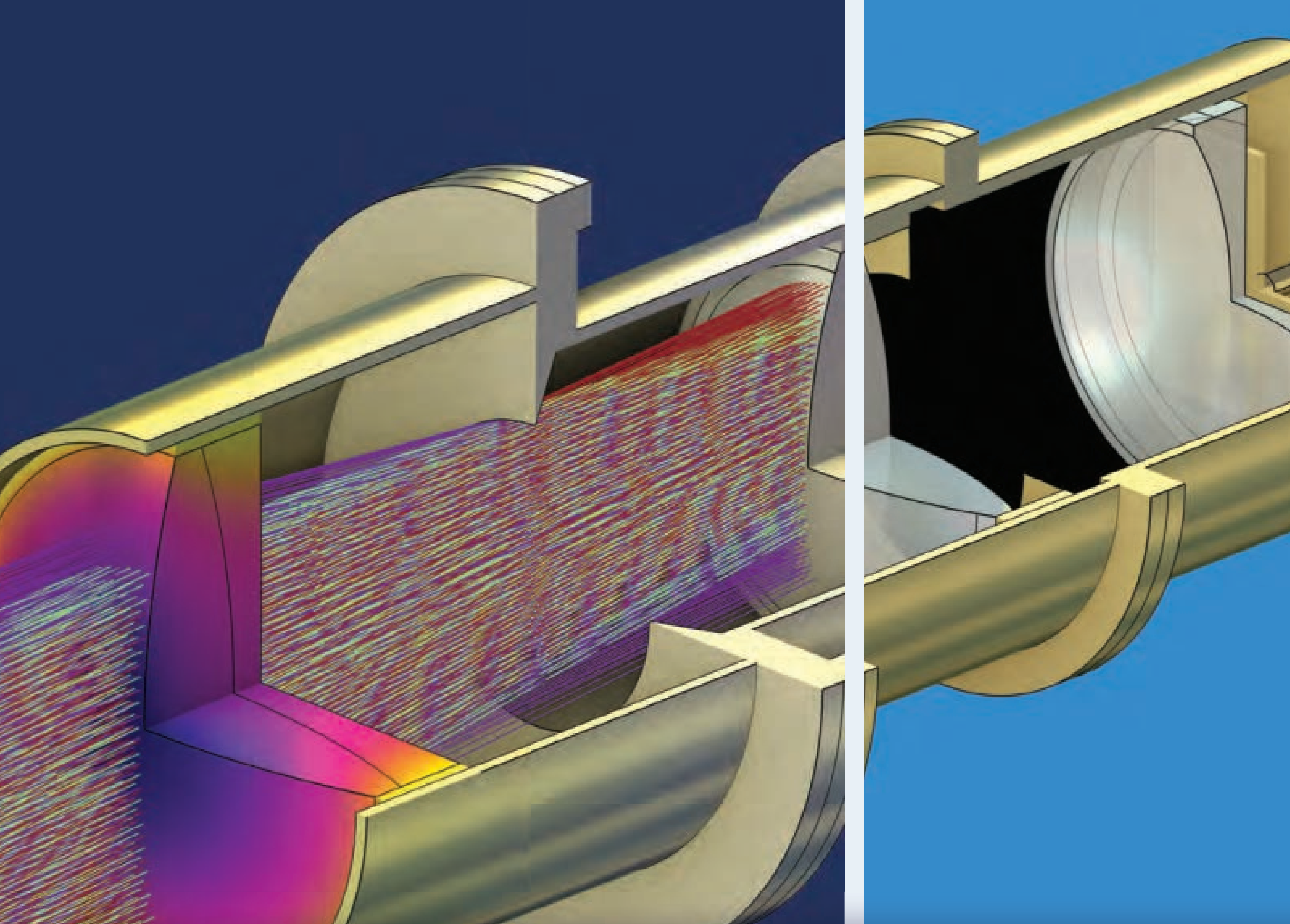

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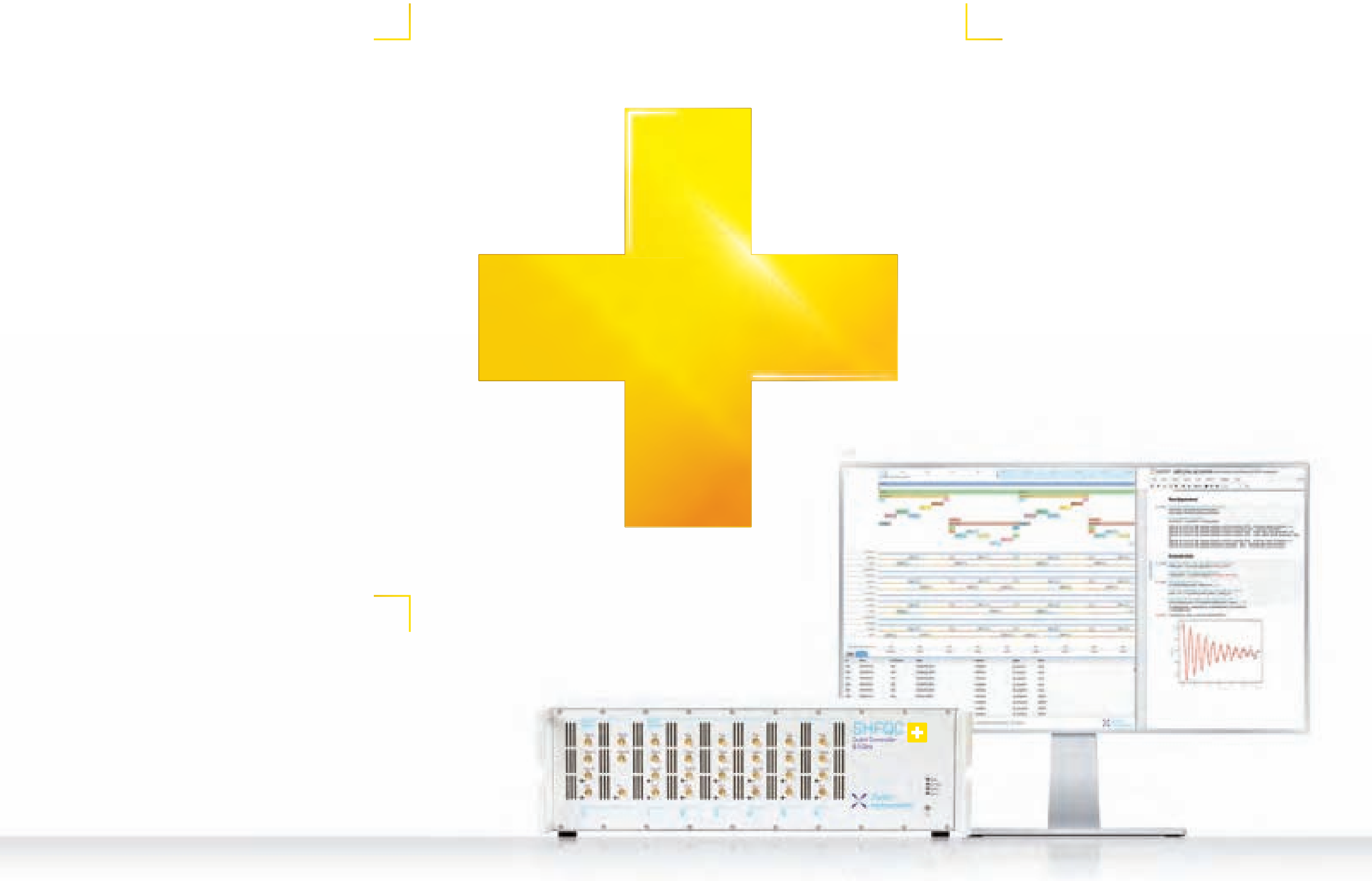

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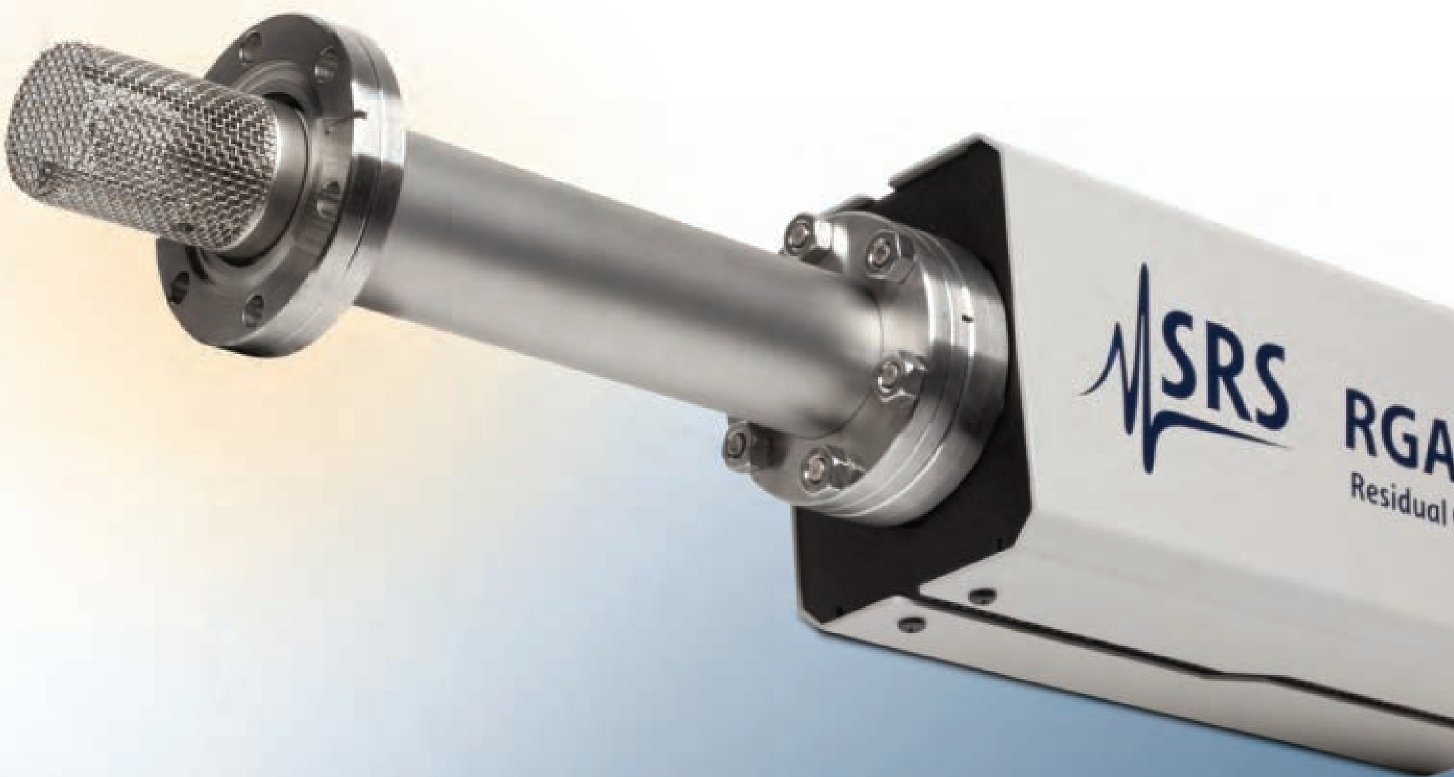

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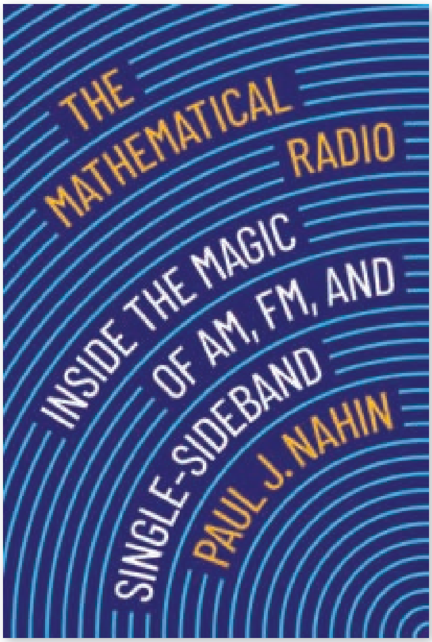

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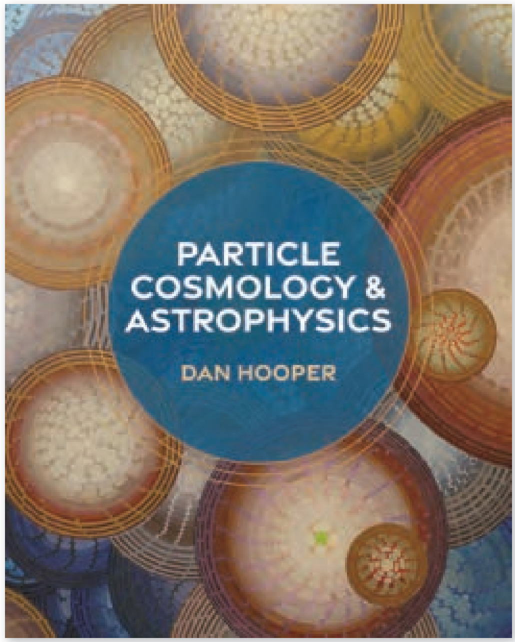

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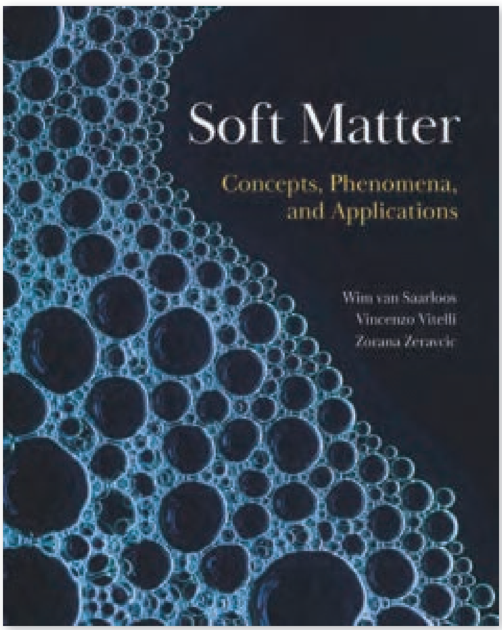

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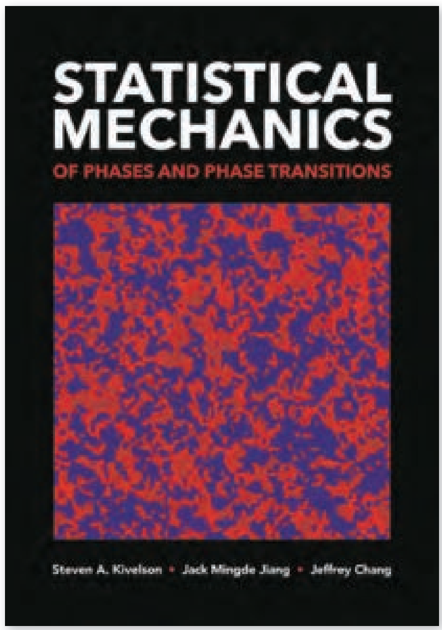

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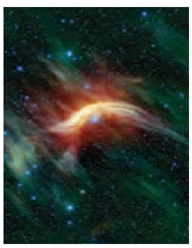

ON THE COVER: This IR image shows a bow shock caused by stellar wind emanating from a bright star. Interstellar shocks can also be created by the exhalations of dying stars. As shocks propagate through the interstellar medium, they can give rise to new stars that are enriched with heavier elements. On **page 36**, Cecilia Ceccarelli and Claudio Codella discuss how interstellar shocks influence the composition of the Milky Way. (Courtesy of NASA/JPL-Caltech/UCLA.)

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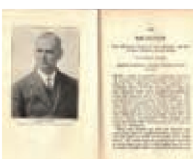

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Einstein essay contest

In 1920, at the height of public obsession over Albert Einstein and his theory of general relativity, *Scientific American* held a contest for the best essay explaining it. Willem de Sitter and Henry Norris Russell were among those vying for the generous cash prize. The winner, however, was an unknown amateur.

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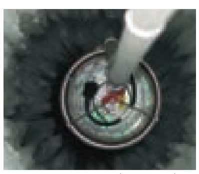

MARK KRASBERG/ICE CUBE/NSF

Cosmic tau neutrinos

A decade ago, researchers using the IceCube Neutrino Observatory in Antarctica detected high-energy neutrinos that originated beyond our solar system. Now, by identifying seven candidate tau neutrinos, IceCube researchers have confirmed that cosmic neutrinos come in all three flavors.

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Electric fish

An electricity-emitting fish uses its peers to help perceive its environment, a new study reveals. Researchers show how an African elephantnose fish can expand its sensing range by receiving signals emitted from both itself and nearby fish. The benefit is maximized when the fish are in certain arrangements.

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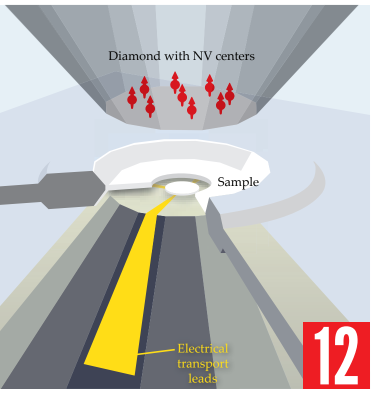

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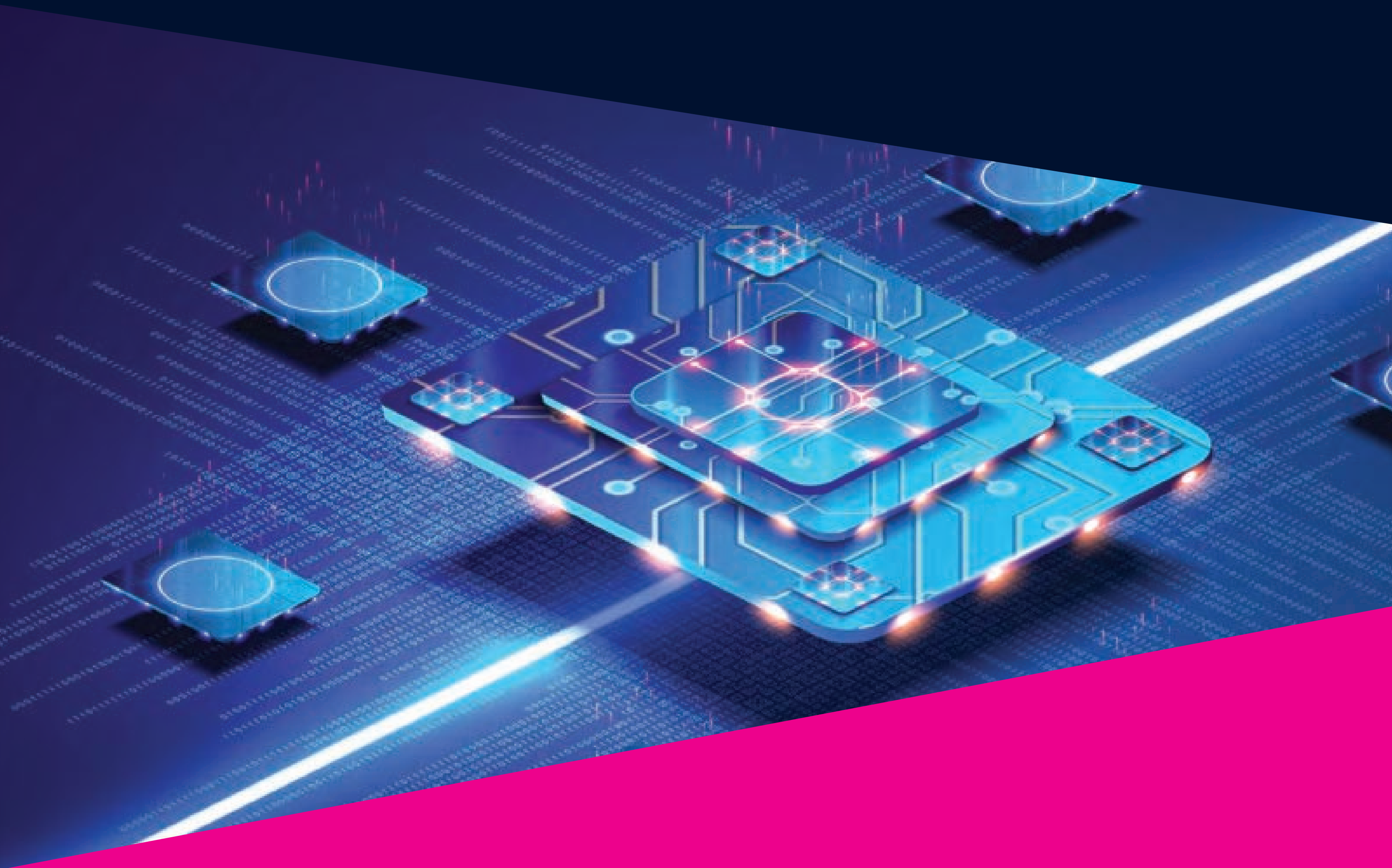

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The roles of research and "fit" in tenure

The most recent of Physics Today's annual careers issues (October 2023) provides insightful reading on academic tenure. Toni Feder's feature "When tenure fails" (page 44) includes discussion of the roles that publishing research and being a "good fit" play in the tenure process. The article prompted me to look into my "memory bank" developed over 50 years of involvement with the scientific community. In doing so, I conclude that we should rethink the role that those two factors play in determining the value of academic faculty members.

My views on research criteria are beautifully summed up by Kristine Palmieri in her recent feature on women working at Yerkes Observatory (see Physics Today, November 2023, page 42): "The length of one's research career or the number of one's publications are not the only measures of a scientific life."

ISAAC NEWTON, depicted here experimenting with light, was reclusive and reluctant to publish. Would he have been granted tenure at a modern university? (Acrylic painting by Sascha Grusche, 17 December 2015, CC BY-SA 4.0.)

Physicists working in government and industry often can't publish for various reasons, such as the classified or proprietary nature of their work, but they nevertheless lead productive careers. Leo Szilard published fewer than 30 papers. Some people stop conducting research as soon as they receive tenure or achieve significant recognition. Conversely, if you concentrate too much on teaching, you might fail to get tenure. I can think of at least one well-known physicist to whom that happened; the book he authored nevertheless became a classic text.

My own PhD adviser, recruited straight out of graduate school to an entry-level faculty position, had a tenure evaluation that consisted of no more than a "quiet talk" with his department head, who said that his teaching was satisfactory. He went on to win grants, advise graduate students, become director of a research laboratory, publish 240 papers and 5 books, and edit numerous conference proceedings.

Not only are publications a flawed metric, but they are the outcomes of a flawed process. Even in double-blind review processes, it can be easy to work out who authored a piece, especially in small research communities. That means that personal relationships come into play. A long time ago, I became aware of someone who, whenever he received a manuscript from a certain colleague, would toss it in the trash. (The paper would get published anyway!) I once had a reviewer make uncivil remarks on a paper. When I showed them to the editor, he apologized and told me that he did not know how they "slipped through." Another time, I had a paper rejected but then accepted once it was sent to another referee. All those scenarios exemplify the subjective nature of the process.

Meanwhile, faculty members face the challenge of getting research funding. Federal grant-awarding agencies are accountable to the public and, therefore, have less incentive to fund high-risk, potentially high-impact projects. And although projects may be evaluated by committees of experts, even brilliant scientists are fallible human beings. Ernest Rutherford famously said that any expectation of nuclear reactions producing useful energy is "moonshine." Imagine him chairing a grant committee considering proposals on stellar nucleosynthesis or nuclear reactors—the likelihood of them being funded would be next to nil. But the former was discovered by Hans Bethe and earned him the 1967 physics Nobel Prize, and the latter are a present-day reality. Encouragingly, some nonutilitarian endeavors have recently found a home in places such as the Perimeter Institute for Theoretical Physics and the Kavli Institutes.

