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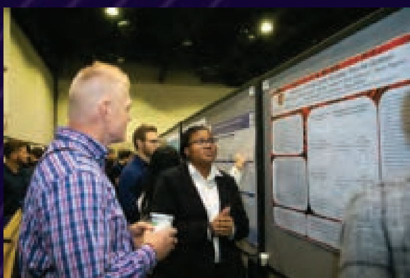

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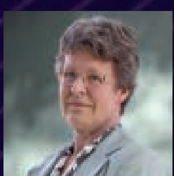

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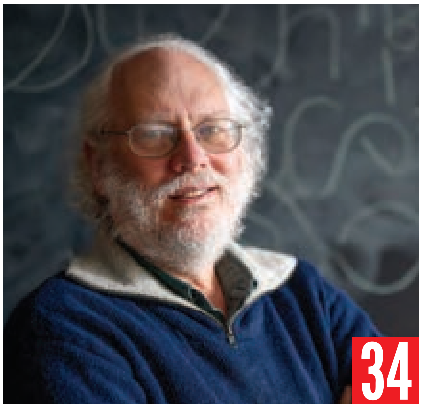
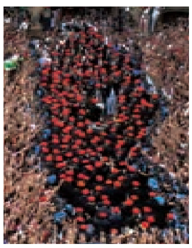
FEATURES





ON THE COVER: Bird flocks, fish schools, and insect swarms have all been studied through the lens of active-matter physics. Studying human crowds, though, presents logistical and ethical challenges. The story on **page 8** describes one research team's solution: observing and analyzing the crowd of revelers at a long-running Spanish festival, a scene from which is shown here. The unique collective phenomena that emerge can be described with a physical model that treats the crowd as a continuous medium. (Photo courtesy of the Bartolo Lab, ENS de Lyon.)

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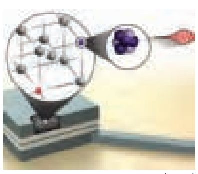

SMOLSKY ET AL., *NATURE* (2025)

Precision neutrino science

Tabletop measurements of the decay of a radioactive beryllium isotope are bringing previously unknown properties of the neutrino into focus. Researchers used the observed recoil energy of the non-neutrino decay product to place constraints on the spatial extent of a neutrino's quantum state.

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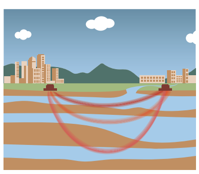

JASON KEISLING

Measuring groundwater

Researchers have used seismic data from Southern California to gain insight into the region's groundwater supply. The method reveals water levels both near the surface and in deeper aquifers, and it is more comprehensive than extrapolating the water supply from the observed levels in a set of drilled wells.

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FREDDIE PAGANI

Dark and quiet skies

Light pollution, radio interference, satellites, and space debris can compromise telescope observations. Astronomer John Barentine outlines the latest challenges facing the observational astronomy community and describes efforts to promote policy changes that preserve dark, radio-quiet skies.

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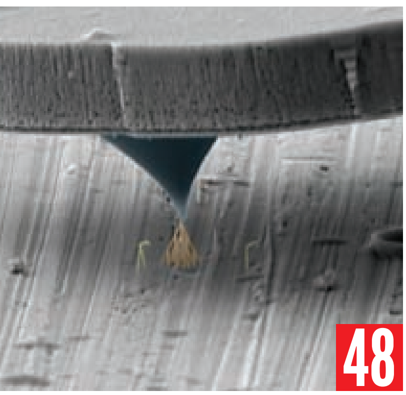

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Clarifications on the Chien-Shiung Wu feature

CHIEN-SHIUNG WU at Columbia University, sometime around 1975. (Photo from American Association of Physics Teachers [AAPT], courtesy of the AIP Emilio Segrè Visual Archives.)

The article "Chien-Shiung Wu's trailblazing experiments in particle physics" (Physics Today, December 2024, page 28) says Elena Aprile "was the second woman to join the [Columbia University physics] department, more than four decades after Wu." Many former Columbia physics students, however, know this to be untrue, having taken the class we affectionately called "Lucy Lab," designed and supervised by Lucy J. Hayner. Her Physics Today obituary (January 1972, page 97) describes Hayner as "a professor emeritus of physics at Columbia University." It says she received a master's degree at Columbia in 1920 and that "after returning to Columbia in 1929, she taught in and later headed the Ernest Kempton Adams Laboratory." As a Columbia undergraduate in the early 1960s, I took Hayner's lab class and Wu's course in nuclear physics. Thus, I experienced the teaching of two women on the Columbia physics faculty at a time when Aprile—who was born in 1954—was not even 10 years old.

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"Chien-Shiung Wu's trailblazing experiments in particle physics" by Chon-Fai Kam, Cheng-Ning Zhang, and Da Hsuan Feng (Physics Today, December 2024, page 28) helps to correct the scientific community's failure to give appropriately enormous credit to Wu for her many accomplishments, especially her leadership of what may well be described as the most important experiment in the history of particle physics: the demonstration that the weak interaction violates parity conservation. The article's brief mention of the test of hidden-variable theories, however, needs more complete referencing.

Following John Bell's celebrated 1964 work in which he derived an inequality that must be satisfied by local hidden-variable theories, it was a paper by John Clauser, Michael Horne, Abner Shimony, and Richard Holt that proposed a practicable experiment that could test the Bell inequalities.[1] As a postdoc at the University of California, Berkeley, Clauser brought that idea to Stuart Freedman, who was then a UC Berkeley graduate student under the guidance of Eugene Commins. It was Freedman who conducted the experiment as his thesis, and the work was published in *Physical Review Letters* in 1972.[2] The experiment provided compelling evidence that local hidden-variable theories were wrong.

As Kam, Zhang, and Feng note in their article, Alain Aspect, Clauser, and Anton Zeilinger received the 2022 Nobel Prize in Physics "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science." (For additional information, see Physics Today, December 2022, page 14.) Just as Wu died without receiving a Nobel Prize
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for her early photon entanglement experiment, Bell and Freedman died without receiving a Nobel Prize for their work whose significance was indicated by the awarding of the prize to Aspect, Clauser, and Zeilinger.

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In the fascinating article "Chien-Shiung Wu's trailblazing experiments in particle physics" (Physics Today, December 2024, page 28), the authors incorrectly describe the result of an experiment testing a prediction by John Wheeler.[1] They report that Ernst Bleuler and Helmut Bradt at Purdue University measured the ratio of perpendicular to parallel polarization of gamma rays emitted from the decay of an electron–positron pair as 2.1 ± 0.64, a relatively large uncertainty. That ratio was for one run; the published result combining all of their measurements was actually a much more respectable 1.9 ± 0.3.[2] Given that Wheeler predicted a maximum ratio of 1.100 and later theorists[3, 4] fixed the error and calculated a ratio of 1.7 for the configuration used by Bleuler and Bradt, the two could at least be given credit for showing that Wheeler's math was wrong and that the new predictions were pretty good.

By adroitly utilizing the latest in scintillation detector technology instead of Geiger counters, Wu and her graduate student Irving Shaknov[5] obtained 2.04 ± 0.08, where the improved theory predicted 2.00 for their configuration. The scientific community accepted this as confirmation of Wheeler's suggestion that the electron–positron pairs decay from a state with zero angular momentum. Wheeler makes no mention of entanglement, whose significance became apparent much later.

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► **Kam, Zhang, and Feng reply:** With respect to Robert Cahn's comments, we agree that John Bell and Stuart Freedman should be acknowledged, just as Chien-Shiung Wu should be, for their contributions to the body of work that eventually earned Alain Aspect, John Clauser, and Anton Zeilinger a Nobel Prize. We wanted to draw attention to Wu and Irving Shaknov being the first to conclusively verify photon entanglement. Considering that Wu and Shaknov's experiment was done only about 15 years after Albert Einstein, Boris Podolsky, and Nathan Rosen first brought the concept of quantum entanglement to light in what's known as the EPR paper, our personal perspective is that it was worthy of a Nobel Prize.

With respect to Stephen Durbin's comments, we agree that the experimental efforts made by Ernst Bleuler and Helmut Bradt should not be dismissed. John Wheeler made no mention of "entanglement" in his paper, and neither did Wu and Shaknov in their letter. When the latter published their results in 1950, the word was not yet a common scientific term. To perform an experiment like that 75 years ago required Wu to be well ahead of her time. We think that she had the concept of entanglement in her mind.

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Comments on "Careers by the numbers"

The October 2024 careers issue of Physics Today missed the mark in more than one way. In Richard Fitzgerald's otherwise excellent article "Careers by the numbers" (page 30), the figure showing new physics PhDs' starting salaries (page 35) confusingly has federally funded R&D centers (FFRDCs) separate from university-affiliated research institutes (UARIs). It lumps the former with government labs and the latter with universities. Both FFRDCs and UARIs are nonprofit entities that are sponsored by various government agencies and perform a broad range of research. But the mission-driven research at several FFRDCs, such as Los Alamos National Laboratory and Sandia National Laboratories, is much closer in nature to the work at UARIs, whereas the discovery science research at other FFRDCs, such as Oak Ridge National Laboratory and Argonne National Laboratory, parallels university-based research.

More egregious, however, was that the other two features in the careers issue focus mostly on academic careers. As Fitzgerald's article lays out, the vast majority of new recipients of physics bachelor's degrees and a majority of new recipients of physics PhDs do not find employment in academia. Why, then, ignore the many and important other ways that physicists contribute to society and the economy? This careers issue contributes to maintaining the myth that the only proper career path for physicists is one that is university based.

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Dense crowds follow their own rules

When thousands of people are packed into a confined space, collective dynamics takes over. The phenomenon can be described with a physical model.

