure that imagining alternatives may be difficult. An ice bath realizes temperature, and to calibrate a thermometer, you stick it into the ice bath and adjust it until it reads 0 °C. But the ice bath can’t measure temperature. An object with a known weight, such as 1 kg, realizes mass. It’s put on a scale, and if the reading is 1 kg, you conclude that the scale works. But the object can’t measure mass.

To measure something that’s around 10 °C or 1.01 kg, you need an interpolating measuring device with tick marks or gradations that are small enough, or have enough digits, to achieve the necessary precision. Such a requirement introduces new sources of uncertainty and means that the traceability chain has at least one link. If you measure a quantity that differs by orders of magnitude from the realization value, the chain grows long, and uncertainties balloon.

With the quantum SI, a realization technique has the potential to function as a measuring device. As the new approach to measurement evolves and matures, the consequences may be profound. With a quantum-SI device, scientists could confidently calibrate their gauges, but they wouldn’t have to. Instead, they could just use the quantum-SI device as a gauge.

Interferometer Gravitational-Wave Observatory.

The traditional definition of pressure is $p \equiv F/A$, where F is a force and A is an area. It's intuitive and useful: Someone who wants to measure pressure can, for example, stack known weights on a piston with a known area. But that definition becomes impractical at pressures lower than 1 atmosphere. Distinguishing a signal of interest from noise in that pressure regime is challenging for a force-measuring device.

Now that the SI has been redefined, however, the ways to define and subsequently realize pressure are constrained by only the laws of physics and fundamental constants. Researchers can find any equation that relates pressure to something that's both directly measurable and able to be calculated from first principles with fundamental constants, which anchor the pressure unit to other units in the SI. Such an equation is not only acceptable as a definition—it has the potential to shorten the traceability chain. If that equation is then implemented into a carefully controlled experiment, a realization of pressure is obtained.

One equation that can be used to develop a realization for low pressures is the ideal-gas law because it has measurable quantities and is anchored to the SI through the Boltzmann constant k_B. For higher pressures, where the gases are not ideal, higher-order terms of the equation of state of a gas must be included.

The corresponding definition of pressure is $p = \rho k_B T$, where T is temperature and ρ is the gas density. Temperature can be observed with an off-the-shelf thermometer, perhaps someday one that is itself a quantum-SI device. Measuring gas density without using a pressure gauge is difficult, and quantum science comes into play.

Liquid-column manometers are traditional pressure-measuring devices in which the height of a column of liquid in a tube indicates the difference in pressure between the two ends. Typically, one end is a vacuum and the other is open to the atmosphere. (The tube is bent in a U shape to keep the liquid from draining out.) Liquid-column manometers are critical in aviation safety, defense applications, and weather forecasting.

Although they have excellent performance, liquid-column manometers are not readily portable. So anyone who needs to make precision pressure measurements must calibrate their instruments with manometers, and that calibration results in a nonzero-length traceability chain. Quantum-based pressure measurements and realizations could shorten or eliminate traceability chains and potentially reduce uncertainty, and thus improve pressure measurements.

To realize pressure with a quantum-based approach, researchers can make optical measurements of the refractivity of a gas. The NIST fundamental thermodynamics group has designed an optical pressure standard (OPS) whose design is based on a dual-channel fixed-length optical cavity (FLOC) and that consists of a glass cell with two laser cavities, as figure 2 shows. One cavity is kept evacuated and serves as a reference cavity while a researcher exposes the measurement cavity to the pressure of interest. Light with frequency ν from identical lasers traverses

each FLOC channel and is combined at the outlet.

The lasers are tuned to be in resonance with their respective cavities. The light that travels through the measurement cavity is slower than that in the reference cavity because of the presence of a gas with a nonunity refractive index, so its resonant frequency is lower. The result of combining the locked laser light is thus a measurable beat frequency.