The matter of "fitting in" is also a very real issue. At Cambridge University, Subrahmanyan Chandrasekhar encountered racism and was ridiculed publicly by his esteemed senior colleague Arthur Eddington for his proposed limit on the mass at which a dying star becomes a white dwarf. Chandrasekhar's limit would eventually become widely accepted, and he would go on to have an impressive career at the University of Chicago, receive a Nobel Prize, and have a NASA x-ray observatory named after him. "Fitting in" may not be a great criterion in determining a team member's value.

Then again, "fit" is important insofar as it refers to civility, decorum, and respectful conduct. Two bright young physicists whom I came across in the distant past saw their careers end prematurely primarily because they antagonized everyone around them. I know of one faculty member who threw a tantrum in the middle of a meeting and had to be sent for anger management training. I remember another who boasted about being known for "colorful language," wearing it almost as a badge of honor. Then there are the so-called leaders who make their staff's lives unnecessarily difficult. Such conduct has no place in a civilized society, let alone the hallowed halls of academia.

Scientists, physicists included, do not generally receive training in communication and other interpersonal skills. But active listening and the ability to engage in amicable discussion and debate are skills that can and should be included in our science curriculum. As the proverb goes, "With all thy getting get understanding."

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A note on 100 kW laser power

The January 2024 Physics Today article titled "The new laser weapons" (page 32), by Tom Karr and Jim Trebes, reports, "In 2015, General Atomics, the contractor for the distributed-gain laser, achieved 100 kW class power—at the time the highest average power ever achieved in an electrically pumped laser." In fact, Northrop Grumman and Textron Defense Systems—in 2009 and 2010, respectively—had already each independently demonstrated 100 kW average power from solid-state slab lasers.[1] I was the vice president of directed-energy weapons at Textron Defense Systems at the time of that work, which took place under the Joint High Power Solid State Laser program, funded by the Defense Department's High Energy Laser Joint Technology Office under contract with the US Army Space and Missile Defense Command.

The subsequent General Atomics demonstration, funded under the Defense Advanced Research Projects Agency's High Energy Liquid Laser Area Defense System program, focused on significant weight and volume reductions compared with the earlier demonstrations in order to facilitate integration into airborne platforms.

Reference

1. J. Hecht, "Photonic frontiers: Military lasers: A new generation of laser weapons is born," *Laser Focus World*, 1 April 2010.

John Boness
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► **Karr and Trebes reply:** Due to length constraints, we omitted discussion of many significant directed-energy efforts, including the Joint High Power Solid State Laser (JHPSSL) program. We regret any misunderstanding resulting from the briefness of our article. It was never our intention to slight the accomplishments of the JHPSSL program, its contractors, or the many other directed-energy-weapons achievements of other contractors.

We are happy to set the record straight. John Boness is correct. The JHPSSL program had two competing contractors: Textron Defense Systems and Northrop Grumman. Both contractors built electrically pumped solid-state lasers. The architecture of both JHPSSL lasers was a coherent phased array of solid-state media pumped by laser diodes and lasing in a "zigzag" geometry. Each demonstrated 100 kW average power with good beam quality in 2009–10. It was a great achievement by both contractor teams, and it motivated the high-energy-laser community to focus additional effort on electrically pumped solid-state lasers. We noted the achievement and included references to work by Textron Defense Systems and Northrop Grumman[1–3] in our initial manuscript. We deleted discussion of the JHPSSL in later revisions, shortening the article and focusing it on current developments. Despite its success, the JHPSSL architecture was not used in any subsequent US Department of Defense high-energy-laser program.

The Defense Advanced Research Projects Agency (DARPA) in 2004 funded General Atomics for its distributed-gain laser—a laser architecture that promised better scaling to higher power, lower specific volume, and lower specific mass than the JHPSSL architecture. The exact power achieved by the DARPA program has not been publicly released; we can say that by 2015 it achieved "100 kW class power." We stand by our statement that General Atomics' solid-state, distributed-gain laser in 2015 had "the highest average power ever achieved in an electrically pumped laser." General Atomics further advanced its distributed-gain laser under the DOD's High Energy Laser Scaling Initiative (HELSI). In 2023 a General Atomics distributed-gain laser achieved average power greater than 300 kW.

In 2022 under the HELSI program, nLIGHT and Lockheed Martin also demonstrated 300 kW average power high-energy lasers with diode-pumped fiber lasers—coherently and spectrally combined, respectively. Northrop Grumman is under contract to achieve a similar milestone. As part of the Solid-State Laser Technology Maturation program, in 2019 the US Navy installed Northrop Grumman's Laser Weapon System Demonstrator—a 150 kW average power diode-pumped fiber laser weapon—on the USS *Portland*, where it stayed until 2023. It is the highest average power directed-energy weapon ever deployed by the US.

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2. Northrop Grumman Corp, "Northrop Grumman-Built Joint High Power Solid State Laser Keeps Lasing . . . and Lasing . . . and Lasing . . .," press release, 8 December 2010.
3. J. Hecht, "Photonic frontiers: Military lasers: A new generation of laser weapons is born," *Laser Focus World*, 1 April 2010.

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An all-in-one device creates and characterizes high-pressure superconductors

Diamond has the ability to squeeze materials to immense pressures and to measure their magnetic properties. Now it can do both at the same time.

The quest for a room-temperature superconductor has grabbed more headlines in recent months for scandal than it has for science. To a packed room at last year's American Physical Society March Meeting, the University of Rochester's Ranga Dias presented findings of "near-ambient" superconductivity in nitrogen-doped lutetium hydride; the results were published in *Nature* at the same time. But by November, the *Nature* paper was retracted—the third high-profile retraction for Dias's group—and in March of this year, the university concluded that Dias had engaged in research misconduct.

The field has made some confirmed progress. Pressurized sulfur hydride and lanthanum hydride, for example, both appear to superconduct at relatively high temperatures. (See Physics Today, July 2016, page 21, and "Pressurized superconductors approach room-temperature realm," Physics Today online, 23 August 2018.) But Dias's results are not the only ones that the controversy-stricken community has had trouble reproducing.

Part of the problem is that the experiments are genuinely difficult. Most of the candidate materials don't even exist unless compressed to hundreds of gigapascals—millions of atmospheres—so they must be synthesized under pressure, a speck at a time, between the tiny tips of two diamonds in what's known as a diamond anvil cell (DAC). Even Dias's supposed near-ambient material, so called because of its relatively gentle 1 GPa pressure, still required a DAC.

And the small sample size and constraints of the DAC make the purported superconductors extremely hard to characterize. Two key properties identify a material as a superconductor: Its electrical resistance drops to zero, and it expels magnetic fields from its bulk. For technical reasons, reliably making just one of those measurements on a microscopic sample inside a DAC is difficult. Performing both measurements on the same sample is nearly impossible.

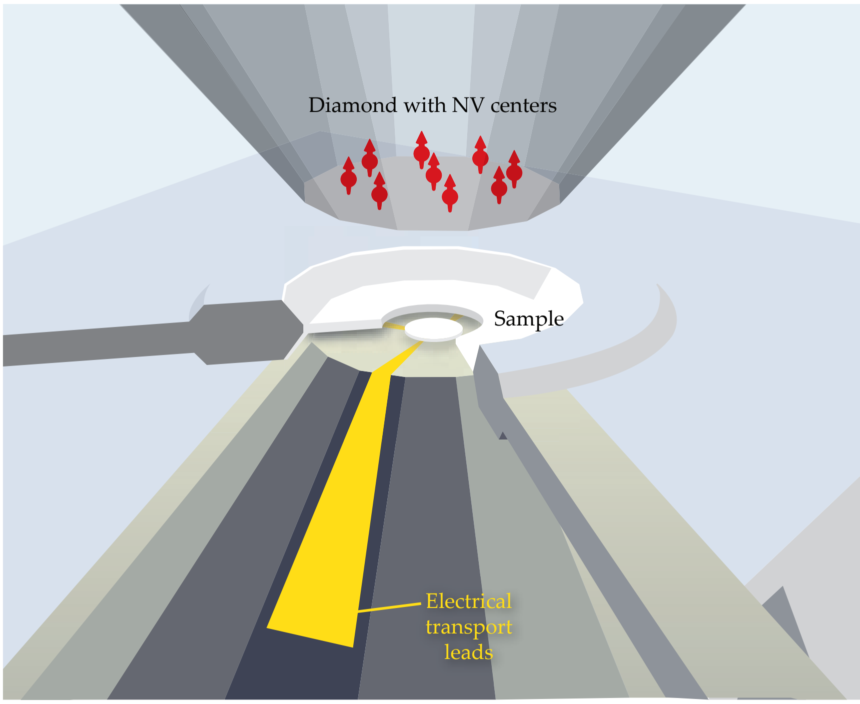

FIGURE 1. A DIAMOND ANVIL CELL, the standard tool for high-pressure measurements, doesn't have much room in it for instruments to probe the compressed sample. But magnetic measurements can now be made with nitrogen–vacancy (NV) centers embedded in the diamond itself. (Adapted from ref. 1.)

Furthermore, there's been no good way to fine-tune the high-pressure synthesis protocols, because there's been no way to tell how finely tuned they are to begin with. Diamond is transparent, so it's possible to view the compressed sample optically. But simply looking doesn't reveal much about whether the whole sample is superconducting or just part of it.

Both those problems may now be solved, thanks to new work by Norman Yao (formerly of the University of California, Berkeley; now at Harvard University), Christopher Laumann (Boston University), and their colleagues. They developed a way to perform spatially resolved magnetometry measurements inside a DAC by using defects called nitrogen–vacancy (NV) centers implanted in the diamond itself.[1]

Combining the NV magnetometry with electrical transport leads, as shown in figure 1, yields a device that can both create and characterize high-pressure superconductors. The technique could establish once and for all whether any given pressurized material is a superconductor or not. And because magnetic fields around different parts of the tiny sample can be measured separately, it provides unprecedented information about how well the superconductor synthesis is working.

Warming up

Superconductors have always been cold. The first known superconductor, mer-

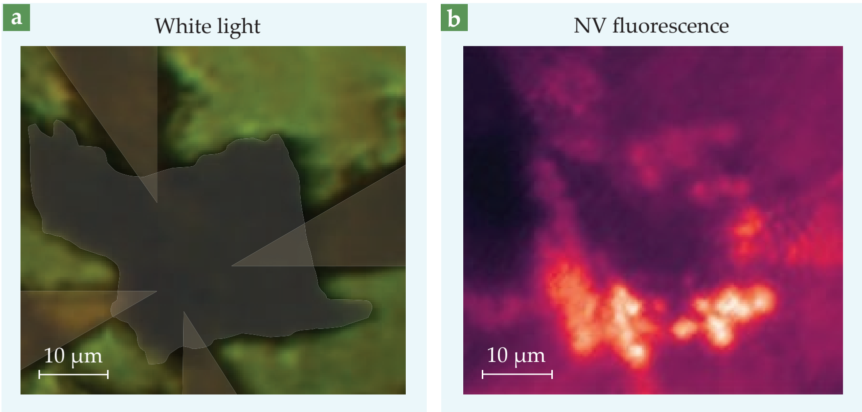

FIGURE 2. SPATIALLY RESOLVED MEASUREMENTS on pressurized samples have always been challenging. **(a)** Optical microscope images, such as this one, can be taken of the inside of a diamond anvil cell, but they don't reveal much about the sample's material properties. **(b)** Through the fluorescence of nitrogen–vacancy (NV) centers, researchers can learn much more about their samples. The bright spots in this image just indicate regions of higher NV center concentrations. But by zooming in on any bright spot and analyzing its fluorescence spectrum in detail, researchers can measure the local magnetic field—a key measurement for understanding whether the sample is a superconductor. (Adapted from ref. 1.)

cury, was discovered in 1911 to superconduct at a chilly 4.2 K, the temperature of liquid helium. Other ordinary metals superconduct at roughly similar temperatures, and the phenomenon is well explained by the Bardeen-Cooper-Schrieffer (BCS) theory of the 1950s: Vibrations in the atomic lattice nudge the fermionic electrons to team up into boson-like Cooper pairs, which condense into a superfluid and flow without resistance.

Even so-called high-temperature superconductivity, whose discovery in a family of cuprate ceramics rocked the physics world in the late 1980s, typically requires cooling to liquid-nitrogen temperature. The unconventional superconductors are not covered by BCS theory, and despite decades of work, the mechanism of their superconductivity is still unknown.

With the latest push for a room-temperature superconductor, researchers are turning back to the field's BCS roots, following two proposals from theorist Neil Ashcroft more than 35 years apart.[2] In the first, Ashcroft predicted that if hydrogen were compressed into a metal, vibrations of the lightweight atoms could be enough to form Cooper pairs even at high temperatures. The requisite pressure, however, was about 500 GPa, which is tough to reach, even with a DAC. So his second proposal—which predicted that hydrogen-rich compounds of heavier elements could manifest the same hydrogen-superconductivity effect at more modest pressures of 100–200 GPa—offered a more practical map for superconductor hunters to follow.

Ashcroft focused on compounds, such as methane, that are stable at ambient pressure. But most experimental implementations of his idea use hydrides that exist only at high pressure. The exotic materials must be synthesized inside an already pressurized DAC, usually by packing the cell with reactants and zapping it with a laser. And that's what makes studying the materials so challenging.

In principle, it's straightforward to measure the electrical conductivity of a sample inside a DAC: Just fit the cell with tiny electrical transport leads, like the ones depicted in figure 1, and measure the resistance when a current is passed between them. But the hallmark of superconductivity—zero electrical resistance—appears only if the superconductor spans the entire gap between the leads. "On the other hand, the leads can short-circuit due to thermal deformation," says Laumann. "So if cooling and heating the cell brings the leads in and out of contact, it can look like you're seeing a superconducting transition when you're not."

To conclusively show that they've found a new hydride superconductor, therefore, researchers must corroborate their electrical measurements with magnetic ones. But the latter measurements are even trickier than the former. There's no good way to put a standard laboratory magnetometer—a wire loop or coil—inside a DAC. So researchers have resorted to putting the DAC inside the magnetometer. "But then you're measuring the magnetism of the whole cell: the screws, leads, wires, and everything," says Laumann. "So it's hard to figure out what the contribution is of just the sample."

Furthermore, the two signatures of superconductivity are almost incompatible measurements to make on a pressurized sample. A DAC that's big enough to contain transport leads is too big to fit in a magnetometer. The usual approach is to use two DACs, one large and one small, for the two measurements. But the two cells may not contain the same material. In fact, given the unreliability of the high-pressure synthesis methods, they probably don't. "Even in the best groups in the world, only a third to a half of their samples show the signals of superconductivity," says Yao.

Much-needed clarity could come from a DAC that's capable of performing electrical and magnetic measurements on the same sample. But how?

Green with NV

An expedient solution is promised by NV centers. As the name suggests, an NV center consists of two adjacent sites in the diamond crystal lattice replaced by a nitrogen atom and a vacancy. The resulting point defect is an atom-like system whose state is readily controlled and probed with visible-wavelength light. Because of their easy manipulability and long coherence times, the centers are often used as qubits (see the article by Christopher Anderson and David Awschalom, Physics Today, August 2023, page 26). And because their spectra are sensitive to magnetic fields, they're also used as miniature magnetometers (see, for example, Physics Today, August 2018, page 16).

Because NV centers are housed in diamond, the very material that's the basis for a DAC, Yao and Laumann's approach of inserting NV centers into the diamond surfaces may seem obvious in hindsight. But NV centers, like many people, don't perform well under pressure. As was first noted in 2014, the more an NV center is squeezed, the noisier its spectrum gets, until at 50 GPa its spectral features all but vanish.[3]

So in 2019, when three groups (including Yao's) published their first explorations of integrating NV centers into DACs as a tool for high-pressure magnetometry, they all focused on pressures of a few tens of gigapascals—too low to access the superconducting hydrides that were starting to emerge.[4] "And even at those pressures, we lost so much in the signal-to-noise ratio," says Prabudhya Bhattacharyya, Yao's former student and the first author on the new paper. "For each measurement, we'd have to wait half a day to a day to see if we were even getting a signal at all."

University of Chicago theorist Giulia Galli helped Yao, Laumann, and colleagues pinpoint the problem. A DAC diamond is usually cut so that the diamond's [100] surface presses against the sample, because that's the crystal surface that's easiest to polish. But in that configuration, an NV center's axis—the line between the nitrogen atom and the vacant site—is oblique to the surface. The pressure at that angle distorts the defect's symmetry, and it's the loss of symmetry that destroys the spectroscopic signal.

By switching to diamonds cut so that the [111] surface faces the sample instead, the researchers positioned the NV centers perpendicular to the sample surface, which preserves their utility up to much higher pressures. "And the signal-to-noise ratio is so much better," says Bhattacharyya. "Now we can get a measurement in 10 or 20 minutes."

Full circle

The NV-endowed diamonds appear to be somewhat weaker than pristine ones, so it remains to be seen how high a pressure the new DACs can actually reach. But once they'd achieved 100 GPa, the researchers realized that they were ready to start testing superconducting hydrides. To begin, they chose cerium hydride, whose superconducting temperature of 91 K is modest by hydride standards—but, importantly, its requisite pressure of around 90 GPa is too.

For the sample synthesis, they turned to Xiaoli Huang and her student Wuhao Chen at Jilin University in China, who'd done the initial electrical-resistance measurements on the material and were some of the only researchers in the world with the knowhow to synthesize it.[5] "I've never met Wuhao in person," says Bhattacharyya, "but we've sent our samples back and forth so many times. One of our samples must have been around the world three or four times." Usually—but not always—the DAC is robust enough to survive the trip through the mail, even under pressure.

Images of the sample are shown in figure 2. On the left, figure 2a shows a white-light microscope image; until now, images like that, along with x-ray diffraction structures, were all the spatially resolved information about their samples that researchers got.

On the right, figure 2b shows an image of NV-center fluorescence. The bright patches in the image don't have anything directly to do with the cerium hydride sample—they're just regions in the diamond with more NV centers. But the researchers can zoom in on any spot with appreciable fluorescence, measure the NV-center spectrum, and deduce from that the local magnetic field.

At a spot that's not directly above the sample, the NV-measured magnetic field was always equal to whatever magnetic field the researchers applied—as expected. At a spot above the sample, however, the local magnetic field was suppressed. Again, that's what's expected for a superconducting material that expels magnetic fields.

But not every spot above every sample showed the same results. "These samples are actually very inhomogeneous at the 5- to 10-micron scale," says Laumann. "There was never a way to characterize them on that scale before—to say, 'Is this grain superconducting and that grain not?'" Cerium hydride indeed appears to be a superconductor, but there's a lot left to learn about how to reliably make it.

Solid footing

With technical improvements to their setup at Yao's new lab at Harvard, the researchers have expanded the range of pressures that they can achieve, and most of the putative superconducting hydrides are now within their reach. "We were starting to study lanthanum hydride," says Laumann, "and we just had our first sample synthesized. But it was one of the unlucky ones that didn't survive shipping back to the US."

A method for reliably testing hydride superconductors could help calm the controversy in the field, but the question remains of whether the materials themselves will ever have practical applications. Certainly, in their present form—existing only in microscopic amounts and under immense pressures—they do not. But as the field advances and the materials are better understood, they could yet reveal clues that lead to a material that really does superconduct under near-ambient conditions.

And importantly, superconducting hydrides aren't the only materials that can benefit from the new high-pressure NV-center measurements. NV-center spectra are sensitive not only to magnetic fields, but also to temperature, stress and strain, and other properties. "We're also working on serpentine, which is a mineral that's relevant to deep earthquakes," says Laumann. "It's kind of an open question what causes those and whether it's a serpentine phase transition."

Johanna Miller

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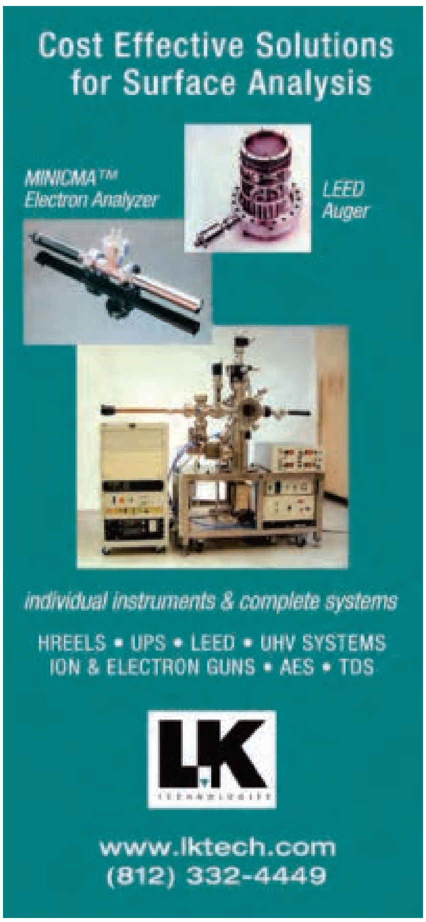

Climate change drives extinction—and always has

Rising temperatures may threaten species regardless of the traits that they have, according to a new paleoclimate and paleobiology analysis.

FIGURE 1. MASS EXTINCTION hit Earth's oceans some 200 million years ago, as illustrated by the difference in the number of organisms before (left) and after (right) ocean temperatures increased. Researchers used fossils of marine invertebrates, such as the nautiluses, snails, and sea lillies shown here, to better understand the causes of extinction over roughly the last half a billion years. (Courtesy of Maija Karala.)

To learn how Earth's species go extinct, scientists have often focused on what's readily available from the fossil record—organisms' intrinsic traits, such as their body size or the geographic range they occupy. Yet some of the largest mass extinctions in the geologic past have also been connected to a different factor: extrinsic climate change. The sparse fossil record makes it difficult to estimate the climate contributions to extinction for specific times and places. Most studies, therefore, have treated intrinsic and extrinsic factors separately.

A 2021 climate study, for example, looked only at temperature over the past 450 million years, when animals and plants became abundant on Earth. It found that a historical increase of 5 °C reduced global biodiversity (see figure 1) by about 75%.[1] That's similar in magnitude to the five largest extinctions.

Now Cooper Malanoski and Erin Saupe of the University of Oxford and their colleagues have found a way to look at the combined effects of intrinsic and extrinsic factors on the extinctions of marine invertebrates across geologic time. In their integrated analysis, they found that even organisms with advantageous traits are threatened by climate change.[2]

"The field of paleontology is making major advances in recent times at moving from simply recognizing patterns of extinction in the fossil record to testing among potential underlying causes," says Jonathan Payne of Stanford University. "This study, to me, is among the most complete ever attempted in that direction."

Mixed model

The history of marine invertebrates is told in their shells. The hard calcified remains are preserved continuously in sedimentary rocks, leaving fossils suitable for analysis. The extinction data—that is, the occurrence of a genus in the fossil record, with the last observation indicating when it went extinct—come from the public Paleobiology Database. The researchers used about 300 000 individual occurrences of various genera.

Why group organisms by genus, rather than by species? The fossil record makes a finer-grained taxonomic analysis difficult. Consider the genus *Felis*, for example, which includes the domesticated house cat and several wildcats. "It'd be really hard to reconstruct precisely when exactly each species

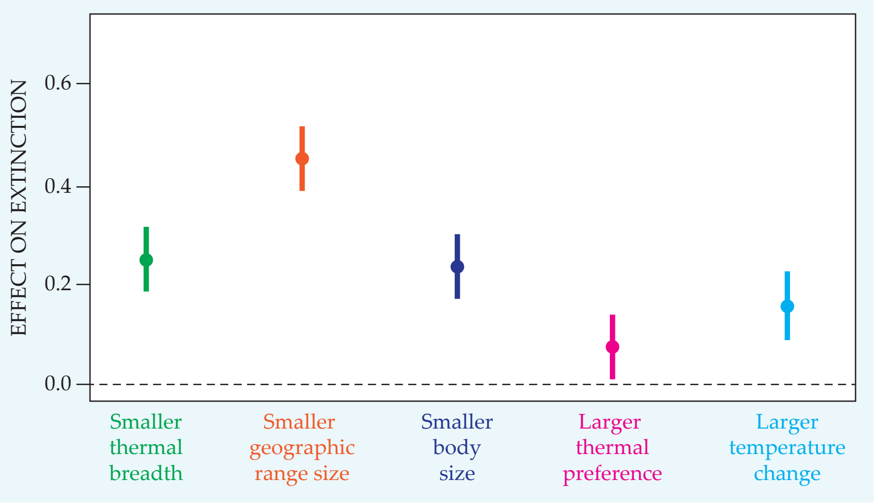

FIGURE 2. EXTINCTION RISK is affected by multiple factors. Although extrinsic temperature change had a smaller effect on extinction than geographic range, it's independent of the other analyzed factors and may thus threaten organisms, regardless of their traits. Thermal breadth is defined as temperature range in the area that a genus occupies; thermal preference is the temperature variation that an organism withstands over a time period. The analysis spans the last 485 million years, and the vertical lines represent the 95th percentile estimates. (Adapted from ref. 2.)

appeared," says Bruce Lieberman, a paleobiologist from the University of Kansas, "rather than say some type of cat belonging to the genus *Felis* appeared 5 million years ago."