"If you want to know why there are riots at some football games, and not at Caltech football games," said then-Caltech professor John Hopfield to an audience at the 1983 Corporate Associates meeting of the American Institute of Physics, "it has to do simply with the scale: 10 people don't riot!"[1]

It was a flippant comment in support of a broader point. In a large enough gathering of anything—whether atoms, cells, insects, or people—collective phenomena emerge that are completely different from anything one might see in smaller groups of the same constituents. Moreover, the collective behaviors can often be meaningfully understood without appealing to the interactions of the individuals at all.

Hopfield was interested in collective behaviors of neurons, and for his work he was awarded a share of last year's Nobel Prize in Physics (see PHYSICS TODAY, December 2024, page 12). But similar principles have come to underlie the field of active-matter physics, in which the tools of areas such as statistical mechanics and fluid dynamics are brought to bear on colonies of bacteria, schools of fish, and more. (See, for example, PHYSICS TODAY, July 2023, page 14.)

FIGURE 1. THE SAN FERMÍN FESTIVAL in Pamplona, Spain, is perhaps best known for the running of the bulls through the streets each 7–14 July. The festivities kick off on 6 July with the opening ceremony, which attracts thousands of revelers to the plaza in front of the Pamplona city hall. Shown here is the beginning of the ceremony, in which security personnel (dressed in blue) and musicians (wearing white) emerge from the city hall and move through the crowd of revelers (whose white clothes by this point are stained pink with sangria). In the hour leading up to the ceremony, the crowd gradually assembles, grows denser, and displays collective dynamics. (Photo courtesy of the Bartolo Lab, ENS de Lyon.)

Now Denis Bartolo, of the École Normale Supérieure (ENS) de Lyon in France, and colleagues have used active-matter techniques[2] to study large, dense crowds of humans—in particular, the opening ceremony of the San Fermín festival in Pamplona, Spain, which draws some 5000 people to the plaza shown in figure 1 each year on 6 July. From video footage they took of the ceremony, they modeled the crowd not as a collection of individuals but as a continuous medium. Their approach is similar to how one might describe the turbulent flow of a fluid from its bulk properties, such as viscosity and density, rather than its intermolecular forces.

The researchers gained new insight into the unusual collective behaviors that emerge in dense crowds only at large scale. Contrary to Hopfield's remark, large crowds don't inevitably result in riots. But they do consistently give rise to periodic orbital motion characterized by spontaneous symmetry breaking.

Crowds in the wild

It's not that physicists have never tried to study crowd dynamics before. (See, for example, the Quick Study by Arianna Bottinelli and Jesse Silverberg, PHYSICS TODAY, September 2019, page 70.) But their efforts have been stymied by a lack of data. As Bartolo puts it, "It's very difficult to test a model if you don't have anything to model."

The same goes for studies of groups of other large animals. Microscopic active-matter systems, such as cells and tissue cultures, lend themselves easily to lab experiments, and they've been studied thoroughly. "But you can't invite thousands of zebras or wildebeest into your physics department," says Bartolo. "You can't push on them with a macroscopic rheometer and measure the response. You have to rely on real-world observations."

A few thousand people are easier to come by than a few thousand zebras. But studies of human crowds are subject to a further complicating factor: safety. The extremely dense regime that Bartolo and colleagues were most interested in is also the most dangerous. For example, an out-of-control dense crowd at the 2010 Love Parade, a music festival in Duisburg, Germany, caused the deaths

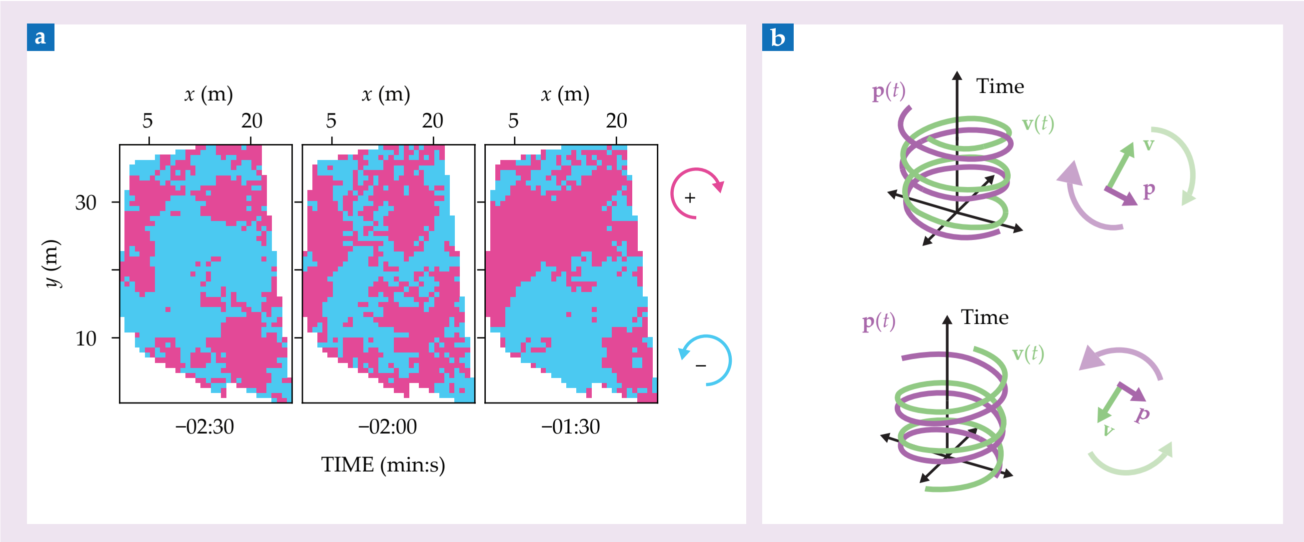

FIGURE 2. MIRROR SYMMETRY is locally broken by the eddy-like undulations in a dense crowd. **(a)** The crowd as a whole, however, has no collective preference for clockwise or counterclockwise oscillations, as seen in these three plots of the handedness of the 2023 San Fermín crowd in the minutes before the opening ceremony. **(b)** An active-matter model shows how the symmetry can be broken spontaneously by initial conditions. In the model, the state of the crowd at time *t* is characterized by the velocity field **v** and the propulsive force field **p**. The two vectors rotate in tandem, with the direction of the rotation determined by their initial relative orientations. (Images adapted from ref. 2.)

of 21 people and injured hundreds more. As a result, the Love Parade, which had been a regular event since 1989, was permanently canceled.

The San Fermín festival presents a happy counterexample. Its opening ceremony has been held for over a century, and although the assembled crowd becomes almost unimaginably dense—with up to nine people per square meter in some spots—no serious injuries have ever been reported. It was an ideal site for a large-scale, reproducible active-matter study.

Breaking symmetry

Bartolo's coauthor Iker Zuriguel, of the University of Navarra in Pamplona, had a friend of a friend who owned an apartment with a view of the plaza where the ceremony is held. And Zuriguel made arrangements with the Pamplona city council to allow the researchers to film the crowd.

The first observations were conducted in 2019—an unlucky time to start, because the COVID-19 pandemic canceled the festival in 2020 and 2021. But the researchers returned in 2022, and during the next three festivals, they started to notice some common features in the crowd.

In the hour leading up to the opening ceremony at noon, the crowd assembles gradually, so the researchers can observe the crowd dynamics as a function of density. Above a critical density of about four people per square meter, the crowd starts to undulate in quasiperiodic circular orbits.

Crowd undulations had been observed before. Participants in the 2010 Love Parade crowd reported a feeling of being jostled back and forth in a wavelike motion,[3] and observers of that and other dense crowds have described the scenes as "turbulent" or "chaotic." But with the help of machine-learning software that automatically tracked the trajectories of all the individuals in the San Fermín festival crowd, Bartolo and colleagues concluded that "turbulent" was not the right word to describe it at all.

In an ordinary fluid, turbulence is characterized by unpredictable motion, eddies that span a vast range of size and time scales, and mixing of the system over time. Bartolo and colleagues didn't observe any of those things. Members of the San Fermín crowds did follow eddy-like orbits, but they predictably circled back to close to their initial positions in an extraordinarily consistent time of 18 seconds—a much longer time scale than the periodicity of any isolated human movement.

Another clue about what's behind the undulations comes from their geometry. A circular orbit in two dimensions breaks mirror symmetry: A clockwise orbit is different from a counterclockwise one. Various causes could give rise to the symmetry breaking. For example, most people are right-handed, and most members of the San Fermín crowd come from countries where people drive on the right. For either of those reasons, or similar ones, revelers at the San Fermín festival may have an instinctive preference to dodge one way instead of the other in a crowded environment.[4]

But if they do, that's irrelevant, Bartolo and colleagues found, because the crowd as a whole doesn't collectively prefer one orbital direction over the other. As figure 2a shows for three snapshots of the 2023 crowd, clockwise and counterclockwise orbits are evenly mixed, and their spatial distribution is not constant. An analysis of all the data from each year showed the same thing: a near-even split between clockwise and counterclockwise, with many individuals switching between both.

A sea of people

If the orbital undulations don't stem from individual actions, where do they come from? To shed some light on the question, Bartolo and colleagues modeled the crowd as a continuous medium rather than a collection of individuals. Like any physical system, it had to obey Newton's second law: The local velocity **v** of the medium changes in proportion to the net force applied to it. Because the medium is made up of people, who are capable of moving under their own power but not perfectly free to choose how they do so, the net force includes a propulsive term **p**.

Both **v** and **p** are vector fields that depend on position and time. Assuming that those two quantities completely characterize the state of the crowd, the researchers wrote down a general model of all the ways that each quantity could deterministically evolve in time. And they found a term that could be key to describing the undulations: **p** changes in time in proportion to $-(\mathbf{p} \times \mathbf{v}) \times \mathbf{p}$.

