PHYSICS TODAY

November 2024 • volume 77, number 11

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Ancient minerals as particle detectors

Maurice Sendak, physics illustrator

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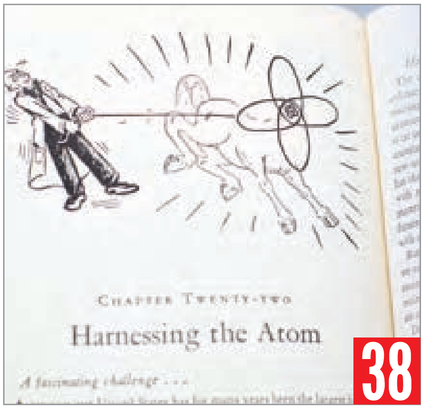

PHYSICS TODAY

November 2024 | volume 77 number 11

FEATURES

ON THE COVER: Of the five big cats in the genus *Panthera*, four can roar: tigers, lions, leopards, and jaguars. Both the size and the shape of their voice boxes contribute to their ability to produce their trademark calls. For more on the physics of roaring, turn to the Quick Study by Ed Walsh and JoAnn McGee on **page 54**. (Image by Jason Keisling.)

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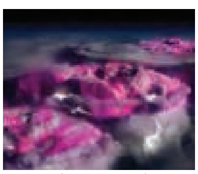

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T-storm gamma rays

The high-energy electric fields that produce lightning can also generate gamma rays. Using a converted spy plane, researchers flew above thunderstorms and observed a new class of atmospheric gamma-ray emission. The work could improve understanding of the physics of thunderstorms.
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Prosthetic hand

A newly developed prosthetic hand responds to muscle contractions rather than to electrical signals from the brain. The hand's movement is dictated by the relative positions of small magnets implanted in a user's arm. A trial participant was able to perform daily tasks such as tying shoelaces.
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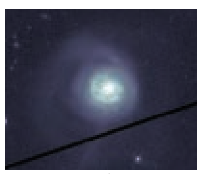

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Galactic boundaries

Where does a galaxy end and intergalactic space begin? Researchers recently charted the surface brightness of a galaxy's gas as a function of distance from the galactic center and found an abrupt shift in the brightness curve's shape. Such an approach could help standardize measurements of galactic size.
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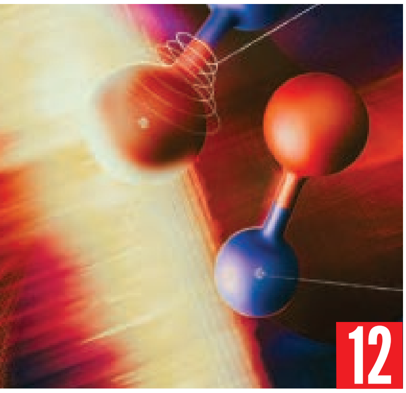

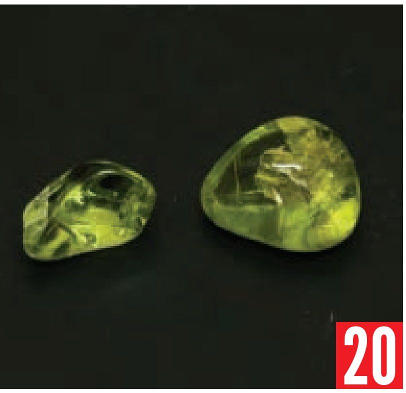

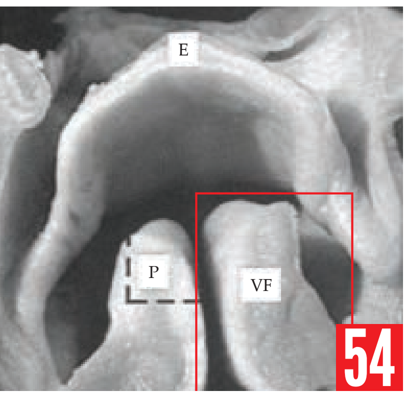

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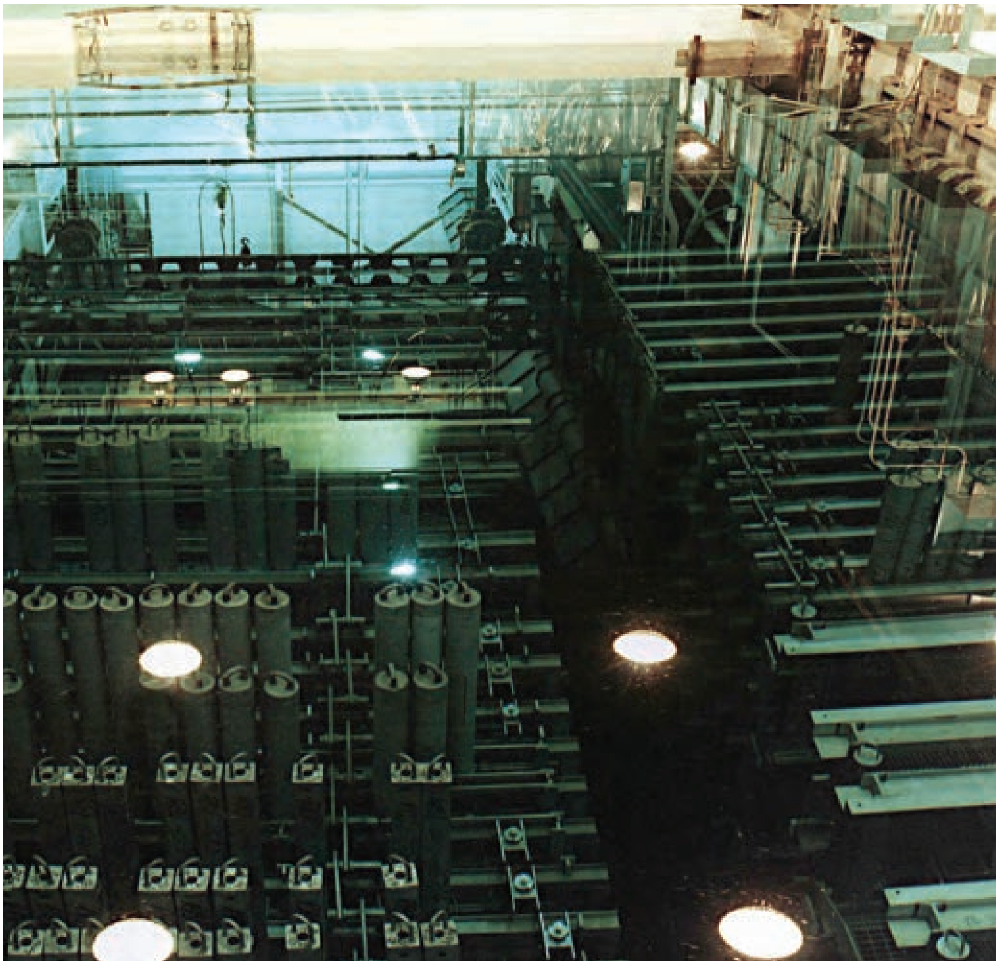
Nuclear energy and climate change

Toni Feder's piece "What is nuclear energy's role in mitigating climate change?" (PHYSICS TODAY, July 2024, page 22) doesn't discuss the need to deal with hazardous wastes. Feder writes, "Proponents say that nuclear energy is necessary in the climate change equation and that to wield influence in the nuclear arena, the US and other Western nations must be at the forefront of nuclear energy development and exports." But no one should receive a permit for reactor construction until the issue of waste disposal is addressed.

Plutonium-239, a byproduct of all reactors running on uranium-235, is radioactive and carcinogenic. There are two main methods for its safe long-term disposal: deep repositories and nuclear transmutation. The first has received serious attention worldwide, and Finland is the closest to operating such a site. But in the US, funding to build an underground waste repository under Nevada's Yucca Mountain was eliminated during the Obama administration. Currently, spent fuel is stored in cooling pools on-site and, after a period typically between one and two years, moved into dry storage casks. "Spent fuel storage at power plant sites is considered temporary, with the ultimate goal being permanent disposal," says the US Nuclear Regulatory Commission.[1]



A RECEIVING BASIN for spent fuel rods at the Savannah River Site in South Carolina. (Courtesy of the US Department of Energy.)

The second method, transmutation, has received insufficient attention. Back in the 1970s, when I was getting my PhD in astronomy at the University of California (UC), Santa Cruz, I teamed up with F. William Reuter III, who was getting a master's in nuclear engineering at UC Berkeley. We investigated the tuned subatomic particle accelerator bombardment of ^{239}Pu to transform it into shorter-lived or stable nuclei as a disposal technique. We calculated that the energy needed to do that for each ^{239}Pu nucleus was greater than the energy liberated from each ^{235}U nucleus. We concluded that it was a losing ball game and never published the result.

It has since occurred to me that renewable energy could be used as the accelerator power source to get rid of the waste, which would avoid the carbon dioxide emission of fossil-fuel power and the energy deficit issue of fission power. Additionally, others have looked at schemes that incorporate the wastes into a reactor designed for the purpose of self-powered transmutation.[2]

Small modular reactors (SMRs)—those generating under 300 megawatts electric (MWe) as opposed to the 1 GWe of traditional reactors—are being promoted as safer and cheaper. To date, one design has been approved by the Nuclear Regulatory Commission. The SMRs' modular uniform design might be better for ensuring safe operation, and their small sizes increase the potential for adjusting electricity generation to meet

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demand, which is desirable for utility operations. But installing and operating a lot of SMRs would increase the need for qualified operators, secure transportation, and waste-disposal sites, and it would mean more reactors spread over the landscape. Proponents of SMRs claim that they create less waste. But one study shows that those small reactors would have a lower burnup of ^{235}U and generate more spent nuclear fuel (high-level waste) and more intermediate and low-level wastes per unit of thermal power output than large reactors.[3]

Other new reactor designs include large plants that use primary coolants other than water and breeders, which convert ^{238}U (not a reactor fuel isotope) to ^{239}Pu. The US's first commercial breeder reactor, Fermi 1, was a failure, and radioactive parts of the facility are still on-site and still in need of further disposal. Other examples of breeders include the uneconomical and now-shut-down Phénix and Superphénix in France; they had numerous problems with their liquid sodium coolant, which ignites on contact with air.[4,5]

Issues such as those mentioned above ought to be resolved with speed. In the meantime, we can supply our electrical energy needs with known renewable energy technologies at lower direct and indirect costs. Renewables come with their own problems, but they do not represent the same regional threats to health or security as nuclear energy does.

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William R. Alschuler
(walschuler@hotmail.com)
California College of the Arts
San Francisco

The mucociliary escalator

Medical and nursing students will doubtlessly find the admirable article "The connection between Darwin's finches and bacterial flagellar motors" (Physics Today, March 2024, page 28) of interest. When teaching about potential and other energy considerations (for example, those associated with gravitation), I've taught my students about the important, similar mechanism of the mucociliary escalator. That system comprises motile cilia, which are waving flagellar-like fronds, on cells that line the main tubes between the mouth and lungs. Each escalator cell has about 200 cilia.

The air we breathe contains dust and other pollutants, and it's necessary to have a protective mechanism to prevent foreign, toxic solid materials from accumulating deep in the lungs. Sticky mucus is continuously produced in the main proximal tubes, and it traps those contaminating particles before they move very far from the mouth and nose. This loaded, contaminated mucus is continuously removed by the mucociliary escalator,[1] which transports it upward. Finally, in the mouth, it is usually then swallowed unconsciously, and so the lungs are continuously cleared of trapped foreign bodies and toxins.

That process is useful for illustrating the conservation of energy to medical and nursing students, but there is an additional bonus: discouraging smoking. Gases emitted by cigarettes and vapes kill cilia, and the steadily increasing amounts of pollutants deep in the smoker's lungs can be removed only through coughing—hence the existence of "smoker's cough," that bout of coughing that each smoker experiences on waking in the morning and clearing contaminated mucus that has been produced but not expelled during sleep.

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Sinclair Wynchank
(swynchank@gmail.com)
University of Cape Town
Cape Town, South Africa PT

Photoemission of core-level electrons is caught in the act

Advances in attosecond x-ray physics enable researchers to glimpse unique electron interactions not seen before in the study of valence electrons.

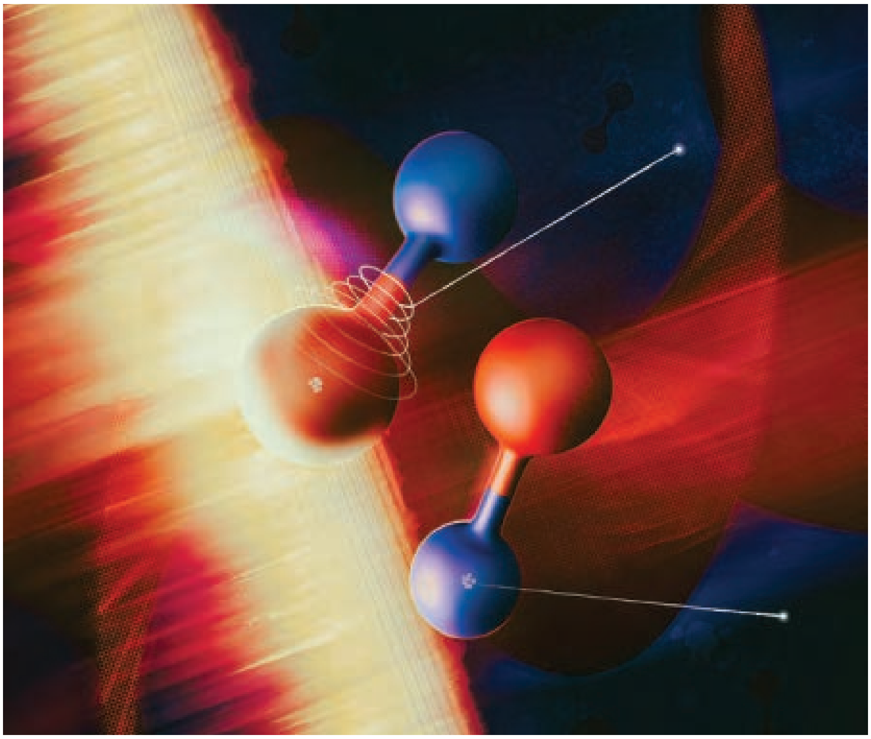

FIGURE 1. AN ULTRAFAST PULSE of bright x-ray light bombards two nitric oxide molecules, initiating photoionization. The time at which the molecules' core electrons (white dots) are emitted can be inferred from the angle at which they are deflected by a circularly polarized IR laser field. (Courtesy of Gregory M. Stewart, SLAC National Accelerator Laboratory.)

Electrons move on the time scale of attoseconds, each of which is a vanishingly short billionth of a billionth of a second. For many years, electron motion was unobservable because no laser was capable of producing pulses of light shorter than a few femtoseconds. The ability to measure motion on such time scales is determined by the duration of the laser pulses: If the pulse lengths are too long, the motion can't be calculated with sufficient precision.

At the turn of this century, the attosecond limit was broken by two groups—one led by Pierre Agostini and another by Ferenc Krausz—both of which relied on earlier nonlinear-optics results from Anne L'Huillier and colleagues. For their experimental contributions, the three researchers received the 2023 Nobel Prize in Physics (see PHYSICS TODAY, December 2023, page 13).

Using ultrafast pulses of light generated from tabletop lasers, the researchers made many observations of processes that were once considered instantaneous. In 2010, for example, Krausz and colleagues found that the photoionization of valence electrons in neon took tens of attoseconds.[1] A follow-up experiment in 2017 led by L'Huillier refined the timing further.[2]

Complex multielectron interactions can be studied with measurements of core electrons—those closest to an atom's nucleus. But their motion and interactions on the attosecond time scale have remained out of reach. The binding energies of such electrons are too high to be studied with attosecond pulses of light from low-energy tabletop lasers.

Now Stanford University's Taran Driver, Agostino Marinelli, and James Cryan and their colleagues have harnessed recent advances in x-ray free-electron lasers (XFELs) to witness the photoelectric effect in core electrons.[3] The new measurement technique, illustrated in figure 1, can shed light on the unique interactions of core electrons with other electrons and how x rays can affect electronic properties of matter.

Shorter, brighter waves

The workhorses of attosecond experiments are the ultrafast light pulses created by high harmonic generation (HHG). An intense IR laser illuminates a target, usually an atomic or molecular gas, whose electrons are then excited and emit higher-frequency harmonics of the driving laser. With such a source, researchers can produce pulses of extreme UV (XUV) light as short as dozens of attoseconds. (For more on HHG, see the article by Paul Corkum, PHYSICS TODAY, March 2011, page 36.)

The XUV pulses produced via HHG have high-enough photon energies to excite valence electrons and short-enough durations for researchers to measure the time scale of the electrons' motion. Exciting core electrons, however, requires soft x rays, which have higher energies than XUV photons but not quite as high as that of hard x rays used for medical imaging. Recent efforts have succeeded in producing HHG-based sources at x-ray wavelengths. But the number of photons in an ultrafast pulse decreases as the photon energy increases. That limitation has prevented researchers from using HHG-based sources to study the photoionization of core electrons.

An alternative source of ultrafast pulses is the XFEL. The kilometer-sized

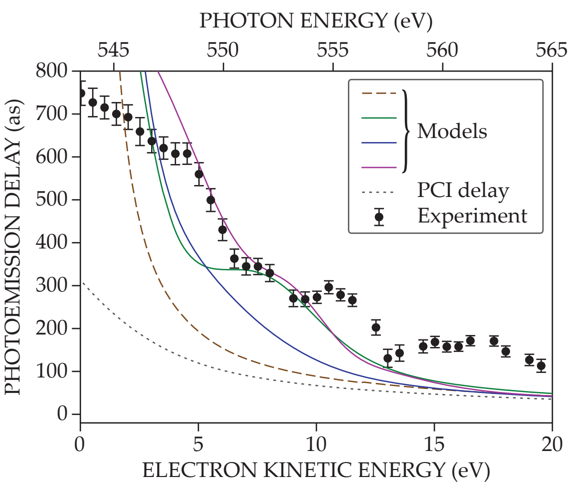

FIGURE 2. HUNDREDS OF ATTOSECONDS is the time it takes for a core electron to be emitted from the shell closest to the oxygen nucleus in a photoionized nitric oxide molecule. To observe such a fleeting event, researchers measured the time delay between the emission of two electrons, which were ejected by an attosecond pulse of light from an x-ray free-electron laser. Especially at the lower and upper ranges of electron kinetic energies, the experimental results differ from model calculations. Some delay (black dotted line) is due to the ejected core electron's postcollision interaction (PCI) with another electron. (Adapted from ref. 3.)

instrument sends a bunch of relativistic electrons through a series of alternating magnets to generate femtosecond x-ray pulses. Compared with tabletop lasers, XFEL sources have several advantages. For example, they generate much more intense pulses of light with a broad range of tunable wavelengths. In addition, the pulse bandwidth is small enough that researchers can home in on particular spectral features of samples.

To create XFEL pulses on the attosecond scale, Alexander Zholents (now at Argonne National Laboratory) proposed a technique in 2005 called enhanced self-amplified spontaneous emission.[4] The resonant interaction of a high-power IR laser with the XFEL electron beam creates an ultrashort current spike in the beam, which could then be used to generate an x-ray pulse that lasts just a few hundred attoseconds.

The type of laser that the method relied on turned out to have many practical and technical challenges. "While these ideas had broad support in the community," says Marinelli, "nobody really knew how to realize them in an experiment, and to this day, nobody has done so. Between 2005 and 2015, not much happened."

Slower than expected

Marinelli studied alternative approaches, and by 2019, he and colleagues had developed a working technique for the Linac Coherent Light Source at SLAC. They realized that rather than using an external IR beam, as Zholents had proposed, they could use the IR radiation emitted in the tail of the XFEL electron beam. The result was a beam with a single high-current spike that generated an isolated attosecond pulse.[5]

Equipped with the necessary attosecond pulses, the researchers measured the photoionization of core electrons in gaseous nitric oxide. Marinelli says, "We did this measurement only a few days after the first-ever demonstration of isolated attosecond soft x-ray pulses at an XFEL."

They made the measurement with the angular-streaking method,[6] in which an ionizing attosecond x-ray pulse is overlapped with a circularly polarized IR laser field. The rotating electric field of the IR laser deflects the photoionized electrons radially, and the time at which the electron is emitted from the molecule can be calculated from the deflection angle.

The new measurement is the first time an attosecond XFEL source was used to measure photoemission delays, and the research team spent a lot of time designing the data analysis, which included a helpful mathematical model by Jun Wang. "To understand what our data were telling us," says Cryan, "we also had to work closely with our theory collaborators, who simulated the physical effects that we had observed."

The timing of the photoionization is defined by the delay of the core electron's ejection relative to a reference event. Compared with the emission of 120 eV valence electrons from the molecule, the oxygen atom's core electrons—with kinetic energies no higher than 20 eV—were emitted as much as 700 attoseconds later, as seen in figure 2. That's sluggish relative to theoretical predictions, especially in the lower portion of the kinetic energy range that was measured.

When electrons meet

Valence electrons are critical for molecular reactions, but the study of core electrons can reveal other processes. On their way out of a molecule, ionized core electrons can interact with the more weakly bound valence electrons. In fact, the researchers' numerical simulations show that some of the core electrons' delay, plotted in figure 2, may be caused by interactions with valence electrons.