In addition to occurrence patterns over time, data from extinct and living genera record two traits that have previously been tied closely to extinction: body size and geographic range. In contrast to what we're familiar with on land—where larger animals are typically more vulnerable—smaller-bodied marine organisms more frequently go extinct. The counterintuitive finding, says Saupe, "is likely due to body size being correlated with metabolic rates, fecundity, and dispersal ability. However, the exact mechanisms are unknown."

To study intrinsic and extrinsic factors together, the researchers came up with a way to calculate thermal predictors of extinction using results from the Hadley Centre Coupled Model (HadCM3). Compared with other general circulation models of Earth's climate, HadCM3 has relatively low resolution, and thus the model runs faster, which is critical when simulating past climates for thousands of years. In 2017 one of Malanoski and Saupe's coauthors, Paul Valdes of the University of Bristol, made a version of the model with several modifications that further optimized it for paleoclimate simulations.[3]

For the new study, Valdes and two coauthors ran a new version of the Bristol HadCM3 model and took sea-surface temperature results from dozens of time slices across the past 485 million years that were matched to the geography of the genera. Then Malanoski and colleagues used the temperature results to calculate two thermal predictors: thermal breadth—defined as the range of temperatures in the area that a genus occupies—and thermal preference, which is the temperature variation that a genus withstands for each time period.

"In the beginning stages of this project, we wanted to compare physiological traits such as thermal breadth and thermal preference to known predictors of extinction risk such as geographic range and body size," says Saupe. "As the project progressed, we had the thought to compare these traits to the amount of climate change that a species experienced." To make the comparison of extinction factors, Malanoski and colleagues used a type of linear regression that tests the relative contributions of each of the intrinsic traits and the extrinsic climate factor. Other potential confounding factors, such as greenhouse gas concentrations, Earth's orbital motion, and the movement of the planet's tectonic plates, were partially accounted for in the model as additional time-varying effects and were used to quantify uncertainty.

Climate consequences

"Our initial hypothesis was that geographic range size would be the most significant predictor of extinction risk," says Malanoski. The regression results, plotted in figure 2, bear that out. The more places that an organism can live, the less likely it is to go extinct.

Some of the intrinsic factors analyzed interacted with each other. An organism with a small body and living in a small geographic range, for example, would be more prone to extinction than an organism with a large body and living in a large geographic range. The interactions highlight the complexity of how organisms may respond to evolutionary pressure or environmental changes.

The absolute temperature change, however, had no statistically significant interactions with the other factors. Climate change, therefore, may have an independent effect on extinction risk—an effect that if large enough may threaten organisms, even if they have large bodies or can live in a vast geographic range. In today's changing climate, the greatest risk of extinction is for genera living predominantly at the poles or the tropics and that have a thermal breadth of 15 °C or less.

Other factors could also affect extinction. Habitat destruction may block the path that organisms would travel to reach other locations (see PHYSICS TODAY, September 2019, page 16), and changes in ocean currents could disrupt reproductive behavior and the abundance of organisms (see PHYSICS TODAY, November 2020, page 17). Measuring or estimating those or other predictors of extinction on geologic time scales would be more difficult, but, Saupe says, "We hope to build on our extinction modeling framework in the future as more variables become available."

Alex Lopatka

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When unmixable metals mix

At the bulk scale, gold and rhodium separate like oil and water, but at the nanoscale, they can mix completely. The reason for the miscibility is on the particles' surface.

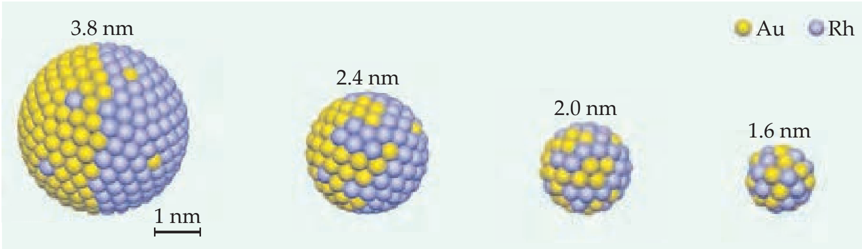


FIGURE 1. GOLD AND RHODIUM ATOMS are phase separated in particles with diameters as small as 3.8 nm. At smaller sizes, the metals begin to intermingle, and in particles less than 2 nm across, mixing of the elements becomes thermodynamically stable. (Adapted from ref. 1.)

Phase diagrams change at the nanoscale. When particles are shrunk down to small-enough sizes, the fraction of atoms on the surface increases, and the free-energy balance of atomic interactions changes. Although that phenomenon has been common knowledge in the nanoscience community for decades, the details have remained fuzzy. Now Peidong Yang of the University of California, Berkeley, and colleagues have filled in some of the gaps by documenting the nanoscale phase transition of gold–rhodium mixtures down to diameters of 1–4 nm.[1]

At bulk scales, gold and rhodium are incompatible metals. Even in particles as small as 3.8 nm, the metals remain mostly separate. In such particles, the two metals segregate into separate regions, as shown in figure 1; they are thus sometimes called Janus particles after the Roman god of duality, who had two faces. But below 2 nm, the thermodynamic balance shifts, and the researchers found that a completely mixed alloy forms.

Gold and rhodium have several qualities that make them an appealing pair to investigate. Nanoparticles of those elements are already used for electrocatalysis reactions, such as the separation of water to make hydrogen fuel. Both elements have cubic lattice structures, so the analysis wouldn't have to account for structural differences. Materials with larger atomic numbers show up brighter in the scanning transmission electron microscopy (STEM) imaging used to study them. Gold, with a relatively high atomic number of 79, thus stands out from rhodium, with atomic number 45.

Small is different

Beyond miscibility, optical and mechanical material properties also change at the nanoscale. For example, semiconductor nanocrystals, known as quantum dots, emit different wavelengths of light depending on their size. Quantum dots' extraordinary properties were highlighted by last year's Nobel Prize in Chemistry. (see Physics Today, December 2023, page 16). Some materials, such as certain ceramics, are also stronger at the nanoscale (see Physics Today, November 2013, page 14).

Previous studies had documented the mixing at nanoscales of otherwise immiscible materials, such as silver with nickel and gold with rhodium.[2] Yet it was unclear whether the nanoparticles were composed of thermodynamically stable alloys or had been kinetically trapped in a mixed form by rapid cooling. Previous work by Yang's research group had found that in particles with diameters of 4–12 nm, gold and rhodium remain mostly separate but begin to mix a little bit.[3] The new study now extends that earlier work to even smaller particles.

The reason the community had been missing data on the changes to multielement phase diagrams at nanoscales, explains Yang, is that it was a formidable task to take on. It's difficult to produce bimetallic nanoparticles of 1–4 nm, and once they've been made, analyzing their mixing state is also a challenge. Such small particles are easily knocked out of place by the electron beams used to image them, and they can't be measured if they're no longer in the beam. To deal with that issue, Yang and colleagues used low-dose STEM.

To reliably estimate the mixing of gold and rhodium in the smallest nanoparticles, the researchers developed a random-walk algorithm that measures the domain size and distribution of the gold in the samples. The algorithm first identifies the brightest pixel in a STEM image of a nanoparticle, which will always be gold (thanks to its large atomic number), and then investigates neighboring pixels until it reaches a threshold decrease in brightness, indicating that it has left the gold domain. Then the algorithm looks at the remaining region. By repeating that process dozens of times, it maps the size and location of all gold domains. Rhodium domains are then mapped simply by subtracting the gold domains from the total image. When the domain sizes become small enough, on the scale of one to four atoms across, the material is considered completely mixed.

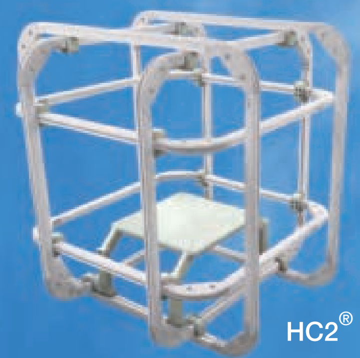
In addition to looking at the effects of particle size, the researchers investigated how different mixing ratios of the two metals affected the results. They found that the elements best mix when the composition is far from 50-50. When a particle has roughly equal volumes of the two metals, they exhibit maximum repulsion. But particles larger than 2 nm do mix when there is much more of one metal than the other. For example, mixtures that are 80% either gold or rhodium will fully mix at 4 nm.

A thermodynamic mystery

After building a detailed experiment-based phase diagram for the metals' miscibility, Yang and colleagues turned to thermodynamic models to confirm their findings. But there was a problem: Theory-based models disagreed with what they had observed. Instead of the evenly mixed alloys seen in experiments, thermodynamic simulations suggested that small nanoparticles should separate into a core of rhodium surrounded by a shell of gold, as shown in figure 2a.

INNOVATION IN MAGNETICS

Helmholtz Coil Systems



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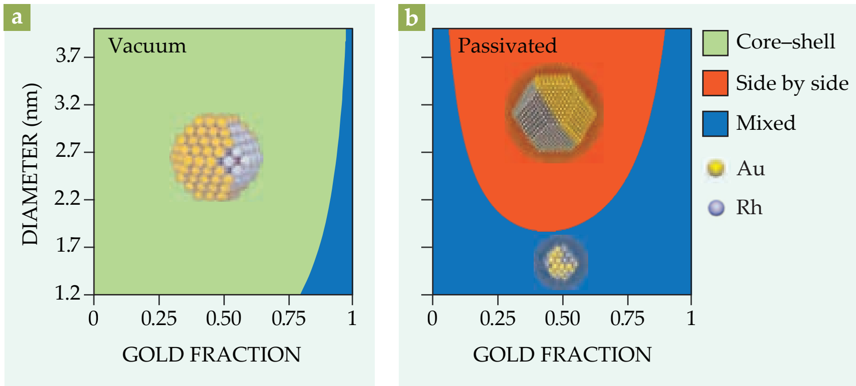

FIGURE 2. THERMODYNAMIC MODELS predict the structure of gold–rhodium nanoparticles. **(a)** Pure gold and rhodium mixtures synthesized in UHV should stratify into a core of rhodium surrounded by a shell of gold. **(b)** Surface passivation of nanoparticles changes their stable structure to either fully mixed or unmixed side-by-side domains. (Adapted from ref. 1.)

The apparent conflict between theory and observation revealed a hidden element that the researchers had missed in their simulations. The nanoparticles of gold and rhodium are synthesized using droplets of organic polymers that are then burned away, and the samples are washed with argon and oxygen plasma. Despite the cleaning step, the polymers used in the synthesis process left behind remnants, such as carbon and oxygen atoms, that had attached to the surface of the nanoparticles. Those remnants, undetectable in the STEM images, reduced the free-energy difference between rhodium and gold, making them less repellent to each other.

Surface passivation occurs when any material is coated with another material that makes it less reactive. It is a method often intentionally used in engineering to reduce weathering and corrosion, but it also occurs naturally. Many metals, such as aluminum and titanium, naturally form a layer of passivating oxides on their surface just from normal air exposure.

Once the researchers accounted for the effects of surface passivation, the experimental phase diagram finally aligned with thermodynamic simulations, as shown in figure 2b. Despite the impossibility of directly imaging the passivating elements, their presence is confirmed by the agreement between the corrected model and experimental observations. The model, like the experiments, showed that 50-50 gold–rhodium compositions are the most resistant to mixing but that they will still mix below a particle size of 2 nm. Only nanoparticles synthesized in UHV should form the core–shell structure, a hypothesis that could be tested in the future.

One might wonder whether the discovery of surface passivation on those nanoparticles could forebode problems for the electrocatalysis reactions that they are valued for, but most nanoparticles are synthesized using polymers, so what is already understood about their catalytic properties should not change. Other recent research shows that passivating elements will dissociate from the surface of nanoparticles during electrocatalysis and may even help enhance reactivity.[4]

"Knowing the phase diagrams at this nanoscopic level will help us design better catalysts," says Yang. The phase diagrams provide a path to targeted engineering of specific structures and pave the way to understanding the behavior of other multielement nanomaterials. For engineers and researchers who want to synthesize gold–rhodium nanoparticles that are phase separated, alloyed, or in a core–shell structure, the conditions needed to achieve those structures are now mapped out.

Laura Fattaruso

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UPDATES

Better batteries for cold weather

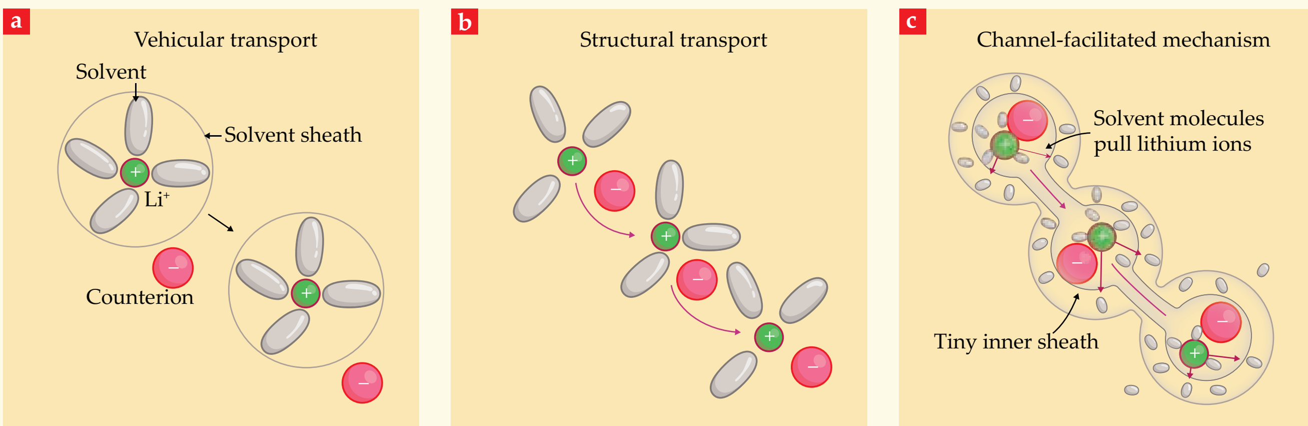
A solvent with small molecules forms channels that increase the speed of lithium-ion transport, even at low temperatures.

CHARGING AN ELECTRIC VEHICLE at the Mt Hood Skibowl EV station. (Courtesy of the Oregon Department of Transportation/CC BY 2.0 DEED.)

A prolonged January cold snap in Chicago left owners of electric vehicles struggling to keep a charge. With reduced driving ranges and charging times taking longer than usual, the performance limitations of lithium-ion batteries in the cold were evident. A new study led by Xiulin Fan of Zhejiang University finds that using a unique organic solvent in the electrolyte of lithium-ion batteries holds promise for faster charging times and improved low-temperature performance.

Conventional lithium-ion batteries use carbonate solvents, which produce two known types of ion transport, as shown in figure panels a and b. During vehicular transport, a lithium cation is carried by a shell made up of the solvent molecules surrounding it. Structural transport occurs when cations hop between solvent molecules. Various factors, including salt concentration and solvent type, determine which transport mechanism occurs, and both can happen simultaneously in the same battery.

Fan and colleagues evaluated the known properties of dozens of solvents. They looked for a solvent with a specific combination of qualities that could promote faster charging and long-term performance: small molecule size, a low lithium-ion transport energy barrier, and low reactivity with electrodes. They landed on fluoroacetonitrile (FAN). With its particular combination



UNTIL NOW, (a) vehicular transport and **(b)** structural transport were the two known mechanisms of cation conduction in lithium-ion batteries. A solvent with unique properties has revealed **(c)** a third mechanism that uses ligand channels to produce ultrafast charging, which is effective even at very low temperatures. (Adapted from D. Lu et al., *Nature* **627**, 101, 2024.)

of properties, FAN could facilitate a previously untapped mechanism of lithium-ion transport that drastically speeds up conduction.

The new ion-transport mechanism, as understood through molecular-dynamics simulations and confirmed by observations, is facilitated by the formation of two layers of solvent sheaths around lithium ions, shown in figure panel c. Solvent molecules in the outer sheath pull lithium ions from the inner sheath and form fast-conducting channels known as ligand channels. The researchers found that because of its small size and low lithium-ion transport energy barrier, the FAN-based electrolyte was able to activate ion transport through ligand channels.

The FAN-based electrolyte produced ionic conductivity that was four times as high as that achieved by typical carbonate-based electrolytes at 25 °C. Further, at −70 °C, it produced ionic conductivity comparable with the room-temperature performance of conventional solvents. And it was more than twice as high as the conductivity exhibited by state-of-the-art liquefied-gas electrolytes at the same low temperature. That higher ionic conductivity could translate into faster charging times, longer running times, and better performance at low temperatures. Battery design and performance depend on many interacting factors, so more work will be needed to integrate the new solvent into commercially available batteries. But the findings offer hope for a future where electric vehicle drivers won't be left out in the cold. (D. Lu et al., *Nature* **627**, 101, 2024.)

Laura Fattaruso

Most automobile brakes emit charged aerosols into the atmosphere

The charges may allow engineers to mitigate the aerosols' contribution to urban pollution.

Automotive brake wear adds significantly to automotive pollution, despite having nothing to do with tailpipe exhaust. Wear particles are produced where the brake pad and rotor meet and generate friction. The heat produces vapors that nucleate into nanometer-sized particles, 35–55% of which become airborne. Those aerosols make up as much as 21% of total traffic-related emissions by mass. Pulmonary inflammation and oxidative stress in the lung tissues of animals are among their health effects.

Led by chemistry professor James Smith, a team comprising doctoral student Adam Thomas, postdoctoral researcher Paulus Bauer, and three of their colleagues at the University of California, Irvine, has now studied the electrical properties of the particles emitted from ceramic and semimetallic brake pads. They were surprised to find that up to 80% of the aerosol particles were electrically charged.

In their experiments, the researchers used a dynamometer that consisted of a brake rotor rotating at a constant speed of 173 rpm and a brake caliper mounted on a rotational torque sensor. Thomas and Bauer, shown in the photo, applied the brakes in a series of hydraulic pulses over periods of one to two hours. In each experiment, they measured the particles' sizes across a wide range—from 10 to 22 000 nm—and found that the number of particles emitted depended on the specific type of brake-pad material that was used. Semimetallic pads resulted in higher rotor temperatures than ceramic pads, while emitting fewer particles. But the two materials shed both positively and negatively charged particles, and each of those particles were found to hold dozens of elementary changes.

UNIVERSITY OF CALIFORNIA RESEARCHERS Paulus Bauer (left) holds a brake rotor and Adam Thomas holds a brake caliper next to the lathe that they and their colleagues used to simulate automotive brake emissions. (Courtesy of Lucas Van Wyk Joel, University of California, Irvine.)

The presence of electric charges on aerosol particles has potentially far-reaching climate significance. They enhance the growth of newly formed particles in the atmosphere and the coagulation rates of larger particles. What's more, they make it relatively easy to remove brake aerosols from the air. Exposing the charged particles to an electric field could sweep them away. (A. E. Thomas et al., *Proc. Natl. Acad. Sci. USA* **121**, e2313897121, 2024.)

R. Mark Wilson PT

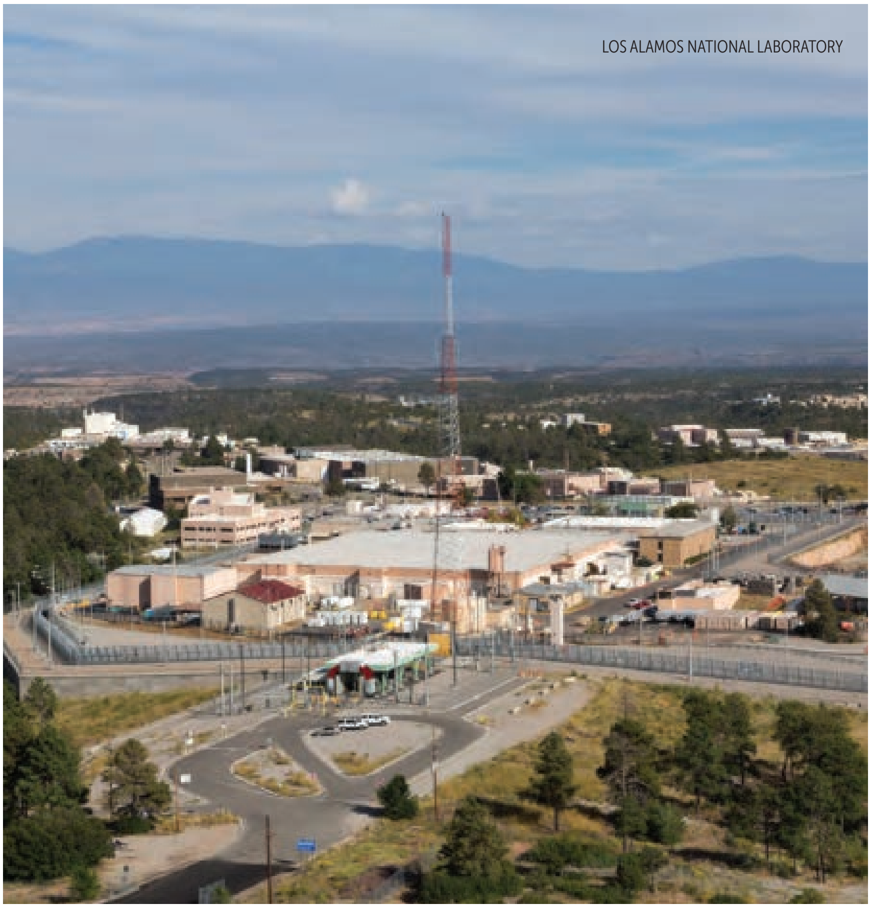
US nuclear agency struggles with production and costs

The National Nuclear Security Administration must cope with resurgent geopolitical threats accentuated by Vladimir Putin's nuclear saber-rattling.

Spending on the nuclear weapons complex has exploded in recent years, and budgets are expected to continue on a steep upward path as the US National Nuclear Security Administration (NNSA) works to juggle refurbishments and modifications of aging weapons systems while replacing crumbling infrastructure and building new production plants.

President Joe Biden's budget proposal for the fiscal year that begins October 1 seeks $19.8 billion for the NNSA's nuclear weapons activities—a 4% increase from the current level. That follows an 11.6% rise from FYs 2023–24. The NNSA budget is one element of the $69 billion included in Biden's budget request for nuclear forces and their delivery systems. In all, NNSA funding has more than doubled in real terms since the Soviet Union's collapse and the ending of the nuclear rivalry between the superpowers (see the figure on page 23).

Today, of course, defense planners and lawmakers are addressing a renewed and multipronged nuclear threat: the buildup and modernization of nuclear forces by Russia, the expected push by China for nuclear parity with the US and Russia, and long-range missile testing by North Korea. The Russian threat has been heightened by President Vladimir Putin's repeated threats to use nuclear weapons in the war with Ukraine. Ernest Moniz, US secretary of energy from 2013 to 2017, says Putin's pronouncements have violated pledges made by Russia and all the declared weapons states to never use such weapons against nonnuclear states. The possibility of a nuclear attack now is at least as great as in the Cuban Missile Crisis in 1962, he says.



LOS ALAMOS NATIONAL LABORATORY

PLUTONIUM PIT PRODUCTION will be housed in the PF-4 building at Los Alamos National Laboratory. PF-4 also will continue to support a wide range of other plutonium functions, including R&D, fabrication of plutonium-238 heat sources for space exploration, nuclear waste processing, and counterterrorism activities.