The first part of the vector product, $\mathbf{p} \times \mathbf{v}$, always points perpendicular to the plane of the crowd, but whether it points up or down depends on whether **p** is angled to the right or the left of **v**. The net effect of $-(\mathbf{p} \times \mathbf{v}) \times \mathbf{p}$ is always to rotate **p** away from **v**. But because **p** is a force that acts on **v**, **v** also rotates in the same direction. The result, shown in figure 2b, is that **p** and **v** circle around and around in tandem; whether they circle clockwise or counterclockwise depends on how they were oriented to begin with. That is, the mirror symmetry is spontaneously broken by the initial conditions.

The model agrees well with the undulations observed in the San Fermín crowds, and it's even consistent with the crowd dynamics at the 2010 Love Parade, as inferred from sparser and grainier video footage of that event. The physical origins of the $-(\mathbf{p} \times \mathbf{v}) \times \mathbf{p}$ term are still murky, but the larger insight is that crowd dynamics can be described by a continuum model at all.

"A group of five people is not suitable to be described with these tools," says Bartolo, just like it wouldn't make sense to use the equations of fluid dynamics to model a cluster of five molecules. "What is the magic number of people where the individual interactions get averaged out? We weren't sure that the San Fermín crowds would be over that threshold. But they were, and we're very happy about that."

Safety in numbers?

The continuum model offers a framework for thinking about what makes dense crowds dangerous in some circumstances but not others. The undulations are an emergent property of the crowd itself, and they're not under the individuals' control. They involve the correlated, collective motion of tens to hundreds of people, with a combined mass of up to tens of thousands of kilograms. If such a group slams into a wall—with no one having the power to stop it—it can exert a crushing force with deadly consequences.

The Pamplona plaza is surrounded by walls. But it also has plenty of side streets that can act as pressure relief valves if too much of the crowd gets compressed near the edge of the square. The Love Parade disaster, in contrast, occurred in the narrow entranceway to the festival grounds, where escape routes were limited. The difference could be key to understanding why the Love Parade ended in tragedy, whereas the San Fermín opening ceremony never has.

Bartolo also points out that crowd undulations start small and grow larger as the crowd density increases. So looking for the undulations while they're still small could be a way for event organizers to tell when a crowd is on the verge of becoming dangerously out of control. "Engineers will have to work hard to develop concrete applications that will prevent real catastrophes," says Bartolo. "But we do think this is potentially useful."

So far, the researchers have limited their study to the average dynamics of the crowd as a whole. They'd like to extend their model to describe how crowds respond to localized stimuli, and they suspect that such an investigation could help clarify the connection between individual behaviors and continuum crowd dynamics. The San Fermín opening ceremony could again provide the setting for a natural experiment, as musicians and security personnel emerge from the city hall and move through the crowd. And every 6 July presents a new chance to gather more data.

Johanna L. Miller

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Plasma channel guides electrons to 10 GeV

Femtosecond-scale laser pulses make a plasma waveguide that helps wakefield-surfing electron bunches keep their energy focused.

High-energy, ultrafast-moving particles have a wide array of both applied and fundamental scientific uses, such as imaging biological tissue in detail and probing questions about the building blocks of matter. But accelerating particles to high energies is not a cheap or easy task. The advanced accelerators being used for that purpose rely on multikilometer-scale facilities. That's because RF cavities—metal chambers that generate the electric fields used to accelerate particles—have fundamental limits that max out their electric field gradients at tens of megaelectron volts per meter. At those gradients, it takes kilometers to get particles up to the tens of gigaelectron-volt energies achieved at facilities such as SLAC and the German Electron Synchrotron (DESY). But there's another approach that can produce electric field gradients that are thousands of times as strong as those produced in RF cavities.

When a laser pulse is sent through an ionized plasma—a sea of electrons and ions—it pushes aside the lighter electrons. The charge rearrangement induces a strong electric field gradient that moves like a wave through the plasma and trails behind the front of the laser pulse, as shown in figure 1. Much like a surfer can ride the wake behind a speedboat, electrons can get trapped in the plasma wave

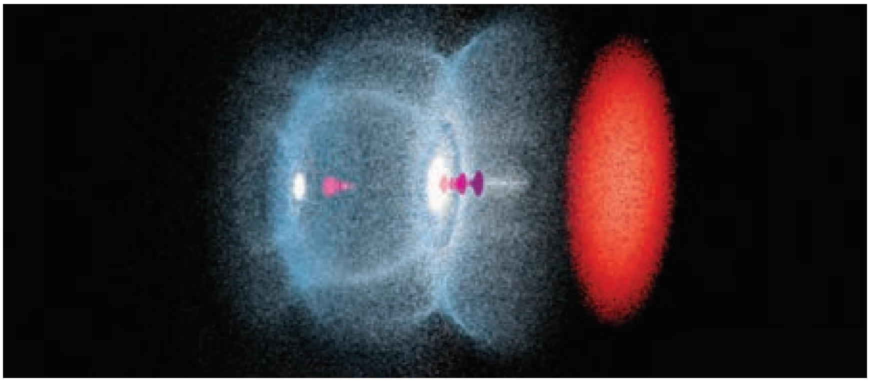

FIGURE 1. AN ELECTRON WAKE (blue in this still from a simulation) trails behind a femtosecond-scale laser pulse (red), with a diameter of about 50 μm, traveling from left to right through a plasma. Electron bunches (magenta) that ride the wake are accelerated to high energies over short distances. (Image courtesy of Carlo Benedetti, Lawrence Berkeley National Laboratory.)

and accelerate to high energies. That's the idea behind the aptly named laser wakefield acceleration method (see Physics Today, January 2015, page 11). Researchers hope that the methodology, conceived of in the 1970s[1] and invigorated by promising electron beams produced by three research groups in 2004,[2] could one day produce powerful electron accelerators that are orders of magnitude smaller than today's.

Now Alex Picksley and colleagues at the Berkeley Lab Laser Accelerator (BELLA) Center at Lawrence Berkeley National Laboratory, in collaboration with Howard Milchberg's group at the University of Maryland, have used wakefield acceleration to produce a well-controlled 9.2 GeV electron beam with charge that extends beyond 10 GeV.[3] "It's a really impressive feat," says Rob Shalloo, an experimental plasma accelerator physicist at DESY. "And they've done it with incredible diagnostics of what's happening throughout the acceleration process. That allows us to learn how we can improve our plasma accelerators and gives us a road map as to where to go from here."

Strictly speaking, 9.2 GeV is not a wakefield record; in 2024, researchers at the Texas Petawatt Laser Facility reported that they had generated 10 GeV electrons in much larger bunches.[4] The feat was achieved by injecting lots of electrons into the wake with the use of nanoparticles, but it also required about six times as much laser pulse energy as the BELLA group's result did and produced a wider energy spread. The accelerator community's enthusiasm about the BELLA result is not only because of the magnitude of the electron energy achieved but also because of the control exerted over several aspects of the process.

Narrowing the channel

A few key challenges plague the wakefield acceleration method. One is to keep the energy spread of the electrons narrow, an important requirement of precision electron-beam applications. Electrons can enter the wake by being injected intentionally and by being pulled in from the surrounding plasma. Electrons that enter the wake a little bit ahead of or behind the ideal position will accelerate to different energies and increase the spread. Another challenge is to keep the drive beam—the laser pulse that creates the wake—focused so that it can impart maximum energy to the plasma wake. Laser pulses can be focused with lenses, but they don't stay focused for long; their radial expansion detracts from the efficiency of the process.

One way to keep the drive beam narrow is to use a plasma waveguide, an approach that has been in use for decades. (See the article by Wim Leemans and Eric Esarey, Physics Today, March 2009, page 44.) In 2018, researchers at the BELLA Center generated 8 GeV electrons,[5] a near-doubling of the record energy for the method at that time. That energy was achieved with a plasma waveguide created by sending nanosecond laser pulses into a plasma-filled tube about the length of a pencil. The pulses heated the plasma, which expanded to produce a shaft of lower-density plasma down the center of the tube that was

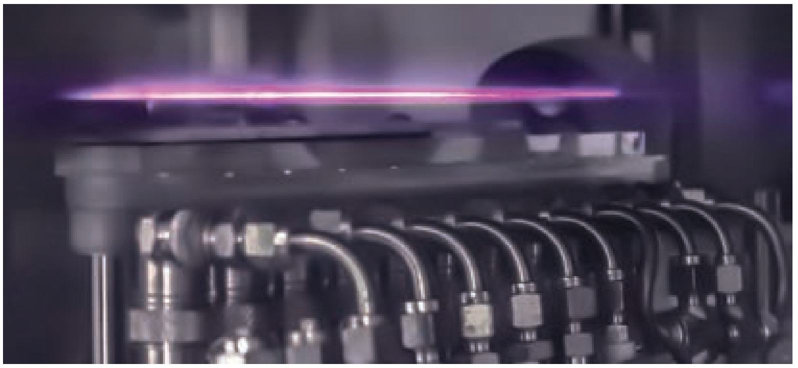

FIGURE 2. A PLASMA CHANNEL, 30 cm long, acts as a conduit for a laser pulse used to create a plasma wakefield that accelerates electrons to high energies at the Berkeley Lab Laser Accelerator Center. The plasma is formed when a 40 fs laser pulse is shot through a sheet of supersonic gas that streams upward out of an aluminum slit. The pink color is a result of the hydrogen gas used to generate the channel. (Photo courtesy of Alex Picksley and Anthony Gonsalves, Lawrence Berkeley National Laboratory.)

surrounded by cooler, denser plasma. The low-density channel helped to keep the laser focused.

But laser heating, which relies on electron–ion collisions, becomes ineffective at the low plasma densities that are ideal for acceleration. So the BELLA team turned to another type of plasma guide, one made with a shorter-duration laser pulse and no tube: a hydrodynamic optical-field-ionized (HOFI) plasma channel,[6] shown in figure 2. (See the Quick Study by Bo Miao, Jaron Shrock, and Howard Milchberg, Physics Today, August 2023, page 54.)