Once it's emitted from its shell, a core electron, unlike a valence electron, is quickly replaced by an electron in a higher-energy orbital farther from the nucleus. Through a process known as Auger–Meitner decay, the energy released when a core vacancy is filled gets transferred to a valence electron, which is then emitted from the molecule after a few femtoseconds.

"Collisions with Auger electrons have not been observed before in photoemission delay experiments," says Kevin Prince, a senior scientist at the Elettra Sincrotrone Trieste research center in Italy. "Multielectron scattering is also new in this context."

Theoretical models have struggled to accurately predict photoemission delay at the lowest electron kinetic energies; figure 2 illustrates the discrepancy between measurements and simulations. The unexpectedly long photoemission delay in the new measurements indicates that core electrons may be more sensitive to multielectron interactions than previously thought. The team has started conducting new XFEL measurements on more complex molecules, which should provide even more information about the unique interactions of core electrons.

Alex Lopatka

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Three glass beads bring into question the timeline of lunar volcanism

Radiometric dating of material returned from the Moon suggests there was active volcanism on the satellite 120 million years ago, nearly 2 billion years more recent than previous estimates.

China's *Chang'e 5* mission brought samples of the Moon back to Earth in December 2020, the first time since the Apollo and Luna missions did so in the 1970s. The next year, the lunar science community was rocked by the finding that volcanic basalts in the new samples were some 2 billion years old,[1,2] about 800 million years younger than any other measured lunar volcanic rocks.[3] Just as theorists were developing models of the Moon's thermal evolution that could explain that finding, Bi-Wen Wang, of the Chinese Academy of Sciences in Beijing, and colleagues are now reporting dramatically younger ages of around 120 million years.[4]

The new age measurements are from 3 glass beads, shown in figure 1, out of a sample of roughly 3000 collected by the *Chang'e 5* probe. Most of the beads have impact origins: When meteorites smash into the lunar surface, small blobs of melted material get thrown upward before cooling and falling to the ground. But glass beads can also be generated by volcanic sprays known as lava fountains. Lunar soils returned by the Apollo missions contained many such beads, all older than 3 billion years.

Although this is the first direct measurement of volcanic material from the Moon to indicate sub-billion-year-old ages, the idea of more recent volcanism isn't totally new. Detailed analyses of lunar surface images have revealed dozens of small volcanic features (see figure 2) known as irregular mare patches (see the article by Brett Denevi, PHYSICS TODAY, June 2017, page 38). The density of impact craters can be used to appraise the age of a lunar surface. That method has yielded estimates that the largest patches could be less than 100 million years old, but there have been no direct measurements to confirm those assessments.[5]

The latest finding has generated a lot of buzz in the lunar science community. Still, not everyone is convinced that the three beads are conclusively volcanic. The University of Florida's Stephen Elardo, who works on thermal evolution models of the Moon, says explaining the latest finding would require going back to the drawing board. "If there's young volcanism on the Moon, we really need to rethink models about how planets cool off with time," he says. "And that isn't just the Moon, that goes for any planetary bodies."

Winnowing candidates

The Moon is thought to have formed after a collision between Earth and a protoplanet early in our solar system's formation, about 4.5 billion years ago

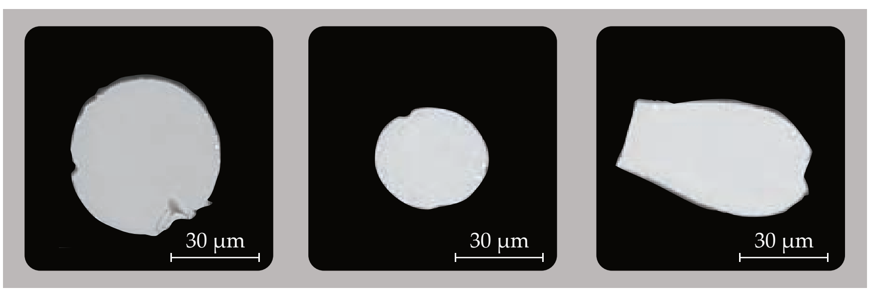

FIGURE 1. BACKSCATTERED ELECTRON IMAGES were used to screen for fractures and compositional variations in glass beads collected by the *Chang'e 5* mission. Three beads from a sample of 3000 were identified as volcanic in origin and found to be 2 billion years younger than any other volcanic material from the Moon. (Adapted from ref. 4.)

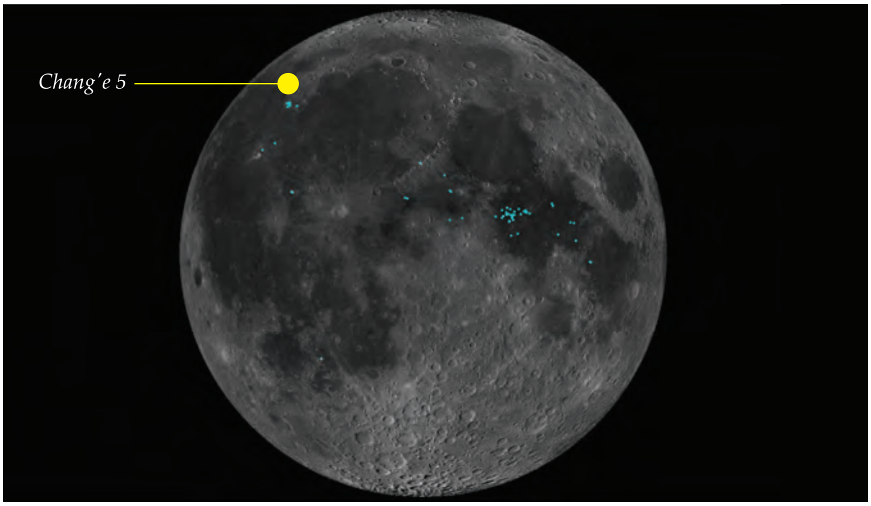

FIGURE 2. THE MOON'S NEAR SIDE was visited by *Chang'e 5* in December 2020. Lunar features known as irregular mare patches, labeled with blue dots, have been interpreted as younger volcanoes that could be the source of the geologically young glass beads found in the return samples from the Chinese mission. (Image adapted from Lunar QuickMap.)

(see the article by Dave Stevenson, Physics Today, November 2014, page 32). Starting from a fully molten state, the lunar magma ocean crystallized into a core, mantle, and crust. Many interacting processes, including magma differentiation, crystallization, mechanical overturning, and mantle convection, produced the variety of rocks and features observed on the Moon's surface today. The oldest rocks reside in the highlands that cover much of the lunar far side. The younger rocks are found in large low plains of dark basalts, known as lunar maria, that cover much of the near side. The landing site of *Chang'e 5* was chosen to target an area expected, based on crater counts, to be on the younger end of lunar basalts.

Wang and colleagues followed multiple steps to identify potentially volcanic beads from the *Chang'e 5* sample. First, they used backscattered electron imaging to screen out beads with obvious signs of impact origins, such as fractures and highly variable compositions. The remaining beads were analyzed for major elements like magnesium, calcium, and aluminum. They used the relative proportions of those elements to separate the beads by origin: either likely volcanic or likely impact. Data from the Apollo missions provided a baseline for classification. That process winnowed the candidates for beads of volcanic origin down to 13.

A radiometric age can be obtained from a bead by comparing the ratio of uranium-238 in the bead with its decay product, lead-206. But volcanic beads that experienced a meteorite impact after they formed could have uranium–lead ages that were thermally reset, since the heat of an impact would have kicked lead out of the sample. To be sure that the 13 beads with volcanic compositions weren't thermally reset, the researchers turned to sulfur isotopes. Regolith from the Moon's surface typically exhibits a higher ratio of sulfur-34 to sulfur-32 compared with a standard reference material from Earth. But volcanic glass beads from the Apollo missions have more sulfur-32, which gives them a lower sulfur-34 isotope ratio, as seen in figure 3.

With the sulfur data from their glass beads, Wang and colleagues make the case that impacts cause degassing from rocks that preferentially kick out light sulfur-32: As total sulfur concentration decreases, the amount of sulfur-34 increases relative to sulfur-32.

The researchers found that 10 of the 13 beads have a heavy sulfur isotope signature and thus ruled them out as purely volcanic in origin. The remaining three are enriched in lighter sulfur isotopes. From that, the team concludes that the three beads are volcanically sourced and would provide reliable ages. The researchers also argue that high levels of rubidium found in those samples, and not in the impact beads, further rule out a resetting of the uranium decay clock because the heat needed to

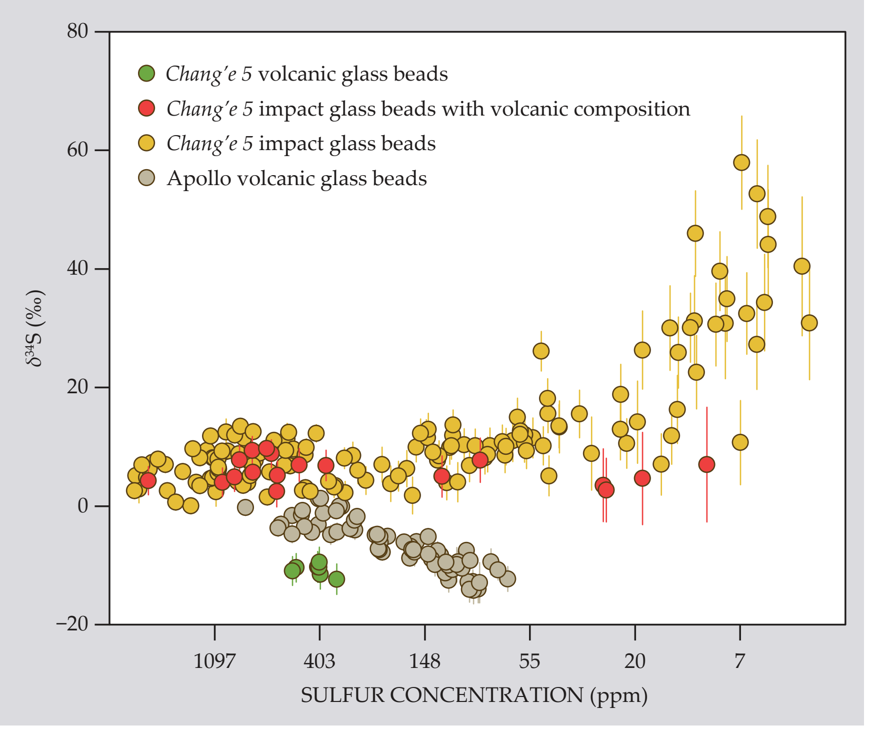

FIGURE 3. SULFUR ISOTOPES measured from lunar glass beads, shown here as a relative ratio of sulfur-34 to sulfur-32 compared to a standard reference from Earth, may help distinguish beads generated by lava fountains from those made during meteor impacts. Out of 13 glass beads with compositions that seemed volcanic in origin (red and green) from the *Chang'e 5* sample, researchers determined that only three beads (green) had sulfur isotope ratios similar to volcanic glass beads collected during Apollo missions (gray). (Adapted from ref. 4.)

kick lead out of the glass would also kick out rubidium. Uranium–lead dating shows the ages of the three beads all clustered around 120 million years.

"Such young volcanoes on the Moon have been expected by remote sensing observations, but we found the ground truth," says Qiu-Li Li, who led the research team.

Wang and colleagues did not measure the ages of any glass beads that they deemed impact related. But a previous study of hundreds of such beads from the *Chang'e 5* samples found that the ages spanned from a few million years to more than 2 billion years old,[6] without the clustering around 120 million years that Wang and his team report for their volcanic beads.

Brown University's James Dottin III, who has studied sulfur isotopes in lunar glass beads, says he agrees that impacts cause sulfur loss, but his own work has shown that impacts don't cause sulfur isotope fractionation.[7] He doesn't see proof of a strong fractionation trend from the *Chang'e 5* sulfur isotope data and notes that it's hard to get reliable data on sulfur concentrations below 10 ppm.

Dottin argues that the separation and concentration of sulfur in lunar glass beads has more complex origins. "Just because the sulfur isotope ratio is negative doesn't mean it's volcanic," he says. He would have liked to have seen images of the samples after the collection of measurements from secondary ion mass spectrometry, which can damage the samples and affect subsequent measurements.

Where's the heat?

As the Moon cooled off and volcanic activity slowed, elements that are incompatible with crystallization became concentrated in the remaining magma and eventually erupted as basalts that are enhanced in what's known as KREEP: potassium, rare-earth elements, and phosphorus. Those basalts also are enriched in heat-producing elements, including radioactive uranium, thorium, and potassium.

Elardo says that thermal models of the basalts recovered by *Chang'e 5* can explain how they melted 2 billion years ago by top-down heating of shallow mantle rocks from a cover layer of KREEP basalts, which acted like an electric blanket.[8] But even radioactive heat slows down with time. Because of uncertainties about the exact volume, placement, and concentrations of KREEP basalts on the Moon, it's unclear whether they could provide enough heat to fuel volcanism within the last 120 million years. "I don't think it's necessarily something that we would expect," says Elardo. "But what we expect is kind of meaningless. What nature makes is more important."

More studies of young lunar volcanism are in the works. NASA has plans to take *in situ* age measurements of the largest irregular mare patch, Ina, as part of the Artemis program, possibly as soon as 2027. The planned instrument suite, Dating an Irregular Mare Patch with a Lunar Explorer (DIMPLE), will use a rover to collect samples and then laser-ablate them to collect rubidium–strontium age data.

Sarah Braden, a DIMPLE payload project scientist, says that the instrument should provide a clear constraint on whether Ina is 30 million years old, as her own crater counts have estimated,[5] or billions of years old. The uncertainty of the rubidium–strontium ages will depend on how much of those elements are in the rocks. If they're able to collect a measurement, even one on the high end of calculated uncertainty, says Braden, that big-picture question should be answered: "It's a way to get answers to questions that would otherwise only be answerable in sample returns."

Laura Fattaruso

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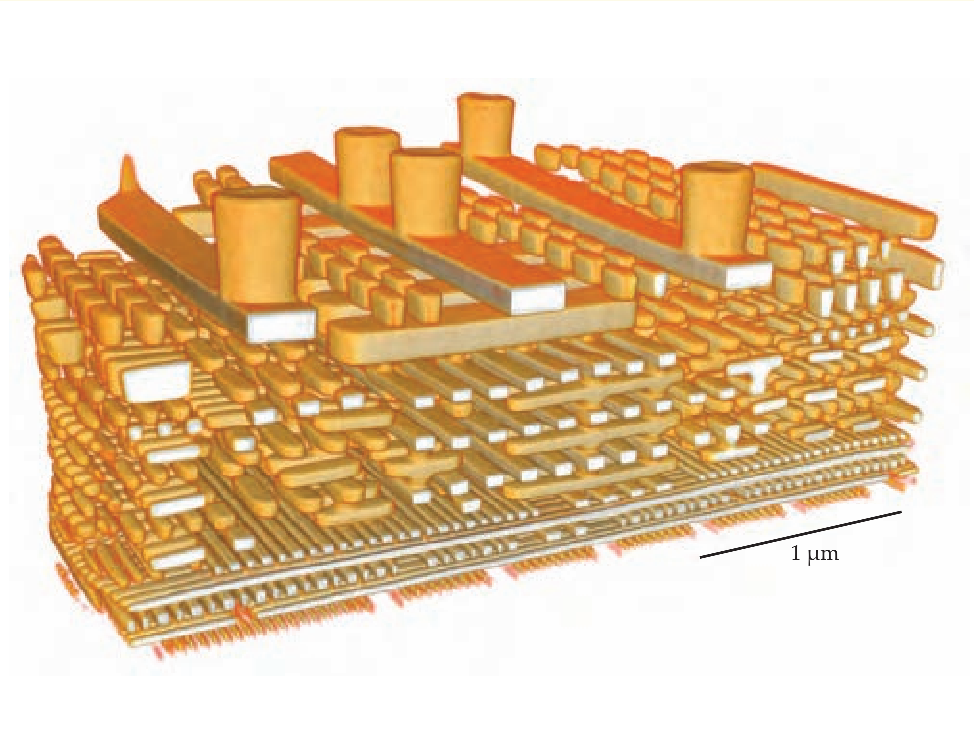
Imaging advance enables 3D maps of the smallest microchips

With improved x-ray tomography algorithms, researchers can analyze nanometer-scale features inside microchips and improve resolution in other imaging applications.



A 3D MAP OF A MICROCHIP'S INNER WORKINGS highlights the metallic interconnections and tiny transistors that make up the integrated circuit. (Adapted from Aidukas et al., *Nature* **632**, 81, 2024.)

Today's microchips contain features nearing atomic length scales. The ability to see inside them is valuable for manufacturing, quality control, and security inspection, but as they continue to shrink, the techniques available to image them can't always keep up. Fine-scale features can be imaged with electron microscopy, but that requires the analysis and then removal of one thin slice of the chip at a time.

X-ray diffraction patterns can be used to visualize the 3D structure, in a method known as ptychographic tomography, without the need to destroy the chip. But until recently, ptychography could only provide a resolution of about 15 nm, not precise enough to capture the tiny transistors in modern microchips. Now, an advancement to that method by Tomas Aidukas, at the Paul Scherrer Institute in Switzerland, and colleagues has pushed the lensless imaging technique to a record 4 nm resolution.

Much like how taking a good photograph requires sufficient light, reconstructing the interior of an object from the diffraction patterns it creates requires a high-enough dose of x rays over a long-enough span of time. But the longer an image is collected, the more opportunity there is for blur. For the new approach, instead of using one long x-ray dose to capture an image with the necessary flux, the researchers used short bursts of x rays to collect several less-blurry images that still captured enough flux when added together. Those snapshots provided the time-resolved data necessary to identify the primary source of resolution-limiting blur—in this case, a slight wobble of the x-ray beam. Combined with the burst snapshots, improvements to the back-projection algorithm enabled more-precise calculations of the relative positions of the sample and the beam, which in turn led to the resolution enhancement.

Though Aidukas and colleagues used the algorithm to correct for a wobble in the beam, the same approach could be used to correct for other sources of inaccuracies in a ptychographic measurement, such as a less stable microscope setup. "As long as you have the computational resources, this could essentially improve resolution at any existing beamline that is doing ptychography around the world," says Mirko Holler, a senior scientist on the research team. That may prove helpful for labs that have implemented ptychography at smaller facilities by taking advantage of recent advancements to lab-scale x-ray sources.

The high-flux x rays used by Aidukas and colleagues came from the Swiss Light Source, a third-generation synchrotron that is currently in the process of an upgrade scheduled for completion next year. With those improvements to the beam flux, ptychographic imaging at 4 nm resolution could be done much faster. The 40 hours of data collection that went into the latest 3D image could, in theory, be shrunk down to an hour. The researchers are also exploring the technique's other potential applications, such as imaging brain tissue. (T. Aidukas et al., *Nature* **632**, 81, 2024.)

Laura Fattaruso

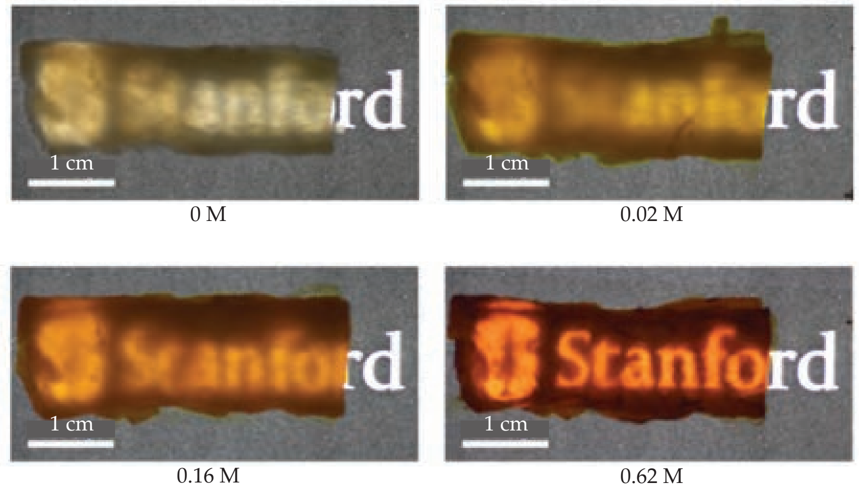
To turn tissue transparent, dye it yellow

The biomedical discovery stems from the subtle physics of how absorption and refraction are related.

Apart from a few pigments, such as melanin, not many of the molecules in your body absorb much visible light. The main reason why human (and most animal) bodies appear optically opaque is because of scattering, not absorption. The tissues are a hodgepodge of watery cytoplasm and interstitial fluid, with refractive indices around 1.35, and protein- and lipid-based organelles and membranes, with refractive indices of up to 1.5. When light rays try to pass through that optical maze, they get hopelessly tangled up.