The NNSA declined to make an official available for an interview. In a written statement, a spokesperson said that the FY 2025 budget request "reflects significant investments in ongoing modernization and efforts to strengthen our response to a deteriorating global environment. The proposal reflects a demanding, expanded mission. More than anything, it reflects our continued investment into the infrastructure of the Nuclear Security Enterprise that prioritizes sustainability and addresses modern threats."

A nuclear deal

The origins of today's soaring US expenditures on nuclear weapons date to 2010, when then-president Barack Obama approved a 30-year, $1 trillion blueprint for modernizing nuclear weapons and their delivery systems. Moniz says that Obama's go-ahead for the new spending was part of a deal for Senate ratification of the New START Treaty with Russia in February 2011. The treaty limited the numbers of deployed warheads and delivery systems on both sides. The price tag of the modernization has since grown to as much as $1.5 trillion by some estimates.

Victor Reis, who was assistant secretary for defense programs at the Department of Energy from 1993 to 1999 (prior to formation of the NNSA), says that the weapons complex was funded at around $4 billion annually in the early 1990s. In the immediate aftermath of the Cold War, DOE was not producing weapons, and a halt had been called to underground testing. “The general feeling was there was a peace dividend,” Reis says, and the political climate was characterized by a sense of wondering why nuclear weapons were needed at all.

In exchange for not insisting on a resumption of testing, Los Alamos, Sandia, and Lawrence Livermore National Laboratories each received a major new experimental facility and high-performance computing assets that would carry out experiments and modeling to simulate nuclear weapons processes. Known as science-based stockpile stewardship, that program has, by all accounts, succeeded in maintaining stockpile reliability to date. (See the article by Reis, Robert Hanrahan, and Kirk Levedahl, Physics Today, August 2016, page 46.)

Three decades into the post–Cold War period, the NNSA has been working to extend the lifetimes of aging nuclear warheads. The NNSA administrator, Jill Hruby, told a Washington, DC, conference in January that the agency had delivered more than 200 refurbished weapons to the military in 2023. The agency is also designing what will become the first post-1980s all-new nuclear warhead, which will top submarine-launched ballistic missiles. The NNSA has been directed by Congress to make another alteration to the venerable B61 bomb, which entered the stockpile in 1968. And Congress just last year authorized a new nuclear-tipped, sea-launched cruise missile.

Pit costs soar

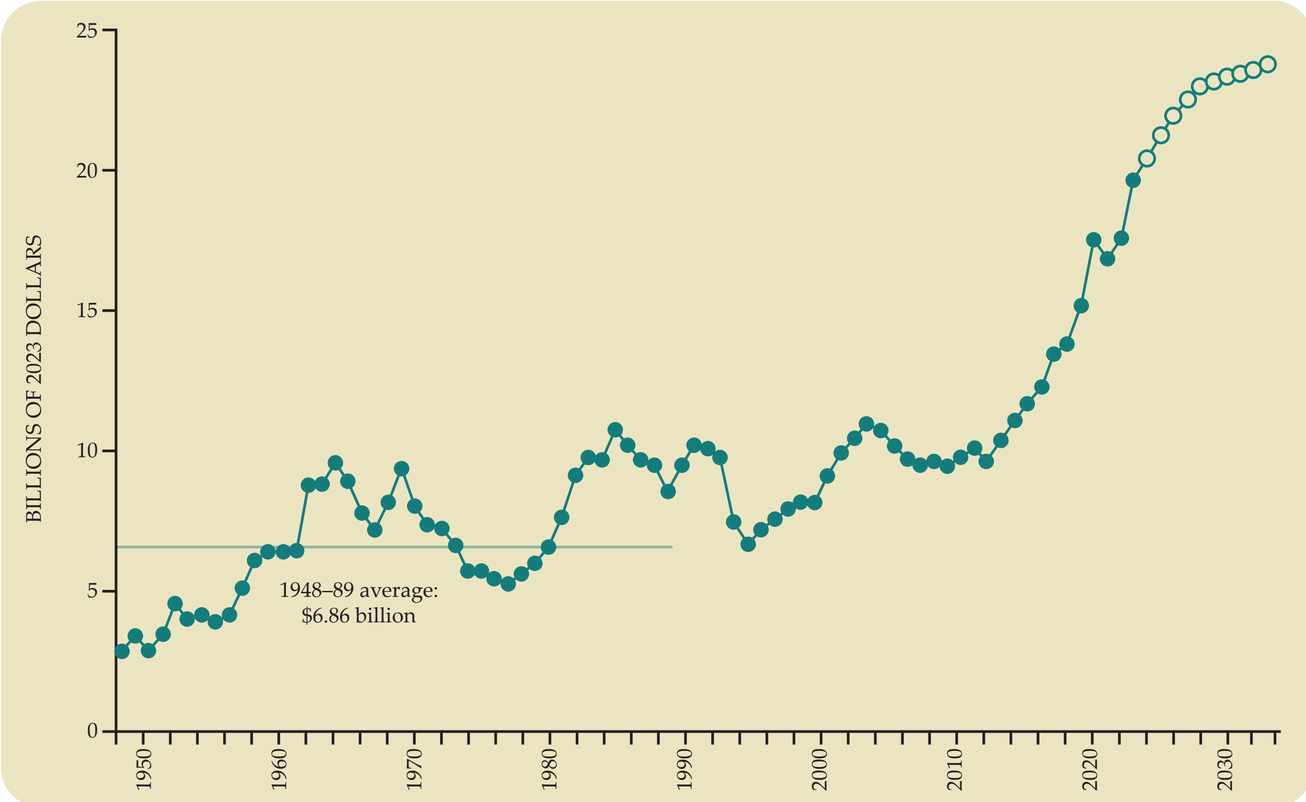
A legislative requirement for new plutonium pits, which are at the heart of all US nuclear weapons, is a large part of the ballooning NNSA weapons budget. Billions are being spent each year to build two pit manufacturing plants, even as a debate continues over whether and when new pits will be necessary. (See Physics Today, April 2023, page 22.) A new review of that question by the JASON advisory committee was ordered by lawmakers last year. An NNSA program of experiments, modeling, and simulations to pin down warhead-pit lifetimes will take 10 years and cost around $1 billion, according to the Government Accountability Office. That’s in addition to the cost of the new infrastructure that is needed to help make the assessment, including the Enhanced Capabilities for Subcritical Experiments facility under construction in Nevada.

In the meantime, lawmakers have kept in place their mandate, first imposed in 2015, for the NNSA to achieve a production capacity of 80 pits per year. The NNSA says it doesn’t expect to fully achieve that milestone until well into the next decade.

Although the budgets of all three nuclear weapons laboratories have surged in concert with the NNSA’s, Los Alamos National Laboratory (LANL) has seen the largest growth: from $996 million in 1992 to a proposed $4.9 billion in FY 2025 (both in as-spent dollars). The bulk of that increase is devoted to efforts to shoehorn a pit factory into a decades-old multifunctional structure known as PF-4. As that work proceeds, the building will continue to be used for other functions, ranging from the conducting of plutonium R&D to the building of plutonium-238 heat sources for space propulsion. The LANL director, Thomas Mason, says that he’s aiming for the lab to attain a capacity of 30 pits by 2028. Not all of those pits, however, will be qualified for nuclear weapons. LANL hired 5000 employees in the last three years alone, Mason told the January gathering, mostly in support of the pit mission. The LANL workforce has expanded from 7400 in 1992 to 11 591 in 2023.

Reis says that the possible impacts of plutonium aging was his major concern while at DOE. He says that Siegfried Hecker, the LANL director at the time, believed that the lab should have the capability to produce at least a single pit as part of its scientific and engineering mission. But he adds that the question of mass production at the lab didn’t arise during his tenure. Hecker declined an interview request.

Budget projections for the LANL pit project are difficult to total, since many of the components are scattered among the other costs necessary to upgrade PF-4. For the line item of the pit-production project, the NNSA’s FY 2025 budget proposal



NUCLEAR WEAPONS SPENDING by the National Nuclear Security Administration and its predecessor agencies has been on a steep upward path in recent years and has doubled in real terms since the end of the Cold War. The chart shows the annual expenditures, including administrative costs, in constant 2023 dollars. Values for 2024 and future years are estimates. (Adapted from a figure provided by Los Alamos Study Group.)

estimates the cost at $5.4 billion, an increase of $720 million from last year's figure. The documents also acknowledge a one-year stretch-out of completion, until 2032. The antinuclear advocacy and watchdog group Los Alamos Study Group estimates pit production at LANL will cost $30.8 billion through 2039.

Some are concerned that LANL may lose its identity. "Can you maintain the Los Alamos–like character of scientific inquisitiveness at the same time you're dealing with an industrial problem? It's a good question," Reis says. The University of California (UC), which until 2006 was the sole managing contractor at LANL, insisted in 1990 that it had no intention of becoming a production site. UC remains one of a trio of entities that operate the lab today.

Manufacturing the proposed 50 pits per year at the Savannah River Site is likely to be more formidable and expensive. Unlike LANL, the facility has no workforce experienced with pits. The NNSA is working to transform a half-completed plant that had originally been designed to produce mixed-oxide fuel for commercial reactors. In its FY 2025 budget request, the agency warns that the existing official cost estimate of $11 billion could balloon to $18 billion–$25 billion.

Such a wide range of cost estimates is indicative of what the Government Accountability Office last year described as a lack of comprehensive schedule and planning by the NNSA for large new facilities. At the Savannah River Site, "the design challenges may have been foreseen with more-thorough planning," notes Dylan Spaulding, an analyst at the Union of Concerned Scientists. He says that the doubled cost estimates are likely to draw increased scrutiny from lawmakers. In her January speech, Hruby said that the NNSA will continue design, construction start, baseline cost and schedule updates, and long lead procurements simultaneously at Savannah River.

Cost overruns

Around 10% of the $1 trillion spending package approved by Obama in 2010 was dedicated to modernizing long-neglected NNSA nuclear facilities. "The DOE production complex desperately needed to be upgraded," says Moniz. "We were dealing with 50-year-old buildings, and the reality is that rather than having an ongoing maintenance and upgrade program over the decades, we let things go."

For two decades, the NNSA has struggled to replace a 1940s-era building in Oak Ridge, Tennessee, that manufactures uranium weapons components. The new uranium processing facility was first proposed in 2004 at a cost of $1.4 billion. By 2013, estimates had grown to $11 billion. Moniz says that he ordered a redesign that year that would result in vastly downsizing the parts of the plant that required the most stringent security standards. Despite being capped in 2018 at $6.5 billion, the project's cost is now expected to rebound to $10 billion, and its completion extended by seven years to 2032, according to the FY 2025 budget request.

The NNSA blames the impacts of the

COVID-19 pandemic for up to half of that cost overrun. Slippage in the project's completion date was caused by contractor performance and the contractor's failure to notify the NNSA of cost overruns in a timely enough manner to inform the budget process, it said in the FY 2025 budget request.

Spaulding sees another factor responsible for the burgeoning costs for maintaining and modernizing the weapons complex: the "pyramid of contractors" that manage the work. The weapons labs are now operated by partnerships that include contractors such as Battell, Bechtel, Honeywell, and BWX Technologies, he notes.

David Kramer

New center for quantum sensing focuses on medical applications

The techniques promise earlier disease detection that can lead to better outcomes.

Clogged arteries. Osteoporosis. Malnutrition. Brain disease. With quantum sensing, those and other ailments could be detected earlier than is currently possible. The emerging field got a boost in late February: a six-year grant totaling about $22 million from the Novo Nordisk Foundation to form the Copenhagen Center for Biomedical Quantum Sensing.

The new center is a collaboration among three university physics groups—two in Denmark and one in the US. The researchers plan to use squeezed light, entangled atomic spins, and purified stable isotopes to develop and implement detection methods that push sensitivity limits in disease diagnostics.

Medical diagnostics is a relative newcomer to the burgeoning field of quantum sensing, which has applications in communications, imaging, seismology, and other areas. A growing number of research groups, perhaps as many as 50 worldwide, are doing work related to what will be done in the new center, notes Eugene Polzik of the Niels Bohr Institute at the University of Copenhagen and the center's director. "Our strength is in collaboration and in our strong focus on applying novel quantum measurement principles toward goals in biomedical applications. We are also working closely with life scientists and medical doctors."

The center fits into a broader quantum strategy that the Novo Nordisk Foundation adopted a few years ago, says Lene Oddershede, the foundation's senior vice president for natural and technical sciences. It had already been funding quantum computing for a while, with the long-term goal of solving problems in the life sciences, she says. "Now we are supporting quantum sensing with the aim of harvesting nearer-term applications in biology and medicine. I believe quantum technology can have an enormous impact on sustainability and health." (See the interview with Oddershede, who left a position as a tenured physics professor to join the foundation, at http://physicstoday.org/oddershede.)

Quantum technologies

Polzik and his research team use atomic spins as magnetic sensors, expanding on techniques that his and other groups

JACKSON WILLIAMS/NOVO NORDISK FOUNDATION

IN THIS QUANTUM MAGNETIC SENSOR, cesium atoms are in a channel that preserves atomic spin state for many milliseconds—long enough for biomedical magnetic field measurements. The channel's cross section is 300 × 300 microns. The sensor, which records collective spin states, was made at the Niels Bohr Institute in Copenhagen by the group of Eugene Polzik, director of the new Copenhagen Center for Biomedical Quantum Sensing.

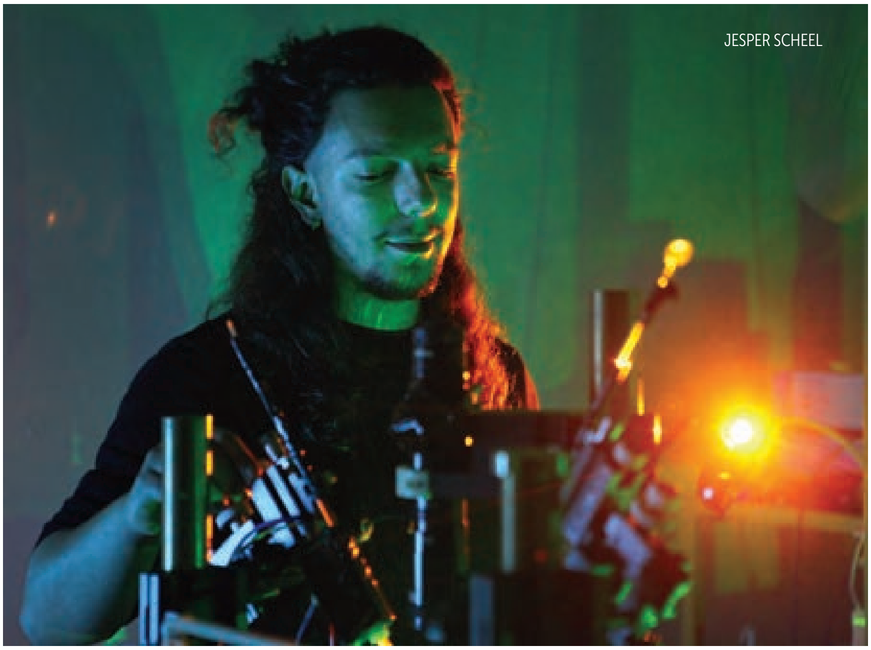
developed over the past decade or so. The sensitivity is not limited by "quantum mechanics taken naively," he says: Take two spins, orient them oppositely, and entangle them. If nothing happens, they remain antiparallel. But if one of the spins is subject to a magnetic perturbation, the two spins will not be exactly antiparallel. The relative orientation of spins can be determined, he says, "so you can measure the deviation from parallelism with sensitivity not constrained by the standard quantum limits that stem from the Heisenberg uncertainty principle for a single spin."

Polzik and his colleagues are keen to take their tricks of getting around standard quantum limits and apply them to "relevant measurements." Improving the spatial resolution of MRI is "the lowest hanging fruit," Polzik says. Small sensors—based on cesium atoms—placed around a patient's head monitor the local magnetic field extremely precisely, which improves the diagnostic potential. His team and his medical collaborators hope to deploy the approach in a couple of years.

A spin-entanglement approach can also detect conductivity in arteries and organs, Polzik says. Changes in local electrical conductivity can indicate changes in health. For example, if vessels become clogged from a heart attack or other heart problem, the conductivity decreases. Doctors currently insert wires to measure conductivity, says Polzik. "Our devices will aim to probe noninvasively."

By generating entanglement to get more precise measurements, Polzik says, "we may be able to get the spatial distribution of conductivity—and then tell you where in the heart or brain a problem is."

A few kilometers north at the Technical University of Denmark in Kongens Lyngby, Ulrik Andersen, a principal investigator with the new center, uses diamond crystals to detect weak magnetic fields in biomolecules, individual cells, and biological tissue. The technique involves creating so-called color centers by knocking out two neighboring carbon atoms from a crystal; one is replaced with nitrogen, which results in a pink tint (and the moniker), and the other remains vacant. Electrons are then trapped in the color centers. A change in the spin of the trapped electrons can be read optically to indicate, for example, a firing neuron. (See the article by Lilian Childress, Ronald Walsworth, and Mikhail Lukin, Physics Today, October 2014, page 38.)


JESPER SCHEEL

LUCA TROISE, a postdoc at the Technical University of Denmark, uses a quantum diamond sensor to measure neural activity in a slice of mouse brain. Magnetic fields from firing neurons affect spins in the sensor, which in turn govern the resulting fluorescence. The project is part of the new Copenhagen Center for Biomedical Quantum Sensing.

"When a neuron fires, a magnetic field is generated, which can be sensed by the trapped electrons," says Andersen. His group collaborates with biologists who prepare samples of mouse brain tissue; the samples remain active for about 24 hours. The diamond sensors can image the magnetic field with high spatial and temporal resolution, he says.

Andersen also works on microscopy techniques that push sensitivity. "With squeezed light, we can manipulate the quantum fluctuations of the light field," he says. The Heisenberg uncertainty principle holds, he continues, but by redistributing the uncertainties among the amplitude and phase, "you can decrease the noise in the amplitude measurement and increase the sensitivity of your measurement." (See, for example, the Quick Study by Sheila Dwyer, Physics Today, November 2014, page 72.) "If we can use such light to image biological systems," he says, "we will be able to increase the imaging speed and quality significantly. That is the next step."

Mark Raizen at the University of Texas at Austin is the third principal investigator with the new center. He developed a method for separating stable isotopes, in which a collimated atomic beam is optically pumped with a laser to change the magnetic moment of a specific isotope, thereby allowing the desired isotope to be separated with an applied magnetic field (see Physics Today, September 2016, page 22). He's now focusing on putting separated isotopes to medical use in combination with squeezed-light sensing techniques. The most advanced application to date involves testing individuals' absorption of iron from food, a collaboration with Steven Abrams, a pediatrician and researcher at Dell Medical School, part of the University of Texas Medical Center in Austin.

"Iron deficiency exceeds all other forms of malnutrition," says Abrams, noting that it can cause developmental delays and brain damage. Half of the world's children and women in low- and middle-income countries are iron deficient, he says. In the US and other industrialized countries, that number is about 20%. Iron is plentiful, but adding it to food such that the taste is tolerable and the iron is absorbable can be challenging.

Abrams screens for iron absorption by adding iron to a food typical to a given test population. He uses the rare iron-58 enriched to more than 90%; the abundance of that isotope relative to the natural presence in later blood tests provides evidence of absorption. The plan to use squeezed-light spectroscopy for the analysis will both simplify the measurement—the method is cheaper and more portable than traditional mass spectrometers—and reduce the amount of blood needed. Raizen has been championing the use of atomic-physics methods for blood tests. "We could detect tiny amounts of iron from a single drop of blood. That's important for infants. A heel prick is sufficient."

For now, Abrams has stocks of iron isotopes from Russia, but the plan is for Raizen to produce those and other isotopes with the separation method he pioneered. They would be produced at his nonprofit Pointsman Foundation.

Tracing isotopes with quantum spectroscopic methods has promise for other health issues too: Calcium isotope ratios can be used to diagnose early-stage osteoporosis and kidney disease; zinc isotope ratios can indicate pancreatic cancer; copper isotope ratios can detect liver and ovarian cancers. By testing early and noninvasively, says Raizen, the treatment options are improved.

Raizen notes that the new center's longer-term plans include setting up satellite isotope-preparation sites to widen the availability of isotopes that can be used in combination with quantum sensors for medical diagnostics. The Novo Nordisk Foundation is looking at possibilities to team up with the Pointsman Foundation on a site in Copenhagen, says Oddershede. "Isotopes will be essential for the applications we envision."

"An important trend"

Martin Plenio is a theoretical physicist and the founding director of the four-year-old Center for Quantum Bio-Sciences at Ulm University in Germany. One of that center's projects, which has spawned a startup company, involves monitoring cell metabolism in tumors: By tagging molecules with carbon-13 and using quantum techniques to polarize and control the isotopes' spins, researchers enhance MRI signals by a factor of as much as 10 000, enabling temporal and spatial measurement of low concentrations of metabolites. The resolution makes it possible to see whether chemotherapy is effective, and if it's not, to change the drugs, says Plenio. "It's much faster than waiting to see if a tumor shrinks in response to treatment." Other studies of cell metabolism at the center use nanodiamonds to measure radical formation in ensembles of cells.

When he first became interested in applying quantum technologies to living systems, Plenio says, "people were skeptical. Now there is a growing recognition that gaining even one order of magnitude in sensitivity can make a huge difference."

Not directly involved in the new Denmark–US center, Plenio sees it as "a significant step in an important trend," because life sciences is an area for which quantum sensing can have a real impact. "I think we will see results fastest in this area of quantum technology."

Toni Feder

The many lives of an 11th-century astrolabe

An art historian uncovers an astronomical device that exposes centuries of cross-cultural exchange.

It started, as internet diversions often do, with a Google search. Art historian Federica Gigante was preparing a lecture last year when a search for one 17th-century art collector, Ludovico Moscardo, happened to return an image of Moscardo's collection. Looking closely, Gigante spotted "something that looked like an astrolabe," an astronomical device often used for timekeeping that was developed in antiquity but is associated primarily with the medieval Islamic world.

The find piqued the interest of Gigante, whose work at the University of Cambridge focuses in part on astrolabes and other Islamic astronomical instruments. After receiving photos of the device from the curator of a museum in Verona, Italy, Gigante went to examine the astrolabe in person (in part, she confesses, because she wanted an excuse to visit her parents).

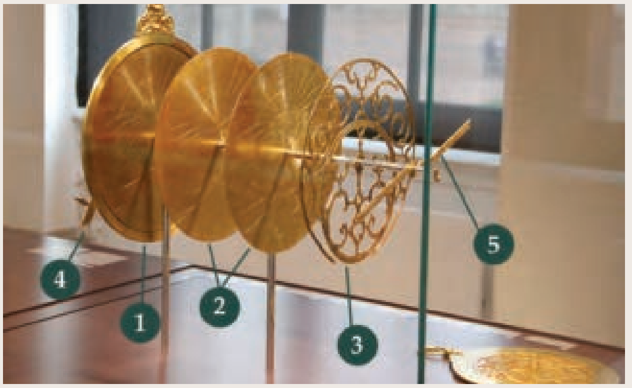
FEDERICA GIGANTE examines the 11th-century astrolabe. She is holding the *mater*, or base disk. Visible on the table are the two removable plates and the mesh-like *rete*.

FEDERICA CANDELATO

Astrolabe 101

Astrolabes consist of five key parts:

1. A base disk known as the *mater*, meaning mother in Latin. It contains markings on its rim that indicate hours of time or degrees of arc.
2. One or more swappable plates. Each plate depicts a 2D projection of the sky at a certain latitude.
3. A mesh-like top called the *rete*, meaning net or web in Latin. It contains a ring that marks the ecliptic and multiple pointers that identify the location of specific stars in the night sky.
4. The *alidade*, derived from the Arabic word for ruler. The rotating bar is attached to the back of the *mater* with sights on each end through which the user locates the Sun or stars.
5. The rule, a rotating bar on the front of the astrolabe that can locate positions on the *rete* or plates.



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A DISASSEMBLED ASTROLABE at the Royal Cabinet of Mathematical and Physical Instruments in Dresden, Germany. (Labels added to original.)