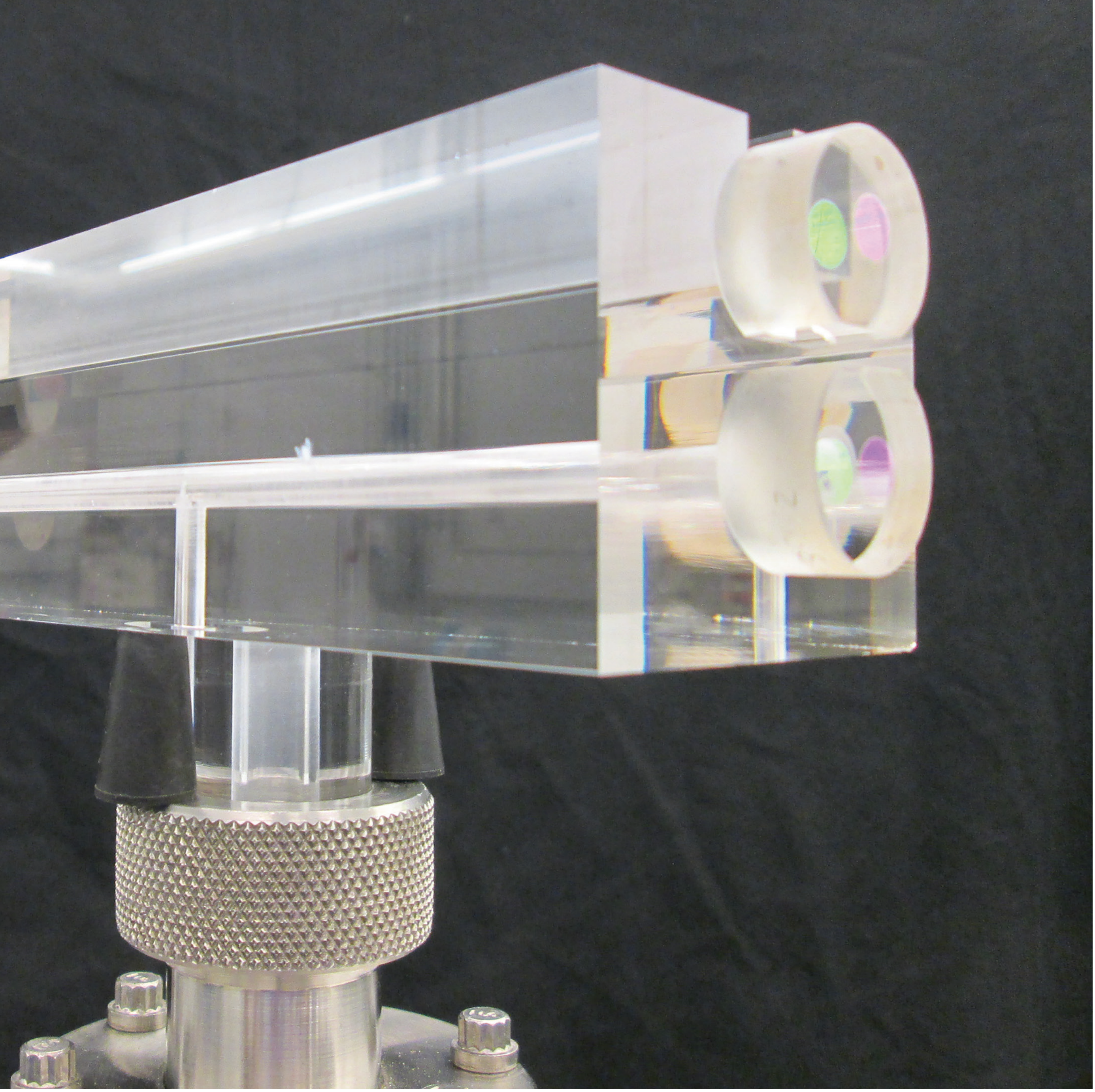

Figure 2. The fixed-length optical cavity is the heart of the NIST optical pressure standard. A researcher fills the upper channel with gas at the pressure of interest and evacuates the lower chamber. Then, laser beams are locked into resonance with the respective channels that they traverse. Once the two beams are combined on the other end of the channels, the measured beat frequency can be used with other properties of the gas to develop a primary realization of pressure. (Photo courtesy of Jacob Ricker and Jay Hendricks.)

If the refractive index is indeed known from first principles, the optical measurement becomes a primary realization of pressure.[3] That realization can be obtained through a measurement of the effective pressure-induced frequency shift Δf, which is approximately equal to the beat frequency. To first order—and ignoring distortion effects and some details about the interrogation—that frequency is related to pressure through

$$p = \frac{k_B T}{2\pi(\alpha + \chi)} \frac{\Delta f}{\nu}.$$

The dipolar polarizability α and diamagnetic susceptibility χ of the gas relate to its refractive index. Those could be measured through an independent experiment, but to make the technique fully primary, the experiment would need to avoid using a pressure gauge, which is a virtually impossible task. To make it fit the quantum-SI paradigm, researchers should calculate α and

χ theoretically, and they have done so for helium using quantum electrodynamics.

NIST has partnered with a pressure-measurement company to develop an OPS product prototype. Preliminary demonstrations of several OPS designs show better performance than the most accurate manometers.[4] NIST is also partnering with metrologists from the US Department of Defense to develop OPS instruments for use on military bases. Both efforts could reach maturity in the next few years, so quantum-SI pressure devices may be seen outside the lab soon.

A new vacuum standard

The traditional definition of pressure as force per area remains impractical at the extremely low pressures that are found in accelerators, gravity interferometers, and outer space. At such pressures, measurement signals are on the order of 10^{-6} Pa, whereas the atmospheric background is 10^5 Pa.