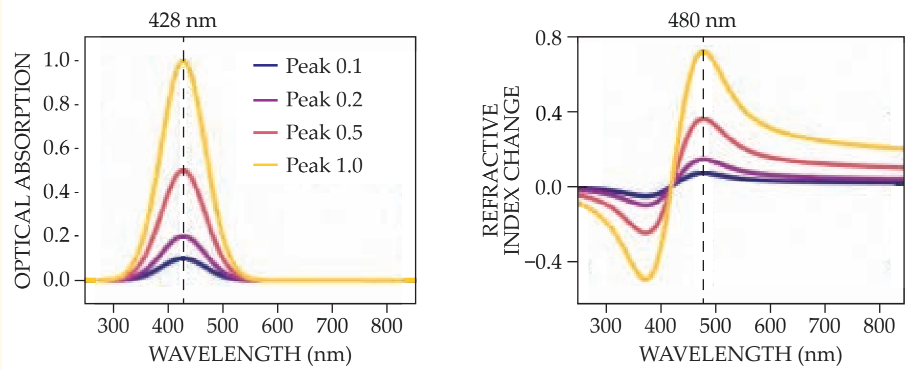
Biomedical researchers have developed a toolbox of techniques for making tissues transparent so they can study the structure of an organ or animal without cutting it up. Most, however, are applicable only to post-mortem tissues. (See, for example, PHYSICS TODAY, June 2013, page 14.) One exception is to replace the water in a tissue with a fluid, such as glycerol, whose high refractive index better matches that of the organelles and membranes. Although displacing the water from a living tissue is not harmless, researchers can use the technique to see through a lab mouse's skin while the mouse is still alive.

Now an interdisciplinary team of Stanford University researchers, led by Mark Brongersma and Guosong Hong, has found a potentially more practical alternative. Instead of glycerol, the re-



THIN SLICES OF RAW CHICKEN BREAST, infused with increasing concentrations of the yellow food dye tartrazine up to 0.62 moles per liter, become progressively more transparent. Rubbing the dye on the skin of live mice gives researchers a view of their internal organs. (Adapted from Z. Ou et al., *Science* **385**, eadm6869, 2024.)

searchers use the yellow food dye tartrazine (known in the US as FD&C yellow 5) to turn tissues transparent, as shown in the images on the opposite page. Tartrazine absorbs blue light, but over the red–yellow half of the spectrum, a tartrazine solution that's mostly water has a refractive index that rivals that of pure glycerol. Because the tartrazine doesn't replace the tissue's water, the researchers can apply it to live mice without causing acute tissue damage.



ACCORDING TO THE KRAMERS–KRONIG RELATIONS, optical absorption and refraction are not independent phenomena, and the refractive-index plots on the right follow from the absorption spectra on the left. Notably, although the optical absorption is zero at wavelengths above 600 nm, the refractive index is still elevated. (Adapted from Z. Ou et al., *Science* **385**, eadm6869, 2024.)

It's no coincidence that making tissues absorb light is the key to turning them transparent. A substance's absorption spectrum and refractive index are the imaginary and real parts of the same function. As such, they're bound by a pair of equations called the Kramers–Kronig relations, which dictate that when a substance has a strong absorption resonance, as in the left-hand plot above, its refractive index must look like the right-hand plot, with elevated values across the spectrum. The effect is not unique to tartrazine—glycerol also gets its high refractive index from an absorption resonance, albeit one deep in the UV—but when the researchers screened for the combination of strong absorption, water solubility, and biocompatibility, tartrazine was a clear winner.

The tartrazine concentrations used in the experiments far exceed the amounts you're likely to encounter in foods, and the method hasn't yet been tested on humans for safety or effectiveness. But in the future, it could be. The mouse studies so far are promisingly benign: The researchers need only rub tartrazine on a mouse's shaved skin to see its blood vessels, muscles, and internal organs. And the skin returns to its normal opacity once the dye is rinsed off with water. If approved for use in humans, tartrazine could, among other applications, help phlebotomists collect blood samples. (Z. Ou et al., *Science* **385**, eadm6869, 2024.)

Johanna Miller PT

Search amps up for signatures of cosmic particles in ancient minerals

Advances in imaging and data handling open new possibilities.

What if a mineral could reveal what it's seen over the millions—or billions—of years it's been sitting deep within Earth? An interdisciplinary global network of scientists is reviving efforts to unlock the secrets that minerals hold. The top goals are to identify dark matter, learn more about neutrinos, and use both as cosmological probes.

Over epochs, even a tiny grain of sand would be exposed to an enormous flux of neutrinos and dark matter. Using such samples trades mass for time: A 1 g, billion-year-old mineral offers the same total exposure as a 1000-metric-ton target mass over one year; for the same exposure, the LUX-ZEPLIN experiment at the Sanford Underground Research Facility in South Dakota, with its 5.5 metric tons of liquid xenon, would have to hunt for dark matter particles for 182 years. And whereas giant conventional detectors provide a snapshot from the period of observation, minerals harbor data spanning the history of their existence.

The idea of using minerals to look for fossils of cosmic interactions is not new. In the 1980s and 1990s, a few researchers used mica to search for evidence of exotic particles and dark matter. Such paleo-detection efforts stalled because neither imaging nor data handling was up to the task. At the same time, the enormous liquid and solid-state detectors that have since become the norm were gaining momentum.

But thanks to advances in imaging, data storage, computation, and machine learning, a smattering of researchers are looking anew at paleo-detection. They are motivated by the limitation of multiton detectors, which cannot be significantly scaled up; the allure of obtaining historical data; and the continued elusiveness of dark matter.

Chris Kelso, a theoretical physicist at the University of North Florida, suggests that looking at the rate of supernova explosions over time is doable in the next five or so years. "We understand the neutrino physics pretty well," he says. "That's an advantage of paleo-detectors—we know there is a signal, so I think we can do this."

Damage tracks

Most approaches to using minerals as paleo-detectors would look at the tracks caused by recoil: When an incident particle hits a nucleus in the mineral, the impacted nucleus is knocked out, leaving a hole and dislodging or disturbing other lattice atoms, thereby creating a trail. "Chemical bonds will be broken and atoms will be displaced," says Patrick Huber, a theoretical physicist at Virginia Tech and director of its Center for Neutrino Physics. "Some of those changes will be permanent."

Damage tracks have been used on larger scales for more than a half century to date rocks: When uranium-238 fissions, the products interact with lattice elements and leave tracks typically up to 20 μm in length. The rock's age can be determined from the ratio of the number of fission tracks to the total number of ^{238}U atoms—obtainable by various methods—in the volume.

Although neutrinos seldom interact with matter, now and then one hits a nucleus and gives it a kick. Dark-matter mineral searches would similarly involve analyzing damage trails. Theoretical physicists calculate that the weaker impulses of dark matter and low-energy neutrinos—inducing nuclear recoils in the range of 0.1–100 keV, compared with the tens of millions of electron volts in fission track dating—would lead to tracks that are nanometers to hundreds of nanometers in length.

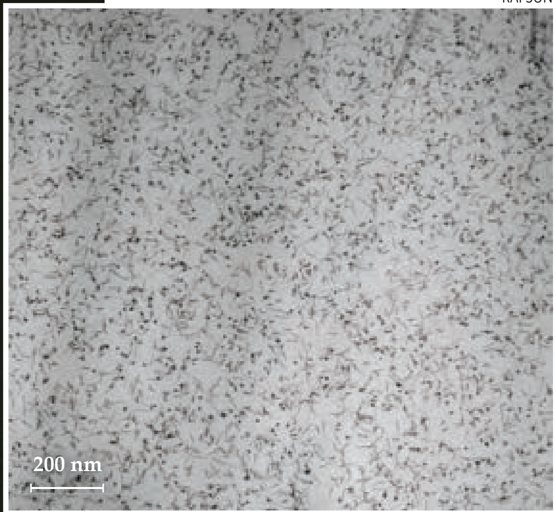
"You model sources of recoil," says Patrick Stengel, a postdoc at the Jožef Stefan Institute in Ljubljana, Slovenia, and one of the theoretical physicists credited with reigniting interest in mining minerals for data. "You wind up with spectra of track lengths, which tell you something about the energy of the incident particles." Through statistical analyses of damage tracks, he says, it should be possible to differentiate among the spectra to identify impinging particles.

Experiments so far have mostly been controls to gear up for analyzing ancient minerals. Shigenobu Hirose is an experimental physicist at the Japan Agency for Marine-Earth Science and Technology. To simulate the 10–100 keV recoils that dark matter would produce, he shoots fast neutrons at processed mica in which tracks have been erased with heat. He then chemically etches the sample to enhance the tracks and render them into pits that are measurable with an optical profiler. "The higher the recoil energy, the deeper the pits," he says.

Hirose has begun searching for evidence of dark matter in ancient mica from a mine in Bihar, India. "We may get some information about dark matter, like the

EMILIE LAVOIE-INGRAM

KAI SUN



TRACKS IN OLIVINE (above) left by incident gold ions and their targets mimic those calculated to be induced by atmospheric neutrinos. The tracks were imaged with scanning tunneling electron microscopy. The ions were shot perpendicular to the image, so the tracks appear shorter than they are. At left are small olivine crystals.

mass and cross section," he says. "Even if we don't find dark matter, we can set limits on those characteristics."

Joshua Spitz, an experimental particle and astroparticle physicist at the University of Michigan, is preparing to search for tracks from atmospheric neutrinos. They are produced from interactions of cosmic rays with molecules in Earth's atmosphere. Tracks from the neutrinos "are surely below our feet," says Spitz. Atmospheric neutrinos "are low-hanging fruit because they create long tracks, up to hundreds of microns in length."

Spitz aims to look at rocks from different places, date them from fission tracks, and plot the atmospheric neutrino rate over time. The solar system orbits the galaxy center roughly every 230 million years. "If you get a billion-year-old rock and others of varying ages, you can probe the cosmic-ray history of Earth over four revolutions," says Spitz. The same can, in principle, be done with dark matter, neutrinos from supernovae, and other cosmic particles.

To get started, Spitz and his group are creating and characterizing tracks in olivine. They shoot gold ions into a sample as a proxy for nuclei recoiling from incident atmospheric neutrinos. The subangstrom resolution of scanning tunneling electron microscopy permits measurement of track width, length, and shape. But it's a 2D probe. To get 3D information, says Spitz, "you have to cut, polish, and scan layers that are about 200 nm thick. It's laborious."

This fall, his university is getting an x-ray machine that will have 17 nm voxel resolution. With that, he says, he will use olivine pebbles up to 0.1 g in size. A 0.1 g, billion-year-old sample is expected to contain about 300 tracks in about 10^{16} mostly empty voxels, he says. "It gets to be overwhelming. You have to store and figure out how to handle the data."

Gabriela Araujo, a postdoctoral researcher at the University of Zurich, is conducting experiments with light-sheet optical fluorescence microscopy. She uses transparent minerals that have been irradiated to form defects, so-called color centers: If an unpaired electron moves into a vacancy created by a recoiling nucleus, she explains, it can absorb and emit light, rendering it fluorescent and thus making the tiny defect visible in optical wavelengths.

The light-sheet microscope shines a 3-μm-thick plane of laser light, causing the defects to fluoresce. The crystal is then moved in steps to create a 3D rendering. A centimeter-size sample can be imaged in minutes, says Araujo. For now, she is using "mimic signals" made with gamma rays, alpha particles, and neutrons in different crystals to gain an understanding of a full range of signals.

Huber's group at Virginia Tech works with Araujo, doing much of the sample irradiation and characterization. In a couple of years, he says, "we should be able to understand reactor neutrinos." His immediate aim is to apply the principles of paleo-detection to nuclear safeguarding: "You could place a clean crystal the size of a Hershey's bar near a nuclear power reactor and come back in three months to change out the bar," says Huber. "The data should agree with the declared use of the reactor."

Mine, image, analyze

Over the past couple of years, the various research groups working in areas related to paleo-detection have come together. Stengel launched an annual workshop, whose first meeting last year in Trieste, Italy, attracted geoscientists, material scientists, and theoretical and experimental physicists from Europe, Japan, and the US. Many of the attendees are now collaborating, and some have recently won grants to work in paleo-detection: Spitz was awarded \$1.25 million over five years from the Gordon and Betty Moore Foundation, and a multi-institutional team led by Huber has \$3.5 million over five years from NSF.

Katherine Freese, director of the Weinberg Institute for Theoretical Physics at the University of Texas at Austin, was involved in the research in the 1980s that spurred the hunt for dark matter and was also part of the team that recently jump-started paleo-detection. "It's really exciting," she says. "We have all these people from all over the world and from all different fields. You learn all kinds of things—for instance, minerals from Europe are no good for paleo-detection, the earth has moved too much. Minerals from the Americas can be useful."

Selecting and collecting minerals for paleo-detection is a challenge. It's best if the minerals are low in uranium and come from places where there is little natural radiation, which can muddy the signals. They should come from deep enough underground to have been shielded from cosmic rays, but not so deep that the heat

GABRIELA ARAUJO AND RICARDO PERES

GABRIELA ARAUJO loads a crystal into a light-sheet fluorescent microscope to create a 3D image of defects. She is studying tracks from known sources to facilitate analysis of ancient minerals. During data acquisition, an arm moves the crystal into an oil immersion chamber (the transparent container at the center). Lenses on either side of the chamber provide the light sheet, and a camera at the back of it captures the fluorescence signals.

melts the signals. Likely sources of minerals are existing mines and bore holes. Scientists also talk about grabbing minerals from beneath the ocean floor and the surface of the Moon.

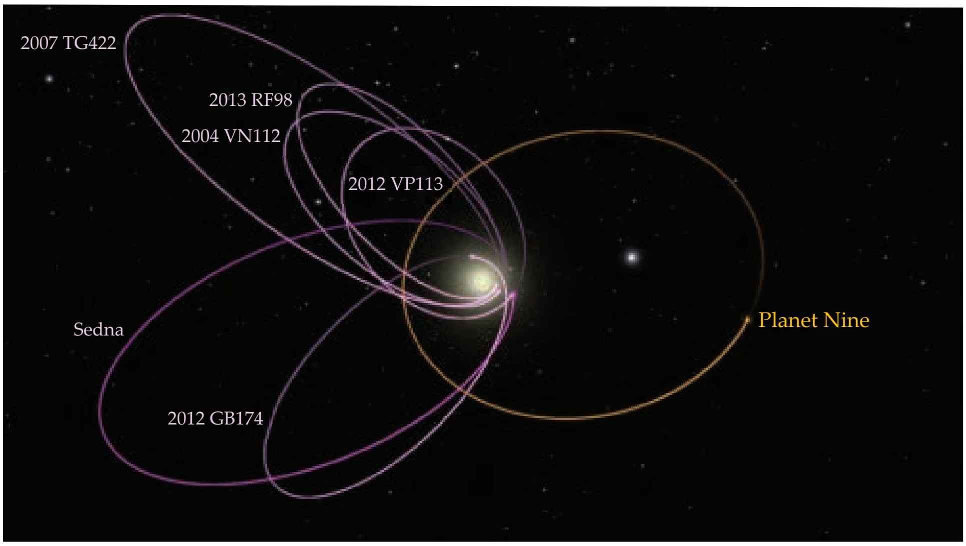
Sorting out the tracks and handling the vast amounts of data will be hard. Artificial intelligence will be needed, says Freese. For example, it could be trained to identify and sort tracks. "I hope to work on that," she says.

"There are a lot of challenges," says Pieter Vermeesch, a geochronologist at University College London who has a hand in paleo-detection. But, he notes, all the existing enormous detectors are extremely expensive compared with paleo-detection. "Even if the chances of success are low with minerals, it's worth it." And developing new readout techniques not only would offer huge benefits to physics but may, he says, "revolutionize geology" by increasing the precision of fission track and alpha-recoil track dating by several orders of magnitude.

Toni Feder

What's up with Planet Nine?

The question of whether it exists may soon be resolved.



THE ORBITS OF SIX EXTREME TRANS-NEPTUNIAN OBJECTS (rendered in magenta) are aligned in one direction, which could suggest the existence of Planet Nine (orbit rendered in orange). (Courtesy of Caltech/R. Hurt/IPAC; diagram created using WorldWide Telescope.)

A decade ago, astronomers Scott Sheppard and Chad Trujillo hypothesized the existence of a sizable planet beyond Neptune. Dozens of papers have since come out with arguments both pro and con and sparked conversations among astronomers and the public alike. Discovery of the planet's existence would raise questions about the solar system's formation and the processes that produced its distant orbit. An additional planet would also explain the behaviors—the paths of the extreme trans-Neptunian objects (ETNOs) that orbit the Sun with trajectories that can't be explained by Neptune's gravitational pull—that led to the initial hypothesis.

Following the 1846 discovery of Neptune, whose existence was predicted before it was directly observed, astronomers wondered if another faraway planet perturbs Uranus's and Neptune's orbits. In 1880, astronomer George Forbes was the first to formally propose the existence of trans-Neptunian planets. Nearly 150 years later, one may be found with the help of the Vera C. Rubin Observatory in Chile, which is slated to begin operations next year.

A group of 13 ETNOs—whose orbits have a semimajor axis of at least 150 astronomical units (AU)—ignited interest in Sheppard, of the Carnegie Institution for Science, and Trujillo, of Northern

OLIVIER BONIN/SLAC NATIONAL ACCELERATOR LABORATORY

THE VERA C. RUBIN OBSERVATORY in Chile will take images of the Southern Hemisphere over the next 10 years, starting in 2025. It will access around 10 billion objects and is poised to detect Planet Nine—if it exists.

Arizona University. They observed that the ETNOs had elongated orbits around the Sun that were too distant to be affected by Neptune's gravitational pull. The pair suggested that another planet was tugging on the orbits.

The puzzle inspired Caltech astronomers Konstantin Batygin and Michael Brown to take a closer look. They published research in 2016 detailing how 6 of the 13 identified ETNOs' orbits point in the same direction in space and tilt about 30° downward from the plane of the solar system. They calculated the chance of both those behaviors occurring randomly to be about 0.007%. After testing and fine-tuning their models, Batygin and Brown supported the idea that a planet herds the ETNOs. They dubbed the hypothetical object Planet Nine. (See the Quick Study by Brown, Physics Today, March 2019, page 70.)

Their models put the planet somewhere between 5 and 10 Earth masses and position it near the outer Kuiper belt, 400–800 AU from the Sun. The small size and great distance mean that very little light would reflect off the planet, making it difficult to detect.

Presenting the evidence

The astronomy community is divided about Planet Nine. David Nesvorny, an astronomer at the Southwest Research Institute in Colorado, says he was skeptical at first. But, he says, "none of my ideas could explain what's going on besides Planet Nine." A ninth planet could be responsible for the retrograde motions observed in some Kuiper belt objects as well as the ETNOs' clustered orbits, Nesvorny says. Using solar-system simulations, he has found that Planet Nine could also explain why some objects make their way inside Neptune's orbit from beyond the Oort cloud, which is located far beyond the edges of the Kuiper belt.

Samantha Lawler, an astronomer at the University of Regina in Canada, remains skeptical about Planet Nine. "I am convinced there are strong observational biases in the ETNOs that we need to be very careful about," she says. Because ETNOs reflect very little light at such great distances, they have been observed only when they are in certain areas of the sky and close to the Sun, she says. Lawler worked on the Outer Solar System Origins Survey, which detected more ETNOs with high perihelion distances. With the added ETNOs, according to the survey's study published in 2017 in the *Astronomical Journal*, there's no evidence of clustered orbits.

Others attribute the ETNO orbits to a dark-matter effect or a misunderstanding of how gravity works, but both theories are "very complicated explanations" for what is likely going on, says Lawler.

Astronomer David Tholen at the University of Hawaii says he is "in the gray area" when it comes to Planet Nine. He says that astronomers use different sets of ETNOs to measure clustering and alignments. Because the "cutoff for which objects are chosen is arbitrary," more data are needed for him to support or reject the hypothesis. "I'm not sure if the evidence is leaning one way or another right now," says Matthew Holman, a Smithsonian astrophysicist and lecturer at Harvard University. But, he adds, the possibility of Planet Nine is compelling enough to warrant research time.

This past April, Batygin and Brown published more evidence that Planet Nine exists. Their study focused on a new set of low-inclination trans-Neptunian objects with orbits that reach the inside of Neptune's orbit. According to the study, those objects could only make their way into the inner solar system if another planet were there to slingshot them. A planet could also explain how the objects were pulled into the solar system and how their orbits were formed.

Planet Nine hunters have their sights set on the Rubin Observatory. It boasts an 8.4-meter telescope and the largest camera ever built for astronomy research. The camera will scan the Southern Hemisphere sky every night over the next decade and is expected to access around 10 billion objects. Planet Nine's estimated brightness and distance fall into the observatory's capabilities. "If we find something moving out around 500 to 600 AU, it will be Planet Nine," says Brown. If Rubin doesn't find Planet Nine within a few years, he adds, "we'll try using radio telescopes."

Hannah H. Means

Q&A: Engineer Stewart Isaacs seeks equitable climate change solutions

Hard work, creativity, and problem-solving are key to Isaacs's success in both science and another passion: jump rope.

STEWART ISAACS

Stewart Isaacs got interested in developing solar-powered chicken egg incubators in 2016, when he was an undergraduate student. The project's goal of supporting self-determination and food sovereignty in West Africa resonated with his desire to use his engineering skills to support communities in need and break down inequities. "I liked what the incubator project was trying to do," he says, "but I didn't think it would be interesting technically. I was wrong."