The researchers make the HOFI plasma channel by sending a femtosecond-scale laser pulse through a sheet of supersonic gas. The pulse optically ionizes a string of plasma that radially explodes into the surrounding gas to form a cylindrical shock wave. The resulting plasma channel lasts for a matter of nanoseconds and appears as a flash of light, tinged with different colors depending on the gas used to generate it. "It has the same operating principle as an optical fiber," says Shalloo, "but is immune to laser damage, as a fresh plasma waveguide is formed each time the laser is fired."

A look inside

With the HOFI channel in place, a second laser pulse acts as the drive beam. The HOFI channel brings multiple benefits: It is narrower than the laser-heated channels, and thus better matches the width of the drive beam; it has a lower-density plasma; and because it is formed in an open space, researchers can easily change its length by changing the length of the gas sheet used to create it. That last property was used to probe details of how the drive beam was behaving inside the plasma accelerator. Although the full channel length was 30 cm, the BELLA team adjusted the channel length for each pulse to see how the laser pulse moved through the full length.

"We were able to peer into the interaction, seeing how the laser pulse evolves as a function of distance," says Anthony Gonsalves, a member of the BELLA team. "It shows us the way, experimentally, that simulations have been showing us for a long time."

With a look inside the process, the researchers could see that the shape of the laser pulse was causing a loss of energy. To maximize energy output, crystal-based petawatt lasers are designed to produce pulses with a top-hat intensity profile—a uniform full-power circle. But the optimal intensity profile for plasma wakefield generation is a Gaussian distribution that is tapered at the edges. Simulations show that with an optimized laser profile and the same energy pulse, the BELLA setup should be able to achieve more than 13 GeV. "Now we have motivation for laser builders," says Gonsalves.

The other HOFI channel advantage—lower-density plasma—was crucial to reaching the 10 GeV range. That's because the energy reached is inversely proportional to the plasma density. As a laser travels through plasma, the refraction of light slows it down. If the laser pulse slows down enough, the wakefield-surfing electrons, which are moving at nearly the speed of light, can catch up to the drive beam and start to decelerate. Lower-density plasma means a faster-moving laser pulse. Additionally, denser plasma leads to more self-trapping of electrons, in which the electrons get pulled from their optimal position in the bubble behind the drive beam and lose energy.

A localized addition of nitrogen gas to the plasma was used to precisely inject electrons at the optimum position in the wake bubble. The controlled injection, which was facilitated by the supersonic gas sheet configuration, resulted in a narrow energy spread and minimized self-trapping. "The guiding technology enabled us to boost the electron energy and control the quality of the accelerated beam a little bit more," says Picksley.

The results offer a clear path for making further advancements in laser wakefield acceleration. Improvements to lasers are part of that path. In addition to a petawatt laser with a Gaussian intensity profile, a laser with a higher pulse repetition rate and improved energy efficiency would make the method more viable for regular use. The team at BELLA sees promise for those qualities in fiber lasers. Another strategy on the table is staging multiple lasers together to combine their power. Although wakefield accelerators aren't yet in common usage, many labs are already exploring their applications. Lawrence Berkeley National Laboratory has used the technology to power a free-electron laser, and DESY has plans to use wakefield acceleration to feed electrons into its PETRA synchrotron light source. The latest result brings tabletop particle accelerators a little bit closer to fruition.

Laura Fattaruso

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UPDATES

Record-setting cosmic neutrino breaks in a new telescope

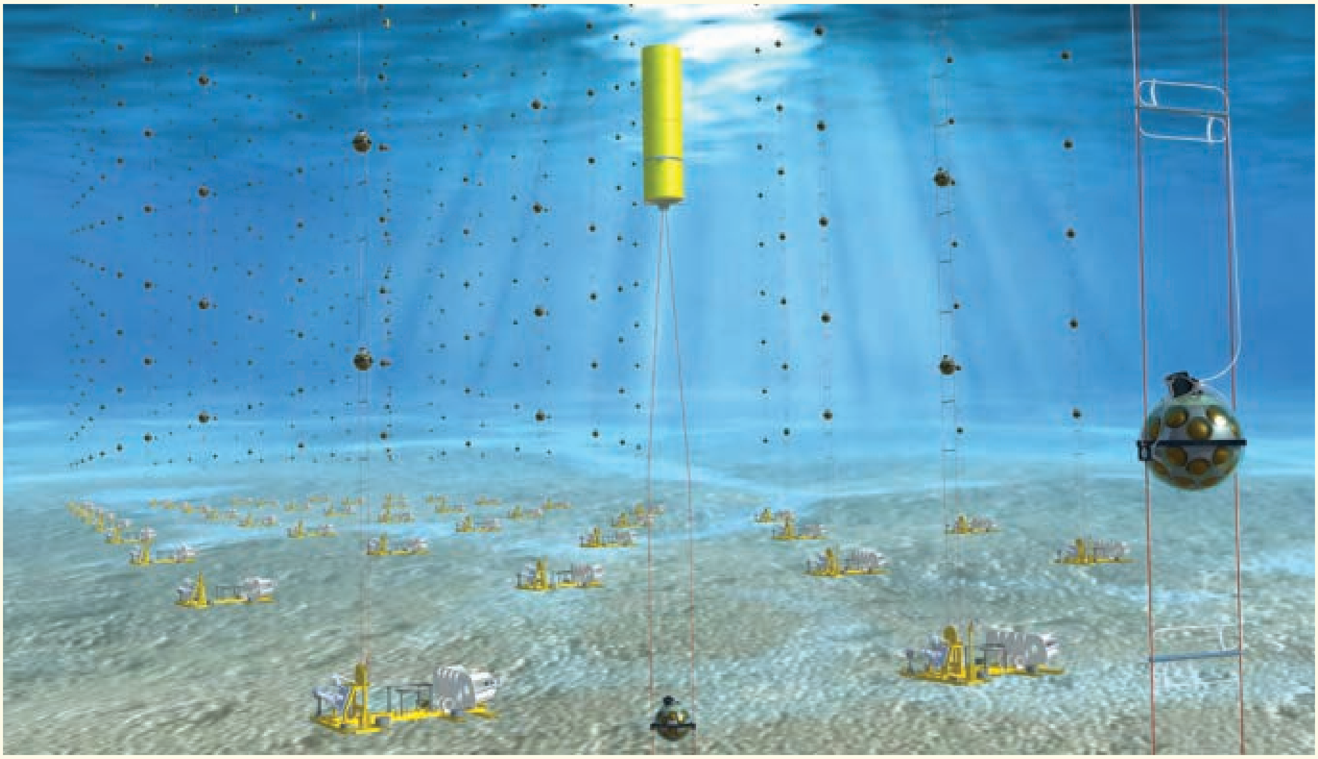
An analysis of the highest-energy neutrino ever detected has researchers questioning the frequency at which such energetic particles pelt our planet.

An incomplete neutrino telescope can still do the job when a can't-miss particle shows up on its doorstep. Researchers with the Cubic Kilometre Neutrino Telescope (KM3NeT) report that their under-construction array of light sensors in the Mediterranean Sea has measured the signature of a neutrino that had on the order of 10^{17} eV (hundreds of PeV) of energy, making it the highest-energy neutrino ever detected. Analysis of the record-setting neutrino, which likely originated beyond the galaxy, could help astronomers understand the universe's most powerful particle accelerators.

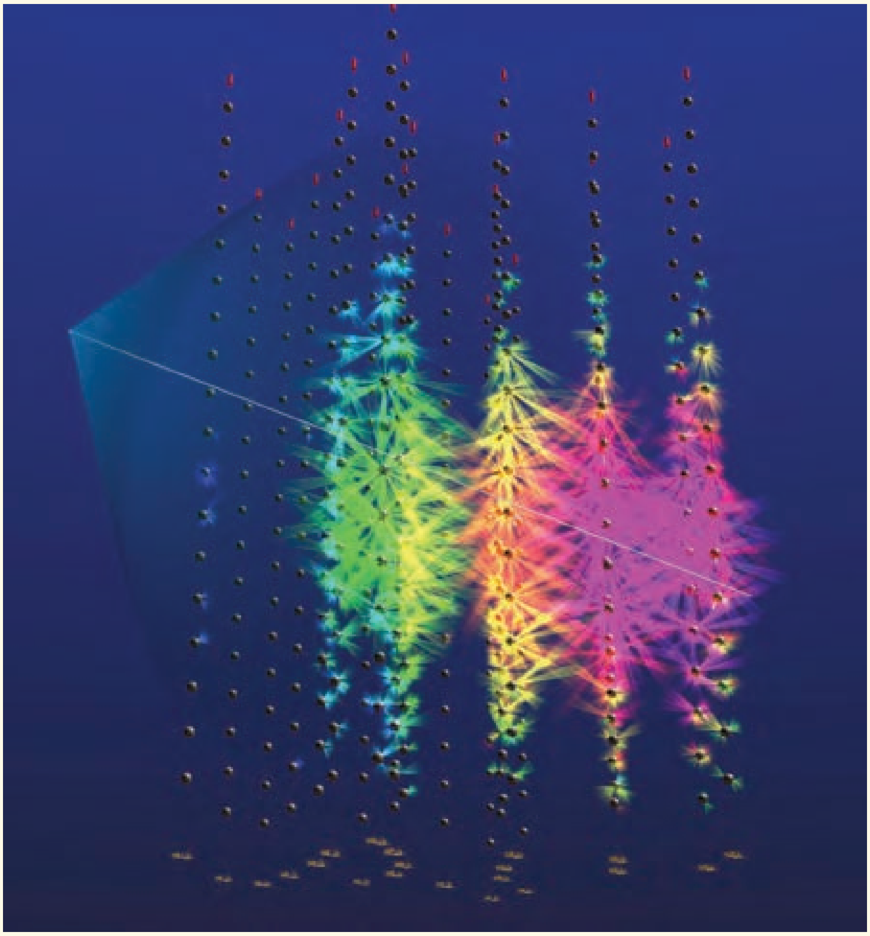
Neutrinos mingle with other matter exclusively via the weak force, and they do so rarely. Unlike charged cosmic rays, the electrically neutral particles are unaffected by magnetic fields and so travel in an unperturbed straight line from their sources. The challenge for doing neutrino astronomy is detecting the reclusive particles. To do the job, KM3NeT and similar projects deploy a vast network of light sensors in a transparent medium—in this case, Mediterranean seawater. Incoming neutrinos occasionally collide with water molecules to produce muons, electrons, and tau particles that travel so quickly in the water that they emit blue light known as Cherenkov radiation (see PHYSICS TODAY, September 2023, page 13).