Metrologists have traditionally achieved realizations at extremely low pressures by using successive comparisons of gauges and techniques with different but overlapping pressure ranges. Recently, researchers at NIST have developed a quantum-based primary realization of pressure at ultrahigh vacuum. The development is possible because in the 1980s, atomic physicists discovered that lasers can cool clouds of neutral atoms to temperatures near absolute zero and that the barely moving atoms can then be trapped in magnetic fields. (For more on such capabilities, see the 1987 *PT* article "Laser cooling," by David Wineland and Wayne Itano.)

Cooling and trapping the atoms require an exquisitely clean vacuum environment. Indeed, the lifetime of atoms in a trap depends inversely on chamber pressure so predictably that it can be used as a pressure sensor. The use of trapped atoms as vacuum realizations is possible because of the redefinition of the SI and advances in collision physics.

Once again, the measurement equation is based on the ideal-gas law. In this case, knowing the density of the gas in the chamber boils down to counting the background particles. The cold-atom vacuum standard (CAVS) is an atom trap that, once correctly configured and operated, does just that. Each time a room-temperature background particle, such as hydrogen or an atmospheric gas, collides with a sensor atom, it ejects the atom from the trap. As the process continues, from fractions of a second to hours, the number of atoms N_s that remain in the trap follows an approximately exponential decay $N_s(t) = N_s(t = 0)\,e^{-\Gamma t}$, where Γ is the loss rate. The number of atoms that remain in the trap follows an approximately exponential decay $\rho_s(t) = \rho_s(t = 0)\,e^{-\Gamma t}$, where ρ is the density of the gas in the chamber and Γ is the loss rate. Figure 3 plots the decay equation.

A measurement of the change in the number of atoms in the trap over some elapsed time, therefore, counts the number of collisions. That process, combined with the thermally averaged collision cross section k_{loss} and the ideal-gas law, results in a measurement and a realization of pressure: $p = \frac{\Gamma}{k_{loss}} k_B T$.[5] Through *ab initio* quantum calculations of the collision cross sections, researchers have made the CAVS into a primary pressure standard.

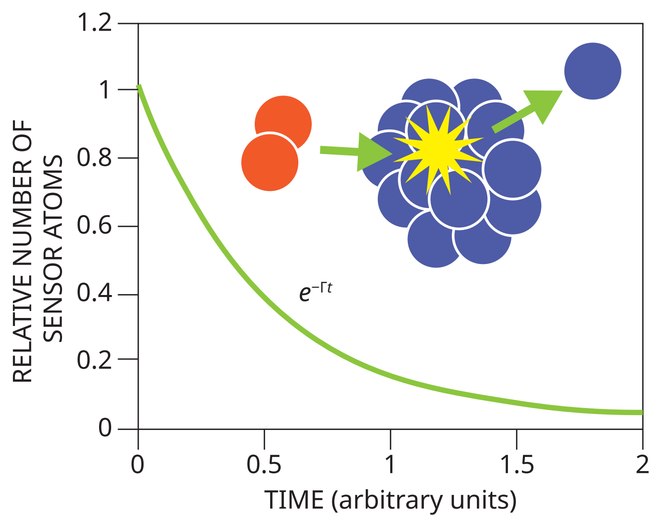

Figure 3. When a room-temperature background particle (red) collides with a cold sensor atom (blue), it ejects the atom from the trap. Each time the process is recorded, researchers count one background particle, and the count is determined by the number of trapped sensor atoms, which decays exponentially with time. Once the decay constant Γ is measured, it's combined with the ideal-gas law and the calculated collision cross section to produce a primary, quantum-based pressure measurement.