Assuming that they knew their latitude and the day of the year, astrolabe users could determine the time of day by sighting the Sun or a star with the *alidade* and reading the markings on the mater's rim. Astrolabes were used not only for timekeeping but also for other reasons, such as locating constellations.

It was a fortuitous decision. As Gigante reports in the March issue of *Nuncius*, a journal devoted to the material and visual history of science, the medieval instrument contains not only Arabic-language inscriptions but also markings in Hebrew and of Western Arabic numerals.

At first glance, the Arabic-inscribed astrolabe at the Museum of the Miniscalchi-Erizzo Foundation did not look out of the ordinary to Gigante. The devices, described in the box above, were widely produced throughout the medieval era by Muslim artisans because the five prayer times mandated by the Koran are determined by the position of the Sun at a specific latitude. Then she noticed the scratches. It's not unusual for a medieval object to be scuffed up, but what was strange was how the markings were distributed: "Scratches have a randomness to them that these didn't have," says Gigante.

The breakthrough came when she found a clear Hebrew inscription on one of the plates that spelled out the equivalent of the adjacent Arabic text. Gigante started looking at the other scratches with the assumption that they were Hebrew letters and realized that they, too, were transliterations of Arabic. Closer examination revealed that the astrolabe contains two sets of Hebrew inscriptions and a series of Western Arabic numerals, the kind we use today, that translate the alphabetical Arabic numerals in the original text.

An astrolabe can be dated using the star pointer on its *rete*, the mesh-like rotatable plate that sits atop the device, because the combination of stars' proper motions and Earth's axial precession gradually shifts the positions of stars in the night sky. Gigante finds that the Verona astrolabe depicts the sky as it was in the late 11th century. Arabic inscriptions on the astrolabe's *mater*, or base, and on one of its two plates refer to the Spanish localities of Cordoba, Toledo, and Medinaceli. That implies that the astrolabe was made in the historical region known as al-Andalus—the portion of present-day Spain and Portugal that was ruled by Muslim states from 711 to 1492 CE.

An inscription on the back of the astrolabe mentions the names Isḥāq and Yūnus, the Arabic translations of the traditional Jewish names Isaac and Jonah. Gigante posits that the astrolabe passed at one point into the hands of al-Andalus's Arabic-speaking Sephardic Jewish community. She suggests that the two sets of Hebrew inscriptions were added once the astrolabe was in Italy, where the Jewish community did not speak Arabic, and that the Western Arabic numerals were added even later by someone who spoke a Romance language.

A few other known Arabic-language astrolabes have had Hebrew inscriptions added, Gigante says. But the Verona instrument stands out because of the sheer number of users who modified it—she counts at least six—and the presence of the Western Arabic numerals.

The intermingling of cultures implied by the inscriptions would not have been all that surprising to contemporaries. Although the medieval and early modern periods in the Mediterranean region saw plenty of conflict between Islamic, Christian, and Jewish populations, lengthy periods of peace and religious tolerance also occurred. Moreover, even the periods of conflict were characterized by dynamic cultural exchange. Although the craftsman who made the astrolabe was undoubtedly Muslim, it's possible that the device was never used by followers of the Islamic faith. "The first owner," says Gigante, "could very easily have been Jewish."

Ryan Dahn

DEPARTMENT OF ENERGY

Q&A: Asmeret Asefaw Berhe reflects on her tenure as DOE Office of Science director

As Berhe returns to academia, the soil biogeochemist discusses the federal agency's work on major research facilities, AI algorithms, and training the next generation of scientists.

Asmeret Asefaw Berhe started in May 2022 as head of the US Department of Energy's Office of Science (SC), which manages the most federal dollars for basic physical sciences research—$8.2 billion for the current fiscal year. She was the first person of color to lead the agency. She resigned in March to return to her professorship in soil biogeochemistry at the University of California, Merced.

Berhe spoke to Physics Today on 21 March, a few days before leaving office, about her accomplishments and SC's efforts in diversity, equity, and inclusion. The text of the interview was edited for clarity and length.

PT: Why are you leaving after less than two years on the job?

BERHE: To be fair, it's been three years since I started this journey, including the 13 months I had to wait for Senate confirmation. It's a combination of personal and professional reasons. I've been gone from my professional career for three years.

PT: What do you consider some of the research highlights at SC labs during your tenure?

BERHE: The excavation of the caverns for the Deep Underground Neutrino Experiment in South Dakota is being completed, and the milestones for the neutrino detectors are being met. The charge to the Particle Physics Project Prioritization Panel, which I issued, has been completed. [See Physics Today, February 2024, page 18.]

We could talk about progress on the Electron–Ion Collider [a proposed facility at Brookhaven National Laboratory that just received approval from DOE to procure long-lead-time items, such as a cryogenic plant and superconducting magnets]; the Stable Isotope Production and Research Center [a $325 million facility scheduled for completion in 2032] at Oak Ridge National Laboratory to shore up the supply of stable isotopes; and quantum technologies at the five quantum information research centers we support across the country. Each is led by a national laboratory and is leveraging world-class facilities.

During my tenure, we celebrated a new era of exascale scientific computing with Frontier [currently rated the world's fastest high-performance computer] at Oak Ridge. And the Aurora at Argonne National Laboratory is already ranked second-fastest computer in the world even before it's been completed. [Aurora is expected to open to users in January 2025.] Those aren't just fast machines; they are among the most energy efficient in the world.

We've made strides in developing an integrated research infrastructure that will apply our computing capacity across the breadth of our science programs. We funded a high-performance data facility at the Thomas Jefferson National Accelerator Facility, a partnership with Lawrence Berkeley National Laboratory. We launched programs in fusion to advance the science as well as to think about what comes after the science is mature enough to be pushed into the technology development phase.

We've worked to upgrade the labs and have added new capabilities, including completing the Linac Coherent Light Source-II at SLAC. I charged SC's six advisory committees with setting priorities for new facilities and facility upgrade priorities for the next decade.

PT: Among the recent initiatives at SC are two diversity, equity, and inclusion programs that awarded their first grants last year. How do those programs work?

BERHE: RENEW [Reaching a New Energy Sciences Workforce] is for training the next generation of scholars. FAIR [Funding for Accelerated, Inclusive Research] is for capacity building at emerging research institutions. They're complementary. Combined, they constitute about 1% of our funding.

Both programs have partnerships with the labs. RENEW leverages SC's national laboratories, user facilities, and other research infrastructures to provide training opportunities for undergraduate students, graduate students, and postdoctoral researchers at academic institutions not currently well represented in the SC portfolio.

I didn't create RENEW and FAIR; they were well underway when I took office. Publicly funded science should serve the public, and broadening participation of people from all walks of life is very important for many reasons. The nation needs a vibrant workforce that can be competitive across all sorts of different avenues. That workforce should come from every part of this country, and we should ensure that it does not remain an exclusive club of only the well-connected people. A student from Iowa, Mississippi, or Wyoming should not have opportunities limited for them just because of geography or the inequitable distribution of public resources.

The DOE ecosystem, including our national labs, have worked tirelessly to ensure that STEM does not remain an enterprise where people from different walks of life are not well represented or there are barriers to their entry. That includes women, people of color, people from rural areas, and those with lower socioeconomic status.

PT: How do you measure success in those programs?

BERHE: There are specific things that the institutions are proposing to do. Once we peer review the proposals and the institutions are selected, we evaluate them to make sure that they've actually delivered. For RENEW, we track how many students we train, and we plan to follow how these internships contribute to career success.

PT: What progress has DOE made on biofuels?

BERHE: Researchers at our four Bioenergy Research Centers have developed dedicated bioenergy crops, including switchgrass and miscanthus, that are tailored for growth on underutilized lands in different parts of the country and that could grow with minimal nutrients and less irrigation. They are now ripe for testing on a large agricultural scale.

There's been major progress in developing methods to break down biomass in an efficient and economic biochemical manner. Scientists are gaining new insights into the composition of the plant cell-wall material.

PT: How is DOE thinking about the potential explosion of new demand for electricity from the rapid growth of AI?

BERHE: Generative AI in particular has major energy requirements, and that rightfully has worried a lot of people. The challenge posed by these large language models comes down to two things: efficiency of the hardware and the algorithms that are used to train and to use the models.

SC funds research into innovative microelectronics technologies that promise to greatly reduce energy usage. We have AI test beds that evaluate new kinds of computing systems from multiple vendors, and we can train models using less energy than is typically deployed in typical GPU clusters. And SC has long funded research on more efficient algorithms. We foresee that we're going to be able to take advantage of our exascale computers to design and validate new energy-efficient AI algorithms.

We're also working to make data training more efficient. Trustworthiness requires high-quality data and state-of-the-art approaches for using that data to train the models. Self-checking AI systems that are appropriate for high-consequence applications will take a lot of data and a lot of computing power and energy. We view energy as the major challenge going forward.

David Kramer PT

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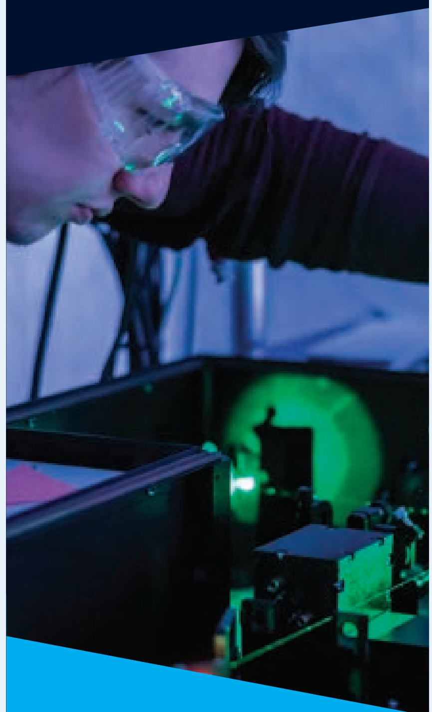

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PHYSICS TODAY

The real butterfly effect and maggoty apples

Tim Palmer

EVEN THOUGH THE NAVIER–STOKES EQUATIONS ARE DETERMINISTIC, IT SEEMS THAT YOU CANNOT MAKE PREDICTIONS BEYOND A FIXED TIME HORIZON, NO MATTER HOW SMALL THE INITIAL UNCERTAINTY.

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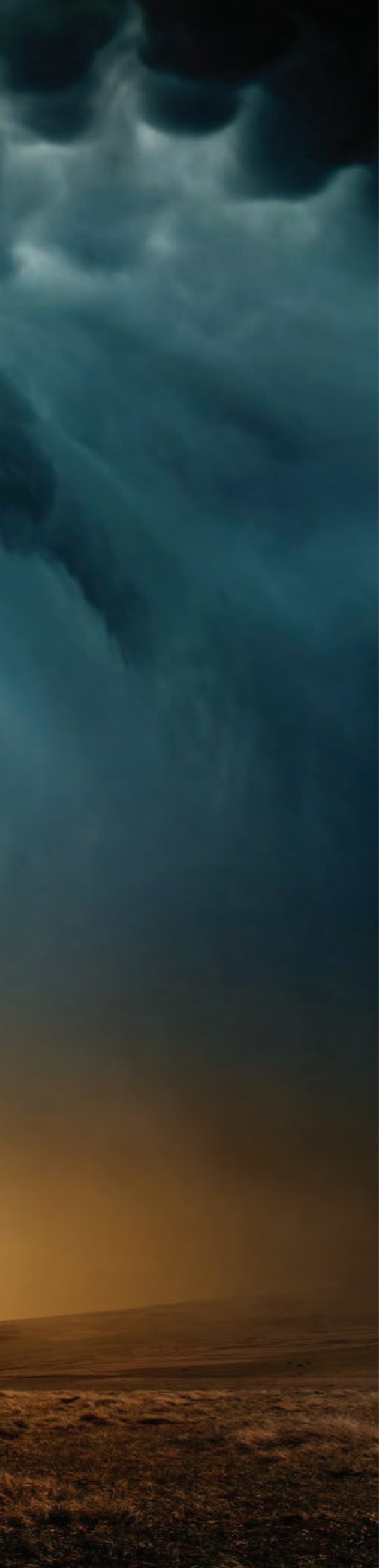

Tim Palmer is a Royal Society Research Professor in Climate Physics at the University of Oxford in the UK.

We think we know why the weather can be so difficult to predict. It's the so-called butterfly effect: The flap of a butterfly's wings in Brazil can set off a tornado in Texas a week later. But because we can't observe all the butterflies in Brazil, we can't reliably predict tornadoes in Texas a week in advance.

As described in James Gleick's masterful 1987 exposition of chaos theory,[1] the discovery of the butterfly effect is generally attributed to MIT meteorologist Edward Lorenz. In 1963 he famously constructed a model of chaos based on three deterministic coupled nonlinear differential equations.[2] Being chaotic, the evolution of the state of that system is extremely sensitive to the specification of the initial conditions. Therefore, Lorenz's three-component model describes both the butterfly effect and the unpredictability of the weather.

At least, that's the folklore. But it isn't quite correct. The butterfly effect was first described by Lorenz in his talk at the 1972 meeting of the American Association for the Advancement of Science.[3] The title was indeed "Predictability: Does the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas?" In the talk, Lorenz noted that errors in forecasting the position and intensity of low-pressure cyclonic weather systems tend to double every three days or so. Errors in the individual clouds that are embedded in those weather systems, however, tend to double on shorter time scales. And errors in individual eddies in the subcloud turbulence double on time scales shorter still.

The nonlinear Navier–Stokes equations of fluid mechanics couple the subcloud, cloud, and cyclone scales together. Hence, Lorenz noted, even if you could perfectly observe the atmosphere on the 1000 km scale of the low-pressure system, you

FIGURE 1. A LOW-PRESSURE CYCLONE system contains many individual clouds. Each individual cloud is a turbulent system comprising many small eddies. The real butterfly effect illustrates how uncertainties in the starting conditions for any of those whirls affect our ability to predict the cyclonic system itself. (Courtesy of Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC.)

would still not be able to predict the structure and intensity of the weather system indefinitely into the future. Initial uncertainties on kilometer or smaller length scales would eventually limit your ability to predict the larger cyclone. The question Lorenz posed was this: How long does it take for uncertainties in the initial conditions on subcloud scales to affect a forecaster's ability to predict position and intensity on the much larger cyclonic scales? (See figure 1.)

The real butterfly effect

Lorenz's 1963 paper cannot address that question—and hence the notion of the butterfly effect as Lorenz intended it to mean in his 1972 talk—because the 1963 model equations do not describe how fluid flows at different spatial scales interact. In fact, in his 1972 talk, Lorenz was informally discussing results from a highly technical paper he had published in 1969 in the Swedish journal *Tellus*. The abstract of the paper, titled "The predictability of a flow which possesses many scales of motion," begins as follows:

> It is proposed that certain formally deterministic fluid systems which possess many scales of motion are observationally indistinguishable from indeterministic systems; specifically, that two states of the system differing initially by a small "observational error" will evolve into two states differing as greatly as randomly chosen states of the system within a finite time interval, which cannot be lengthened by reducing the amplitude of the initial error.[4]

The last clause of the sentence is worth reading a couple of times, because it is so surprising. Lorenz is describing chaotic unpredictability in the extreme. That type of unpredictability is much greater than that in his 1963 model of chaos. In the early model, you can predict as far ahead as you like by making the initial error sufficiently small. From a mathematical standpoint, Lorenz's 1963 model has the property that the evolved state depends continuously on the initial state. As the initial state tends to the true state, so, too, does the forecast state.

On the basis of the Navier–Stokes partial differential equations, Lorenz's 1969 paper describes systems that do not plausibly have that continuity property. Indeed, the limit of vanishing initial error, which I'll discuss in more detail below, is what's known as a singular limit.

Lorenz, in focus

To better appreciate what Lorenz proposed in his 1969 paper, suppose that we can observe the initial state of the atmosphere perfectly, with no errors or gaps. That does not mean that we can forecast perfectly, because to make a forecast of the weather, you must assimilate observations into a computational weather model, thus creating a set of initial conditions for the model.

The weather model approximates the Navier–Stokes and other relevant atmospheric equations using a finite, 3D array of so-called gridboxes. Collectively, the gridboxes cover the whole atmosphere and oceans. (Some models use finite sets of orthogonal functions, such as spherical harmonics, but that doesn't change the argument.) Inside a gridbox, the weather model erroneously assumes that the atmosphere is completely homogeneous. The horizontal size of each gridbox in the very best global weather-forecast models is currently around 10 km.

Next, let's suppose that we can make accurate weather forecasts of low-pressure systems on average up to seven days ahead with our weather model. In the idealized case of perfect observations, the source of error that limits the forecast's accuracy lies in the gridbox-homogeneity assumption. Hence, it is reasonable to ask (our employers) for a bigger computer that would allow the weather equations to be integrated with a gridbox half the size. The incorrect homogeneity assumption would then be restricted to scales smaller than before by a factor of two.

Would that factor of two double the range of forecast accuracy from 7 days to 14 days? In his 1969 paper, Lorenz argues that it does not. The errors associated with small scales that were unresolved in the old model but are subsequently resolved in the new one would grow faster than errors in the smallest scales resolved in the old model. For example, if the error-doubling time of the newly resolved scales was half the error-doubling time of the previously resolved scales—meaning that the errors grow twice as fast—the predictability time with the new weather model will only increase by a factor of $(1 + \frac{1}{2})$, which is significantly less than a factor of two.

Indeed, if later still we could afford a computer that would

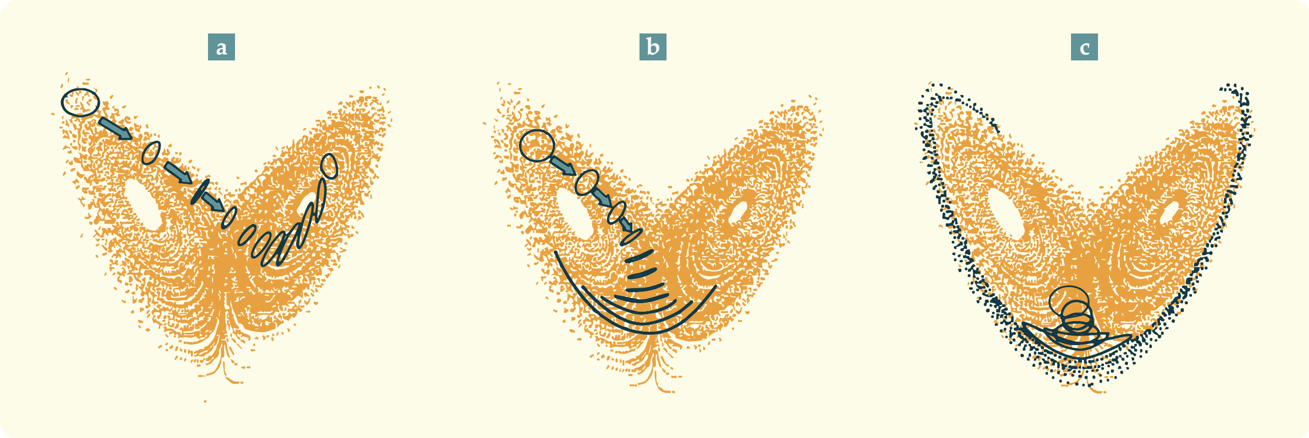

FIGURE 2. PREDICTABILITY in a nonlinear system, such as this Lorenz attractor, is dependent on the initial conditions, whose uncertainties are represented by the size and location of a circular ring. **(a)** The ring of uncertainty does not grow in time at all. **(b)** Started from a lower position, the ring distorts into banana and boomerang shapes, making it unclear whether the actual system undergoes a transition from the left-hand lobe to the right-hand one. **(c)** With the ring initiated almost midway between the lobes, the time evolution of the attractor is now very uncertain, and there is no predictability. (Adopted from ref. 11.)

allow a further halving of the size of the gridboxes, the predictability time would only be increased from (1 + ½) × 7 days to (1 + ½ + ¼) × 7 days. If you carried on like that—halving the gridbox an infinite number of times—the predictability time would not be infinite. Rather, it would be (1 + ½ + ¼ + ⅛ + 1⁄16 . . .) × 7, or 14 days. With infinitesimally small gridboxes, forecasters would have increased the predictability time of the original model by only a factor of two. (The existence of that finite limit is consistent with the Kolmogorov energy spectrum for 3D fluid turbulence.)

Singular limits

But that sounds contradictory. After an infinite number of gridbox halvings, the (now infinitely powerful) computer represents the Navier–Stokes equations precisely. And because those equations are completely deterministic, we should be able to forecast infinitely far ahead.

To understand what accounts for the short forecast range, imagine having a bucket of apples that contain maggots. If you bite into an apple and discover half a maggot, then you have eaten half a maggot—an unpleasant experience. However, if you bite into an apple and discover a quarter of a maggot, then that's even worse because you have eaten three-quarters of a maggot. More generally, if you bite into an apple and discover $1/n$ of a maggot, you have eaten $1 - 1/n$ of a maggot.

The larger the value of n, the greater the fraction of the maggot you have eaten, and the more unpleasant the experience. You might therefore imagine that the limit $n = \infty$ of a sequence of such apple bitings describes the most unpleasant experience. But it doesn't. If you bite into an apple and discover no maggot, you may not have eaten a maggot at all! (A tiny maggot fraction is qualitatively different from no maggot.)

That example, first described by theoretical physicist Michael Berry, is known as a singular limit (see his Reference Frame, Physics Today, May 2002, page 10). Such limits abound in physics. For example, blackbody radiators never experience a UV catastrophe—the prediction that the intensity of their emitted radiation goes to infinity as wavelength decreases—provided that Planck's constant h remains nonzero (no matter how small it is). Set h precisely to zero, however, and the classical Rayleigh–Jeans spectrum diverges.

In another example, as long as a fluid's viscosity remains nonzero, it is able to generate aerodynamic lift across an airfoil, no matter how small the viscosity may be. If viscosity is set to zero, however, the boundary condition across the airfoil qualitatively changes. The lifting force of a 3D body in incompressible, inviscid, irrotational flow is zero, a phenomenon known as d'Alembert's paradox.

There is also a singular limit at the heart of what I call the real butterfly effect.[5] No matter how small the initial uncertainty, the butterfly effect limits predictability to a finite time horizon. Only when the initial uncertainty is identically zero can you potentially predict arbitrarily far ahead with the Navier–Stokes equations. That's an unrealistic limit, of course. Is the singular predictability limit a rigorous mathematical property of the Navier–Stokes equations? No one knows. The problem of whether solutions depend continuously on initial conditions is related to the unsolved Clay Mathematics Institute Millennium Prize Problem concerning the existence of smooth, unique solutions to the Navier–Stokes equations.

Indeterministic results

That is not to say that Lorenz's more famous 1963 model of chaos has nothing useful to say about the predictability of weather. I have used the model on many occasions to demonstrate that the predictability of a nonlinear system is not a fixed quantity. It varies from one initial condition to another, as shown in figure 2. Hence, although the average predictability of day-to-day weather may be around two weeks, it can sometimes be longer and sometimes shorter than that. Meteorologists can estimate such flow-dependent predictability by running ensembles of forecasts—typically 50 are run from almost but not quite identical initial conditions. When the atmosphere is in a predictable state, the ensemble forecast spread will be relatively small. When the atmosphere is in an unpredictable state, the spread will be relatively large.

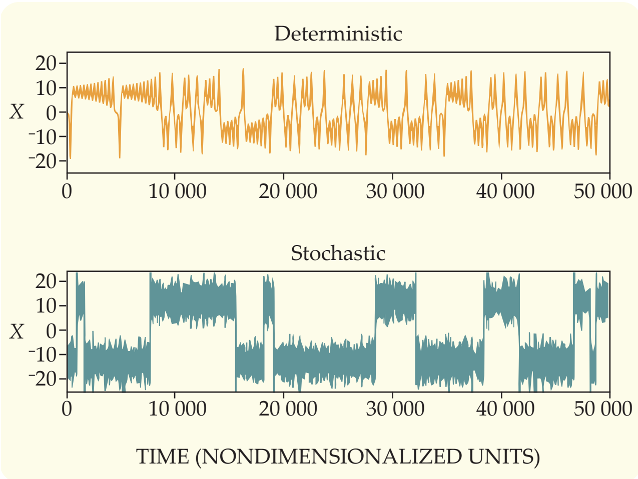

FIGURE 3. ADDING NOISE to Edward Lorenz's 1963 system of equations describing chaos affects its dynamics in a nonintuitive way. The top plot shows a time series of the *X* variable in the standard (deterministic) Lorenz model. The bottom plot has a much more pronounced structure because noise is present. The noise effectively stabilizes the regimes of the Lorenz attractor, shown in figure 2. (Adapted from ref. 11.)