Even as he pursued a master's degree in aeronautics and astronautics, Isaacs kept a hand in the ongoing egg incubator project. He visited Burkina Faso to see the project in action. Then, in 2019, when he finished his master's, he flew to Ghana to learn more. Propelled by nagging questions about the incubators' solar power conversion, he decided to go for a PhD, which he earned this past May. He is now a postdoctoral fellow at MIT pursuing research that addresses both climate change and social inequities through the development of clean energy systems.

Aside from his research, another passion of Isaacs's is the sport of jump rope. He won the 2017 Grand World Championship in single rope freestyle; see him compete at https://www.youtube.com/watch?v=2yZz_HIP1so.

PT: How did you get involved in solar-powered egg incubators?

ISAACS: When I was a senior at Stanford University, I met Dena Montague, a researcher from the University of California, Santa Barbara, who was looking for students to support her in developing solar-powered chicken egg incubators for use in West Africa. The project was well aligned with my goals: I was interested in using my skills to support communities in need, especially Black communities.

It took a few years before we got to the point where the incubators were functional. One of our primary design goals was for the system to be locally manufacturable, so that when things inevitably break, the users can fix the incubators and make sure they meet their needs.

PT: What did you do in Ghana?

ISAACS: Dena has a nonprofit, ÉnergieRich, that initially worked with a community in Burkina Faso. I didn't think MIT would pay for a trip to Burkina Faso because the US State Department had a Level 3 warning about travel there, so I went to neighboring Ghana. I thought it would be a nearby alternative, where I could still learn and start to question some of the assumptions I had.

While I was there, I looked for partners to support the development of the incubators. I also accepted a position as a teaching fellow at Ashesi University. I taught mechanics and thermodynamics. And I learned a lot from my students—especially about how to live without infrastructure, like how to store water in large containers in case the water goes out and to ensure electronics stay charged for if the power goes out.

PT: What were some of the assumptions you were questioning?

ISAACS: I didn't think there was a lot of manufacturing capability in the region, but there is. A lot of people have programming skills and access to technology.

Another thing I learned was that the solar panels were not converting as much energy as we had calculated. Ultimately, that problem led me into my research for my PhD.

PT: Had you always intended to do a PhD?

ISAACS: I had gone back and forth. Some of it was realizing there was an opportunity to do research on solar energy conversion and to play a role in making sure that communities can get the energy they need. A lot of it was also my experience at Ashesi University. The students I worked with had at the forefront of their minds, How can I use engineering to support my community? How can I bring clean water? How can I help clean up the air? Teaching is a way to support people

STEWART ISAACS

THE SOLAR PANELS behind a hospital near Koupéla, Burkina Faso, inspired Stewart Isaacs to do his PhD research on the impact of dust on solar energy output.

in getting their needs met. It made me realize the power of academia. Because of that, and because of my questions about the solar-powered incubators, I felt that getting a PhD would be right for me.

PT: You returned to MIT. What was your PhD topic?

ISAACS: The fact that the solar panels powering the egg incubators were not converting as much energy as we thought was a big deal. It turns out it was related to the Harmattan—the annual dry, seasonal wind in the region—when, from November through March, dust from the Sahara desert blows in and obscures sunlight. It can reduce the energy output of the panels significantly.

So for my PhD, I asked, What is the impact of the dust on the solar panels? And what can we do about it? I wrote a proposal that was funded by the NASA Jet Propulsion Laboratory for me to do the project. For the next few years, I spent time using remote sensing data from satellites and other sources, developing models, quantifying the impacts of dust on these panels, and looking for ways to mitigate the impact. When systems like these fail, you can lose food, medicines, and more.

With the remote sensing data, I began to estimate the accumulation of dust on the panel surfaces as well as the amount of dust in the air and to calculate the impact on the net power output. I looked at the physics of adhesion and removal of dust particles from the panel surfaces and at how the wind interacts with dust particles. I wanted to see if changing the shape of the panels could enhance the wind removal of dust and improve the power output.

PT: And?

ISAACS: I don't know yet. From our modeling, my collaborators and I see that there could be some benefit. But we won't know for sure until we do tests *in situ*. We need experimental data. I'm continuing to work with researchers at Ashesi to set up monitoring systems so we can measure the influence of dust on these panels.

PT: Are you leading your own program?

ISAACS: The ideas are mine, and I am heading up the research. I get support from my advisers, in particular Wesley Harris, and I have several undergraduates working with me on wind tunnel tests of different panel shapes.

PT: Your interest in mitigating climate change didn't start with solar energy; for your master's, you modeled carbon dioxide emissions from various processes for creating synthetic jet fuel from air and water. Why focus on the intersection of climate change and social inequities?

ISAACS: My theory is that addressing climate change is entangled with addressing large inequities in the world. If we are not intentional about addressing the inequities as we solve climate change, we will continue to perpetuate them. And that shoots us in the foot.

I want to go the faculty route. There are not enough people doing the research that I feel the world needs when it comes to developing energy technologies to support communities. It feels well aligned with how I want to live in this world.

PT: Describe some of your community-building activities.

ISAACS: At MIT, with other graduate students, I cofounded AeroAfro, a community group that brings together Black graduate students in the aeronautics and astronautics department. The group creates a space for us to be ourselves, and it's also a useful way to advocate for policy changes that improve the department for everyone.

For example, our department recently started an HBCU [Historically Black Colleges and Universities] outreach program. We work with researchers from Howard University and other HBCUs to have students join us at MIT for our summer research programs. We also offer support to those students when they apply to graduate school. A few have joined our department.

I've also been in leadership in the MIT-wide Black Graduate Student Association. The idea is to be in community with one another, and to be able to speak out together about issues that we are facing.

PT: Where does jump rope fit in?

ISAACS: My elementary school had a jump rope team. My sister wanted to join, and I was like, "Me too." I started when I was five years old, and I haven't really stopped. I slowed down when my PhD started eating into my time and my priorities shifted a bit. But I still do it, and I am considering competing next June in the national championships in South Dakota.

PT: Do jump rope and your research feed into each other? Are there synergies?

ISAACS: Yes. In jump rope, you have the basic building blocks of tricks. You need to combine them in ways that look interesting and are creative and fun to do. In engineering, you have the basic building blocks of physics. When you need to solve a problem, you need to come up with a creative solution to get there. And jump rope is hard. To be really good at it takes a lot of effort. The habits of working hard and problem-solving are also very useful in engineering.

Toni Feder

NASA urged to boost R&D at expense of near-term missions

An independent committee says the space agency must urgently rebalance its budget to invest in people, research, and infrastructure.

DENNY HENRY/NASA

AN ENGINEER adjusts equipment at NASA's Goddard Space Flight Center.

NASA's long-term success requires the space agency to invest in R&D, scientists, and infrastructure, even at the expense of initiating new missions, says a new report from the National Academies of Sciences, Engineering, and Medicine. Congress requested the consensus study report, titled *NASA at a Crossroads: Maintaining Workforce, Infrastructure, and Technology Preeminence in the Coming Decades*, as part of the 2022 CHIPS and Science Act to review what NASA needs to achieve its long-term strategic goals and mission objectives.

Released on 10 September, the report concludes that "to avoid a hollow future" for the agency and to keep up with increasing international competition, particularly from China, NASA must rebalance its priorities—even if that means making some difficult choices. "In an opportunity-rich environment, such as NASA has confronted over the years, the choice has too frequently been to pursue near-term missions at the expense of investing in the ostensibly invisible foundational assets of the organization," the report states. "The inevitable consequence of such a strategy is to erode those essential capabilities that led to the organization's greatness in the first place."

Insufficient funding and uncertainty surrounding NASA's long-term budget are highlighted in the report as "often incompatible with the scope, complexity, and difficulty" of the agency's work. The report notes that in recent years, NASA's missions budget as a percentage of its total budget has increased from 79% to 85%, whereas its budget for activities that support multiple missions, such as developing new technologies, has decreased from 20% to 14%. The result is that "each dollar of mission support that previously had to sustain a dollar of mission activity now has to support $1.50 of mission activity, effectively a 50 percent increase." The report recommends that NASA "aggressively increase investment in internal research and development to advance early-stage, future mission critical technologies that are not commercially available."

The report highlights that NASA faces competition for scientists and engineers from the private sector, which frequently offers better pay, benefits, and work flexibility. The growth of the space economy also means that NASA is no longer the only employer offering "challenging hands-on work in the field of space exploration," the report says.

The report also recommends that NASA grow its in-house technical competencies by avoiding outsourcing early-stage activities to contractors. "The nation cannot afford to have NASA just become a funding agency for industry," said Lester Lyles, a report committee member and chair of the NASA Advisory Council, during a 10 September webinar on the report findings. Lyles emphasized the importance of NASA employees understanding what they are developing instead of simply outsourcing everything to industry partners. Finding the right balance with industrial partners can be achieved through contracts and cooperation, said Lyles, but NASA needs to address that balance quickly.

Aging infrastructure is becoming a major issue for NASA, as it is for other science agencies, including the Department of Energy and NIST (see PHYSICS TODAY, June 2023, page 18). The report says that 83% of NASA facilities are past their design life. NASA should work with Congress to establish a working capital fund to help eliminate the agency's $3.3 billion maintenance backlog over the next decade, the report says. It suggests that an annual contribution of about $600 million would meet NASA's property repair and renewal goals through fiscal year 2028.

"The bottom line of all this, I think, would be to say that, for NASA, this is not a time for business as usual," said Norm Augustine, report committee chair and former Lockheed Martin CEO, during the webinar. "The concerns it faces are ones that have built up over decades. And NASA truly is, in our view, at a crossroads."

Lindsay McKenzie

Longitudinal study tracks why undergrads stick with or leave physics

Many students entering college with an interest in physics don't end up pursuing it. Why do those who stay, stay? And why do those who leave, leave? A five-year study by the American Institute of Physics (AIP; publisher of Physics Today) considered those and related questions. The data, analysis, and recommendations for boosting the numbers of physics majors are presented in the recently released report *Attrition and Persistence in Undergraduate Physics Programs*.

For the study, AIP Research surveyed 3917 students in introductory physics courses at four large, predominantly white US universities during the 2018–19 and 2019–20 school years. Students were asked whether they were interested in majoring in physics; 745 said yes or maybe. The AIP researchers sent those students follow-up yearly surveys by email through spring 2023—or until they said they were no longer interested in the major—to see how factors such as race, gender, high school preparation, physics course experiences, self-perception of math proficiency, and self-confidence in physics tracked with their outcomes. The researchers also had one-on-one interviews with 75 students who graduated in physics and 39 students who lost interest.

Among the reasons that students gave for persisting in physics are a feeling of accomplishment and the field's relevance for math and other sciences.

More than 70% of the students who did not stay in physics left by the beginning of their second year. The interviewed students who had left the major cited both "pull" reasons, such as being more interested in another subject or career path, and "push" reasons, such as negative experiences in a physics course or physics department (see the chart).

"When students leave a physics major because of burnout or negative experiences in physics classrooms, I think it's a missed opportunity," says AIP's Anne Marie Porter, a coauthor of the report. "These students care so much about physics, and if circumstances were different, they would have been able to stay in the major."

The most common major to switch to from physics was engineering (71%), followed by math (46%). Other popular destinations were astronomy or astrophysics (44%), computer science (37%), and chemistry (21%). The most common non-STEM choice was business (14%).

Of the students who left physics, those from underrepresented groups and women were more likely than their white counterparts and men to report encountering discrimination and otherwise having more unsatisfactory social experiences in their programs. African American and Hispanic students were less likely to report feeling that they received encouragement from physics professors. Women were more likely to say that they believed that they performed worse on physics assignments than their peers.

The study also delivers on the question for which it was originally crafted: When do women lose interest in physics? It's not that the field of physics is driving away women but rather that "women are a lot less interested than men in majoring in physics," says coauthor Rachel Ivie. "It happens way before college." The director of higher education programs and grants at the American Association of Physics Teachers, Ivie designed the study when she was director of AIP Research. The motivation for the study, she says, was the drop in female representation from more than 50% in high school physics classes to about 20% of physics majors, where it's hovered since 2005.

Recommendations to assist physics departments in attracting, retaining, and increasing the number of enrolled students can be found in the report. They include supporting undergraduate research programs; discussing physics careers early in the college experience; designing shorter, more flexible physics course sequencing; and prioritizing inclusion and retention.

Tonya Gary

Reason for leaving physics	Percentage of interviewees who cited each factor
Pull factors	
Interest in another subject	74
Interest in a different career path	32
Positive course experiences in another subject	29
Positive department climate in another subject	5
Push factors	
Negative course-sequencing experiences in physics	38
Negative course experience in physics	28
Negative department climate in physics	3

(Adapted from *Attrition and Persistence in Undergraduate Physics Programs*, table 11; https://ww2.aip.org/statistics/attrition-and-persistence-in-undergraduate-physics-programs.)

INTERVIEWS WITH 39 STUDENTS WHO LEFT PHYSICS revealed several broad classes of reasons for their decision. Some students were "pulled" toward other majors because of positive experiences and interests, and some were "pushed" away by negative experiences within physics, such as the long, rigid sequence of courses. Many of the students provided multiple reasons for leaving the field, so the percentages add up to more than 100%.

FYI SCIENCE POLICY BRIEFS

US ramps up semiconductor workforce training programs

The Department of Commerce announced the first awards in September for the National Semiconductor Technology Center's new Workforce Center for Excellence, which is set to receive $250 million from the department over 10 years. The initial awards total $11.5 million for seven institutions; the department expects that they will help train more than 12 000 people over the next two years. One award will establish the Center for Education of Microchip Designers at UCLA that will teach hundreds of undergraduate and graduate students how to design, fabricate, and test their own chips. Other funded projects target high school and college students, semiconductor technicians, and hardware verification engineers. Also in September, NSF and the Commerce Department announced a $30 million funding opportunity to establish a hub that will manage the National Network for Microelectronics Education, which plans to spend up to $200 million preparing people for roles in the microelectronics workforce. —CZ

Quantum cryptographic standards ready for use

NIST is urging IT administrators to employ its newly released encryption tools designed to withstand attacks by future quantum computers. The three tools, unveiled in August, are the first global standards for post-quantum cryptography, according to the White House, and are designed for general encryption across public networks and for digital signatures. Two of the new standards are based on structured lattices and the other on hash functions, making the algorithms more difficult for quantum computers to break than current ones that multiply large prime numbers. (See PHYSICS TODAY, November 2023, page 21.) Meanwhile, the agency is evaluating two other sets of algorithms that could one day serve as backups in case an attack defeats the main standards. The new standards are the culmination of an eight-year effort managed by NIST. Their release starts the clock on a series of actions required by a 2022 presidential memorandum on quantum cryptography, including that the secretary of commerce release within 90 days a proposed timeline for moving as many systems as possible off quantum-vulnerable cryptography over the next decade. —CZ PT

FYI (https://aip.org/fyi), the science policy news service of the American Institute of Physics, focuses on the intersection of policy and the physical sciences.

AIP | FYI

THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

TENURE-TRACK FACULTY POSITIONS IN PARTICLE PHYSICS AND COSMOLOGY

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

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

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

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

Separate applications should be submitted online for each position below:

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

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

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

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

Cornell University

TENURE-TRACK ASSISTANT PROFESSOR OF EXPERIMENTAL OR THEORETICAL CONDENSED MATTER PHYSICS

The Laboratory of Atomic and Solid State Physics (LASSP) at Cornell University invites applications for a tenure-track appointment at the assistant professor level, to begin July 1, 2025. We encourage applications in any and all areas of experimental or theoretical condensed matter physics. Review of applications will begin on November 14, 2024.

Areas of interest include (but are not limited to) biophysics; cold atoms and molecules; hard and soft condensed matter physics; quantum materials synthesis; optics; quantum information and devices; statistical mechanics of adaptive systems, information geometry, and materials; x-ray physics; and physics education research. Candidates must hold a doctorate in an appropriate field. They must have demonstrated an ability to conduct outstanding research and show promise for future excellence in research and teaching within the physics department. They should be committed to enriching the diversity and excellence of Cornell's academic community.

For more details and to submit your application, please visit Academic Jobs Online, Position ID #28591. All applications must include: curriculum vitae; publication list; research statement (~4 pages); teaching/mentoring statement (~1 page); at least three letters of recommendation.

The research statement should include a summary of prior work and a proposal for future work. It should explain the importance of the candidate's research, disambiguate their role in multi-author publications, and present both a short-term and long-term vision. The teaching/mentoring statement should give an account of prior teaching and mentoring experience and describe the candidate's approach, philosophy, and ambitions. We ask applicants for all faculty positions to share their approaches to fostering learning, research, service, and outreach in a diverse community. Applicants may choose to submit a stand-alone statement or embed the information in other parts of their application materials.

Pay Range: $83,200-$125,000

Actual salary offers in the College of Arts and Sciences will be based on education, experience, discipline, and relevant skills.

Cornell University embraces diversity and seeks candidates who will contribute to a climate that supports students, faculty, and staff from all identities and backgrounds. We encourage individuals from underrepresented and/or marginalized identities to apply.

ERIC STOCKLIN PHOTOGRAPHY

From left: Evgeni Gousev, Jesse Thaler, Valerie Browning, Walter Copan, and France Córdova, moderator.

France Córdova is chair of the AIP Foundation Board of Trustees, president of the Science Philanthropy Alliance, and a former director of NSF. **Valerie Browning** is vice president of research and technology for Lockheed Martin's Corporate Technology Office, and she is on the AIP Board of Directors. **Walter Copan** is vice president for research and technology transfer at the Colorado School of Mines and a former director of NIST. **Evgeni Gousev** is senior director of engineering at Qualcomm Research and board chair of the tinyML Foundation, and he is on the AIP Foundation Board of Trustees. **Jesse Thaler** is a professor of physics at MIT and director of the NSF Institute for Artificial Intelligence and Fundamental Interactions.

Physics, AI, and the future of discovery

France Córdova, Valerie Browning, Walter Copan, Evgeni Gousev, and Jesse Thaler

Leaders from industry, government, and academia discuss the potential impact of AI on physics—including neutrinos, exoplanets, term papers, outreach, and workforce gaps—and of physics on AI.

Artificial intelligence and physics are changing one another, with implications that stretch from the classroom to the stars. The impacts can be seen across academia and industry, defense and security, granting and governance.

Leading physicists in academia, government, and industry came together earlier this year for a panel discussion to share their hopes for how machine learning and generative AI could transform discovery, creativity, intellectual property, training, communication, and the workforce. Convened by the AIP Foundation on 11 April 2024 at the American Center for Physics in Washington, DC, the event was chaired by former NSF director France Córdova. (The AIP Foundation is part of the American Institute of Physics, which publishes Physics Today.) She noted how AI is revolutionizing so many aspects of science: "Artificial intelligence is in everything, everywhere, all at once, like an artful phantom, or a worrisome one, depending on your point of view."

The following text is adapted and condensed from the transcript of the event.

CÓRDOVA: How is AI changing physics research? Is it accelerating discovery or catalyzing incremental advances?

France Córdova

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JESSE THALER (MIT and NSF): I was skeptical in 2016 when people were talking about the deep-learning revolution. I'm a theoretical physicist, so I do "deep thinking" with my chalk and chalkboard. I've since realized how the time-tested strategies of physics can merge with machine-learning strategies for processing large data sets. That has led to many advances.

Here are just three examples from my institute. We'd like to understand the strong nuclear force. To that end, 10% of all open supercomputing resources in the US are now devoted to solving the equations of lattice quantum chromodynamics, which describe the strong interaction that binds quarks and gluons into protons and neutrons and then into nuclei. Some of my colleagues are using a kind of generative AI to do first-principles calculations of hydrogen and helium and march through the periodic table.

Neutrino physics is another strategic area that the US is investing in. An experiment is being built to send beams of neutrinos from Fermilab to a mine in South Dakota (see the article by Anne Heavey, Physics Today, July 2022, page 46). The detector relies on liquid-argon time-projection chambers that give exquisite access to information about neutrinos. We can't process this complex data—and reliably reconstruct neutrino events—without AI.

Those are both examples of how AI can influence physics research. But how can physicists influence AI research? I like the example of grokking. This is when a machine-learning algorithm is running and running and not learning, then suddenly has an epiphany. To a physicist, that sort of abrupt change is a phase transition. And indeed, what happens in grokking is that a gas of information suddenly crystallizes into knowledge. A lattice structure emerges in the latent space of learning architecture. Physicists are uniquely positioned to understand this process.

I'm holding on for dear life as my junior colleagues drag me deeper and deeper into this world that I so distrusted at first. In 2016, two graduate students showed me their machine-learning paper. It was in direct competition with my work. I had toiled to do quantum field theory calculations, and here they were with some neural network. I told them all the things that were wrong with their paper: "It's not interpretable. You don't have the uncertainties. You don't understand the concepts involved." I thought they'd go work for someone else for their PhD. Instead, their theses basically addressed all my concerns.

This experience showed me how we should not just take AI off the shelf and use it as is. To adapt these methods for physics, we need to include all the things that we usually do in pursuing our high standards of scientific discovery.

> "We have seen a revolutionary shift in federal science and technology investment in AI."
>
> —Copan

Walter Copan

ERIC STOCKLIN PHOTOGRAPHY

WALTER COPAN (Colorado School of Mines): There are so many ways that I see artificial intelligence coexisting with physics research.