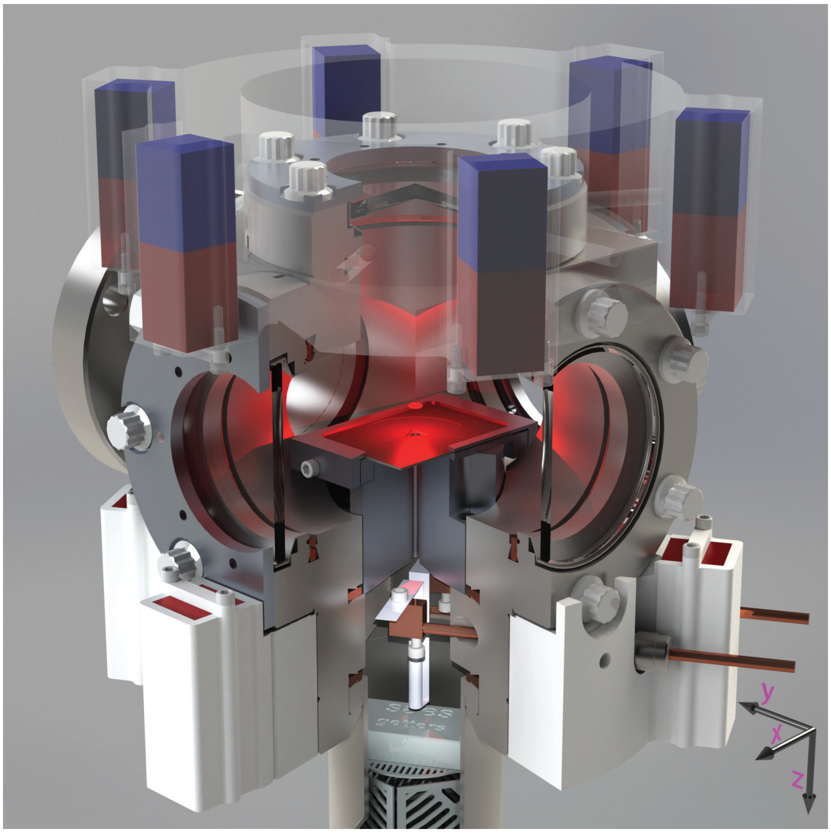

Figure 4. The portable cold-atom vacuum system was developed at NIST. It is designed to use the ideal-gas law and collision physics to measure pressure from first principles. The goal of the quantum-based metrology approach is to develop a practical, deployable device for various high-precision applications. (Image courtesy of Daniel Barker and Stephen Eckel.)

The cross-section calculations of k_{loss}, which were previously possible only with approximate methods of limited applicability, are now in reach because of advances in computing capabilities. Calculations have been carried out for a large sample of possible sensor–background particle pairs[6] and have enabled researchers to test theory against experiment.[7]

A lab-sized version of the CAVS device has been built so that all aspects of the experiment can be fully controlled. The magnetic fields are produced by electromagnets with an elaborate coil geometry, and various field configurations are possible.[8] Either lithium or rubidium can be used as the sensor atoms, and the trap depth can be fine-tuned. Using a purpose-built traditional vacuum apparatus called a dynamic-expansion chamber, researchers can inject an arbitrary gas into the CAVS device at pressures as low as 10^{-12} Pa, the lowest level achievable on Earth. Full control of experimental conditions allows for the uncertainty of the technique to be characterized. Measuring uncertainty is important in any experiment but is essential for modern metrology—driving down uncertainty is often the entire point of a project.

A room-sized apparatus, of course, has no future as a metrological instrument, except maybe at a national metrology institute. So NIST developed a portable version, pCAVS. It uses a grating to replace most of the optical components. Figure 4 shows a rendering of the device, which is about 1.3 L in volume and is supported by multiple lasers and electronics.[9] Practically all systematic uncertainties are negligible, and the pCAVS instrument is more than adequate for deployment in various circumstances, including on accelerator beamlines and in nanofabrication foundries.

In a recent experiment, the CAVS and pCAVS devices were used to measure the loss rate Γ, the dynamic-expansion chamber was used to set and measure the pressure p, and then k_{loss} was determined.[7] In all cases, theory and experiment agree within the error bars. If the pCAVS and CAVS instruments were deployed, the theoretical collision cross sections would be used to be consistent with the quantum SI.

The pCAVS prototype constructed at NIST is ready to be developed into a product, and the NIST OPS is under development both as a commercial pressure gauge that doesn't require calibration and as a standard for the direct calibration of aircraft sensors. With a direct calibration, the traceability chain has only one link.

The future of the quantum SI

Other groups are pursuing realizations of quantum-SI pressure. To make trapped atoms into vacuum standards, researchers in Canada are using quantum diffractive collisions with trapped rubidium[10] and, in collaboration with scientists in Germany, developing a dual-species device that uses rubidium and potassium.[11] In China, researchers are taking an approach similar to that of NIST.[12] Likewise, several efforts around the world aim to develop OPS devices for use on airplanes, in commercial factories, and in national metrology institutes.[13–16] Although quantum-SI devices may become widespread in the near future, such systems will still need quality checks and regular maintenance.

The originators of the metric system wanted it to be "for all times, for all people." Now that the physics underpinning the metrology measurements is no longer a cause of disagreement, the promise of the slogan is coming into being. Perhaps the most important aspect of the quantum SI is that it's available to anyone who has access to the cavities, lasers, magnets, and other equipment necessary to interrogate the physics. No trip to France is required.

The mention of commercial equipment, instruments, or materials in this article does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose. PT

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Julia Scherschligt is a staff scientist at NIST in Gaithersburg, Maryland. She is the chair of the Working Group on Pressure and Vacuum, which is part of the Consultative Committee for Mass and Related Quantities at the International Bureau of Weights and Measures near Paris. She is also a former leader of the NIST group responsible for developing quantum-based standards for pressure measurements.

WHAT CAN PHYSICISTS DO?

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

Kevin Ingles

writes code for electrical engineering applications

By Toni Feder

Computational research scientist, applied electromagnetics division, Applied Research Associates

BS, physics; BS, mathematics and statistics; University of South Alabama, 2018
PhD, physics, Ohio State University, 2023

What was your research focus?