Ensemble prediction has transformed weather forecasting over recent years. For example, it determines the probability of precipitation on your weather app. More importantly, it is changing the way in which humanitarian and disaster relief agencies respond to extreme weather events. In the past, the unreliability of deterministic predictions meant that they would typically wait for an extreme event to occur before sending in medicine, food, water, and emergency shelter to stricken regions. Now, on the basis of a cost-benefit analysis, those agencies predetermine a threshold probability for extreme weather. And if the ensemble-based forecast probabilities exceed the threshold, the agencies take what's known as "anticipatory action," sending in emergency supplies ahead of the weather event.

The real butterfly effect implies that although the governing partial differential equations are deterministic, any computational representation of the equations will be indeterministic. That's not, however, the way weather and climate models have traditionally been formulated. The processes in such models that cannot be resolved explicitly—cloud formation, the flow of air over small mountains, and ocean mixing, for example—have been represented by deterministic parameterization formulas that mimic molecular viscosity and diffusion.

The real butterfly effect, however, implies that no consistent way to represent those subgrid processes by deterministic formulas exists. One way to alleviate the problem is to make the parameterization formulas in weather and climate models explicitly stochastic.[6,7] The first stochastic-parameterization scheme was introduced into a weather forecast model in 1999. And today, most weather models incorporate some form of stochastic parameterization.

Even so, many climate models—even those contributing to assessment reports from the Intergovernmental Panel on Climate Change—are still formulated with deterministic closure schemes. Such models are inconsistent with the Navier–Stokes equations' scaling symmetries, which contributes to their (sometimes substantial) long-term systematic errors.[8] Stochasticity can have unexpected effects in nonlinear models.[9] Figure 3, for example, shows that adding noise to the Lorenz 1963 equations helps to stabilize the Lorenz-attractor regimes. The stabilizing effect is quite counterintuitive until you realize that the model makes transitions from one regime to the other in small regions of state space. Those transitions can be disrupted (and thus the regimes stabilized) by small amounts of noise.

Weather forecasting with artificial intelligence?

Artificial intelligence (AI) is now being used to make weather forecasts with levels of skill comparable to more traditional physics-based models. For both training and forecasting, those AI-based models still use sets of gridded, global atmospheric states, in which atmospheric observations have been assimilated into a global physics-based model. Can such AI forecast systems simulate the real butterfly effect?

To answer that question, Tobias Selz and George Craig (both at the German Aerospace Center in Oberpfaffenhofen) compared the growth of estimates of forecast uncertainty using AI and physics-based models last year.[10] The estimate of the initial uncertainty was obtained by taking the difference between two randomly chosen members of an ensemble of data assimilations, which are used in ensemble weather forecasting. The members of the ensemble differ only in the precise values of the observations being assimilated into the model—the variations in those precise values being consistent with observational error.

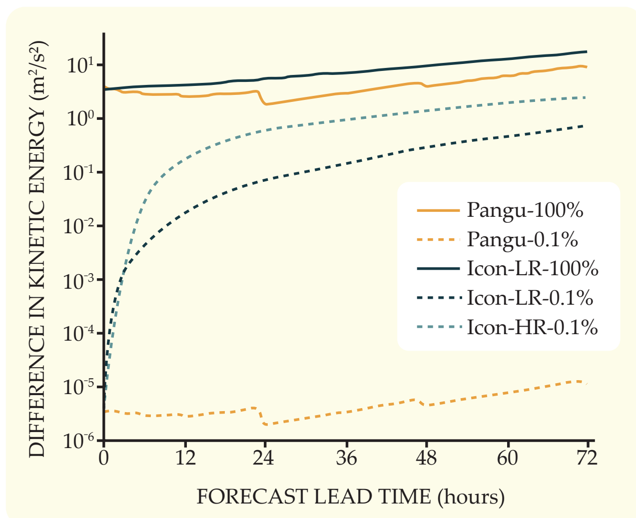

FIGURE 4. THE DIFFERENCE IN A MEASURE of atmospheric kinetic energy between pairs of forecasts as a function of forecast time. The solid black and orange lines show results from a physics-based (Icon) and artificial intelligence (Pangu) model, respectively, when the initial difference between the pairs is comparable with the typical uncertainty in the initial conditions. The dashed lines show differences in kinetic energy when the initial difference is reduced by a factor of 1000. The blue and black dashed lines show the difference in a high- and low-resolution physics-based model, respectively. The orange dashed line shows the lack of growth from an AI model with similar reduced initial perturbation. AI-forecast systems don't capture the physics of the real butterfly effect. (Adapted from ref. 10.)

By construction, the initial error for a weather forecast is spread across a range of scales—from weather systems with a horizontal wavelength of thousands of kilometers down to the model's grid scale of 10 kilometers or so. The theory of data assimilation predicts that if the spacing between atmospheric observations is typically a few tens of kilometers, then observations do well at determining the large-scale initial weather patterns, with little error. On kilometer scales, however, the errors will become almost as large as it is possible for them to be. Small-scale errors in the initial conditions are thus almost saturated, while large-scale errors have plenty of opportunity to grow. Accordingly, errors grow almost immediately at the large scale but not at all at the small scale.

To study the real butterfly effect, Selz and Craig divided the initial-error field by a factor of 1000. Then, the small-scale errors were far from saturated. Because they grow so much faster than the large-scale errors, the errors should be dominated by the small scales. That is precisely what is seen when a physics-based model is used. And Selz and Craig used both a low-resolution and a high-resolution physics-based model to demonstrate it. Figure 4 shows the divergence of pairs of forecasts with small initial differences.

The high-resolution model did a much better job at simulating the rapid growth of the small-scale errors, but the low-resolution model was not completely hopeless; the growth was simply less dramatic. By contrast, the AI system completely failed to predict the growth of small-scale errors. That's perhaps not surprising. In the real world, as I mentioned, the small-scale errors are already saturated at the initial time. The AI system never learns about the real butterfly effect from its training data. The results demonstrate that you must be cautious when applying AI to the weather-forecast problem; it does not contain the physics of the real butterfly effect.

As I discuss in my book *The Primacy of Doubt*,[11] studying the predictability of weather and climate reveals some deep and important properties of nonlinear systems. They are relevant to many problems in applied and fundamental science—in various fields, including social science and the foundations of quantum physics. In short, taking a rigorous approach to the science of uncertainty can help us improve our ability to both predict and understand our very chaotic world.

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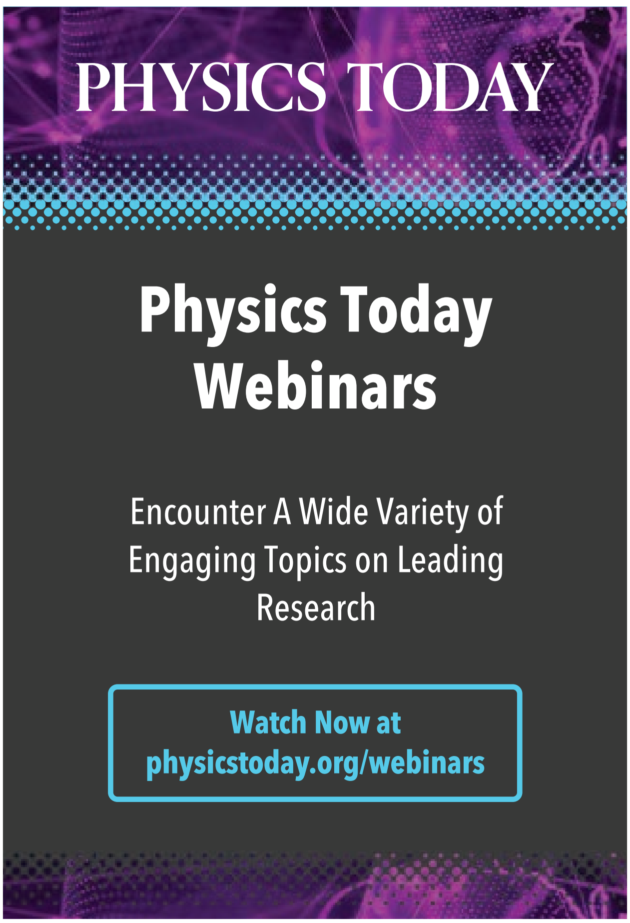

A shocking beginning to star formation

Cecilia Ceccarelli and **Claudio Codella**

The birth of stars is tightly entangled with interstellar shocks, which makes shocked regions a paradise for astrochemistry.

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NASA/ESA/CSA/STSCI/KLAUS PONTOPPIDAN (STSCI)/ALYSSA PAGAN (STSCI)

Looking up at the night sky, dotted with distant lights that slowly precess, one might be fooled into thinking that the universe is serene. In fact, it is racked with violent collisions and explosions that send shock waves of all scales throughout interstellar space. Those shock waves aren't just cosmic waves in the ocean; they kick-start the formation of stars and set up surprising astrochemical laboratories.

In general, a shock is created when fast-moving gas travels through a medium at a speed greater than the speed of sound. At large scales, galactic flyby encounters, catastrophic galaxy merging, and black holes at galactic centers all create interstellar shock waves that can travel across the galaxy for tens of parsecs and hit whatever is in their path. In the context of star formation, shocks are generated by gigantic collisions between molecular clouds, supernovae explosions, and stellar winds. Even events as common as star births will propel gas through the interstellar medium (ISM) and potentially trigger more star formation.

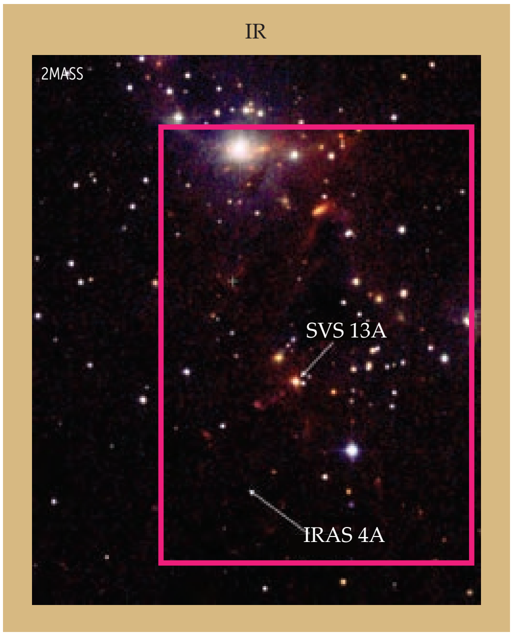
The space between stars is not an empty void. Rather, the ISM is filled by tenuous and cold gas and dust. The story that will eventually end up with the birth of a star and its planetary system starts inside gigantic ISM cold clouds of molecular hydrogen. Within the clouds are regions known as prestellar cores. They are regions of cold (10–20 K) gas that extend to several thousand astronomical units (AU). Their densities are about 10^5–10^6 cm^{-3}, which correspond to extremely low pressures that are difficult to achieve in terrestrial laboratories (see box 1). That density is large enough to make the gravitational force prevail over any force, especially the outward pressure from the movement of atoms, or thermal pressure, that prevents the collapse.[1,2]

The interplay between molecular clouds and interstellar shocks turns the study of shocks into a study of star formation. Understanding how shocks form and how they enrich the gas around them helps astronomers understand the evolution of our universe. The overdensity can be caused by the turbulence inside the molecular clouds, or sometimes by violent events that create interstellar shocks.

A shocking origin

Most dying stars don't extinguish quietly. They eject most of their interior material either in massive winds or explosions. In both cases, shock waves expand out in all directions, traveling through much of the galaxy. When the waves interact with a molecular cloud, they compress the gas, which increases its density. If the density becomes large enough, it will trigger a collapse of the molecular cloud (see box 1).

Supernova explosions also cause shocks in the magnetized gas of the surrounding ISM and create cosmic rays, particles with teraelectron-volt energies that permeate the



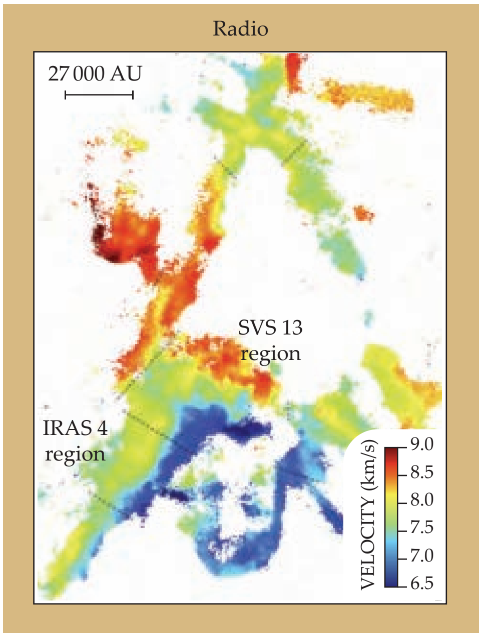


FIGURE 1. THE MOLECULAR CLOUD NGC 1333 is one of the closest stellar nurseries to Earth. It is too cold to be seen in visible light, and only a few of its protostars—SVS 13A and IRAS 4A—appear in the IR (left). Instead, radio observations (right) are used to see the molecular cloud and its movement in the line-of-sight direction. NGC 1333 is being shattered by interstellar shocks pushing different parts of the cloud at different speeds and in different directions. (Adapted from ref. 9.)

NASA, ESA, CSA, STSCI, JOSEPH DEPASQUALE (STSCI), ANTON M. KOEKEMOER (STSCI), ALYSSA PAGAN (STSCI)

Box 1. The nurseries of stars

Molecular clouds contain the progenitors of planetary systems. They are huge in size, from a few to several tens of light-years in diameter, and contain hydrogen, the most abundant element in the universe, in the molecular form, H_2. Despite their size, the clouds are tenuous with respect to terrestrial standards. Molecular clouds contain about 10^3–10^4 particles/cm^3, equivalent to a pressure of about 10^{-13}–10^{-12} torr. To put that in perspective, pressures of 10^{-13}–10^{-9} torr are obtained with ultravacuum techniques in terrestrial laboratories. In other words, the clouds are regions almost void of matter.

Although they are almost void, molecular clouds still contain large amounts of matter, from a few to millions of solar masses, more than enough to form stars and planets. In addition, molecular clouds have very low temperatures, about 10 K, which makes their pressure caused by the movement of atoms low. In regions with relatively larger densities (10^5–10^6 particles/cm^3), called prestellar cores, the gravitational force will eventually dominate expansive forces. The collapse will lead to the formation of a star and its planetary system.[1,2]

The picture to the right, taken in the IR by the *James Webb Space Telescope*, shows the region called the Pillars of Creation in the Eagle Nebula. The region contains many molecular clouds, where several star and planetary systems are in the process of forming. Because this image was taken using IR wavelengths, we can see through much of the dust to the young stars within.

FIGURE 2. TWO SUPERSONIC JETS (left) emanating from a young protostar (here, HH 211, imaged in the IR) in opposite directions are shaped by various shocks erupting from the birth of the star. The jets flow away from the star, with the farthest gas being the first to escape. Shock types (right) exist on a spectrum that ranges from jump shocks (J type) to continuous shocks (C type); which type of shock depends on how gradually the velocity decreases over time. A smoother velocity change indicates the presence of a magnetic field.

galaxy and interact with molecular clouds, triggering the formation of molecules like carbon monoxide. Radiation emitted in transitions between CO's rotational states (so-called rotational lines) then cools the cloud to a mere 10–20 K, which reduces the thermal pressure and triggers a cloud collapse and subsequent stellar birth.

Interstellar shocks can additionally be triggered by star formation. Young, massive stars (more than 8 solar masses) emit large amounts of UV photons that ionize the surrounding gas. The resulting so-called HII regions expand into the ISM and create shocks at the interface of molecular clouds.

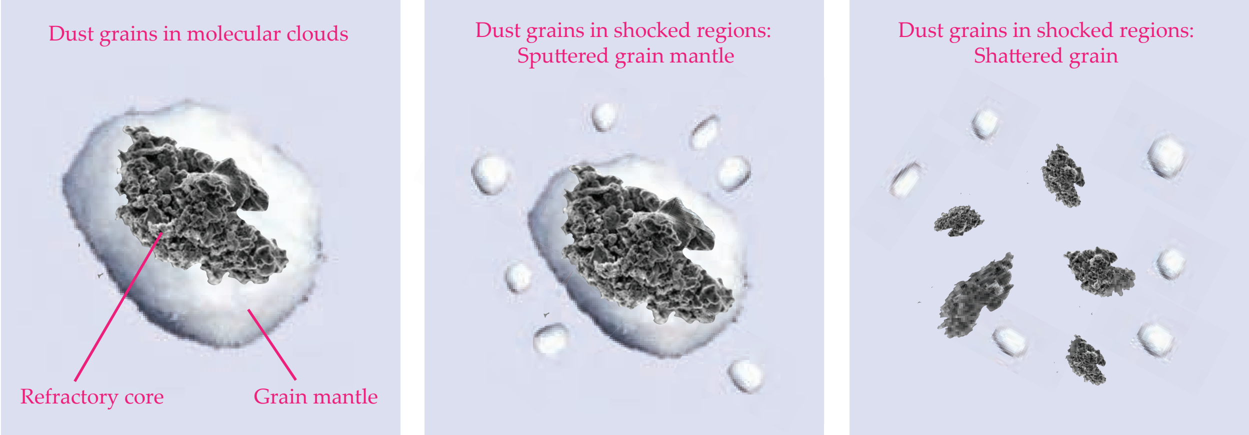
Less massive stars don't emit enough UV radiation to create shock waves, but they do create protostellar jets when they are born. A star is formed in a prestellar core, which extends thousands of astronomical units but will eventually form a planetary system only a few tens of astronomical units

Box 2. Interstellar dust grains

Interstellar dust grains are submicron solid agglomerates of silicates and carbonaceous material that permeate most of the interstellar medium. Although the dust particles represent only about a hundredth of the mass of the interstellar medium, they have a huge role in molecular cloud formation and evolution.

In molecular clouds, dust grains are composed of refractory silicates and carbonaceous cores, encased by volatile mantles. The mantles contain water, carbon dioxide, carbon monoxide, and other less abundant but more complex molecules, such as formaldehyde and methanol. Most of them do not have enough energy to return to a gaseous state but instead remain frozen on the dust-grain surface.

Interstellar shocks can send those frozen molecules back into a gas phase through two processes: mantle and grain sputtering and shattering. In the former, ions and atoms propelled by shocks hit the grains and eject molecules and atoms from the mantles and refractory cores into the gas. In the latter, the shocks are so violent that the grains collide and fragment, causing the species in both the mantle and the refractory core to be injected into the gas.



across. Prestellar cores are embedded in the Milky Way, which rotates as a rigid body. When they collapse, they acquire an angular momentum that needs to be eliminated. The most important mechanism to accomplish that is the ejection of a large fraction of the collapsing gas by protostellar jets. Those supersonic jets produce molecular outflows emanating from the forming star. Eventually those jets will collide with surrounding material and create disruptive shocks.

Probes of molecular shocks

How do astronomers study invisible shock waves? They are adept at analyzing a phenomenon by observing its effects on the surrounding environment. As an example, figure 1 captures NGC 1333, a region in the Perseus molecular cloud where several Sunlike stars are forming. Although the gas is too cold to be visible in the optical or IR spectrum, radio observations reveal the velocity of the molecular cloud. Expanding holes and moving filaments modify the morphology of the cloud on a large scale in reaction to the star formation. Shocks from protostellar jets emanating from several protostars alter the gas on a smaller scale. The current molecular cloud, however, doesn't tell astronomers which kinds of shocks caused the change in morphology, nor which mechanism caused the shock. To learn that, they need to look at the molecular makeup and the magnetic field.

In the molecular gas, where the ionization is low (the relative electron abundances with respect to the hydrogen atoms are less than 10^{-4}), there are two major types of shocks, as seen in figure 2: Jump, or J, shocks have an abrupt change in physical parameters; continuous, or C, shocks are mediated by the presence of a magnetic field. Those types are the two extremes of the range of possibilities regulated by the strength of the magnetic field with respect to the velocity of the shock.[3]

The most important consequences of the passage of the shock wave are gas compression and heating. But shocks also are crucial in enriching the gas. As the shock wave passes through, the interstellar grains of dust are sputtered and shattered, and molecular species that were previously frozen into icy mantles that envelop the grains are released (see box 2). Although the gas remains compressed, its temperature decreases because of H_2O molecules injected from the icy mantles, which emit photons that cool the gas.

As a result, several molecules are abundant in the shocked gas, regardless of shock type. Because some of those molecules are almost exclusively present in shocked regions, it is easier for astronomers to find and study them. The molecule used most often to trace interstellar shocks is silicon monoxide, primarily because more than 99% of it is trapped in interstellar dust grains and only a tiny fraction is gaseous. In a molecular gas, the few silicon atoms not locked into dust grains form SiO, a linear molecule whose rotational transitions can be observed with ground-based telescopes operating between radio and millimeter wavelengths.

The measured abundance of gaseous SiO with respect to H_2 in molecular clouds is 10^{-12} or less. The sputtering and shattering from molecular shocks, however, makes gaseous SiO a million times more abundant. Once in the gas phase, SiO can be observed at high spectral and spatial resolutions, thus allowing astronomers to study the physical structure and properties of the triggering shock.

Water is another tracer of shocks, even though it is not as exclusive as SiO. Water molecules are mostly formed on the grain surfaces by the successive addition of hydrogen atoms to frozen atomic oxygen. That means gaseous water is scarce in molecular clouds and becomes abundant in shocked regions.

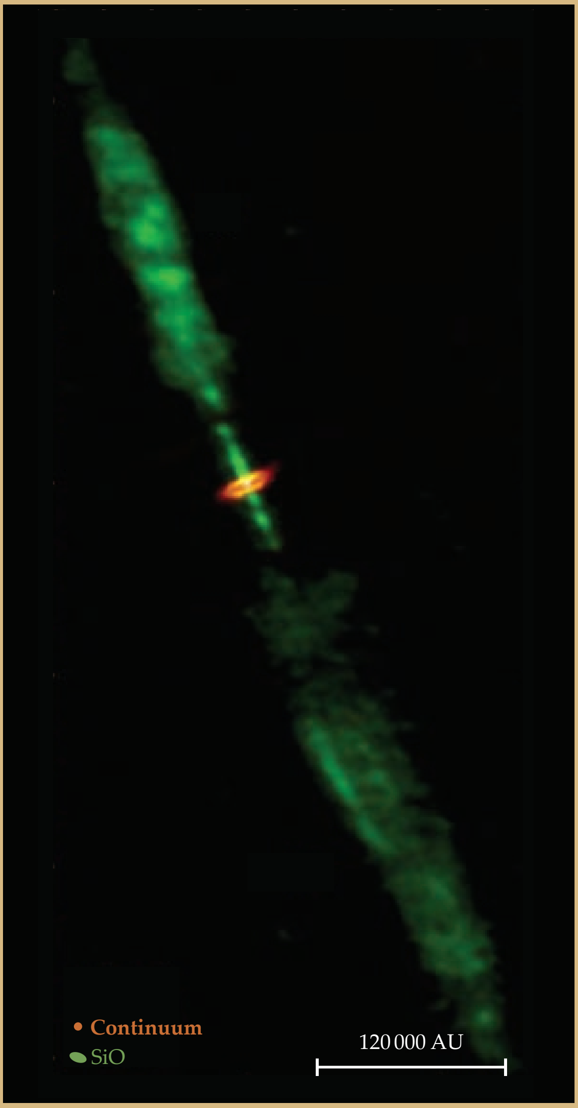


FIGURE 3. THE SHOCKED GAS in the jet and outflow emanating from the young protostar HH 212-mm, shown in continuum light, is traced by silicon monoxide, abundant because the shocks caused by the jet sputter and shatter silicate grains in the interstellar medium. The silicon liberated from the grains is quickly oxidized into SiO, which can be easily observed with ground-based radio telescopes. (Adapted from ref. 4.)