Take the hardware of big physics experiments. AI control systems are enabling setups that used to take graduate students months, such as the control of exquisite laser experiments on really complex optical tables, or how we shape beams and particle accelerators to deliver exactly what is needed at the energy distribution required.

Exoplanets are another great example. AI was at the heart of finding or validating many of the 5000 planets discovered so far. They're normally spotted because of variations in the intensity of the signals coming from a star when a planet orbits it. Artificial intelligence is absolutely suited to that kind of pattern-recognition phenomenon in time.

Indeed, AI pattern recognition can speed physics research and the discovery process anywhere massive amounts of data are involved, such as at the Large Hadron Collider or what we anticipate from the Electron–Ion Collider experiments at Brookhaven National Laboratory.

VALERIE BROWNING (Lockheed Martin): Now with large language models and generative AI, artificial intelligence is evolving from being a very valuable computational tool into more of a collaborator. That will further accelerate discovery. There is real promise in several areas: the intersection of quantum computing and machine learning, the

Jesse Thaler

ERIC STOCKLIN PHOTOGRAPHY

> "Generative AI can bring together technical experts and the public and create more opportunities for exchange."
>
> —Thaler

discovery of new materials for renewable energy systems, and at the nexus of physics-informed neural networks and machine learning.

CÓRDOVA: What is the perspective from industry?

EVGENI GOUSEV (Qualcomm Research and tinyML Foundation): In Silicon Valley, we develop leading-edge AI technologies, both hardware and software: all the tools used for scientific research. But developmentally, AI is at the toddler stage. You can teach a teenager to drive a car in about 10 hours. We've spent billions of dollars and more than a decade on autonomous driving, and it is not there yet. AI technology is still at the very beginning. Under the hood, it is running some basic probabilistic equations, doing matrix multiplication. This brute-force approach is not sustainable.

That's where physicists can add value. We're trained to solve problems and to connect dots. There are huge opportunities for us to help make AI more explainable, reasonable, reliable, and scalable.

CÓRDOVA: Are there risks for research?

BROWNING: Nothing about AI negates the need for due diligence and the scientific method. The risk comes in when you try to put things into practice. Models or insights that were developed using AI and machine-learning tools may have been valid in certain regimes or with certain constraints. There is risk when those caveats don't flow into the engineering process.

In aerospace and defense, a mistake can be life-threatening. So a lot of what we do is to bring in that engineering rigor. Evaluation, validation, and verification is a challenge when you're trying to anticipate all the edge cases—the rare events—that might arise in a very dynamic and potentially resource-constrained environment.

COPAN: Risk is a trust-but-verify situation. Take AI and exoplanets again. The accuracy of the discovery process was over 96%. We can learn from what is not being predicted and from where we see false positives.

NIST has a key role with regard to standards for trustworthy AI. It is important for a range of applications to have test beds, where protocols for artificial intelligence can be validated and their accuracy can be verified independently.

CÓRDOVA: How is AI changing education?

THALER: On our campus, there's a divide between people who are enthusiastic about AI and the ostriches who are putting their heads in the sand and saying that AI is not going to be relevant. But if we aren't bringing these tools into the classroom, then we're basically not doing our job as faculty to teach.

And once you force students to use generative AI, it really changes the type of exam you need to write. These days, a student can use a ChatGPT-style bot to answer a question about how to run, say, the kind of code that crunches data from the Laser Interferometer Gravitational-Wave Observatory. The chatbot can even generate example code. My MIT colleagues are developing a chatbot for scientific workflows. It is an incredible learning resource. Students who might not even know how to pose questions can interact with a chatbot to find out answers to things buried in the technical literature.

COPAN: Artificial intelligence and machine learning are now the basic tools with which science is conducted. It is impor-

ERIC STOCKLIN PHOTOGRAPHY

"Now is a great time for physicists to shine.... We can bring more explainability, efficiency, and common sense into the current chaotic world of AI."

—Gousev

tant that students become AI literate. They are the ones who are going to be advancing physics through AI and vice versa.

CÓRDOVA: Is AI altering science communication?

THALER: Here, possibilities have grown in a surprising way, as I found out through an April Fools' joke at my expense called ChatJesseT. It is a chatbot that knows all my papers, my Wikipedia entry, and my webpage. ChatJesseT speaks very enthusiastically about physics and AI. The students and postdocs at MIT built it using retrieval-augmented generation—drawing from a trusted corpus of text—plus some prompt engineering. This inspired us to train a chatbot on all of J. Robert Oppenheimer's papers. It can give answers about technical concepts, such as the Born–Oppenheimer approximation, and about issues at the intersection of society and physics.

We found that the bot, Open-AI-mer, can spark a dialog with the public about the promise and perils of AI. Visitors to the Cambridge Science Festival were very interested to talk to Open-AI-mer and then to ask the physicist at the stand whether the bot's responses were hallucinated or real.

With my curmudgeon's hat on, I used to think we'd never be able to use a language model for scientific discovery because the argot of physics is equations. I've come to appreciate that a ton of data is in the form of text. For instance, a high school student and a postdoc used AI with a database of *Hubble* images—it had the images from the *Hubble Space Telescope* and the proposals used to justify the telescope time. They put together the textual data and image data and created a new way of interacting with a scientific data set.

We physicists are realizing, perhaps to our chagrin, that language is actually a powerful means of communication. Generative AI can bring together technical experts and the public and create more opportunities for exchange.

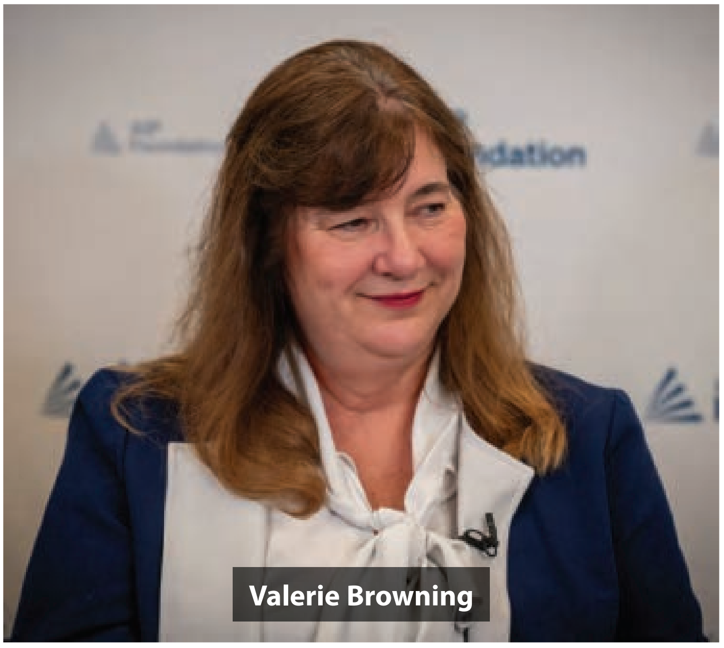
Better still, we'll be able to customize our own chatbots—ChatFrance, ChatWalt, if you will—to meet our needs. My wife is a lawyer. Her prompt-engineered version responds to certain types of legal questions in a format that's useful for her professionally. Even if we don't have programming expertise, we can program such tools to do various tasks that otherwise would be quite onerous.

CÓRDOVA: What are the key policy considerations for government funding agencies?

BROWNING: Approximately 70% of the roughly $4 billion budget that DARPA [Defense Advanced Research Projects Agency] is investing in R&D is either leveraging AI or advancing it.

COPAN: We have seen a revolutionary shift in federal science and technology investment in AI. It naturally takes time for policy and regulation to catch up with the scale and pace of scientific discovery and technology. Now that the US wants to be the global leader in artificial intelligence, agencies will start to question if researchers are not using AI to achieve their results in a way that's cost-effective and that ultimately develops scalable models that can be used for other purposes. Clearly, the opportunities across all science agencies will be tempered with the need to utilize the scientific process to validate models.

But the extent to which the US can capitalize on artificial intelligence as a force multiplier, as an enabler, and as a driver of efficiencies within the economy is also a workforce issue. There are gaps across the labor force that need filling, within



ERIC STOCKLIN PHOTOGRAPHY

> "Nothing about AI negates the need for due diligence and the scientific method."
>
> —Browning

and beyond the scientific enterprise, now and in the future. These have policy implications.

CÓRDOVA: Industry has most of the AI resources right now. Universities need these tools to pursue basic research questions. These tools are expensive and scarce. What's the solution?

BROWNING: The challenge exacerbates the broader and longer-standing problem of inequities in high-power computing, including access to graphics processing units at our academic institutions. This hampers experiential learning. A student with access can work on some challenging real-world problems, and that experience can open doors that are shut to those who have fewer resources. Fixing this needs focus, consideration, and investment.

As a country, we recognize that access is a problem. The CHIPS and Science Act, for example, proposes big increases in funding to support greater access to STEM fields, including quantum and AI, and to strengthen research infrastructure and advanced computing. But there is more that needs to be done for today's students.

GOUSEV: Part of the problem is that right now everything's overhyped, from prices to order volumes. But AI is not a one-size-fits-all tool. Universities have to use it in a smart way, starting from the problem you're trying to solve. The data in the cloud is pretty much already consumed by the GPT-type models. But there's a lot more data in the real world. That's what we need AI to collect and make actionable.

The hype is going to lessen. More capacity is coming as more startups enter the space to develop new approaches, innovations, techniques, and hardware. Algorithms will get more efficient. A human brain consumes 20 watts of power, and we can do very complex tasks. Graphics processing units can consume kilowatts—they're super inefficient. I'm optimistic that AI is going to become more and more efficient and affordable.

AUDIENCE MEMBER: Are people with the right skills holding the reins of AI development?

GOUSEV: Now is a great time for physicists to shine. We've been a bit in our shells since a lot of physics discoveries were made in the 20th century. It's time to come back. We can bring more explainability, efficiency, and common sense into the current chaotic world of AI.

COPAN: In training physicists, we've got to work on the whole package and give them the ability to communicate persuasively and clearly so they can build consensus and teams. What is needed now is a combination of physics, business acumen, emotional intelligence, and communication skills: physics-plus.

THALER: At our NSF AI institute, we are training incredibly talented interdisciplinary experts who go on to jobs in industry. They are top-notch problem solvers. Once you get those people on the ground floor of influential companies, they're going to rise all the way to the top.

AUDIENCE MEMBER: What role does AI play in innovation and creativity?

THALER: We don't take enough advantage of the ability of computers to explore vast landscapes of possibilities. Part of me wonders whether some of the pinnacles of human achievement could have been reached through exhaustive search. Could Einstein's relativity have come from an optimization principle? Did it really need the understanding of the geometry of spacetime? Was there some other way to get to that insight? Part of me thinks that we might have gotten lucky in the physical discoveries of the past. Things were simple and perturbative. Physicists could use basic rules to progress.

Vint Cerf

ERIC STOCKLIN PHOTOGRAPHY

Maybe the problems we now face are intrinsically complex. Maybe physicists need to be careful about reducing things too far, to their simplest forms. Maybe we must embrace some level of complexity. Maybe for breakthrough physics insights, we need to start to think a little more like a computer and churn through many, many different options. Perhaps brute force is the future of creativity.

COPAN: Experimental design and discovery are intrinsically human activities. We are in a very interesting symbiosis now with machines. There's the patentable part of a discovery and the wild landscape of copyrightable work. What constitutes the beginning of one creative process, and what was the role of AI or of a machine-assisted program?

The US Patent and Trademark Office and other intellectual property offices around the world have made certain policy decisions about inventive activity and the role of the human inventor vis-à-vis machines. But in some ways, these are artificial constructs. It's an evolving landscape.

BROWNING: There are examples in which AI has rediscovered laws of physics that we know. Who's to say we're not on the verge of AI discovering something new? And AI can explore lots of different options with just some prompts. Say I want to design a heat exchanger with particular properties but without the biases of what a heat exchanger looks like today. AI comes up with some pretty creative options. Pair that with new manufacturing techniques and materials, and I think there's promise.

CÓRDOVA: We happen to have the father of the internet, Vint Cerf, in the audience. [Cerf is vice president and chief internet evangelist at Google and a recent trustee of the AIP Foundation.] It seems fitting to give him the last word.

VINT CERF: It's important to distinguish between general machine-learning models and specific large language models. The former have shown an ability to discover correlations that we might not have noticed. Noticing correlations is an important part of discovery in physics. With the large language models, I think we don't fully appreciate what the hell is going on. We know that they are generative, and we know that they can hallucinate, but interestingly, they do bring together some unexpected juxtapositions as a result of the training methodology.

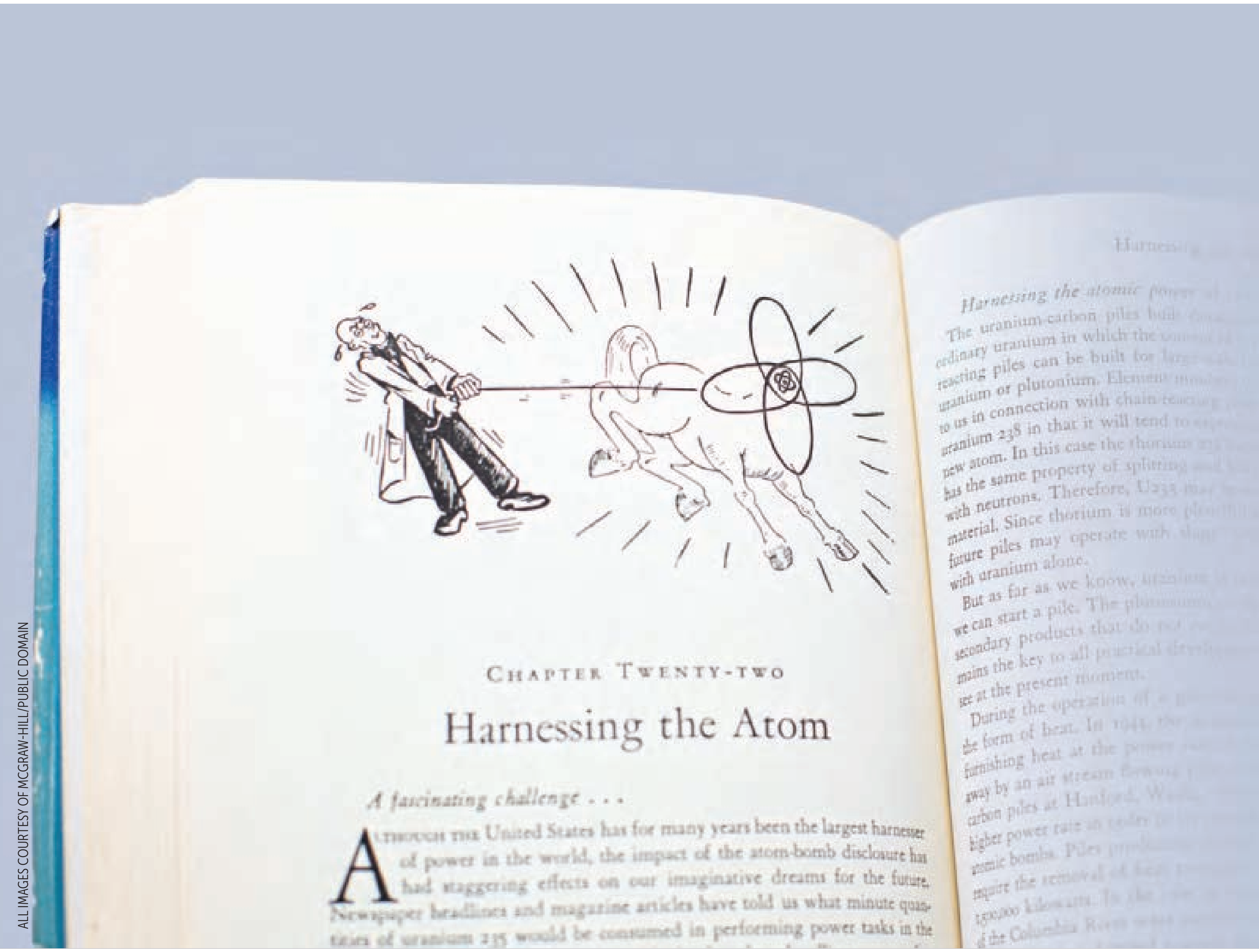
The thing is that they don't have enough context. I tested this by asking a large language model to write an obituary for me, and it generated a 700-word bio. It gave a date, which I thought was way too soon. It talked about my career. It gave me credit for stuff I didn't do. It gave other people credit for stuff I did. It made up family members I don't have.

This illustrates how large language models produce the verisimilitude of human discourse. They respond as if we had asked, "If you were a human being, what would you say to this prompt?" That's all. But hiding within is some notion of knowledge because the statistics reflect real texts that have meaning. And so it can feel as if there's a ghost in there that understands something.

Here's a poignant example. One of our employees asked a chatbot to reverse a string of random characters. It produced the reverse string and added: "By the way, here's a Python program that does that." It stopped us in our tracks. Machine learning and generative AI are just tools for the most part. We have to be smart enough to distinguish between hallucination and vision. PT

Watch the full conversation at
https://www.youtube.com/live/cUeEP15KN8M

WHERE THE ATOMIC NUCLEI ARE:



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Ryan Dahn is a senior associate editor at PHYSICS TODAY and a historian of science.

MAURICE SENDAK, PHYSICS ILLUSTRATOR

RYAN DAHN

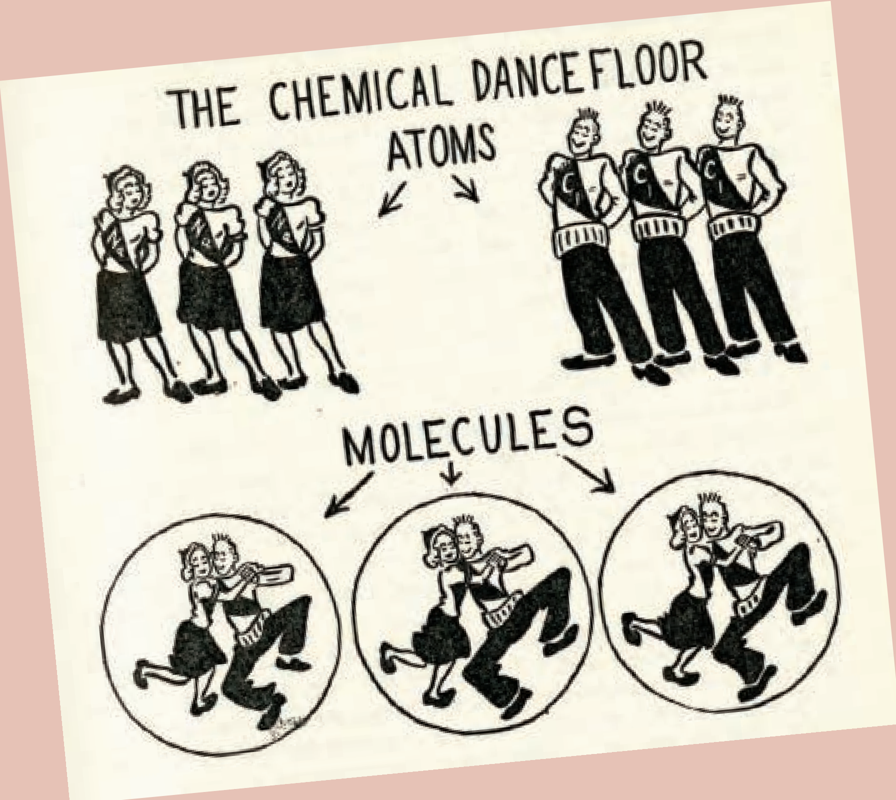
The first credited work of the famed children's book author was a set of illustrations in a 1947 popular-science book about nuclear physics.

Well before Maurice Sendak became famous for *Where the Wild Things Are*, he was an 18-year-old high school senior in Brooklyn, New York, looking for his first paying art gig. Already known at his school as a talented artist, Sendak was asked in 1946 by his physics teacher, Hyman Ruchlis, to illustrate a popular-science book titled *Atomics for the Millions*. In the book, Ruchlis and coauthor Maxwell Leigh Eidinoff, a professor of chemistry at Queens College in New York City and veteran of the Manhattan Project, aimed to demystify nuclear science for laypeople in the wake of the Hiroshima and Nagasaki bombings.