Most detected neutrinos are produced in Earth's atmosphere and rain down on the telescope with energies at the scale of teraelectron volts. But the extraordinary signal recorded in February 2023—when the array dedicated to neutrino astronomy was operating with just 21 of 230 planned lines of sensors—clearly did not stem from an atmospheric neutrino. The muon's light saturated some of the telescope's sensors, and it propagated not downward but horizontally. The researchers estimated the energy of the muon at about 120 PeV and that of the original neutrino at 220 PeV. Though there is considerable uncertainty in those estimates, the neutrino almost certainly packed more energy than the previous record holder, a roughly 10 PeV neutrino spotted by the IceCube Neutrino Observatory in Antarctica.

The exceptional energy of the neutrino suggests that it was produced, directly or indirectly, in a violent astrophysical process. The neutrino may have formed in a relativistic jet of material ejected by an active galactic nucleus or other powerful celestial accelerator (see the article by Francis Halzen and Spencer Klein, PHYSICS TODAY, May 2008, page 29). But the KM3NeT researchers found no clear match corresponding to the direction of the incoming neutrino in catalogs of such objects. Alternatively, the neutrino could have been cosmogenic, meaning that it was generated when an ultrahigh-energy cosmic ray—itself likely produced by an active galactic



AN ARRAY OF SENSORS for the KM3NeT experiment is anchored to the Mediterranean seabed in this illustration. (It is much darker at these depths, 3.5 km below the surface, than depicted.) The detectors capture flashes of light emitted by muons and other particles that were produced in neutrino interactions. (Image copyright Edward Berbee/Nikhef, from KM3NeT/CC BY-NC 4.0.)



THE TRACK OF THE UNUSUALLY ENERGETIC MUON detected on 13 February 2023 by the KM3NeT array was reconstructed by the arrival times of light at various sensors. Unlike many of the particles spotted by the detectors, the muon was traveling horizontally (right to left along the line). (Image from KM3NeT/CC BY-NC 4.0.)

nucleus or similar object—struck a photon in interstellar space.

The mystery of the neutrino's source is tied to another: How lucky was it that KM3NeT, during a yearlong observing run with a skeleton of a detector array, snagged a particle that was more energetic than any cosmic neutrino that has been spotted during a decade-plus of searches by IceCube and other observatories? Using IceCube data, the KM3NeT researchers estimate that the detection of such an energetic neutrino with their small array is a roughly 1-in-70-years event. A more satisfying answer to the question requires pinning down the cosmic neutrino flux in coming years. IceCube, the still-in-progress KM3NeT, and other existing and planned neutrino telescopes will aid in that effort. (The KM3NeT Collaboration, *Nature* **638**, 376, 2025.)

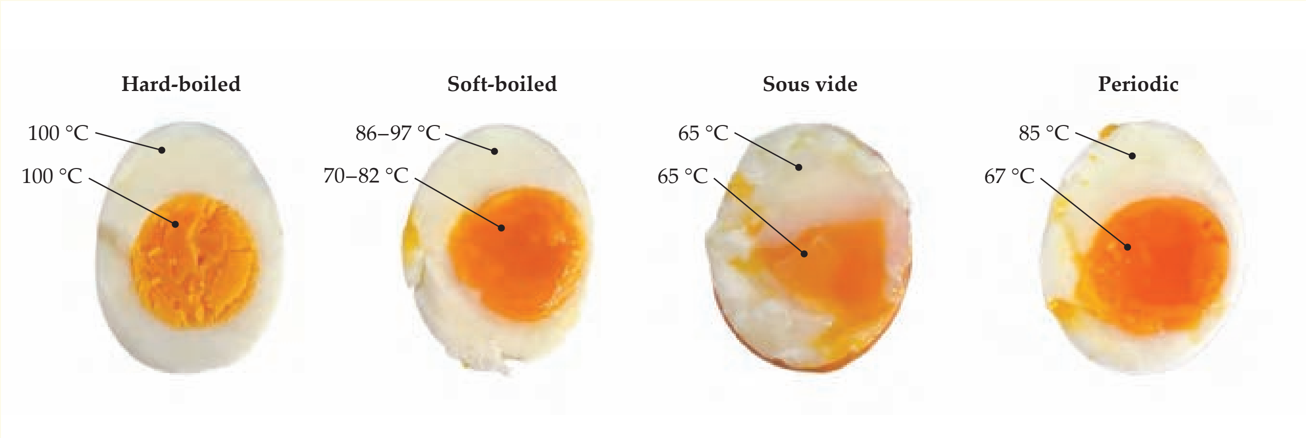
Andrew Grant

A meticulous thermodynamic recipe for cooking eggs

Cycling eggs between boiling and tepid water creates the firm white typically attained by soft-boiling and the creamy yolk usually achieved by sous vide cooking.

AN EGG WITH A CREAMY YOLK AND A FULLY SET WHITE was the result of a 32-minute periodic cooking procedure inspired by polymer engineering. (Photo courtesy of Emilia Di Lorenzo and Ernesto Di Maio.)

For many people, a perfectly cooked whole egg would have a yolk that is creamy and an albumen, commonly called the white of the egg, that is set. The yolk reaches a creamy texture at 65 °C, but the albumen becomes fully set at 85 °C. Common cooking methods often lead to a solid, flaky yolk (hard-boiling), a runny yolk (soft-boiling), or an unset white (sous vide, in which eggs are submerged in relatively low-temperature water).



DIFFERENT EGG-COOKING METHODS yield different results. Hard-boiling often creates a flaky yolk; soft-boiling, a runny yolk; and sous vide, a white that isn't fully set. Periodically switching eggs between boiling and tepid water can achieve internal temperatures that yield a creamy yolk and a fully set white. (Figure adapted from E. Di Lorenzo et al., *Commun. Eng*. **4**, 5, 2025.)

Realizing two specific temperatures within an object is a familiar problem to Ernesto Di Maio, of the University of Naples Federico II in Italy, and his colleagues. They expose polymer foams to time-varying pressures and temperatures to induce the formation of layers with different densities or morphologies. Because eggs have both an internal boundary and foaming capacity, Di Maio asked his student Emilia Di Lorenzo to determine if similar engineering principles could be applied in the kitchen.

Guided by their previous experience, Di Maio and colleagues predicted that alternating the exterior temperature would be the best way to manipulate the interior temperature of the two egg regions in different ways. Di Lorenzo created simulations based on basic heat-transfer equations and kinetic models of gelation to refine the cooking temperatures and timing. Then, the team broke open the egg cartons.

The trick, the researchers learned, was to alternate between cooking the eggs in 100 °C and 30 °C water every two minutes, for a total of 32 minutes. The two regions of the egg respond differently to the alternating temperatures because it takes 10–100 seconds for the heat to transfer across the boundary into the yolk. The albumen oscillates in temperature, which rises and falls with each transfer between pots before it eventually settles at around 85 °C. The yolk does not respond as quickly; instead, its temperature slowly rises until it reaches 67 °C, slightly above the average of the two cooking temperatures.

Satisfied with the temperature readings, Di Maio and colleagues also found that the two regions of the periodically cooked eggs had the desired textures. Adjusting the temperature of the pots or changing the time the egg remains in each can tailor the exact outcome to accommodate personal preference in cooking. The extra time to cook might not be worth it for the average home cook, but Di Maio and Di Lorenzo—who does not even like eggs—predict that restaurants may experiment with their method. In the meantime, they have turned their attention back to multilayered polymers. (E. Di Lorenzo et al., *Commun. Eng*. **4**, 5, 2025.)

Jennifer Sieben

The protection required to deliver a powerful underwater punch

The structure of a smasher mantis shrimp's clubs protects their tissue from damaging shock waves.