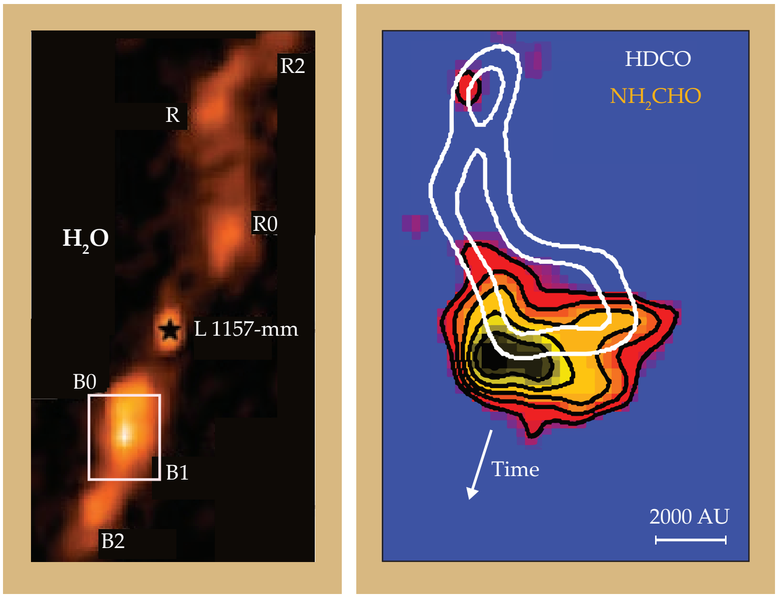


FIGURE 4. FORMAMIDE (NH_2CHO) is an astrobiologically important molecule that is also formed in interstellar shocks. The molecular outflow in different regions of the protostar L 1157-mm (left) is traced by water. The B1 region (right) is abundant with deuterated formaldehyde (HDCO), indicated by the white contours. The fact that the contours of HDCO lag behind those of NH_2CHO, indicated by black contours, means that the former was created after the passage of an older shock. (Left image adapted from ref. 5; right from ref. 8.)

Both tracers are used to observe shocks around young protostars. Figure 3 shows the protostar HH 212-mm traced by SiO, and figure 4 shows the protostar L 1157-mm traced by water.[4,5] Both protostars possess jets emanating outward for hundreds of astronomical units that create shocks, traced by SiO and water.

Celestial chemistry laboratories

In addition to releasing SiO and water into the gas phase, shocks also liberate whichever other molecules are frozen into dust-grain mantles (see box 2). That makes shocks a rich laboratory for astrochemistry. In those regions, astronomers are able to glean crucial information about the chemical composition of nascent planetary systems.

Molecules that previously were frozen into grain mantles can be observed in their gaseous state via their rotational lines by powerful ground-based telescopes, which are capable of detecting small relative abundances down to approximately 10^{-13} with respect to H_2. To put that in perspective, frozen SiO and water molecules can be observed in IR wavelengths by less powerful telescopes that can detect only abundances greater than 10^{-7}.

Two properties make shocks unique for astrochemistry studies. The first is that shocks liberate the components of the grain mantles into the gas. The second is that astronomers can pinpoint almost exactly when the shock passed, providing one of the most elusive pieces of information in astronomy—a clock. The two aspects make it possible to study the abundance evolution of the molecules, whose release into the gas phase and formation are triggered by the interstellar shocks. There are almost no other objects for which that kind of study can be done.

One molecule that can be studied in shocks is formamide (NH_2CHO). The small, abiotic molecule may be at the origin of large prebiotic genetic and metabolic compounds. Raffaele Saladino and colleagues argue that the presence of a small drop of formamide in the early Earth may have been the starting point of life—it would solve the question of whether metabolism appeared before genetics or after.[6] Astronomers know that formamide is relatively abundant in regions that will eventually form planetary systems similar to our solar system, but they do not know how or when the molecule is formed.[7] The answers may lie in closer study of molecular shocks caused by protostellar outflows.

For example, formamide rotational lines were observed in the shocked region L 1157-B1 of the protostar L 1157-mm. Combining the measurements of formamide abundance and the age of the shock, we and our colleagues were able to identify what caused the shock: a chemical reaction that can occur in every region that forms a solar-type planetary system.[8] If formamide is a key molecule for the emergence of life, as Saladino and colleagues purport, then life may be rather common. As unlikely as it may seem, studying interstellar shocks may provide astronomers with that information.

Interstellar shocks profoundly shape the morphology and evolution of galaxies by directly and indirectly triggering the formation of stars. Shocks of all velocities, sizes, and properties can cause the collapse of molecular clouds. Amid the dramatic interactions, they can provide astronomers with an almost unique set of information about the regions that form solar-type planetary systems and give clues about our own origins. One could say that interstellar shocks are the behind-the-scenes, mysterious Drosselmeyer of the galactic Nutcracker ballet: They distribute the toys and control the plot: the life and death of stars and of the galaxy itself.

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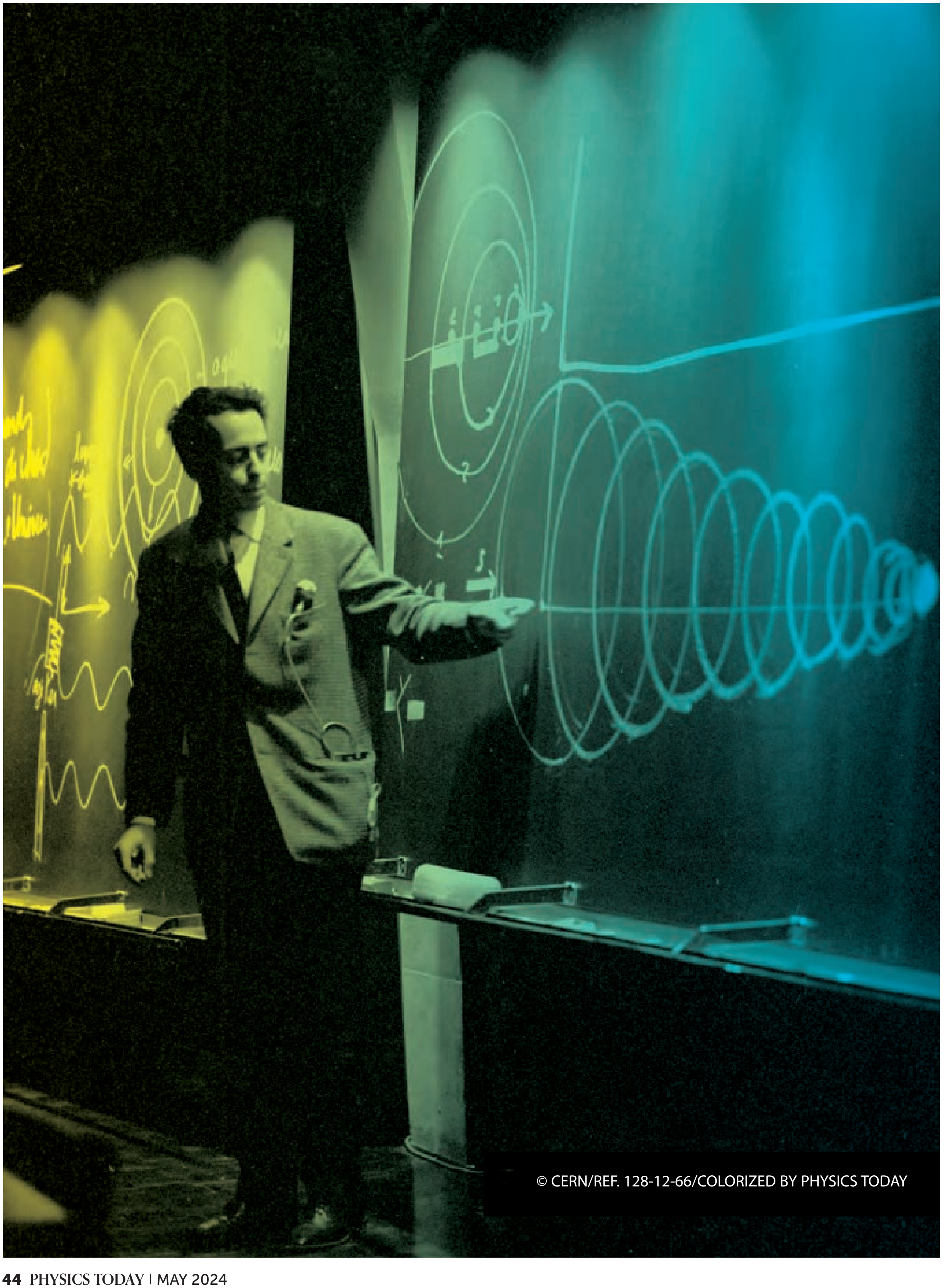

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Barbara Hof is a postdoctoral fellow at the University of Lausanne in Switzerland. A historian of computing and physics, she is currently working on a book project that analyzes the role of knowledge sharing in Cold War science diplomacy.

Science for All at CERN

Barbara Hof

In the 1960s CERN initiated a series of popular-science talks for nonacademic staff in the belief that getting them interested in science was key to its becoming a world-leading laboratory.

Almost 60 years ago, CERN began offering lectures to its nonscientific personnel on dinosaurs, science in the Middle Ages, nuclear fusion with lasers, salt mines, gold in the ocean, permafrost, the birth of stars, Mars's surface, plant transpiration, and much more. Those lectures were part of a wide-ranging series titled Science for All, which was aimed not at the outside public but at CERN's technicians, secretaries, laboratory assistants, operators, and craftspeople. Collectively, they made up 84% of the workforce—1842 of 2191 people in 1965 when the program was introduced.[1] Management believed that CERN's physicists would more easily achieve their goals if the behind-the-scenes support staff could be motivated to appreciate science.

CERN is well known today as a prestigious particle-physics laboratory, the world's largest accelerator complex, the birthplace of the World Wide Web (see the article by Bebo White, Physics Today, November 1998, page 30), and a symbol of European integration and international cooperation after World War II.[2] Although it is a prominent model of Big Science and science diplomacy, little has been written about the internal dynamics that contributed to CERN's success. Alongside the scientific collaborations it managed on an ever-increasing scale, CERN also instituted educational programs as it became a world-leading laboratory. Science for All is the most striking manifestation of those efforts, which is why it is worth remembering today.[3]

Introducing staff training

Science for All was only one of several educational programs that CERN started in the 1960s. To understand the reasons for their introduction, it is important to look first at the wider political context and understand how transatlantic knowledge transfer kick-started the development of high-energy physics in Europe after World War II.

In the war's aftermath, physicists in several European countries arrived at the idea of founding an international research laboratory. They realized that if they joined forces, they would have the funds and skills to build a large accelerator similar to those in the US, where great progress was being made in particle physics. A joint laboratory was also seen as a means toward European integration. One of those who proposed such an institution was the French physicist Louis de Broglie in 1949.

The following year, I. I. Rabi, the US delegate to a UNESCO meeting in Florence, Italy, summarized those plans when he presented a formal proposal for the establishment of a European physics center similar to Brookhaven National Laboratory in Long Island, New York, which had been founded in 1947.[4] US officials supported closing the gap in research opportunities between the two continents because scientific collaboration was

CERN staff receive technical training in electronics in 1975. (Courtesy of © CERN, ref. 53-3-75/colorized by PHYSICS TODAY.)

seen as instrumental to helping forge a Western alliance in the emerging Cold War. Precisely because of that potential influence on European affairs, French and Swiss Communists lobbied against the creation of CERN, arguing that the joint scientific project lacked political neutrality.[5]

Those objections proved ineffective: CERN was officially founded in 1954. Transatlantic cooperation provided staff members with some of the necessary knowledge to build the world's then-largest proton synchrotron, which was inaugurated in 1960. Europeans learned about its design from peers in the US, including Hildred Blewett and John Blewett.[6] In its first decade, CERN received additional US help in the form of consultations, colloquia, visits to the construction site, briefings, paid fellowships, and guest stays of CERN's leading physicists at the Berkeley and Brookhaven laboratories. Those informal learning opportunities helped CERN overcome what its founders saw as its knowledge deficit.

But CERN management, led by its director general, the Austrian-born US physicist Victor Weisskopf, soon recognized that the structured training of personnel was fundamental to securing the laboratory's future success. Shortly after Weisskopf's election in 1961, the CERN Staff Association, asked to work closely with management to improve working conditions, provided him with a report on training needs. The report was endorsed in March 1962 by the organization's Scientific Policy Committee,[7] and the laboratory's top authority, the CERN Council, soon approved the introduction of educational programs.[8]

CERN's in-house training was closely tailored to research, which distinguished it from the content offered at other educational institutions. The goal was to provide staff with the specialized knowledge needed for their job tasks. Management believed that workers' skill sets needed to be improved so that they could adapt to rapid advances in research. For the same reason, the Scientific Policy Committee also recommended offering training for graduate students.[7]

Since CERN's founding, its theoretical physicists had held seminars to discuss ideas. That was now expanded and termed academic training. As a counterpart to it, and because technical and programming expertise was in high demand at the accelerators, at detectors, and in the offices, technical training was introduced for engineers, technicians, mechanics, applied physicists, and other staff. Because those structured training programs were well attended during a trial period in fall 1962, CERN formed the Training and Education Section the next year under the leadership of the Belgian physicist Guy Vanderhaeghe.[9]

Why the support staff?

CERN's academic and technical training courses prepared staff for their specific tasks. Trainees gained experience in the Fortran programming language, discussed theoretical considerations and experimental findings, improved their skills in mathematics, or learned more about new accelerator uses and designs. In addition, CERN began offering graduate training to doctoral students of member states. At a time when instruction in particle physics was not yet part of the standard physics curriculum at many universities, CERN's graduate training helped participants gain familiarity with the basics of the field and current trends.

CERN management also hoped to foster a broader and deeper understanding of physics, which led the organization in 1962 to introduce general lectures "for the whole of the staff."[10] Those talks focused on the basics of neutrino physics, a highly topical subfield at the time. But they were discontinued after a year.

The organization decided to try again in 1965. Gearing the lectures toward the support staff, most of whom came from nearby French-speaking communities, CERN decided to hire a permanent instructor, Rafel Carreras, to lead the organization's in-house general education offerings. Carreras, seen at the blackboard in the opening image, had studied physics and biology and had a keen interest in explaining science to laypeople. And he had experience lecturing in science at two Swiss universités populaires (open universities), which were specifically aimed at giving learning opportunities to adults who did not have the formal qualifications required to study at a university.

Carreras ended up teaching at CERN for more than 30 years.[11] During his first decade at the organization, he offered two general education programs. The first, Understanding CERN, familiarized new members of the laboratory's support staff with its overall scientific mission in the belief that

A theory seminar at CERN in 1962. (Courtesy of © CERN, ref. 5314/colorized by PHYSICS TODAY.)

informed personnel would collaborate better with the scientists. The program consisted of lessons in the organization's history, its accelerators and detectors, the production and use of particles, and the nature and classification of particles. The Education and Training Section believed that giving employees an overview of CERN's activities would help increase efficiency in the workplace.

Aiming to motivate

The second general lecture series that Carreras began offering in 1965 was called Science for All (or Science pour Tous in the original French). That title is reminiscent of Science for the People, a late-1960s movement of concerned scientists in the US who opposed the Vietnam War. Those activists criticized leading US physicists for their contribution to weapons development and military strategies and demanded radical change in the academic system.[12]

CERN's Science for All was the opposite of Science for the People: It was not about overcoming the hierarchy and division of labor in the laboratory, even if the communication of scientific material to nonacademics arguably partially embodied liberal ideals of giving access to knowledge. Carreras held antidiscriminatory views and Vanderhaeghe was an advocate of trade unionism, which certainly influenced the educational programs at CERN. To what extent the nonacademic personnel appreciated Science for All cannot be reconstructed from the archival holdings. But it is clear that CERN management saw it as a tool to help secure a positive reputation for the laboratory among its nonscientific staff.

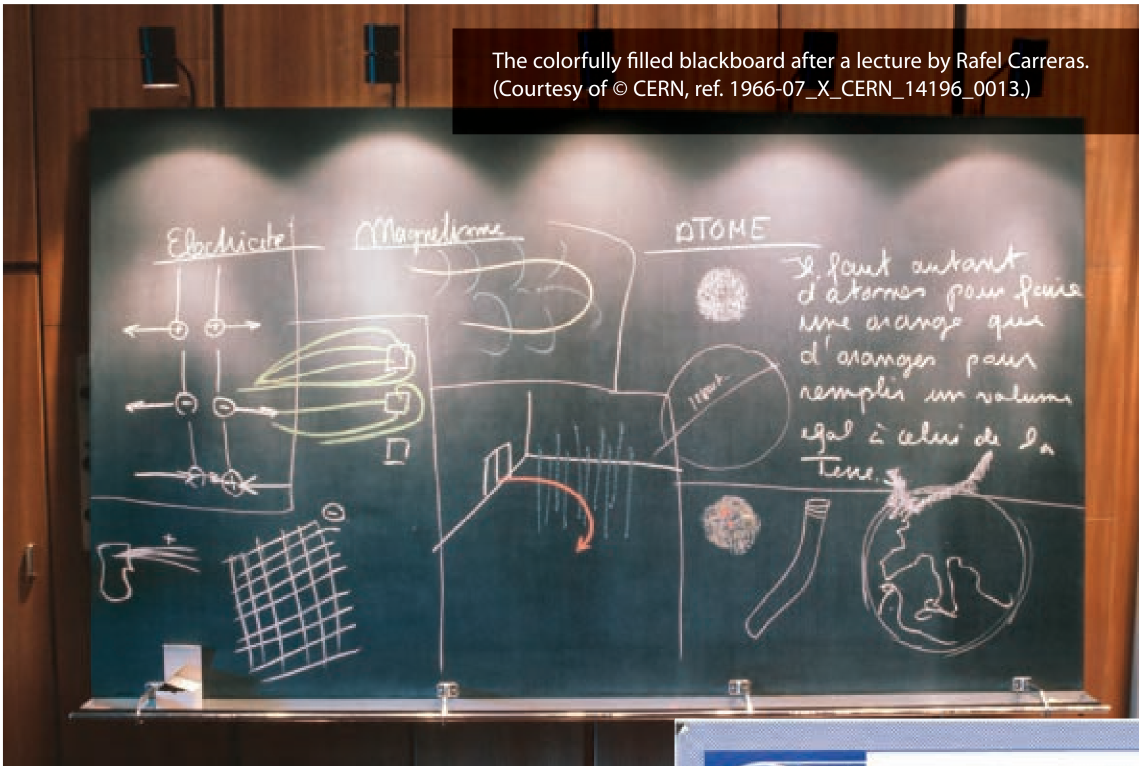
At the time when Science for All was introduced, CERN was in the midst of an organizational reform aimed at helping it cope with the growing number of research projects and increasing demands from visiting physicists who sought to use the accelerator complex for their own research purposes.[13] Workflows had to be well organized. As a result, CERN introduced a management training program to help its senior scientists improve their communication and motivational skills.

Science for All, on the other hand, was designed not to meet day-to-day demands but to inspire staff members about science. CERN did not introduce the series to help it catch up with US laboratories, to maintain its central position in the dissemination of knowledge throughout Europe, or as a way to pass on its core mission. The lecture series was simply intended to get nonscientists interested in science and encourage them to be proud that they worked at CERN.[14]

Carreras was given the freedom to design Science for All as a motivational learning program open to all staff. To do that, he presented scientific findings and discussed them with participants in French, the language spoken by the local population. The weekly program was inaugurated in December 1965 with a lecture on the use of laser beams on living cells. The free lectures, held outside official working hours, were announced in the *CERN Bulletin*, a newsletter for the CERN community. In addition to giving talks, Carreras ran sessions during which the audience was invited to ask questions. The CERN amphitheater where lectures were held was usually well filled, with at least 50 and sometimes as many as 400 participants in attendance.

Each Science for All lecture was about 30 minutes long, and Carreras used the chalkboard or overhead projector to

One of Rafel Carreras's first lectures at CERN in 1966. (Courtesy of © CERN, ref. 136-12-66/ colorized by PHYSICS TODAY.)



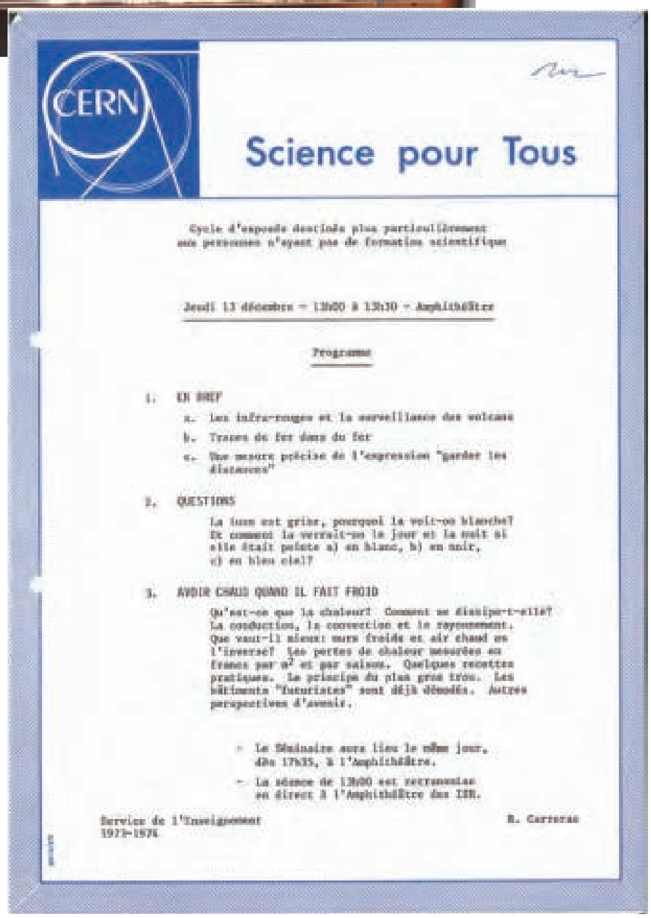
The colorfully filled blackboard after a lecture by Rafel Carreras. (Courtesy of © CERN, ref. 1966-07_X_CERN_14196_0013.)

provide visual content. He typically covered trends and new developments from the world of science, but his lectures also occasionally summarized news that he felt was of general interest, such as the Apollo missions. Lectures explored, for example, why CERN was so big, the invention of the microscope, the state of science 50 years ago, volcanoes, echoes, nuclear explosions, particle collisions, and how the end of the US Atomic Energy Commission in 1975 affected high-energy physics. Carreras chose the topics himself or by popular demand. He also based some lectures on popular-science books such as Weisskopf's *Knowledge and Wonder: The Natural World as Man Knows It*.[15]

Science for All was not meant to inspire nonacademically trained staff to study for a university degree but to awaken their general interest in science. Because the lectures popularized scientific ideas, representatives of CERN's Training and Education Section noted in 1972 that some of them might be of interest to a wider audience and thus fell within the realm of public information. Although the activities of CERN's Public Information Office, which communicated decisions and research results to the general public, were never merged with Science for All, management decided to open Carreras's lectures to nonemployees as well.[16]

The other side of Big Science

Science for All is a reminder that Big Science encompasses more than the science itself: In CERN's case, it also involved cultivating enthusiasm for science among the nonacademic staff members to better integrate them into the organization's workflow. The educational program was intended to motivate employees and spread a positive image of CERN among its support staff, which largely came from the surrounding region. Its introduction was more strategic than idealistic, even if it



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   La lune est grise, pourquoi la voit-on blanche? Et comment la verrait-on le jour et la nuit si elle était peinte a) en blanc, b) en noir, c) en bleu ciel?

3. AVOIR CHAUD QUAND IL FAIT FROID
   Qu'est-ce que la chaleur? Comment se dissipe-t-elle? La conduction, la convection et le rayonnement. Que vaut-il mieux: murs froids et air chaud ou l'inverse? Les pertes de chaleur mesurées en francs par m² et par saison. Quelques recettes pratiques. Le principe du plus gros trou. Les bâtiments "futuristes" sont déjà démodés. Autres perspectives d'avenir.