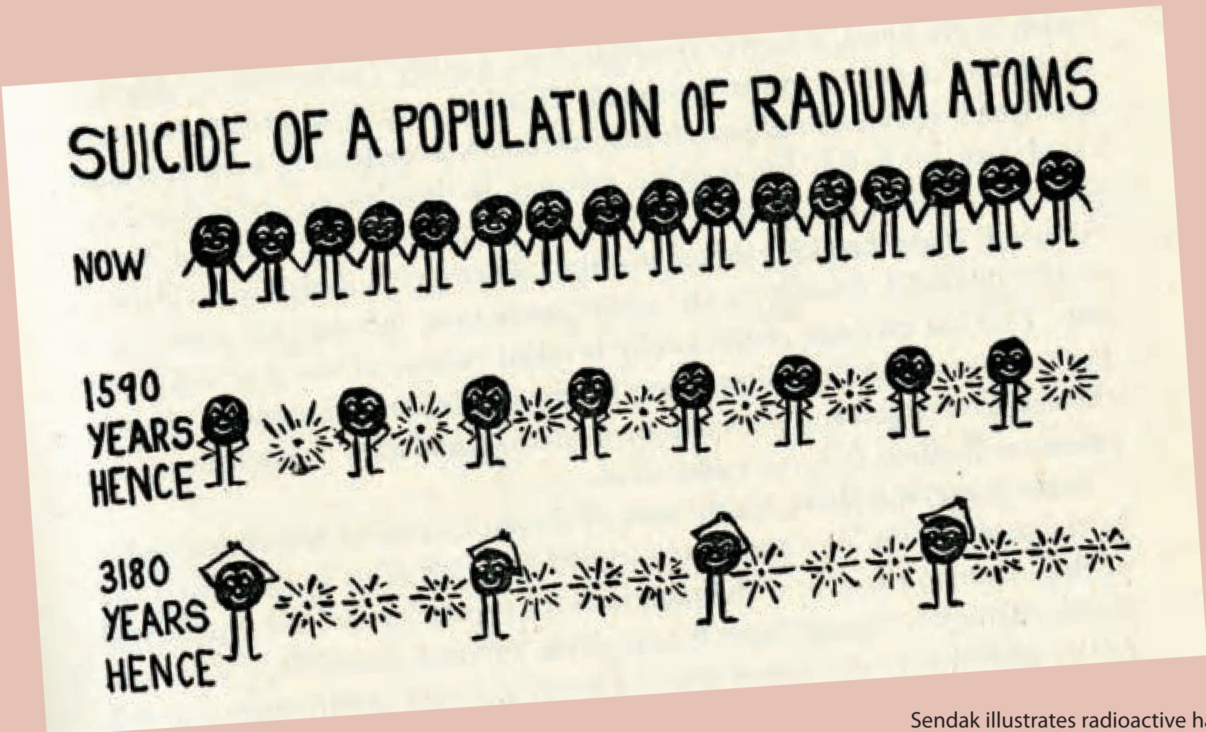
Sendak agreed to do the work for 1% of the royalties, of which he received an advance of $100, about $1600 today. He also negotiated a title-page credit as the book's illustrator—added to the contract in a handwritten addendum at the last minute—and, allegedly, a promise from Ruchlis that he'd receive a passing grade in his physics class. Published in 1947 by a McGraw-Hill imprint, *Atomics for the Millions* was Sendak's first credited work, and copies are now sought by collectors.

A perfectionist, Sendak apparently expressed disappointment later in life with his illustrations for the book. But one can clearly see inklings of the artist's budding talent in the whimsical drawings, cartoons, and diagrams he created. Along with elucidating concepts from atomic physics, the art also supported the broader claim made by Ruchlis and Eidinoff in the book: With the atomic genie out of the bottle, humanity needed to choose between a peaceful future fueled by nuclear energy and a devastating nuclear war.

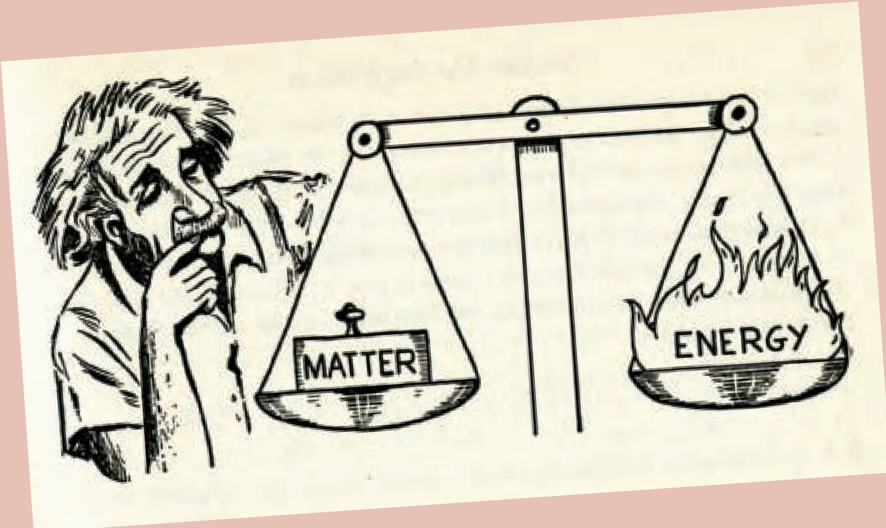
The following pages present an annotated selection of Sendak's illustrations from *Atomics for the Millions*. The decorative motifs are also taken from the book.



In many of his drawings, Sendak anthropomorphizes atoms, molecules, and subatomic particles to convey the otherwise esoteric details of nuclear science. Here, he shows sodium atoms, taking the form of young women reminiscent of 1940s bobby-soxers, and chlorine atoms, represented by strapping young men, meeting on the "chemical dance floor" and forming sodium chloride molecules.

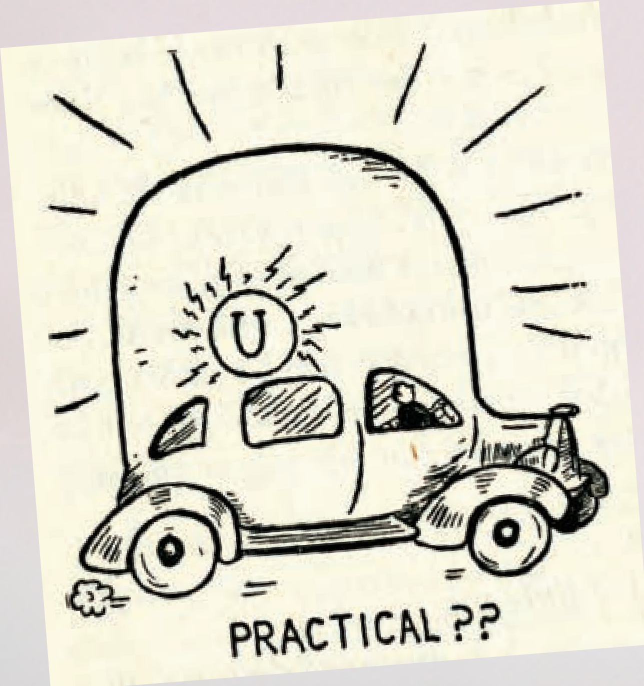


Sendak illustrates radioactive half-life by using radium. He shows the element's atoms holding hands in the top row. After its half-life of 1590 years has passed, half the radium atoms remain, on average; after 3180 years, only a quarter of the atoms are intact. Sendak's use of the word "suicide" in his caption is striking: The artist struggled with depression throughout his life and was open about having had suicidal thoughts.



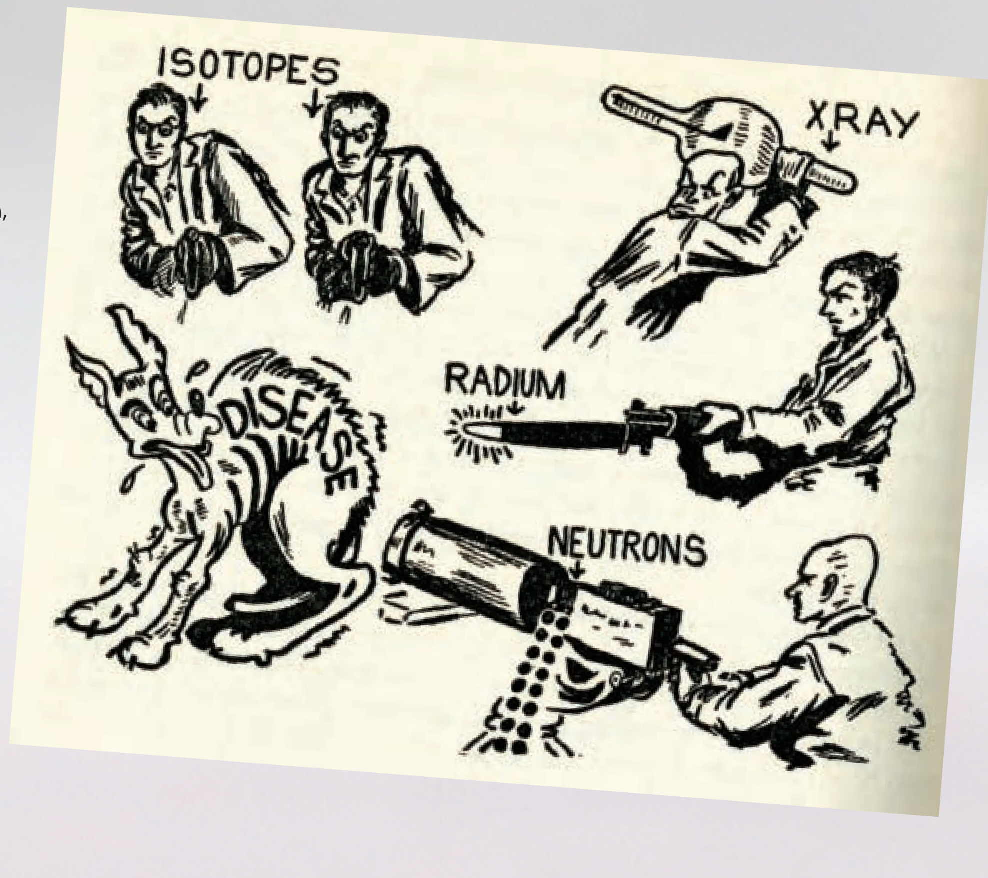
No popular-science book about 20th-century physics would be complete without a discussion of Albert Einstein and $E = mc^2$. In their "Modern Alchemy" chapter, the authors explain the process of nuclear transmutation, the transformation of one element into another through radioactive decay or other nuclear reactions, by analogizing it to alchemy in the Middle Ages. Sendak's illustration shows Einstein, deep in thought, pondering a balance—an alchemist's tool—whose two arms are equally loaded with matter and energy.

Long before the days of email, chain letters asking recipients to pass along a message to several others arrived in one's physical mailbox. The authors use that common experience to explain chain reactions in nuclear reactors. In Sendak's image, a chain letter begins multiplying and quickly buries a harried postal worker under a deluge of mail.

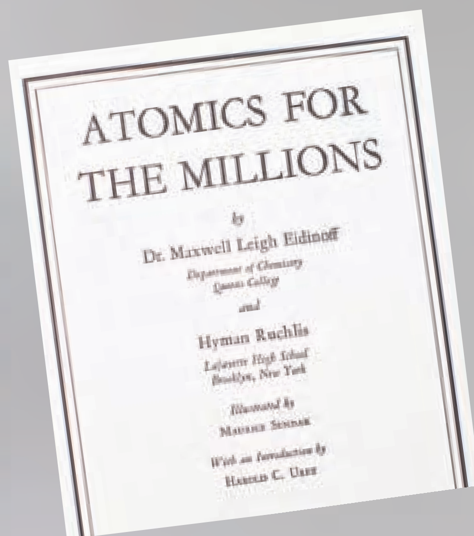


During the early atomic age, nuclear utopianism met US automobile culture in the form of the hypothetical nuclear-powered car: a vehicle that one could drive thousands of miles without refueling. Authors Ruchlis and Eidinoff pour cold water on that idea by arguing that reactors would never be small enough to power a personal vehicle. Sendak's illustration captures the absurdity of the concept.

Sendak's drawing for a chapter dedicated to the medical applications of synthetic isotopes echoes World War II–era military imagery. Medical practitioners attack a mangy dog labeled "disease" with what appear to be a neutron machine gun, a radium-tipped bayonet, an x-ray bludgeon, and isotope tommy guns.



Sendak's final illustration in the book makes vividly apparent the binary choice between nuclear utopia and nuclear oblivion that the authors believed humanity was facing. Some might argue that the drawing lacks nuance, but one could say the same of the authors' characterization of the future of the atomic era.


ATOMICS FOR THE MILLIONS

by

Dr. Maxwell Leigh Eidinoff

Department of Chemistry
Queens College

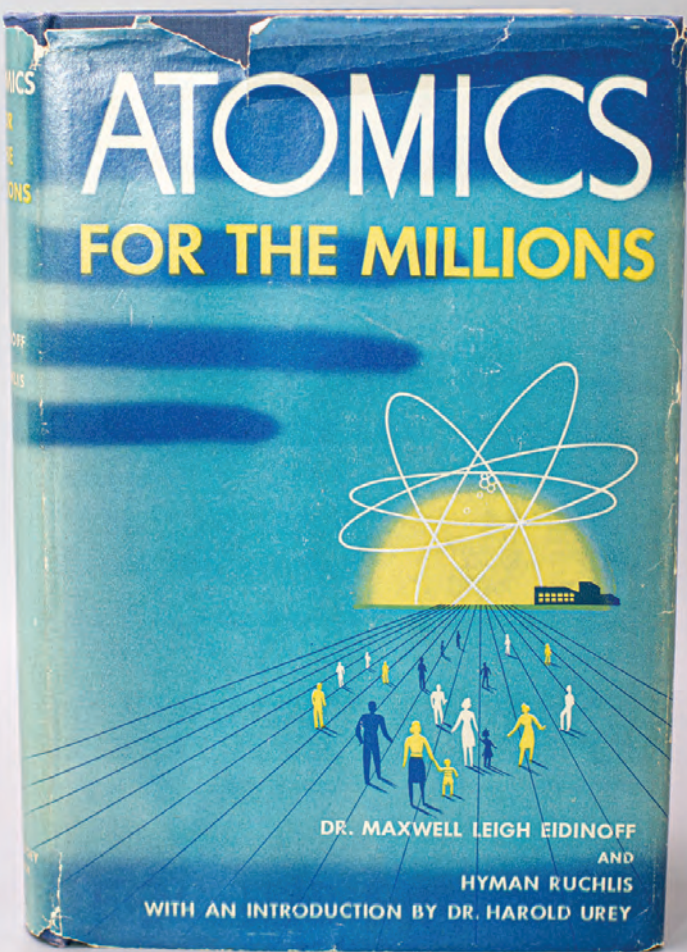
and

Hyman Ruchlis

Lafayette High School
Brooklyn, New York

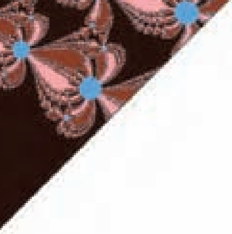
Illustrated by
Maurice Sendak

With an Introduction by
Harold C. Urey



The book's dust jacket shows families and individuals walking toward what appears to be an idyllic atomic-powered future. This copy of *Atomics for the Millions*, which the illustrations were scanned from, is held at the Niels Bohr Library & Archives in College Park, Maryland. The library is part of the American Institute of Physics, which publishes Physics Today. PT

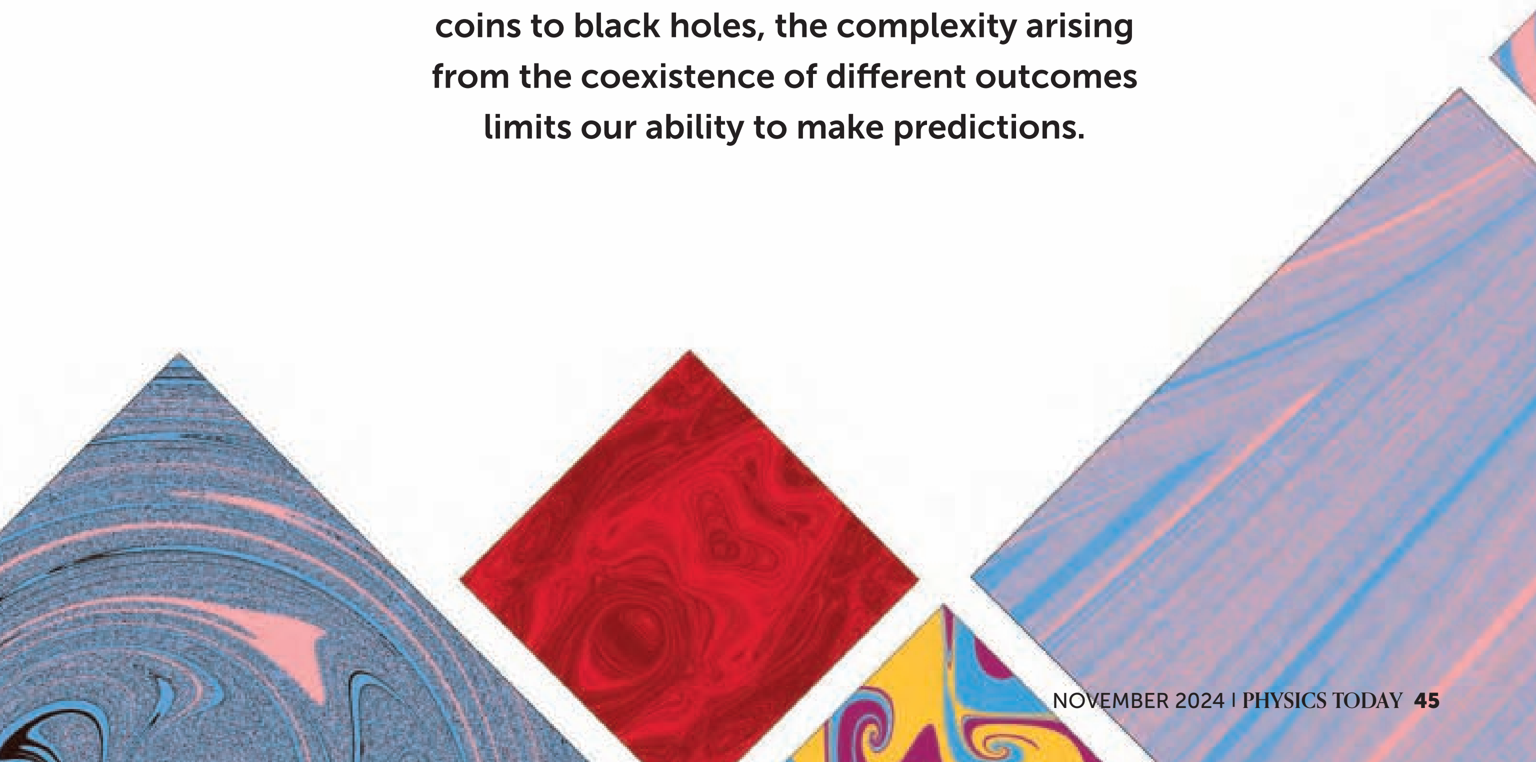
Álvar Daza and **Alexandre Wagemakers** are associate professors of physics and **Miguel A. F. Sanjuán** is a professor of physics at Universidad Rey Juan Carlos in Spain. Daza is also an associate in Harvard University's physics department, and Sanjuán is a full member of the Royal Academy of Sciences of Spain.

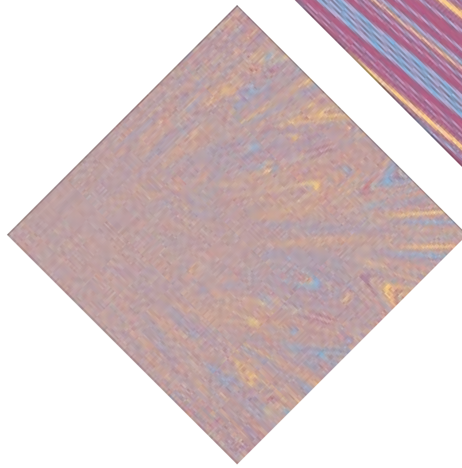


MULTISTABILITY AND UNPREDICTABILITY

Álvar Daza, Alexandre Wagemakers, and Miguel A. F. Sanjuán

In numerous physical systems, from tossed coins to black holes, the complexity arising from the coexistence of different outcomes limits our ability to make predictions.





Decision making can be tough. Transferring the choice to an unbiased authority, like a coin or a die, may help to relieve the pressure. Indeed, for just a few dollars, you can buy a decision-making toy (see figure 1), consisting of a rigid rod and three magnets typically labeled with different outcomes: yes, no, and maybe. Just pull the rod away from equilibrium and let it swing erratically until it points to the answer. The whimsical pendulum makes the choice for you.

Nevertheless, issues arise when you apply a bit of physical reasoning. The equations of motion of such a magnetic pendulum can be easily derived through consideration of the attractive force between the magnet and the rod.[1] Given the initial conditions, those deterministic equations will precisely predict where the pendulum will end up. Therefore, you are actually the one making the decision, on the basis of your particular choice of initial conditions! In fact, you could place the rod very close to your secretly desired outcome, but that feels too much like cheating. So how much control do you really have over the final outcome?

It is a fun mathematical problem to consider, but the principles can be applied to more than just toys. Any system with multiple stable outcomes that are determined by the initial conditions is known as a multistable system. Such systems have historically been modeled by nonlinear equations of motion and solved with numerical methods. Yet even small errors in the initial conditions—due, perhaps, to finite numerical precision—can lead to significantly different predictions in chaotic systems. Statistics textbooks often use rolling dice or flipping coins as examples of randomness for that reason: Although in principle their motion can be described by classical mechanics,[2] the precise initial conditions affect the final stable outcome.