Particle phenomenology and nuclear theory, with a focus on strong interactions.

What were you looking for in a job?

I was convinced I would be a professor. But a year into my postdoc, I decided to leave academia. I had burned myself out, and seeing how hard all my previous mentors worked sent up red flags for my long-term mental health.

I looked for jobs that required computational physics. And, both to be close to my partner and to collaborate in person, I wanted to find a job in Columbus, Ohio.

How did you find your job?

LinkedIn and other job sites. I read blog posts and watched YouTube videos to learn how to craft my résumé. I emphasized that I wanted to write C++ code and use programming to solve complex technical problems.

In May 2024, I applied to 40 or 50 jobs. I got three interviews. I started at Applied Research Associates in July 2024. The company provides services, products, and applications in electromagnetic propagation, microelectronics, and computational modeling, among other areas. Clients include the US military, aerospace companies, and related commercial industries.

How do you spend your time?

I work primarily on our simulation code base, fixing bugs and building new features. The simulations help clients evaluate and improve the performance of antennas, sensors, and other technologies before they're built or deployed.

I also communicate technical concepts to nontechnical colleagues and support business development. I coauthor at least one proposal or application a month.

What do you like about your job?

I enjoy making a bit of code work harder, faster, better, or at larger scales. I like that projects move quickly. Contract timelines are typically two to three years.

How do you use your physics in your job?

Through critical thinking, comfort with equations, and quantitative reasoning.

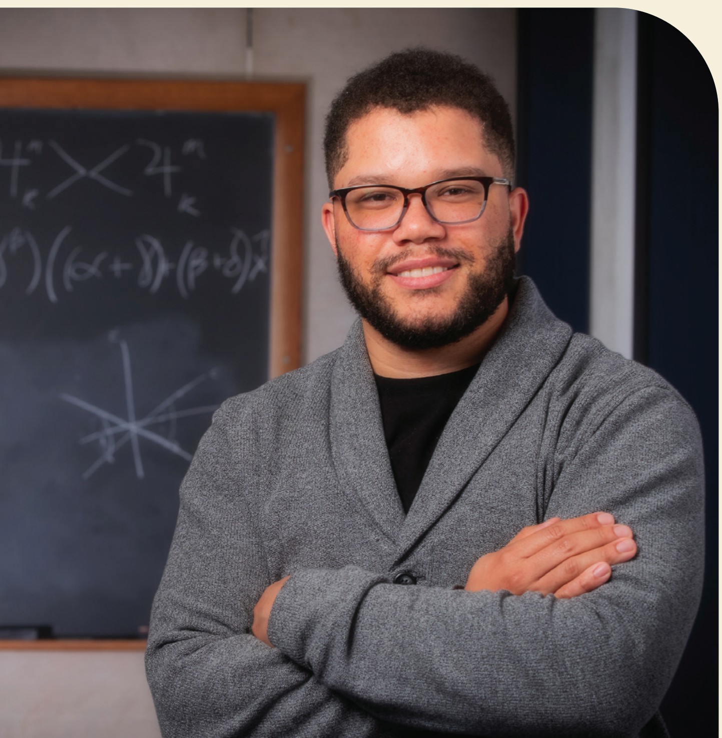
What new skills have you needed?

I've learned to be pragmatic, focusing on solving the immediate problem rather than tackling an entire class of problems. I've also had to grow comfortable delegating tasks to others.

Is there anything you'd like to add?

People should remember that it's more common to not be an academic. I do miss teaching, but every now and again I get an opportunity to lecture, and I get excited. PT

(Photo courtesy of Kevin Ingles.)



Read more interviews in the series at https://physicstoday.org/wcpd.

QUICK STUDY

Matching pipe organs to room acoustics

New research aims to help organ builders better predict how the massive instruments will sound once installed.

By Judit Angster, Josep Llorca-Bofí, and András Miklós

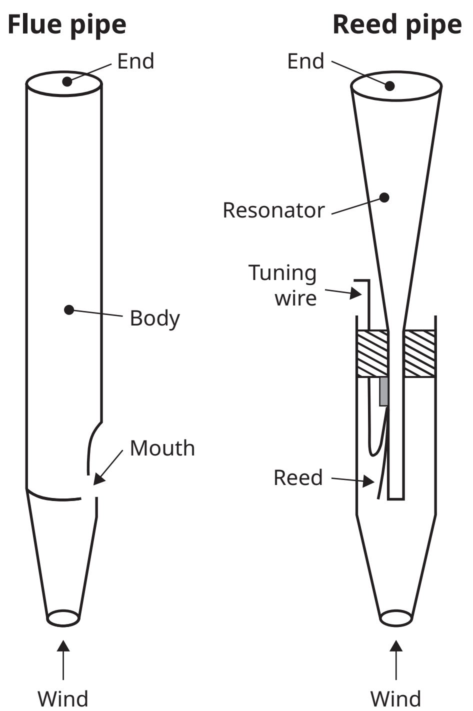
No other musical instrument can be compared with the pipe organ in terms of size, tonal range, loudness, or complexity. The largest organs have thousands of pipes, the longest of which can extend 32 ft (9.75 m) or more in length. Unlike smaller instruments, which are typically produced according to standard designs, every pipe organ that is constructed must be specifically tailored to the acoustic properties of the space—typically a church or concert hall—in which it will be installed. In other words, an organ's sound cannot be judged independently of its venue.