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- La séance de 13h00 est retransmise en direct à l'Amphithéâtre des ISR.

Service de l'Enseignement
1973-1974

R. Carreras

A TYPICAL ANNOUNCEMENT for a Science for All lecture. (Courtesy of the Archives of William Owen Lock, 1927–2010, ref. CERN-ARCH-WOL-160, CERN Archives.)

resonated with contemporary notions of equality. Nevertheless, Science for All represented a universalistic approach to knowledge—namely, the ideal that science should reach everyone. As Carreras stated in a lecture on his retirement in 1997, his talks had provided staff with knowledge that enabled them to talk about anything related to science and about problems at the intersection of science and society.[17]

Since the introduction of the first structured training programs in 1962, CERN has expanded its learning opportunities for graduate students, postdoctoral fellows, visiting scientists, and research associates. It continues to invest in employee orientation and the professional development of support staff. While Science for All was always a somewhat modest effort, it was also a pioneering experiment in science communication. It was an initiative to get people excited about science and a step toward building the global audience that CERN enjoys today.

I am grateful to Rafel Carreras for comments on a previous version of this article. It reflects only my views, but I thank Matthew Adamson, Hendrik Adorf, and two anonymous reviewers for their feedback. Special thanks to James Gillies and Jens Vigen for their support and to Sandrine Reyes for her help at the CERN Archives.

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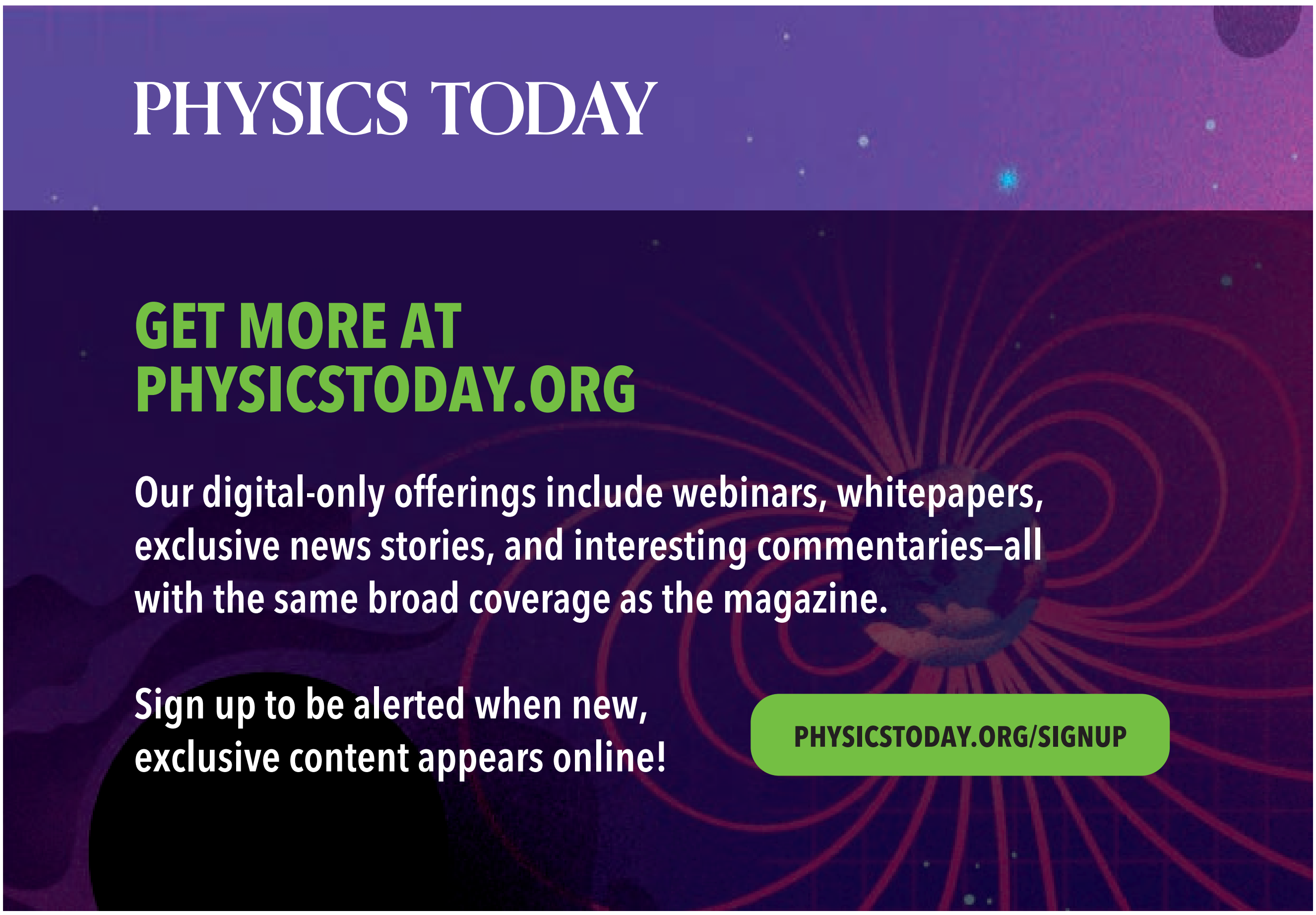


NEW PRODUCTS

Focus on lasers, imaging, microscopy, and nanoscience

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

Andreas Mandelis

High-resolution laser wavelength meters

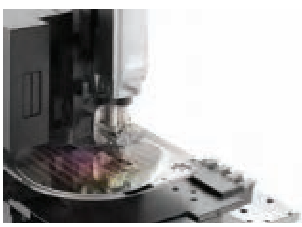
Bristol Instruments has announced a series of wavelength meters for the frequency stabilization of lasers. According to the company, its 872A-VIS and 872A-NIR laser wavelength meters combine high measurement resolution with reliable accuracy. The 872A models support laser wavelength measurements from 375 to 1700 nm and offer a frequency resolution better than 300 kHz at 300 000 GHz, which results in high sensitivity to wavelength deviations. With a built-in proportional-integral-derivative controller and a 1 kHz sustained measurement rate, the 872A system is well suited to precisely stabilize lasers used for applications such as atomic cooling and trapping. ***Bristol Instruments Inc***, *770 Canning Pkwy, Victor, NY 14564, www.bristol-inst.com*

Ultrafast femtosecond fiber laser

The VALO Tidal femtosecond laser from Hübner Photonics offers ultrashort pulse durations of less than 50 fs (full width at half maximum), a pulse energy greater than 66 nJ, and a pulse repetition rate of 30 ± 1 MHz. Operating at a wavelength of 1050 nm with an accuracy of ±10 nm, the compact, low-noise laser features an output power of more than 2 W, a peak power of 1.6 MW, a dispersion compensation range of −30 000 to 5000 fs^2, and beam divergence of up to 2 mrad. The Tidal laser's high peak powers, low average power, and ability to produce bright, high-contrast multiphoton images enable longer imaging times and higher cell viability. Those qualities make it suitable for multiphoton microscopy imaging, optogenetics, two-photon polymerization, terahertz generation, supercontinuum generation, and spectroscopy applications. ***Hübner Photonics Inc***, *2635 N 1st St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com*

Sample scanning AFM

Mad City Labs designed its MadAFM sample scanning atomic force microscope (AFM) for ease of use and simple installation. For precise movement of the sample and probe, the MadAFM includes the company's piezo closed-loop nanopositioners with proprietary PicoQ sensors. The sensors enable the *xyz* nanopositioners to deliver the lowest noise and highest resolution available, according to Mad City Labs. Together with the company's resonant probe AFMs, they yield true decoupled motion with less than 1 nm out-of-plane motion over the scan range. The AFM also integrates intelligent-control motorized micropositioners for long-travel, high-stability micropositioning. The MadAFM can accommodate samples up to 50 × 50 × 40 mm in size and supports multiple microscopy modes. Those include phase microscopy; magnetic, electric, and lateral force microscopy; and scanning tunneling and Kelvin probe microscopy. ***Mad City Labs Inc***, *2524 Todd Dr, Madison, WI 53713, www.madcitylabs.com*



Scanning microwave impedance microscopy

For its research atomic force microscopes (AFMs), Park Systems has introduced PrimeNano's ScanWave scanning microwave impedance microscopy (sMIM) as an imaging mode. The sMIM technique uses microwave reflections from the tip–sample nanometric interaction to gather local electrical properties, such as permittivity and conductivity, of a sample. The properties can then be converted to dielectric constant, capacitance, resistivity, and dopant concentration for semiconductors at the nanoscale. Knowledge of those properties helps users reliably process and maintain the quality of such materials as semiconductors, thin films, and dielectrics. ScanWave offers several advantages over other electrical AFM modes: Because it is based on a microwave signal, little to no sample preparation is required. Because no current flows through the sample, no path to ground is needed, and floating insulators and dielectrics can easily be directly imaged. ***Park Systems Inc***, *3040 Olcott St, Santa Clara, CA 95054, https://parksystems.com* PT

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PHYSICS TODAY | JOBS

Ben Weiss is the Robert R. Shrock Professor of Earth and Planetary Sciences at MIT in Cambridge, Massachusetts. **Lindy Elkins-Tanton** is a Foundation and Regents Professor of Earth and Space Sciences and vice president of the Interplanetary Initiative at Arizona State University in Tempe. They work together on NASA's *Psyche* mission, with Elkins-Tanton as the principal investigator and Weiss as the deputy principal investigator and magnetometry investigation lead.

Journey to a metal world

Benjamin P. Weiss and Linda T. Elkins-Tanton

A mission en route to the unusual asteroid Psyche may be humanity's only opportunity to visit the core of a planetary body.

Jules Verne almost had it right back in 1864. In *Journey to the Center of the Earth*, a geologist and his team descend into a volcano in Iceland to explore Earth's hidden metal core. But it turns out that visiting our planet's center is and will remain an impossible feat for many human lifetimes: The core is hotter than the surface of the Sun and its pressure more than 3.5 million times that on Earth's surface (see PHYSICS TODAY, October 2023, page 12).

Just 12 years before Verne wrote his book, Annibale de Gasparis, an astronomer in Naples, Italy, discovered the 16th known asteroid, which he named Psyche. Since that time, astronomers have been observing how strongly Psyche's gravity tugs on passing asteroids, bouncing radar waves off it, and measuring the spectrum of light reflected from its surface. Collectively, these observations now tell us that Psyche is weirdly dense—so dense that, like Earth's core, it must be made mainly of iron–nickel metal. To understand how that came to be, on 13 October 2023, NASA launched a robotic mission to investigate Psyche up close.

For 50 years astronomers have been sending probes to investigate our solar system. They have visited rocky bodies like Mercury, Venus, the Moon, and Mars; icy bodies like Europa and Enceladus; and gas-rich bodies like Jupiter and Saturn. But they have never traveled to a body with a metal surface.

The main reason is that the bodies are rare: Only about 10% of known asteroids seem to be largely metallic. Psyche is by far the largest, with an effective diameter of about 220 km. Even so, in our highest-resolution images of the asteroid, it is just a few pixels wide.

Studying Psyche will help us learn about a previously unobserved building block of Earth and the other rocky planets—the metal-rich materials that form their cores. Furthermore, if Psyche is the remnant of an early-formed metal core, it may give us the only glimpse of one that we will ever have.

How to make a metallic world

Our best guess is that Psyche formed as the metallic core—the iron-rich central region—of a planetesimal, a tiny planetary body the size of a city or a continent (see schematic). As the building blocks of the planets, planetesimals were ubiquitous during the first few million years of our solar system's 4.5-billion-year history. Because radioactive isotopes with short half-lives were abundant in the early solar system, many planetesimals were largely molten. As a result, metal in those bodies sank under gravity to form a dense, central core surrounded by lighter silicate rock, similar to the structure that rocky planets have today. Such metal-silicate differentiation was the primary process that concentrated metal on a planetary scale in the solar system.

Psyche may be the battered remnant of one of those planetesimals. Impacts may have removed much of its silicate-rock exterior, revealing the metal core. Current models of the formation of Earth and the other rocky planets require the accumulation of many planetesimals and their larger descendants, planetary embryos. Many of those bodies were already differentiated, such that their metal cores merged to form Earth's core. The Psyche asteroid, therefore, may be an example of a primary, original metal–silicate differentiation event.

Although our fiducial model of Psyche is that it fomed as a planetesimal core with residual rocky material, we may well be wrong. The asteroid might instead be material that never melted. In particular, it may have somehow formed from the preferential aggregation of materials that are much more iron rich than the bulk composition of the solar system.

Determining how Psyche became so metal rich is important because it could point the way to understanding how other metal-rich worlds formed. For example, although it has a rocky surface, the planet Mercury also has a mysterious abundance of metal. Furthermore, we know of a dozen or so Earth-sized planets around other stars with similarly high densities.

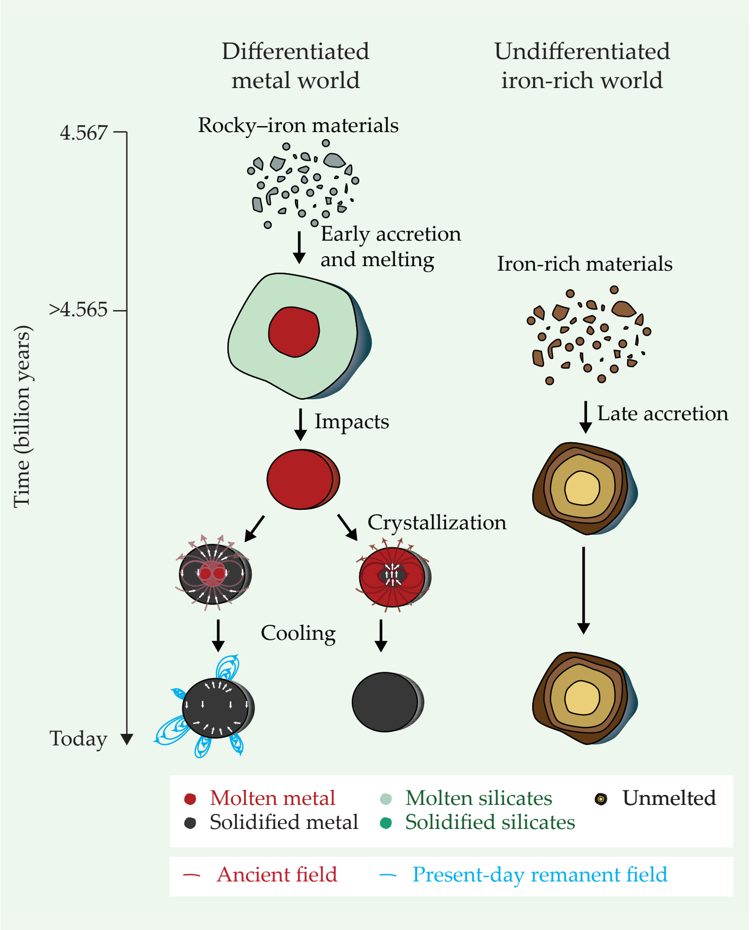
Measuring an unknown object

Because Psyche is unlike any object previously explored *in situ*, our team faced a fascinating challenge in designing a spacecraft that is prepared for the unknown. To determine whether Psyche is indeed part of a core, the spacecraft carries a multispectral imager to detect spectral absorption signatures of metal and rock, a gamma-ray and neutron spectrometer to measure the elemental composition of the surface, and a magnetometer to detect any remanent magnetic field emanating from the asteroid. We will also track the spacecraft's velocity by observing Doppler shifts of radio waves from the spacecraft's telecommunications antenna to measure Psyche's gravity field.

If Psyche is a core, we will be able to learn things that are largely unknown for most planetary cores, including Earth's. We will be able to determine the minor elements it contains and how they relate to its interior structure; that's important because it could tell us about the conditions under which metal–silicate differentiation occurred and how the body later solidified. We could also find out whether and how the churning of Psyche's metallic liquid once generated a magnetic field 4 billion years ago like Earth's core does today. And if the asteroid is not a core, there may exist processes that can build primordial iron-rich planets without requiring later stripping by impacts.

Looking ahead

Psyche lies in the outer asteroid belt, about three Earth–Sun distances from the Sun. To reach the asteroid, the spacecraft first has to go through three phases of propulsion. The first was the big boost it received from its launch vehicle, the SpaceX Falcon Heavy. It now is gently but efficiently being propelled by ionized xenon sent through thrusters that convert the solar panels' electrical currents into thrust. The final step will be a slingshot following a flyby of Mars in 2026. After the spacecraft arrives at Psyche in 2029, it will orbit the asteroid at various altitudes and eventually approach within 75 km of the surface.



A METAL-RICH PLANETESIMAL, UP CLOSE. Rocky–iron materials (left) melt by radiogenic heating and may be stripped by mantle-abrading impacts. Differentiated bodies could generate a magnetic field, but only a planetesimal that crystallized from the inside out could have recorded the magnetic field in its outer layers, as shown at bottom left. The late formation and preferential accretion of iron-rich materials (right) could produce a metal-rich, unmelted body. It would not have generated a magnetic field.

The history of planetary exploration tells us that when a spacecraft visits a new kind of planetary object, the unexpected awaits. The Voyager probes found that Jupiter's moon Io, despite being just a quarter the size of Earth, is a hellish world of erupting volcanoes. The *Galileo* spacecraft discovered that Europa, despite its frigid, roughly −225 °F surface, contains a vast, global subsurface ocean. And *Cassini* was showered by geysers erupting from Saturn's moon Enceladus.

For now, Psyche is a dark and blurry smudge on a photograph and a playground for our imaginations. It could, like Io, have a surface stained yellow from sulfurous volcanoes that erupted more than 4 billion years ago as it first cooled. It may, like rare metallic meteorites called pallasites, be studded with bottle-green olivine crystals that could be the remnants of Psyche's overlying silicate proto-mantle or the mantles of early impactors. The metal lips of craters created by meteor impacts might have frozen in mid-splash, leaving spires and cups on the asteroid's surface. Psyche might have one of the strongest magnetic fields observed around a body in our solar system, or it may have none at all.

The *Psyche* mission is also a stepping stone in exploration. A hundred years from now, landers may probe the innards of asteroids with seismometers, and commercial missions may mine the vast riches of nearby metallic asteroids. For now, the next milestone comes in 2029, when we get our first up-close glimpse of a metal world.

Additional resources

► L. T. Elkins-Tanton et al., "Observations, meteorites, and models: A preflight assessment of the composition and formation of (16) Psyche," *J. Geophys. Res.* **125**, e2019JE006296 (2020).
► L. T. Elkins-Tanton et al., "Distinguishing the origin of asteroid (16) Psyche," *Space Sci. Rev.* **218**, 17 (2022).
► M. K. Shepard et al., "Asteroid 16 Psyche: Shape, features, and global map," *Planet. Sci. J.* **2**,125 (2021).
► B. P. Weiss et al., "The Psyche Magnetometry Investigation," *Space Sci. Rev.* **219**, 22 (2023).
PT

Making an educational splash

Roberto Zenit teaches a course that connects art and fluid mechanics. "The challenge is to convey fluid mechanical ideas without equations" to physics majors and nonmajors alike, says the Brown University engineering professor. As part of the course, Zenit asked students to photograph droplet splashes with an off-the-shelf digital camera. By using an external flash and a programmable microcontroller, the students can play with the camera's timer delay to capture the moment that the droplet splashes on the surface. Students also decide which fluids they photograph, the colors, and other details of the setup. This photo—of a pink-dyed ethanol droplet impacting a mixture of water, glycerin, milk, and food coloring—was taken by Lucian Sharpe, Sofia Gilroy, Kiara Vong, and Himanssh Pettie this semester. It was voted the best by the class because of its colorful artistry and the clarity of the splash.

In the class, Zenit focuses on teaching three concepts: viscosity, surface tension, and hydrodynamic instability. He also explains how the features of the splash form. The lab exercise gives students an opportunity to appreciate the beauty of fluid flow and to learn about fluids visually. Zenit's inspiration came from Harold Edgerton's famous 1936 photograph *Milk-Drop Coronet Splash*, for which he used a stroboscope with its many flashes of light per second to capture the splash of a falling milk droplet. Zenit says that "teaching this course has been inspiring, challenging, and fun." (Image submitted by Roberto Zenit.) —AL

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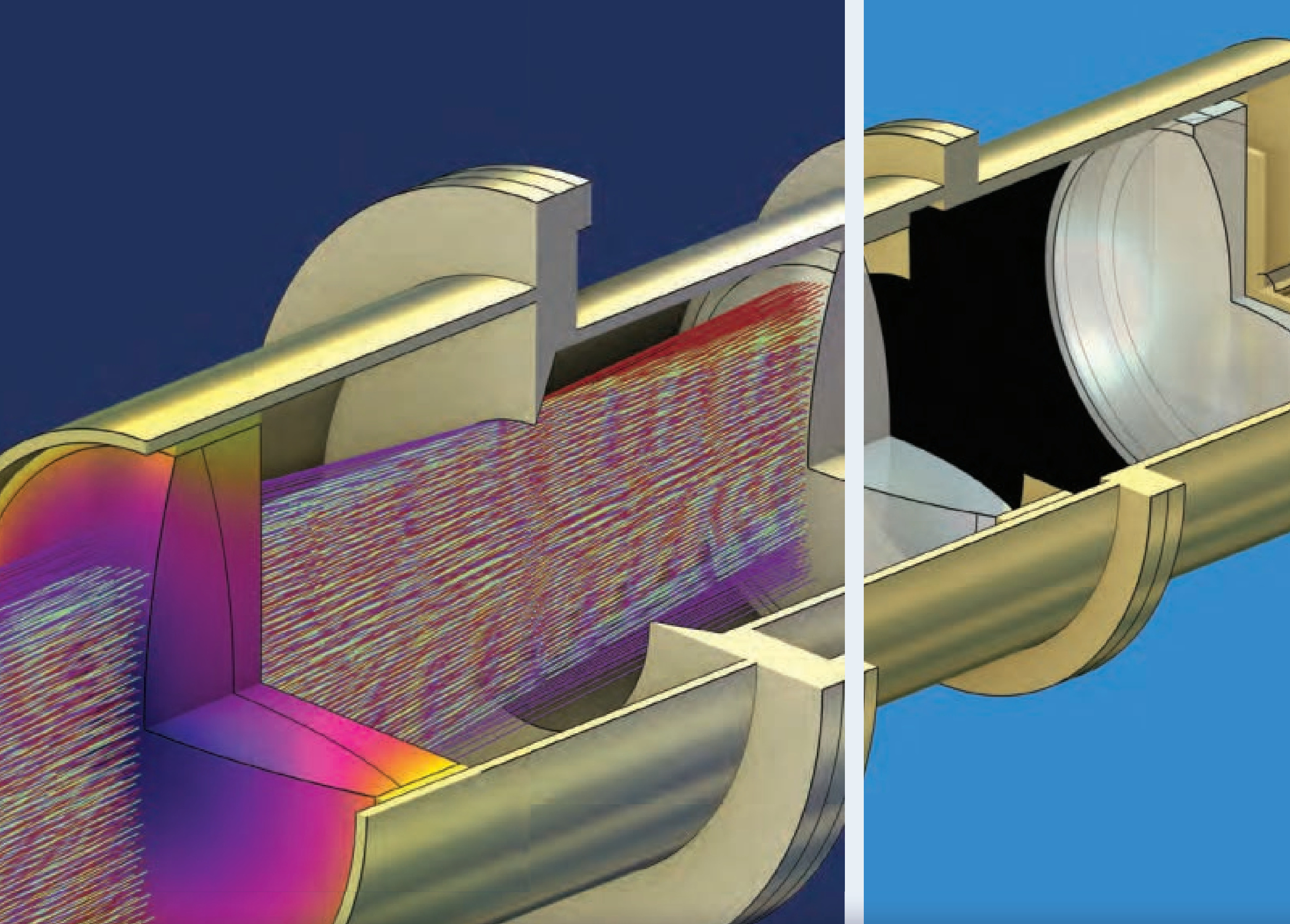

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