Multistability is found in many areas of physics, ranging from the quantum world to general relativity, spanning basic probability and complex atmospheric models. Indeed, the inherent nonlinearities of Albert Einstein's field equations often lead to multistable situations.[3] For example, when two black holes orbit each other, the path of light around them is complicated by the competing gravitational wells and is difficult to predict. As illustrated in figure 2, photons face three possible outcomes in that scenario: being absorbed by black hole one, being absorbed by black hole

Fractal dimension

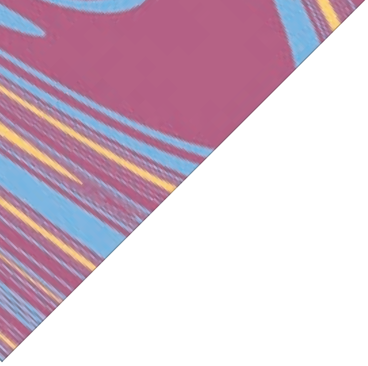
The concept of dimension is more complex than what is taught in school. In fact, dimension can be calculated using a constructive approach called the box-counting method. It involves overlaying a grid of boxes of side length ε on a set of interest and counting the number of boxes $N(\varepsilon)$ that contain some part of the set. The process is repeated with a series of decreasing values of ε. The value of $N(\varepsilon)$ is expected to increase as ε decreases. In fact, $N(\varepsilon)$ is proportional to ε^{-d} for small ε, where d is the box-counting—that is, fractal—dimension of the set.

For simple Euclidean sets like line segments and disks, the box-counting method may seem unnecessary because their dimensions are already known (1 for a segment, 2 for a disk). For more-complex geometric objects, such as fractals, the method becomes extremely useful.

Fractals are geometrically complex sets that have a noninteger dimension. An example of a fractal object is the boundary between Hudson Bay and Atlantic Ocean drainage basins. The draining of different geographic positions into distinct basins resembles the sensitive dependence of outcomes on initial conditions in a dynamical system.

This series of maps illustrates the application of the box-counting algorithm to the basin boundary (red). Each time we double the resolution, the number of boxes (gray) covering the curve increases. Continuing the process to very small values of ε, we can find a scaling law in which the exponent gives the fractal dimension of the curve.

In general, fractals have a fractal dimension greater than their topological dimension (1 for a line) but smaller than the dimension of the space in which they are embedded (2 for a surface). Multistable systems often present basins of attraction with fractal boundaries, which have fundamental consequences for the system's predictability.



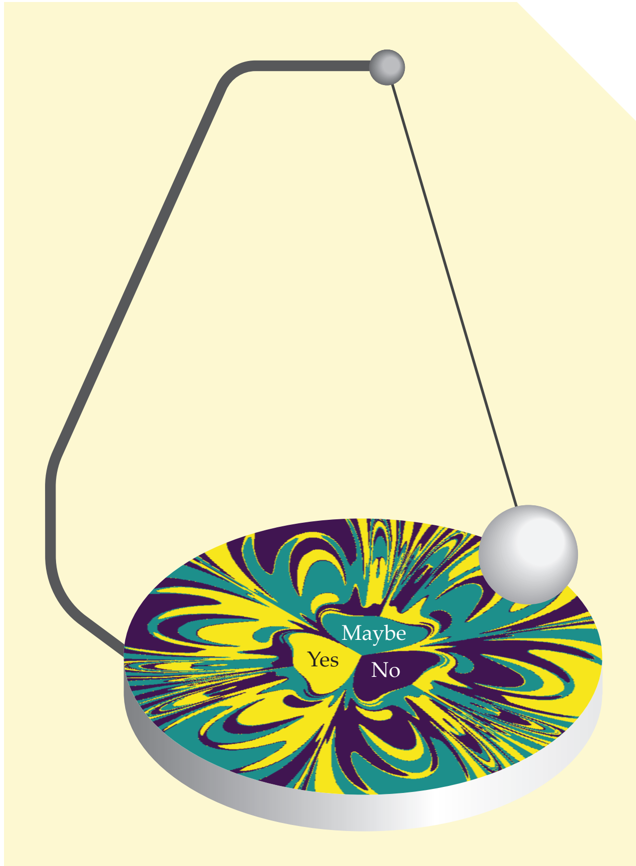
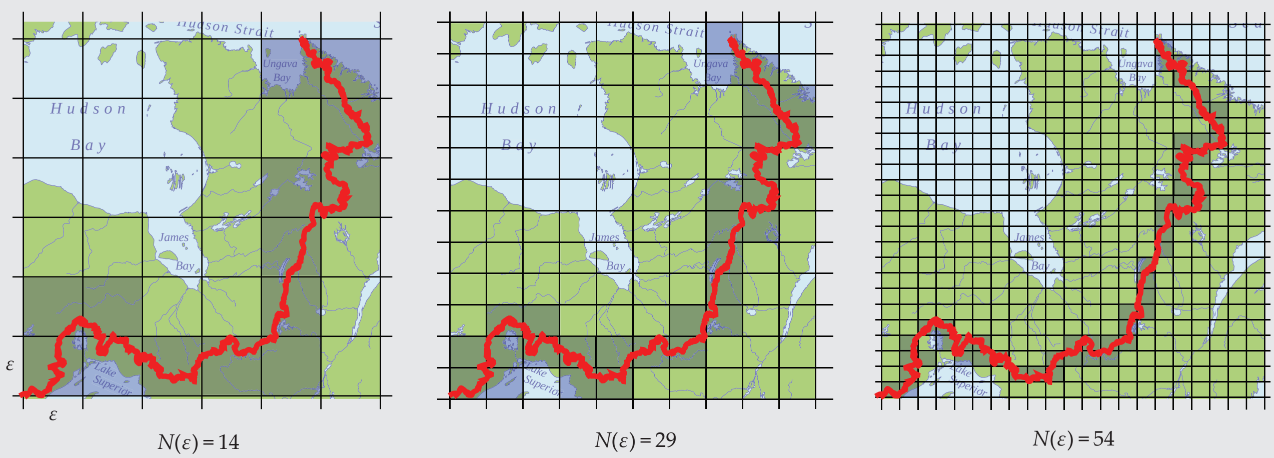


FIGURE 1. A DECISION-MAKING PENDULUM TOY has three possible outcomes: yes, no, and maybe. The magnet in the pendulum is most likely to stop right above one of the three corresponding magnets. The complex interplay between the initial conditions and the multiple ending positions makes the pendulum a multistable system. The final answer given by the pendulum may seem random, but the system can be modeled by three basins of attraction (colored), each of which represents a different answer. Knowledge of the initial release point will inform where the resting point will be.

two, or escaping. Although photons around binary black holes differ significantly from magnetic pendulums, the two systems share several defining features.

Multistable systems pop up in other scientific disciplines too. The genetic toggle switch is a gene-regulation mechanism that tends to the expressed or silenced state, depending on the initial concentrations of proteins.[4] Such simple motifs allow for the construction of complex regulatory networks. The analysis of the system's multistability may lead to a better understanding of gene expression.

Asymptotic states are not limited to steady states. Complex scenarios can include periodic or even chaotic orbits. For instance, the multiple stable solutions of a swinging bell[5] are various modes of oscillation. And figure 3 illustrates the pulsating modes of a modulated laser, which depend on the initial conditions.[6] In general, if any characteristics allow us to distinguish between different asymptotic



states, then we can and apply the theoretical framework of multistability.[7]

Fractal basins of attraction

One approach to investigating the behavior of multistable systems is building a map connecting initial conditions to their final outcome. Such a map is known as the basins of attraction. In figure 1, for example, the decision-making pendulum will come to rest above the yellow answer if it is released from the yellow basin of attraction. The term is borrowed from hydrology, in which a river basin is the area of land where rainfall ultimately gathers in a particular body of water. In nonlinear systems, the inherent unpredictability often results in intricate, sometimes even fractal, basin shapes. (Various basins of attraction adorn this article.)

When a basin of attraction has a fractal boundary, common intuition regarding outcome predictability is useless.[8] That is what allows a system like the decision-making pendulum to appear random. In a system with smooth basin boundaries, an enhancement in the precision of initial conditions by a factor of 10 yields a corresponding improvement in the overall predictability of the system. For fractal basins, increasing the precision 10-fold may result in only a two- or threefold improvement in predictions, or in extreme cases, no improvement at all. That scenario recurs at every scale because of the self-repeating nature of fractals.

Fractals are widely recognized for their complex structure across all scales and their noninteger dimensions (see the box on page 46). The conventional topological dimension can be understood as the number of coordinates required to determine a point within an object: One coordinate is adequate for defining a position on a curve, two coordinates suffice for a point residing on a surface, and so forth. The fractal dimension generalizes the concept and offers insight into how extensively an object occupies space. For instance, a plane curve with a fractal dimension of 1.53 occupies more space than a line but less than a surface. The number is a proxy to describe how close we are to those limiting cases.

Nonetheless, the peculiarities of fractal boundaries extend beyond self-similarity and noninteger dimensions. They are just the tip of the iceberg, since the array of fractal basins encompasses extraordinary phenomena with fundamental implications for predictability.

Cataloging unpredictability

Typically, boundaries divide two regions, as a border between countries does. Occasionally, isolated points separate more than two regions—for example, Four Corners marks the boundary point between Arizona, Utah, Colorado, and New Mexico.

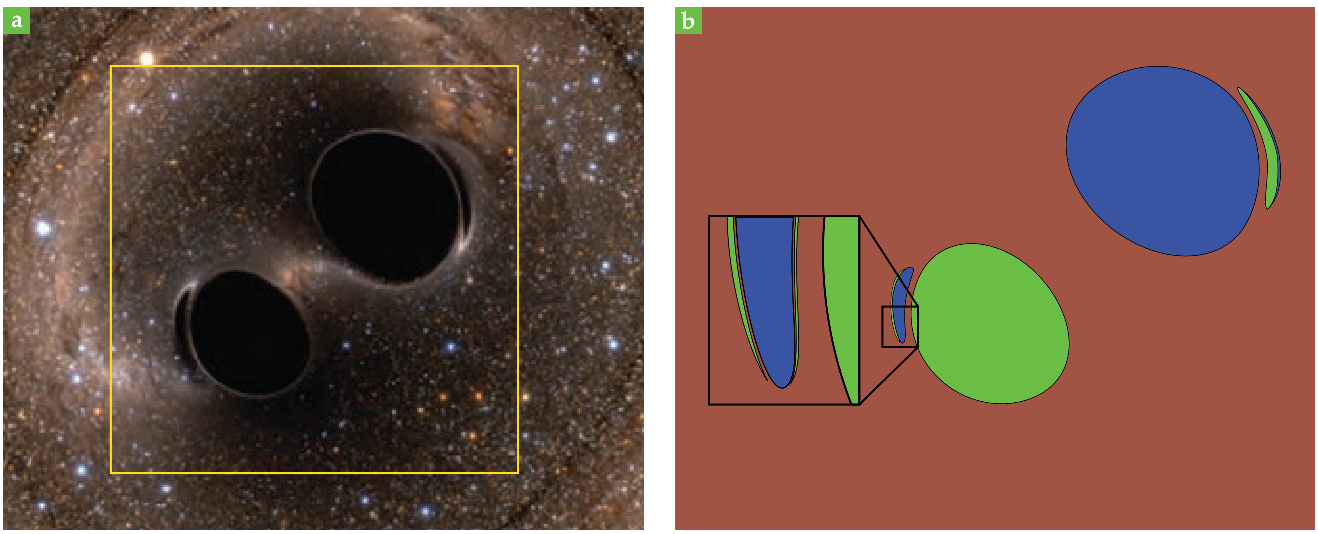
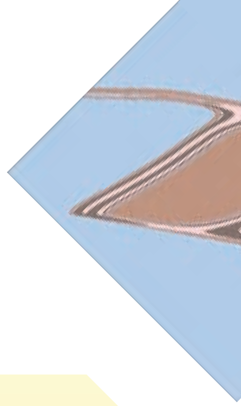


FIGURE 2. BINARY BLACK HOLES, like the ones shown in the simulation (a), form a multistable system. (Courtesy of the Simulating eXtreme Spacetimes project.) They can be represented by different basins (b), illustrated here as a photon in the vicinity of such a system with three possible end states: trapped by the first black hole (blue), trapped by the second black hole (green), or escaping both. In narrow regions known as eyebrows, the influence of the farther black hole is stronger than the closer one. Some models predict a fractal hierarchy of eyebrows, which adds complexity to the prediction.



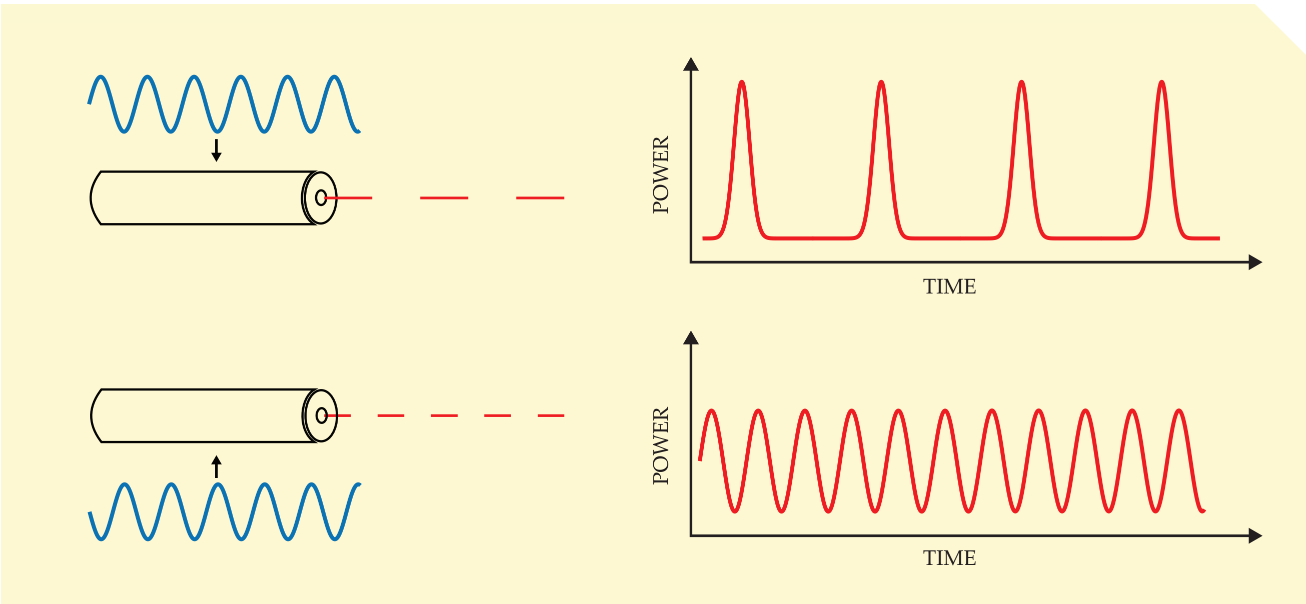


FIGURE 3. A MODULATED LASER DEMONSTRATES MULTISTABILITY when initial conditions of the setup are changed.[6] In the top illustration, the initial conditions cause the output power (red) to feature large pulses at a third of the frequency of the modulation signal (blue). In the bottom illustration, the output power and modulation signal have the same oscillation frequency.

Points like that have a higher level of unpredictability, and a deviation from the exact boundary point can have more than two possible outcomes: For example, someone at Four Corners who gets pushed down could end up in any of the four states. What happens when a boundary is composed entirely of such points? Although such a boundary may seem implausible, fractal objects often challenge conventional understanding.

In the early 20th century, Japanese topologist Takeo Wada proposed a method for creating such a mind-boggling structure: three connected sets with a common boundary. Wada basins, named after him, refer to three or more fractal basins separated by a single boundary. That topological property is not just a fanciful oddity; Wada basins are ubiquitous even in simple systems, such as a damped pendulum subjected to continuous forcing.[8]

Wada basins are not the basins with the most unpredictability. Some fractal curves, such as Peano curves and Hilbert curves, can fill the space. A boundary occupying the whole space means that the slightest uncertainty will lead to an unknown outcome. Despite being deterministic and regardless of how much the precision is improved, the system will always be unpredictable. Scenarios like that are modeled by what are known as riddled basins. In a way, riddled basins can be considered a bridge between determinism and randomness. In addition to Wada and riddled basins, multistable systems give rise to many more peculiar species, including sporadically fractal basins, intermingled basins, and basins with tentacles.[9]

Usually, one of the first steps in analyzing a dynamic process involves allowing the state to evolve until an asymptotic behavior is recognized. A decision-making pendulum can still be moving slightly when it becomes clear which marked magnet the pendulum will stop above. Trials with different initial conditions may uncover alternative outcomes. Nonetheless, in some systems, that process is far from trivial, since the basins of the system can be hidden.[10] That situation arises when the basins are located away from their corresponding outcomes and there are no transient processes leading to them. The detection of such elusive basins requires special procedures.

Basins located close to their corresponding attractor can also be problematic when those attractors are found everywhere. Extreme multistability[11] can arise when conservative chaos meets small dissipation; it leads to an overwhelming quantity of different attractors. Indeed, an arbitrarily large number of attractors can arise in that kind of situation. Still, manipulation of the system allows for custom-made scenarios of multistability. Two peculiar examples of such are megastability[12] and matryoshka multistability,[13] in which attractors are nested and form an onion-like structure.

Furthermore, changing the parameters of the object of inquiry sometimes gives birth to two possible outcomes, an event called bifurcation. The same system may present a huge variety of situations depending on its precise parameters. The rich diversity of basins and associated phenomena are why creating tools to understand their unpredictability and classify them is necessary.

The multistability toolkit

The most straightforward method to quantify the unpredictability associated with basins is measuring their relative volume. Consider a loaded die for which the basin of one face occupies a volume 20 times as great as the volume of all the other faces combined. Clearly, a die will land with the biased face up most of the time. That simple measure, known as basin stability,[14] has been successfully applied to the characterization of multistable networks and high-dimensional systems, such as atmospheric models.

But basins are much more than just their size. Equivalent basin volumes in two systems do not necessarily imply the same predictability for both. Not only does the basin volume matter, but its morphology does also. For example, a bistable system with symmetric basins separated by a smooth boundary (imagine a two-by-two chessboard) and a system with riddled boundaries (imagine TV static) can present identical volumes. Even though the basin stability is the same in both cases, the situations are very different. The basin entropy,[15] a recently developed tool, incorporates both aspects to provide a quantitative measure of uncertainty.

Basin entropy can be understood as a nonlinear combination of multiple factors, including the fractal dimension of the boundaries and the number of attractors within a basin. In that way, the entropy accounts for the basin's morphology and allows for the creation of a rational taxonomy.[16] For example, Wada basins maximize the number of attractors separated by the boundary, while riddled basins maximize the fractal dimension. Beyond quantifying asymptotic unpredictability in multistable systems, the basin entropy also quantifies fractal boundaries, bifurcations, and other defining characteristics.

Yet we are not simply doomed to observe the complexity of multistable systems; we can attempt to tame it.[17] You might find yourself trapped in one state but want to transition to another. In such cases, it is crucial to determine the minimal perturbation needed to move the system out of a basin of attraction. Interestingly, that minimal action provides yet another measure of the sensitivity associated with the basins. Instead of taking a static approach, you can use a carefully timed perturbation to drive the evolving trajectory from one asymptotic state to another. Regardless of the method, once the optimal window is identified, an external control can lead the system to the desired state. But how to make that optimum perturbation may not be known *a priori*. Alternatively, other techniques bypass that difficulty by employing feedback methods.

Delving into the realm of multistability transforms our perception of everyday objects and unveils a world of new possibilities. This article began with a discussion of a frivolous decision-making toy, but an understanding of multistability is pivotal in advanced topics such as neuroscience.[18] By leveraging the vocabulary derived from the study of nonlinear dynamics—akin to equations of motion governing a simple pendulum—we can gain a deeper understanding of the intricate mechanisms underlying cognitive choices. The interplay among attractors in multistable systems mirrors the complex cognitive processes at play when individuals navigate decisions.

Multistability is a prevalent phenomenon observed across various realms of physics, including classical mechanics, quantum mechanics, and cosmology. Its pervasive nature highlights its significance in unraveling the complexities of physical phenomena across different scales and domains. Insights derived from the study of elementary dynamical systems often have profound implications for addressing challenges encountered in diverse fields. The lessons learned in simple systems provide valuable perspectives and methodological approaches that offer fresh insights into long-standing questions across physics. Thus, the exploration of multistability not only enriches our understanding of fundamental physics but also fosters interdisciplinary synergies.