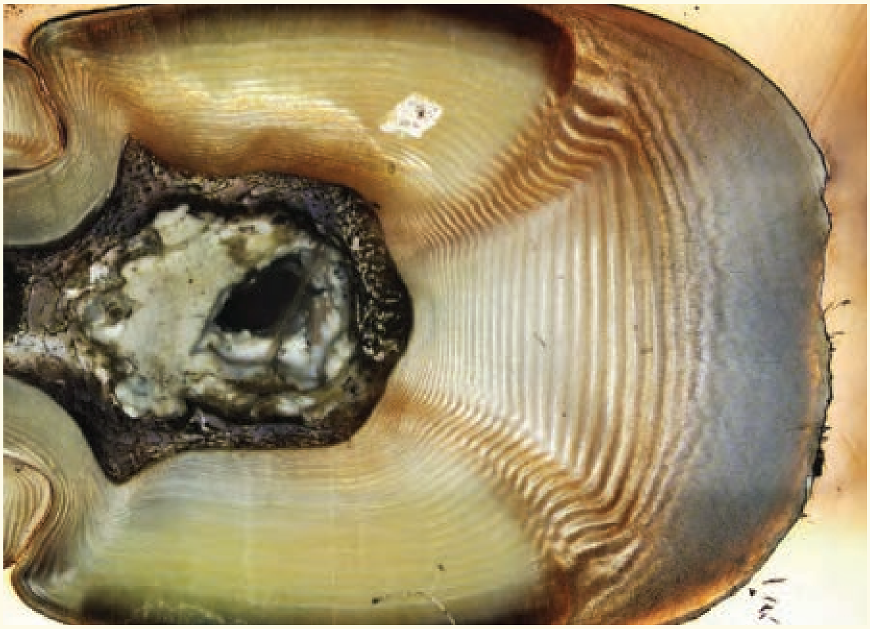
The smasher mantis shrimp is small, but it packs a large punch. It has evolved to use its specialized front appendages—the dactyl clubs, the two red bulbous structures in the photo on page 16—to shatter seashells with peak forces of around 1500 N delivered in less than 50 μs. That is the strongest self-powered strike by any known animal on Earth. Although other animals have similar attack mechanisms, they typically sustain damage, and they can attack only once per molting cycle. The mantis shrimp's attacks are not similarly limited. Now Horacio Espinosa of Northwestern University and colleagues have provided the first experimental evidence that the clubs' internal structure is what prevents substantial damage.

When a dactyl club strikes a shell, two impacts occur: one from direct contact and another from the collapse of cavitation bubbles formed in the surrounding water when the club retracts. Espinosa had learned from previous experience in studying underwater explosions that shock waves could be dangerous underwater, even if they don't generate as much force as a contact blow. The collapse of the bubbles generates both pressure waves and shear waves, with the latter being particularly harmful to biological tissue.

Previous theories suggested that phononic bandgaps—structural mechanisms for filtering stress waves within specific frequency ranges—help reduce damage to the clubs. Espinosa and his team used acoustic-wave analysis to examine how shock waves are filtered in a club. They discovered that the high-frequency waves generated by the bubble collapse match the frequencies that a dactyl club's internal structure is able to filter.

THE PEACOCK MANTIS SHRIMP—a variety of smasher mantis shrimp—uses its two dactyl clubs, the red bulbous appendages shown folded backward above the legs, to shatter various seashells, including those housing hermit crabs. The clubs' internal structure protects them from damage. (Photo by iStock.com/mantaphoto.)

Each dactyl club has a hierarchical design with multiple regions. The impact surface behaves like a ceramic: hard but resistant to fracture. Beneath that outer layer, the club contains two regions of fine chitin fibers, with the innermost region arranged in a helicoidal pattern, known as a Bouligand structure. In typical shattered glass, cracks form radially outward. In a helicoidal fiber architecture, however, cracks follow complex curved paths, which makes the material resistant to crack propagation.



A BISECTED VIEW OF A PEACOCK MANTIS SHRIMP'S DACTYL CLUB. Periodic layers of chitin fibers give it a striped appearance. The structure filters shear waves and reduces damage to the shrimp, so it can attack multiple times. (Image adapted from N. A. Alderete et al., *Science* **387**, 659, 2025.)

The periodicity of the Bouligand structure is also crucial to filtering propagating shear waves. The chitin fibers are stacked at varying angles, with the periodicity of the stacks decreasing closer to the club's core. That gradient enhances wave filtering across a broader frequency range, thereby reducing the energy transmitted to the shrimp's soft tissue.

Espinosa and colleagues used lasers to excite and measure waves propagating within a bisected dactyl club of the peacock mantis shrimp (a variety of smasher mantis shrimp) to confirm the filtering effect. Their experiments and analysis of the resulting phononic spectra showed that the club was selectively filtering harmful frequencies. Although the structure operates similarly to a phononic crystal, replicating it synthetically would require advanced nanomanufacturing techniques. (N. A. Alderete et al., *Science* **387**, 659, 2025.)

Jennifer Sieben PT

INTERNATIONAL YEAR OF
Quantum Science and Technology

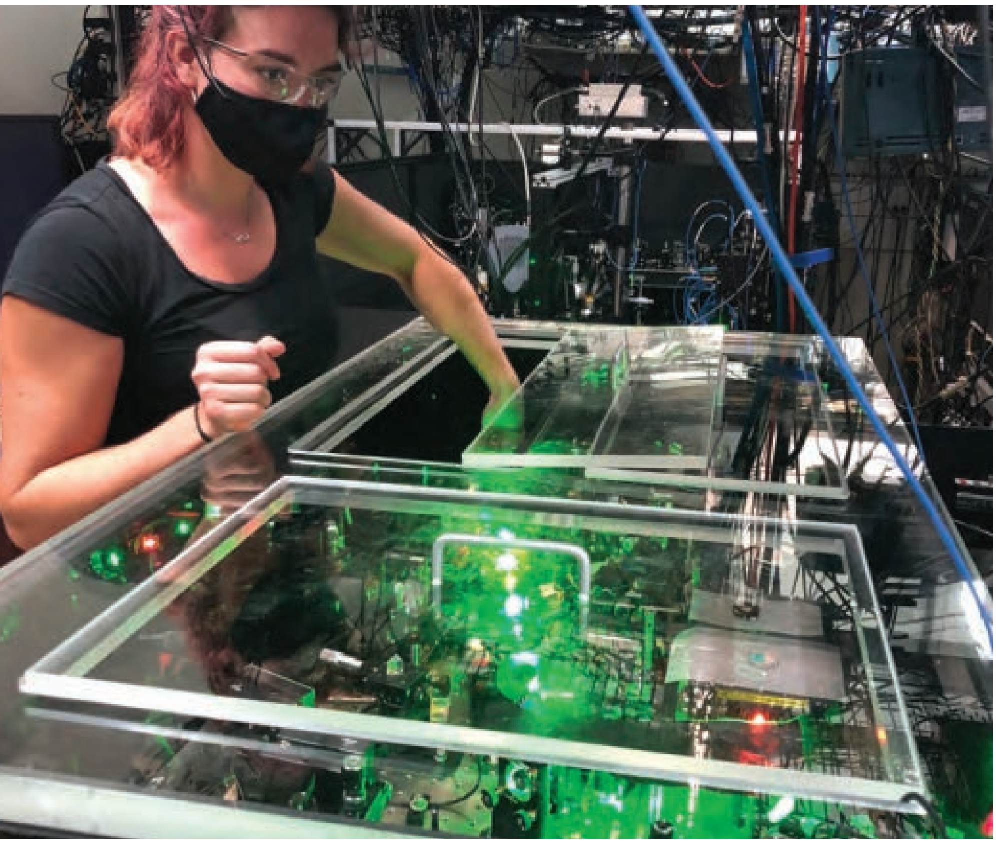
Not all quantum jobs require quantum skills

To go commercial, quantum science needs a sizable workforce.

Quantum technologies of the future could secure sensitive data from foreign adversaries, offer unparalleled precision for medical imaging, and unlock new battery chemistries to accelerate decarbonization, among other applications.

Yet roughly one in two jobs in quantum technology in 2022 remained vacant globally as companies struggled to find workers, according to an analysis by management consulting firm McKinsey & Company. Demand for workers in the field is expected to grow rapidly in the next decade as more quantum-enabled technologies go mainstream.

To meet that demand, recruiters will have to reach out to STEM workers who may not realize that they are competitive candidates for quantum roles, which can include programming, business development, basic research, and equipment manufacturing. "Even those with a fundamental scientific background often perceive quantum science as an overly complex, counterintuitive theoretical subject confined to research labs," says Syracuse University's Moamer Hasanovic, a professor of electrical engineering who leads the EdQuantum project for developing quantum curricula. And emerging research in the US suggests that joining the quantum workforce doesn't require deep knowledge of quantum mechanics or, in some cases, any prior quantum experience at all.



QUANTUM INDUSTRIES are hungry for workers to fill the workforce gap. Most quantum jobs are STEM-related roles and intersect with physics, engineering, computer science, math, and chemistry. Here, a NIST scientist conducts research in quantum logic spectroscopy. (Photo courtesy of A. Collopy/NIST.)

For startups and tech giants looking to expand their pool of potential candidates, that's good news because the number of recent STEM graduates isn't large enough to fill the talent gap. The fastest and easiest way to fill that gap would be to retrain other STEM workers to come help in the quantum field, says Jacob Douglass, a technical business development specialist at Sandia National Laboratories.

The quantum workforce

Quantum technologies today can be divided into quantum computing, quantum sensing, and quantum communication. Quantum computing, the most well-known field, receives the lion's share of private investment. Quantum sensing houses some of the most mature technologies, including sensors found in everyday products such as GPS trackers and MRI scanners. Quantum communication is an emerging field that focuses on securely transferring encrypted information.

No estimate of the size of the US quantum workforce exists, but two regional tech hubs have published tallies. Colorado-based Elevate Quantum and Chicago-area Bloch Quantum both received special tech hub designation from the US Economic Development Administration in 2023 as part of the CHIPS and Science Act. Elevate Quantum reports that about 3000 workers in Colorado are currently employed in quantum technologies, and the number could grow to around 30 000 by 2035. Chicago Quantum Exchange's Bloch Quantum estimates that more than 400 workers in the Chicago area are in quantum-related jobs, and the group projects a total of up to 191 000 jobs in the Illinois-Wisconsin-Indiana region in the next decade.

What companies are looking for

The most common roles that US quantum technology companies are trying to fill range from highly specific, like quantum algorithm developer and error-correction specialist, to much more general, like roles in business, software, and hardware, according to a 2020 survey of 57 US quantum companies by the Quantum Economic Development Consortium (QED-C). Many of the position skills that the surveyed companies listed as necessary were general STEM skills rather than quantum skills. For example, an engineer in quantum control systems must be proficient at circuit and systems testing, control theory, noise measurement, and analysis, none of which are quantum specific. Not surprisingly, jobs that are more closely related to quantum technology necessitate more quantum-specific skills. An error-correction scientist requires knowledge in quantum algorithm development, quantum science, and theoretical mathematics and statistics.