When an organist pushes down a key or a foot pedal, an electric blower provides pressurized air—termed wind—to a pipe. As shown in the diagram below, there are two basic types of pipes: flues and reeds. In a flue pipe, sound is produced by means of a vibrating air jet. The pitch is determined by the pipe's length. In a reed pipe, the air stream is regulated periodically by a metal reed, which vibrates at a specific pitch. The pipes in an organ are organized into rows, known as ranks or stops, which each have a different sound character, or timbre.

Design challenges

When designing an organ, the goal is for the completed instrument to fill the room with sound when an audience is present. It's a daunting task: Because the radiated sound power of each pipe is determined by its geometry and wind pressure, its loudness is fixed once the instrument is constructed. Organ builders have traditionally used several rules of thumb to estimate pipe loudness. Larger-diameter pipes are louder than narrower ones, for example, and higher wind pressure increases loudness.

But estimating pipe loudness remains challenging for three reasons. First, the typical model used for room acoustics struggles to account for the sound produced by a pipe organ. The model works well when acoustic room resonances—the pitches that resonate more strongly in a space—cannot be recognized in the way the instrument sounds in the



Schematic diagrams of the two types of organ pipes: flues **(left)** and reeds **(right)**. In a flue pipe, pressurized air, termed wind, enters at the bottom. It is then driven through a small gap at the mouth, and that causes the air column to vibrate. In a reed pipe, wind enters at the bottom and is directed toward the reed, which vibrates at a specific pitch that is set using the tuning wire. The resonator helps determine the timbre, or sound quality, of the pipe. (Diagrams by Freddie Pagani; right diagram adapted in part from Cor anglais 16/Wikimedia Commons/CC BY-SA 3.0.)

A pipe organ constructed by the Mühleisen company in Leonberg, Germany, for acoustic research at the Fraunhofer Institute for Building Physics in Stuttgart. (Photo by Roman Wack/Fraunhofer Institute for Building Physics.)

room. Because room resonances get closer together as frequency and room volume increase, they usually cannot be distinguished in concert halls at frequencies of 100 Hz or higher. But larger pipe organs can have notes with frequencies as low as 16.4 Hz, which means that the lowest two and a half octaves on the instrument may fall below the 100 Hz threshold.

In that low range, it's possible for the average separation between room resonances to be comparable with the separation between two consecutive notes in the chromatic 12-tone scale used in Western music. The tone of a low-pitched organ pipe may thus coincide with room resonances or antiresonances, and that can cause the pitch to be significantly louder or quieter in certain areas of the room. It can also create an audible shift in the pitch because the frequency of the room resonance that is excited may differ from the pipe frequency.

Second, organ builders lack reliable data about the sound power emitted by organ pipes. The data are needed to estimate a pipe's loudness and, thus, the loudness of the instrument as a whole.

Finally, organ builders have specific requirements for room acoustics that vary for the instrument's different pitch ranges. Because human ears are less sensitive at lower frequencies, it is preferable for a space to have longer reverberation in the low register—below approximately 130 Hz—so that the sounds from different stops can blend.

In the middle register, with frequencies from about 130 to 520 Hz, it is important for the room's reverberation time—the time it takes for a sound to fade away—to be relatively short. Thus, each sound in the range is recognizable by the audience. That is particularly important in polyphonic music, in which multiple independent melodies are played at the same time.

Because human ears are better at distinguishing the direction of higher-pitched sounds, a high degree of diffusivity in the space is necessary for pitches above roughly 520 Hz. That way, it does not appear to the audience that sounds are coming from different directions.

Addressing the problem

To help organ builders ameliorate the risk of building a faulty instrument, two of us (Angster and Miklós) conducted a research project in collaboration with several prominent organ manufacturers. We found that the sound of an organ pipe can be modeled by setting up two simple sound sources in the space in which the pipe will be installed.