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Andreas Mandelis

Helium-saving laboratory cooling system

The fully automated Infinite Helium cooling system from Lake Shore Cryotronics enables a continuous-flow cryostat to operate cryogen-free, with base temperatures reaching as low as 2 K. It offers single-button cooldown operation, with no manual valve adjustments required. Intelligent features reduce user error to ensure consistent and optimal performance. Samples can be exchanged easily without the system being warmed up, allowing for fast turnaround times. The system can run continuously for six months or longer without requiring servicing. Suitable for physics or materials research laboratories challenged by liquid helium shortages and costs, the Infinite Helium cooling system seamlessly integrates with various continuous-flow cryostats, such as the Lake Shore ST-500 cryostat for low-vibration microscopy applications and ST-400 series cryostats for UHV and beamline applications. The system also provides an option for reducing vibrations in a measurement to ultralow levels—to 1 nm vibration at greater than 10 Hz—when it is used with the ST-500. ***Lake Shore Cryotronics Inc**, 575 McCorkle Blvd, Westerville, OH 43082, www.lakeshore.com*

Oscilloscope for fast data acquisition

Rohde & Schwarz has developed the industry's first application-specific integrated circuit (ASIC)–based zone triggering and implemented it in its new MXO series oscilloscopes. The company says the MXO series offers the world's fastest zone trigger update rate, which reaches up to 600 000 waveforms/s, and less than 1.45 μs blind time between trigger events. The new functionality enhances the oscilloscopes' ability to precisely isolate events in which traditional triggering does not provide the needed flexibility. The MXO zone triggering allows oscilloscope users who are testing and debugging in the frequency domain to draw specific zone areas. The oscilloscope will trigger or activate when a certain tone exceeds a set power level within those zones, or users can simply draw a zone for RF chirps or pulses. With the MXO's new free-run mode, the oscilloscope captures data as fast as possible without looking for an edge-trigger event. Combining that mode with zone triggering can enhance power integrity measurements and electromagnetic interference debugging. ***Rohde & Schwarz GmbH & Co KG**, Muehldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*

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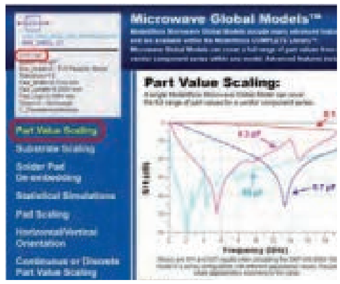
Richard Fitzgerald, Publisher

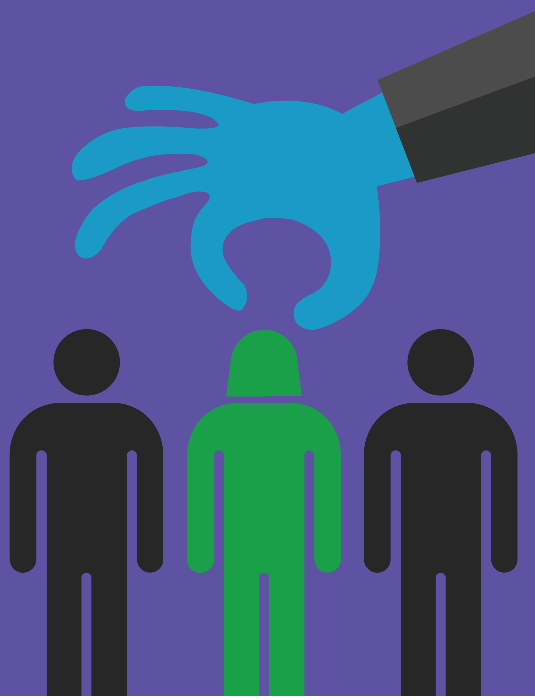
Software for electronic design automation

Modelithics, which provides accurate RF/microwave models for multiple EDA (electronic design automation) simulation software tools, has introduced its Exemplar Library for MATLAB. The library adds to the company's large collection of highly accurate circuit-simulation models, and it includes almost 50 Microwave Global Models, representing nearly 3500 components for many component suppliers. Developers of wireless communications, radar, and signal integrity applications use Modelithics models within the RF Toolbox, a MATLAB add-on from MathWorks, to build networks of RF components, such as filters, transmission lines, matching networks, amplifiers, and mixers. The company's Microwave Global Models for MATLAB include advanced model features, such as part-value scalability, solder pad size scaling, de-embedding, and substrate scaling. The part-value scalability makes the Microwave Global Models suitable for tuning and optimization; it is not necessary to manually substitute individual models during a design process. ***The MathWorks Inc****, 1 Apple Hill Dr, Natick, MA 01760, www.mathworks.com*



Low-noise magnetometer

Bartington Instruments has brought to market the Mag-13Q, a very low-noise variant of its Mag-13 fluxgate magnetometers, which provide high-precision measurements of static and alternating magnetic fields. This model features less than 5 $pT_{rms}/\sqrt{Hz}$ at 1 Hz (70 and 100 μT measurement ranges only). The series' field sensors are available in a range of enclosures, including environmentally sealed, unpackaged, and submersible. Those enclosures make them suitable for use in the laboratory, in the field, and underwater. They are easy to integrate into users' measurement platforms and can be combined with the company's power supplies and data acquisition units to create complete measurement systems. The Mag-13 series can be used for magnetic field monitoring, feedback sensing in active magnetic field cancellation systems, magnetic signature measurements, and electromagnetic surveys, in the fields of physics, geophysics, bioelectromagnetics, mineral exploration, defense, and space. ***Bartington Instruments Ltd****, 10 Thorney Leys Business Park, Witney, Oxon OX28 4GG, UK, www.bartington.com* PT



QUICK STUDY

Ed Walsh is the director and **JoAnn McGee** is the codirector of the Auditory Neurobiology Laboratory at the VA Loma Linda Healthcare System in Loma Linda, California. Their research focuses on the intersection of biomedicine and bioacoustics.

What makes a big cat roar?

Edward J. Walsh and JoAnn McGee

Long, rectangular-shaped vocal folds enable lions, tigers, leopards, and jaguars to produce their trademark vocalizations.

Imagine that you're sitting around a campfire in the Far Eastern taiga in the dark predawn hour, when a spine-chilling cry suddenly echoes through the awakening forest. It is the mournful-sounding call of a Siberian tiger: a deep-throated, mesmerizing *ahh-rooom*. Known as the long-distance advertisement call, its purpose is to draw attention to the animal's location, size, and fitness. The call is intense, and it delivers a clear message to prospective mates and adversaries alike: I am here, and this is my dominion.

Only four of the five big cats belonging to the genus *Panthera* can roar: tigers, lions, leopards, and jaguars. The differences between roaring and nonroaring cats can be appreciated by comparing the vocal hardware of the nonroaring fifth cat in *Panthera*, the snow leopard, with the considerably larger hardware of the jaguar. The size difference between their voice boxes, shown in figure 1, is unmistakable. But an examination of the biophysics of big-cat vocalization reveals that the voice-box size only partially explains why the four cats can produce their intense long-distance roars.

The voice box

The functional center of mammalian vocalization lies in the larynx, a cartilaginous structure that is connected to the trachea (or windpipe) below, and to the pharynx (or throat) above. The pharynx expands into the nasal and oral cavities and, in some species, also into a collection of other mucosal membrane–lined air chambers. Those interconnected spaces function in the same way the bell of a trumpet helps radiate sound: They collectively shape the output of the cat's vocal system.

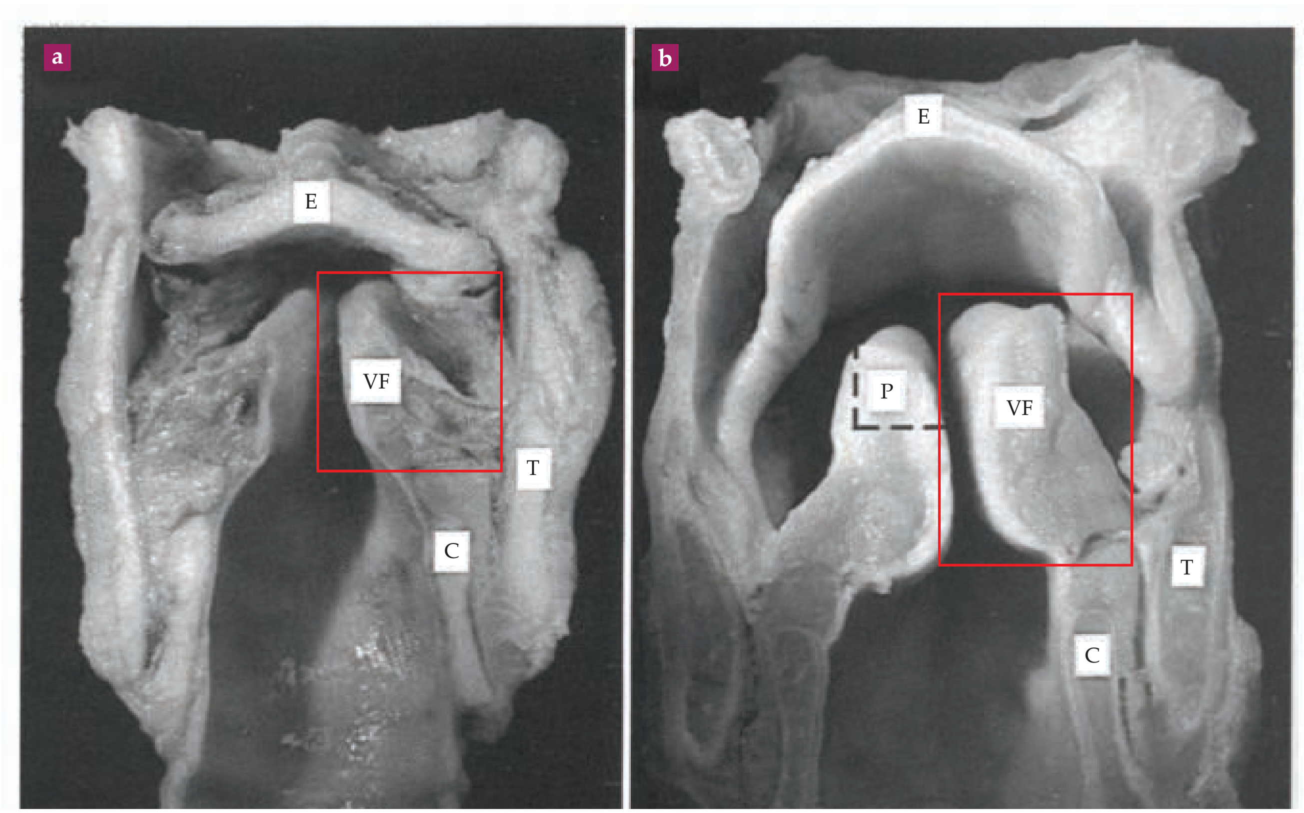


FIGURE 1. BIG-CAT VOICE BOXES. The voice box of **(a)** the nonroaring snow leopard has triangular-shaped vocal folds (VF), while that of **(b)** the roaring jaguar, along with other roaring big cats, has large rectangular-shaped vocal folds. Also pictured are the epiglottis (E), thyroid cartilage (T), cricoid cartilage (C), and pad (P) of fibroelastic tissue. (Adapted from M. H. Hast, *J. Anat.* **163**, 117, 1989.)

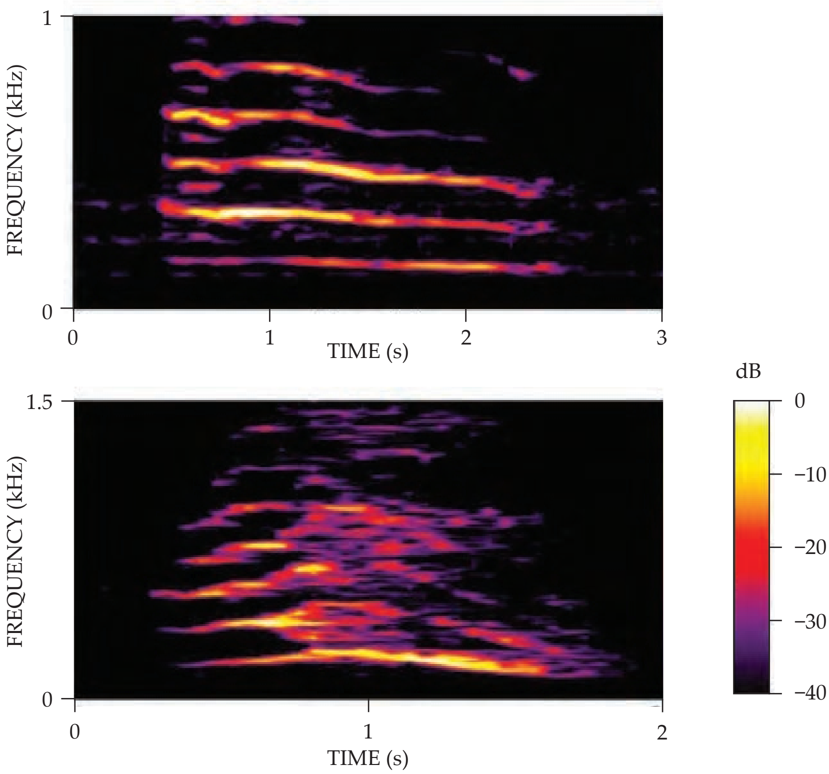


FIGURE 2. TWO EXAMPLES OF SPECTROGRAMS of a tiger's long-distance advertisement call, which illustrate the harmonic nature of the roar and its aperiodic components.

The fundamental structural element of voicing is a bilateral pair of laryngeal protrusions known as vocal folds, commonly referred to as vocal cords. Together they create an opening in the middle of the airway known as the glottis. The epiglottis, shown in figure 1, sits atop the airway, where it acts like a lid that protects the respiratory system from ingested material. It has also slowly evolved into a resonator.

Like all voiced sounds, long-distance roaring is produced during exhalation as warm, moist air flows through the glottal aperture. The air flow sets the vocal folds into vibration at their resonant frequency. Glottal pulses formed by the vibrations are transferred to the oral cavity and associated nasal cavities, where the emergent voice is shaped.

Aerodynamic efficiency

As seen in figure 1, the jaguar's vocal folds are larger and longer than the snow leopard's. Indeed, vocal-fold length scales with body mass. Longer and more massive vocal folds produce lower fundamental frequencies, much like how longer strings on a musical instrument produce lower notes.

Two spectrograms displaying tiger advertisement calls are seen in figure 2. They capture the changes in a call's frequency over time. The amplitudes of component frequencies are shown colorimetrically: White and yellow represent elements with higher sound pressure levels, and red and purple represent lower levels. Perhaps the most evident feature of the call is that expression frequencies are harmonically related—that is, the call is periodic in nature. The harmonic structure is complemented by aperiodic components that make the call spectrally noisy, as seen in the bottom spectrogram in figure 2. The aperiodic component of the call reflects contributions produced by nonlinear intra- and supralaryngeal interactions among various resonating structures scattered throughout the vocal tract and oral cavity. The nonlinear features of a call convey essential information related to the vocalizing animal's sex, fitness, and identity.

But the size of big-cat vocal hardware is not the only reason why the cats can produce the long-distance roar. Adaptations in the shape of their vocal apparatus are another crucial factor. Roaring-cat vocal folds are square or rectangular in shape. Those of other mammals, including nonroaring cats, are typically triangular. Rectangular-shaped vocal folds, with their thick and compact medial surfaces abutting one another, are more aerodynamically efficient than triangular ones, and that higher efficiency manifests in the form of a wide range of output levels. At the low end of the range, rectangular-shaped folds support the production of remarkably low phonation thresholds. In other words, a relatively small amount of lung pressure can vibrate the vocal folds and produce low-level sounds. At the high end, powerful contractions of thoracic muscles and the diaphragm help produce intense big-cat roars.

Roaring-cat vocal folds are also resilient to the powerful forces produced by intense vocalizations. That is due in part to a unique anatomical feature: fat deposits deep in the body of the vocal folds that not only influence their shape but also function as a cushion to absorb deformations associated with the extreme vibrations that occur during roaring. In addition, the vocal folds' epithelium intertwines with the underlying connective tissue to produce a large surface area that strengthens the vocal-fold tissue when it undergoes extreme mechanical stress. As a result, roaring-cat vocal folds possess a remarkable capacity to withstand powerful shearing and stretching forces that would injure those of species with less robust vocal hardware.

Our understanding of the physics of roar production is derived in large part from tissue engineering and biomechanics investigations. But roaring also illustrates how slow-moving evolutionary pressures have caused subtle but essential changes in a small cluster of tissues lining a modest stretch of the larynx that enables production of the long-distance roar.

Additional resources

- M. H. Hast, "The larynx of roaring and non-roaring cats," *J. Anat.* **163**, 117 (1989).
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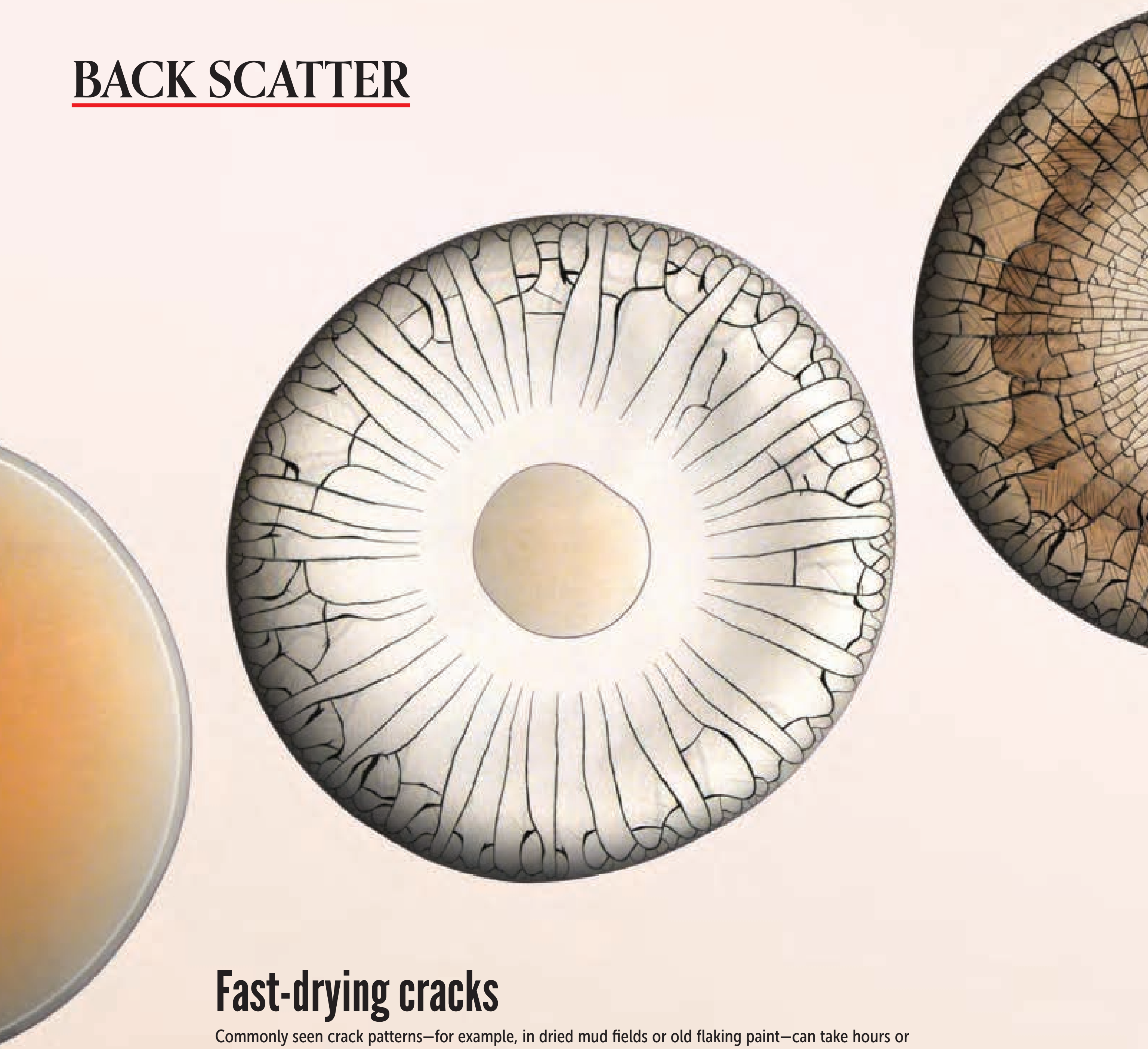
- S. A. Klemuk et al., "Adapted to roar: Functional morphology of tiger and lion vocal folds," *PLoS One* **6**, e27029 (2011).
- I. R. Titze et al., "Vocal power and pressure–flow relationships in excised tiger larynges," *J. Exp. Biol.* **213**, 3866 (2010).
- I. Titze, T. Riede, T. Mau, "Predicting achievable fundamental frequency ranges in vocalization across species," *PLoS Comput. Biol.* **12**, e1004907 (2016). PT

BACK SCATTER



Fast-drying cracks

Commonly seen crack patterns—for example, in dried mud fields or old flaking paint—can take hours or even years to form. But the ones shown here took shape in just two minutes. MIT's Paul Lilin, Mario Ibrahim, and Irmgard Bischofberger probed the crack-formation dynamics and found that in a millimeter-sized drop of water with suspended nanoparticles, the nanoparticles accumulate and form a solid deposit at the drop's outer edge (left). As the water evaporates, the solid deposit grows inward, drying stresses build in the deposit, and radial cracks form (center). After two minutes of drying, the solid deposit covers the entire area of the drop and includes many cracks in the radial and orthoradial directions (right).

Spurred by their wealth of quickly acquired crack data, the researchers developed a model to estimate where cracks may form as a function of both preexisting cracks and the varying thickness of the deposit. Improved predictions of crack dynamics have value beyond simply explaining patterns found in nature. A better understanding of cracks found in the paint of old artwork, for example, has been used to decipher what methods an artist may have used and the condition of the work. (P. Lilin, M. Ibrahim, I. Bischofberger, *Sci. Adv.* **10**, eadp3746, 2024; image submitted by the authors.) —AL

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