The QED-C survey found that employers are looking for a range of degree levels to fill new positions. "If you have an undergraduate or master's, getting a little bit of quantum under your belt would make you quite well qualified for a lot of different kinds of positions," says Celia Merzbacher, QED-C executive director. A separate analysis by the Chicago Quantum Exchange obtained similar results: More than half the 5000 global quantum jobs posted between 2022 and 2023 required no more than a bachelor's degree.

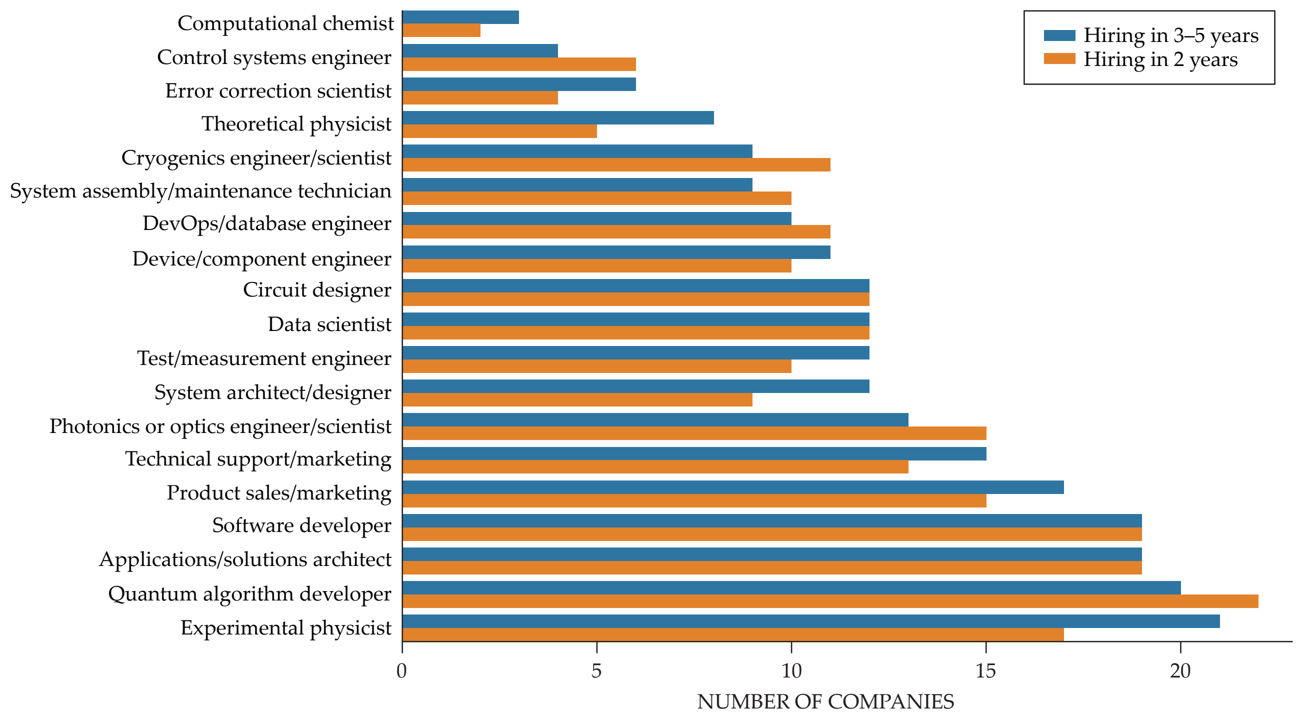
Professionals who join quantum startups today could receive significant financial benefits if a venture succeeds. Sectors as wide ranging as chemicals, life science, and finance could gain as much as $2 trillion in economic value by 2035 from advancements in quantum technology, according to a 2024 McKinsey report. Workers could also advance their careers in larger organizations by becoming a part of burgeoning quantum teams.

Entering a fast-paced field early puts workers at the leading edge, says Douglass. "You could have real, true, meaningful contributions to actually realize what this technology could do."

Jenessa Duncombe

Resources for retraining

- The Quantum Economic Development Consortium maintains a public quantum jobs board on its website: https://quantumconsortium.org/quantum-jobs.
- Researchers at the Rochester Institute of Technology and the University of Colorado Boulder provide an interactive map of nearly 9000 quantum courses in the US: https://quantumlandscape.streamlit.app.
- Professional societies occasionally host quantum-related programming, such as events at the American Physical Society's Global Physics Summit: https://summit.aps.org.



IN-DEMAND QUANTUM JOBS, according to a 2020 survey of 57 US-based quantum companies. The positions span multiple STEM disciplines, and most do not require quantum-specific skills. (Figure adapted from C. Hughes et al., *IEEE Trans. Educ.* **65**, 592, 2022/CC BY 4.0.)

Rallying for science across the US

Crowds gathered on the National Mall in Washington, DC, and in cities across the US on 7 March to protest the Trump administration's actions undercutting US science. Federal agencies have slashed or paused research funding, deleted public data, ordered mass layoffs, and attacked diversity, equity, and inclusion (DEI) initiatives. "We are looking at the most aggressively antiscience government the United States has ever had," said astronomer Philip Plait. He was among the speakers in the nation's capital at the Stand Up for Science rally, which drew 5000 federal employees, affected scientists, and others.

Several attendees at the DC rally spoke to Physics Today. A plasma physicist talked about early-career scientists and graduate students losing their jobs and funding. National Institutes of Health employees said layoffs and funding cuts have shrunk their labs and slowed their scientific research. A professor at Howard University said she worries about the removal of DEI funding that supports much of her lab's work.

"The administration is firing, and bullying, and threatening scientists and workers across the government who make the world a better place," said speaker Gretchen Goldman, an environmental engineer and president of the Union of Concerned Scientists. She added that "we stand together today to raise our voices together and to tell the administration that we will not back down."

Jenessa Duncombe

THE STAND UP FOR SCIENCE RALLY in Washington, DC, drew about 5000 protesters. (Photo by Laura Fattaruso.)

Ukrainian physics journal celebrates a half century

The editors of *Fizyka Nyzkykh Temperatur* (*Low Temperature Physics*) have continued publishing despite Ukraine's war with Russia.

Not a month has passed since 1975 without the release of a new issue of *Fizyka Nyzkykh Temperatur* (*FNT*). The journal, which is published jointly by the B. Verkin Institute for Low Temperature Physics and Engineering and the National Academy of Sciences of Ukraine, marked 50 years in January. It is translated into English and published as *Low Temperature Physics* by AIP Publishing. (AIP Publishing is owned by the American Institute of Physics, which publishes Physics Today.)

Publishing *FNT* has been tough in the three-plus years since Russia invaded Ukraine in February 2022. The

AN EDITORIAL MEETING of the Ukrainian journal *Fizyka Nyzkykh Temperatur* that took place before Russia's 2022 invasion of Ukraine. (Photo from *Fizyka Nyzkykh Temperatur*.)

THE JOURNAL HEADQUARTERS in Kharkiv was damaged by multiple bombings early in the war. (Photo by Volodymyr Repin, deputy director of the B. Verkin Institute for Low Temperature Physics and Engineering of the National Academy of Sciences of Ukraine.)

issues put together in the days and weeks following the invasion were the slimmest in the journal's history. They were also the most difficult to prepare and publish. That's according to Yurii Naidyuk, Konstantyn Matsiyevskiy, and Olexandr Dolbyn, respectively the journal's editor-in-chief, its managing editor, and the acting director of the B. Verkin Institute for Low Temperature Physics and Engineering, where the journal is headquartered. (Ukrainian physicist Boris Verkin founded both the institute and the journal.) The three physicists responded jointly via email to Physics Today's queries.

In the first few months of the war, bombs and artillery repeatedly damaged the institute, which is in Kharkiv, some 40 kilometers from the Russian border. More than 500 of the institute's windows were destroyed, and its buildings were left without heat, electricity, water, or sewage services, according to the three physicists.

Editors and staff first had to "save their own families and children from the daily raids of enemy aircraft and artillery shelling," the physicists wrote, noting that many employees sought refuge in western cities of Ukraine and in other European countries. For a while, the physicists added, editorial work and the monthly printing of the magazine from "within the walls of the institution was out of the question." The Institute of Low Temperature and Structure Research of the Polish Academy of Sciences in Wrocław provided editorial space and computer servers for saving data and the journal's website.