Using the results of our trials, we've developed a system in which two speakers emit sounds that were recorded at the mouth and end of real organ pipes. The distance between the speakers can be adjusted to simulate different pipe lengths. An accompanying software package, which contains data about different types and sizes of pipes and different wind pressure values, enables manufacturers to simulate the sound power of a pipe. Our hope is that the system will allow organ builders to better estimate the dimensions of organ pipes and better adapt instruments to the spaces in which they will be installed. PT

Additional resources

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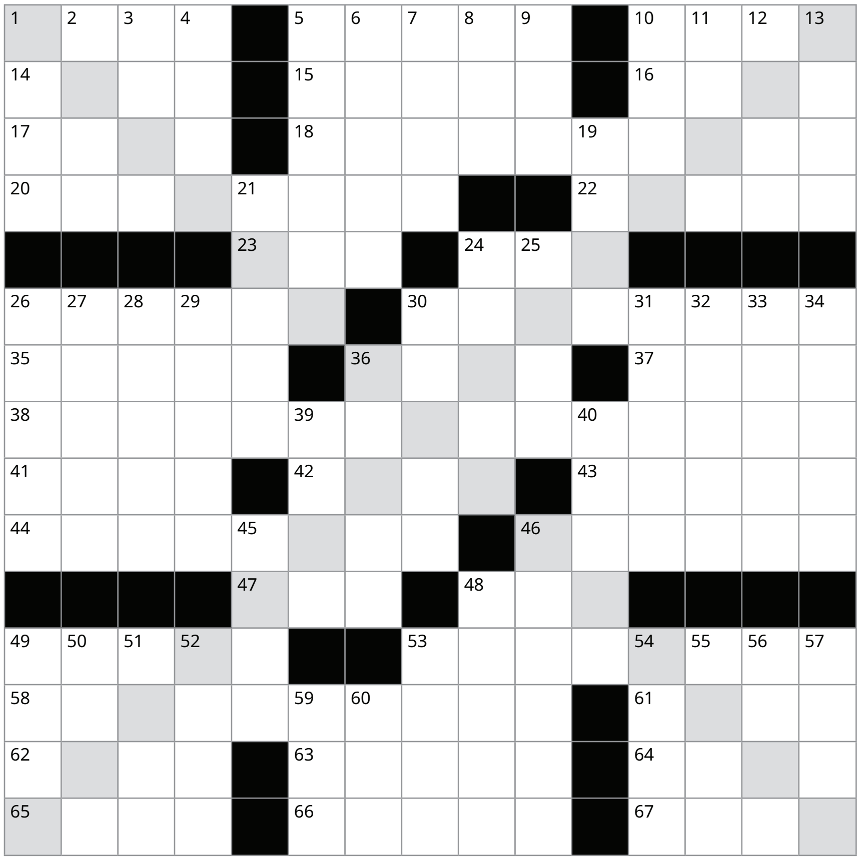
Judit Angster and **András Miklós** are senior scientists in the department of acoustics at the Fraunhofer Institute for Building Physics in Stuttgart, Germany. **Josep Llorca-Bofí** leads the urban and architectural acoustics research group at the institute.

CROSSWORD



Divergence versus convergence

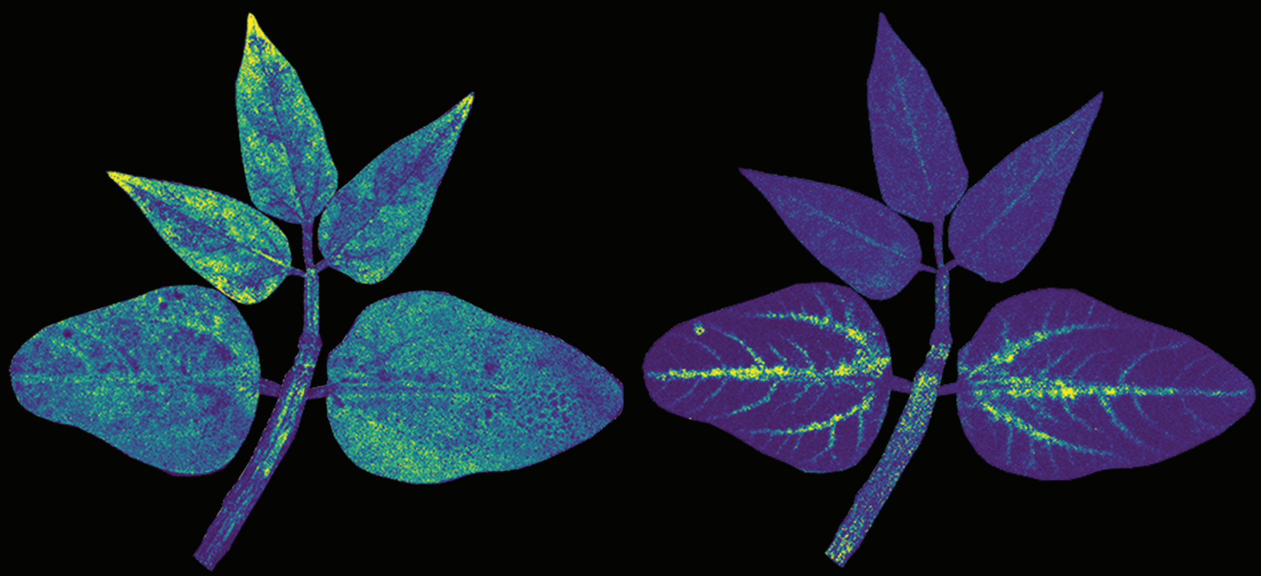
By Doug Mar

ACROSS

1 German sausage, for short
5 Useful resource
10 Opposite of fem. in Romance languages
14 This symbol: €
15 Earthworm relative
16 Nobel Prize cat.
17 Prefix for mid-level clouds
18 Landing in this could be touch and go
20 Relative of a trial balloon
22 Eroded
23 Frozen wasser
24 Spoil
26 Blogging platform bought by Yahoo for $1.1 billion
30 Congratulatory words after an athletic contest
35 Triumphant cry
36 Traditional music genre
37 “Put ___ my bill”
38 Playground for a Mariner or a Marlin
41 Tolkien tree creatures
42 Fly in the face of
43 Slowly, in music
44 Crunchy taqueria offerings
46 Shuttle astronaut Collins
47 Registry no. system in which 58-08-2 designates caffeine
48 UK fliers (abbr.)
49 It never occurs above the Arctic Circle during the summer solstice
53 Ride cost before taxes, fees, and extras
58 Set of all possible states of a system, in which trajectories may be plotted
61 Anakin’s daughter
62 Frequency ___, which contains many discrete, equally spaced spectral lines
63 Radioactive isotope that aids in tracking or assaying molecules
64 Parabolic paths
65 Blueprint detail, for short
66 Physics 101, for instance
67 Creator of a limerick or a haiku

DOWN

1 Stir rapidly to combine
2 Govern
3 The *A* in STEAM
4 Train whistle sound
5 Name of a bright star in the Summer Triangle
6 Sam-I-am’s creator
7 Parched
8 Institution that manages 14-Across, for short
9 Opening day of a golf major (abbr.)
10 Convene
11 Skin condition
12 Aptly named music style encompassing soul and calypso
13 Comparison site for tech gear
19 Oreo ingredient until 1997
21 A-list person, for short
24 Tainted with fungus
25 Rocky ___, founder of the Benihana chain
26 One side of Mount Everest
27 Name of the seventh planet, in Oaxaca
28 Requirements
29 Endowed with (var.)
30 Drives without a car?
31 Character in the Hebrew alphabet with numerical value 3
32 Do penance
33 ___ Carlo simulations
34 Orthographic viewpoint that is neither top-down nor frontal
36 Small pests that are wingless
39 Words before dash or pinch, in recipes
40 “Get ___!”
45 Entr’___ (theater break)
46 Stands that display artwork
48 Speed contests
49 Modern term for people who can’t seem to think for themselves (abbr.)
50 Breakfast chain that wants you to “leave happy”
51 Go or Go Fish
52 London-based financial corp. founded in Hong Kong
53 Type of rum cake
54 Movable part of an aircraft wing
55 Bubbly textured Nestlé chocolate bar
56 Component of arancini and donburi
57 Direction of runway 09
59 Utah airport inits.
60 Buddy



Covalent organic frameworks aid in mass-spectrometry imaging

By Ryan Dahn

These mass-spectrometry images of a cowpea plant reveal two embedded compounds: dinotefuran (left), a pollutant with which the plant was irrigated, and histidine (right), an amino acid naturally produced by the plant as part of its metabolic process. The light regions in both images show the molecules of dinotefuran and histidine, respectively, as determined via their distinct mass-to-charge ratios. The dinotefuran has spread throughout the plant, whereas the histidine molecules have accumulated in the vascular areas of the larger, mature leaves.

To determine mass-to-charge ratios in a mass spectrometer, the sample needs to be ionized. That's a trivial task for simple substances, but historically, researchers have had trouble with large biological molecules, which tend to fragment when ionized. That began to change in the 1980s and 1990s with the development of such techniques as surface-assisted laser desorption/ionization (SALDI), in which the sample is deposited onto a substrate that absorbs energy from the ionizing laser. But the nanomaterials used to fabricate the substrate can be laborious to create and difficult to consistently mass produce.

To generate mass-spectrometry images of an entire cowpea plant, a feat that had not been done before, a team led by Zhibin Yin at the Institute of Advanced Science Facilities in Shenzhen, China, developed a new type of SALDI substrate that adds nanofilms made of covalent organic frameworks to a commonly used substrate base made with titanium oxide nanotubes. Because the new substrate can be easily produced and integrated into the methods typically used to prepare biological specimens, the researchers hope that it will become standard in the laboratory and enable the imaging of even larger organisms. (Y. Xu et al., "Interface-engineered plasmonic covalent organic framework nanofilms on TiO_2 nanotubes for universal mass spectrometry imaging," *Sci. Adv.* **12**, eadx8264 (2026); images courtesy of the Zhibin Yin Laboratory, Institute of Advanced Science Facilities, Shenzhen, China.) PT

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