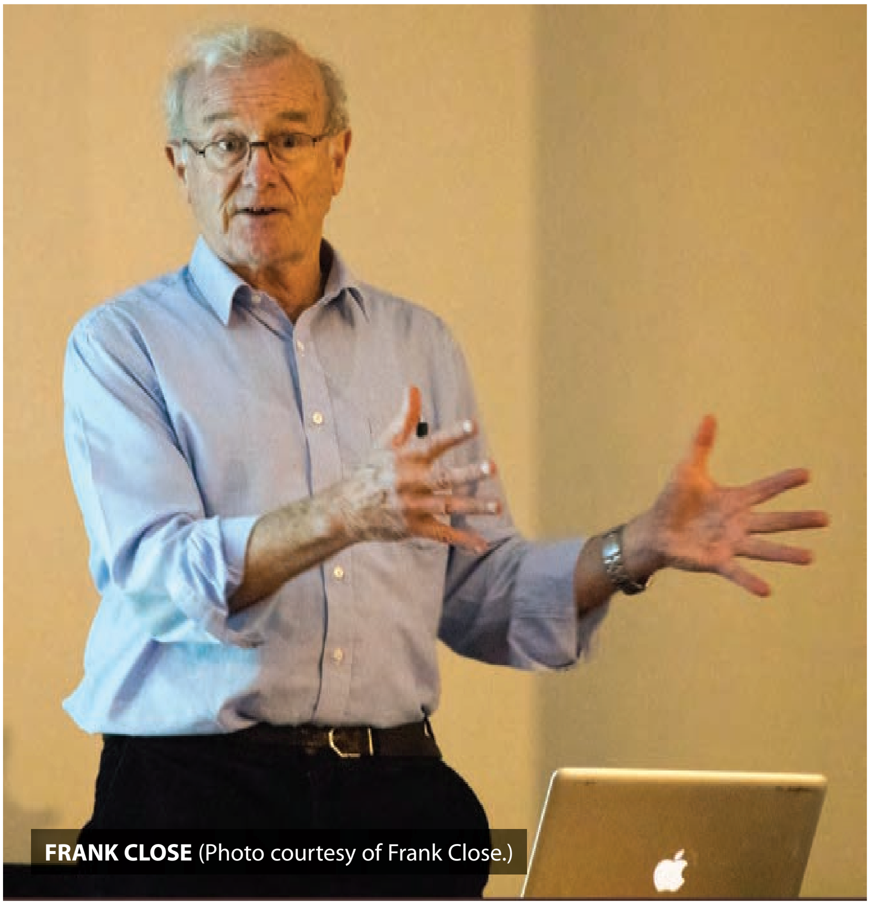
Six months after the invasion, *FNT* resumed publishing from its Kharkiv headquarters. The bombings and raids continue, and the editorial team is still scattered—in Ukraine, Poland, Switzerland, and beyond. As of press time, *FNT* had published 477 articles in the three years since the invasion. Authors hail from around the globe, but after the invasion, the journal stopped accepting submissions from Russia and Belarus, the *FNT* physicists wrote.

Over the half century of its existence, *FNT* has published some 10 000 articles in areas including quantum liquids, disordered systems, biophysics, and methods in low-temperature experiments. It has featured many special issues, including ones celebrating the centenary of the production of liquid helium (2008), the 30th anniversary of the discovery of high-temperature superconductivity (2016), and advances in quantum materials (2023).

Toni Feder

Q&A: Frank Close probes quarks and popularizes science

He has written books on quarks, protons, spies, nuclear threats, and more.



FRANK CLOSE (Photo courtesy of Frank Close.)

Writing about science for a broad audience and researching in the rarefied area of quarks bear some resemblance, according to Frank Close. He should know.

For much of his career as a theoretical physicist, Close was also writing articles and books for the public, and he has continued writing since retiring from research in 2010. His books—21 and counting—include a coffee table collection of images from particle physics; a profile of Peter Higgs and the boson named for him; the cold fusion controversy; and dives into Klaus Fuchs and Bruno Pontecorvo, physicists who both worked on the Manhattan Project and were, respectively, confirmed and suspected spies.

His 22nd book, *Destroyer of Worlds: The Deep History of the Nuclear Age*, is due out in June. He wrote it over the course of 27 weeks in 2023 while undergoing chemotherapy and radiation for non-Hodgkin's lymphoma. The irony, he says, is that he was writing about how nuclear physics led to bad things while he was benefiting from some of its good things—PET scans, radiology, and the like.

Researching for a book is "like a classical scientific research project," Close says. Much research in science is not greatly different from being a detective in the police force or what have you, he adds. "It's trying to find out, How much do we know? What are the known unknowns?"

For his scientific research, Close focused on quantum chromodynamics (QCD), quarks, and gluonic hadrons. After earning his PhD at Oxford University in 1970, he did postdocs at SLAC and CERN, and then he spent most of his research career at Rutherford Appleton Laboratory in Oxfordshire, UK.

PT: Why did you go into physics?

CLOSE: My high school chemistry teacher told us that everything was made of atoms and that atoms of one element and another element differed only by the number of electrons whirling around the central nucleus. That was a mind-blowing revelation.

I thought, "If I can understand how that works, I can derive all the other stuff from it." Six decades later, I haven't managed to do that, but that was how I suddenly understood that physics underlies everything.

PT: Describe your career path.

CLOSE: I happened to be starting my PhD research in 1967 in Oxford, one of the few places in the world that took quarks even semiseriously at the time. Luckily for me, I got in on the ground floor.

In the summer of 1968, I was talking to my supervisor, Dick Dalitz. I was depressed that I was doing a thesis on something that I had no evidence for at all. He told me to talk to Don Perkins, a professor who worked on neutrinos.

Perkins had just returned from a conference in Vienna at which [Wolfgang] Panofsky from Stanford [University] had announced the first experiments on deep inelastic scattering, which today we know were the first evidence for the reality of quarks. When I told Perkins what I was doing and why I was depressed by it, he went to a drawer in his office and pulled out a sheet of paper with a graph on it and said, "If that's not a quark, I don't know what is."

When I eventually finished my thesis, I went to Stanford, where the experiments that produced evidence for the existence of quarks had been done. For two years, I felt I was at the center of the universe. It was perhaps the most exciting time of my life.

PT: What came next?

CLOSE: For the next 40-odd years, I worked either on the constituent quark picture of hadrons or on applying QCD to the deep structure of hadrons.

PT: How did you get into popularizing science?

CLOSE: In 1976, I attended the International Conference on High Energy Physics in Tbilisi, Georgia. For some random reason, I got a communication from *Nature* asking me to write about the conference for their News & Views section.

Because I suddenly had a reason to be there, it meant I had to concentrate. The headline was "Iliopoulos wins his bet"—a reference to John Iliopoulos's having said two years earlier that he was prepared to wager a whole case of wine that the next conference in the series would be dominated by discussion of the charm quark.

That's how I got started. For about 20 years, until the mid 1990s, I continued to write for News & Views. I covered a really exciting period, including the discoveries of charm and the W and Z bosons. (See, for example, Physics Today, November 1983, page 17.)

I also wrote for the *Guardian* newspaper. That's where I got the best education in writing—from Tim Radford, the science editor. I would compare line by line what I had sent him with what was finally published. From that, I started learning to say things more concisely.

Over the years, I have also been a guest on the BBC radio show *In Our Time*. We've had a program on the electron, the proton, the neutron, the photon. We've had programs on antimatter, neutrinos, Paul Dirac, the Pauli exclusion principle. I do it roughly once a year. It's great fun.

PT: How did you go from writing short pieces to books?

CLOSE: The 1980s were a messy time in the UK for particle physics. Other areas of science were beginning to question why so much money was going into CERN and particle physics. Was Britain better off out of it all? Money could be used for other things. I thought about writing a book about this.

Popularization of physics was not yet a big deal. Steven Weinberg's *The First Three Minutes* changed all that when it came out in 1977 (see Physics Today, June 1978, page 53). It was about the first three minutes of the universe. I thought I could write something complementary about particle physics. That became *The Cosmic Onion*, which was published in 1983. Members of the committee that was investigating whether Britain should stay in CERN read my book. Thankfully, in the end, we stayed in CERN—not because of my book, but the book was in the background.

PT: How do you choose book topics?

CLOSE: In 2006, I wrote Ray Davis's obituary for the *Guardian*. He had spent 40 years chasing neutrinos from the Sun. The obituary won a prize for best science writing in a nonscientific context. I developed that into a book.

In the course of researching that book, Bruno Pontecorvo's name kept coming up, which led me to research him. That eventually led to my book *Half-Life: The Divided Life of Bruno Pontecorvo, Physicist or Spy*. One thing leads to another.

PT: How did you come to write about Klaus Fuchs, who worked on the Manhattan Project and spied for the Soviet Union?

CLOSE: When I was getting to the end of my book on Pontecorvo, I decided to see what the National Archives had on Fuchs. It turned out there were 25 volumes. For both Pontecorvo and Fuchs, there was also a personal connection: They had lived in Abingdon, not far from where I live. And I knew Rudi Peierls, who knew them both and was like a father to Fuchs.

I opened the first file and saw a photostat sheet of Fuchs's travel expenses. I discovered something: He had gone to a meeting at Cambridge, and his travel expenses said he'd done 220 miles. He'd gone a couple of other times, and it was 180 miles. And the longer trip was on the same date that he later admitted he met his Russian contact in London. The date caught my eye because it was the same as a family birthday.

"If only someone back then had noticed that the trip took another 40 miles," I thought. "I bet nobody has seen this before." That's what started me on Fuchs.

PT: Did you uncover anything interesting about him?

CLOSE: The really scandalous thing I discovered was that when he moved over to the US from the UK, the British decided not to alert the Americans about suspicions they had about his proclivities for communism. I found an astonishing letter in the files. It said that Fuchs was unlikely to meet any fellow travelers over there. How wrong could you be?

If General [Leslie] Groves, who [oversaw the Manhattan Project and] was always suspicious of the whole British involvement in it, had been aware of that letter back in 1943, the Brits would have been hung out to dry.

But Fuchs was a very successful spy. He spied for nine years and didn't make a single mistake. It was the Russians who failed him. His information was sent by cable to Moscow after encryption using a one-time pad. Use the pad once only and it is uncrackable. But for some reason, the Russians used a one-time pad twice. That mistake ultimately led to his being uncovered.

PT: What about cold fusion? How did you get on to that topic?

CLOSE: When the news was announced in 1989, everyone was asking, "What's going on? What does it mean?" I started off thinking this is a great thing to be on top of because if it's indeed correct, it's the greatest discovery since who knows what, and it will be fascinating to describe how the new revolution happened and how science developed from this thing to the great golden future.

But if it turns out not to be true—and very quickly we suspected that was the case—how will science establish that? I thought it was an opportunity to describe how science works in real time, on a story that everybody is interested in and has heard about. I had great hopes that I was going to chronicle a great moment in human culture. I never anticipated that my investigation would result in a headline, above the fold of the *New York Times*, "Cold fusion claim is faulted on ethics as well as science."

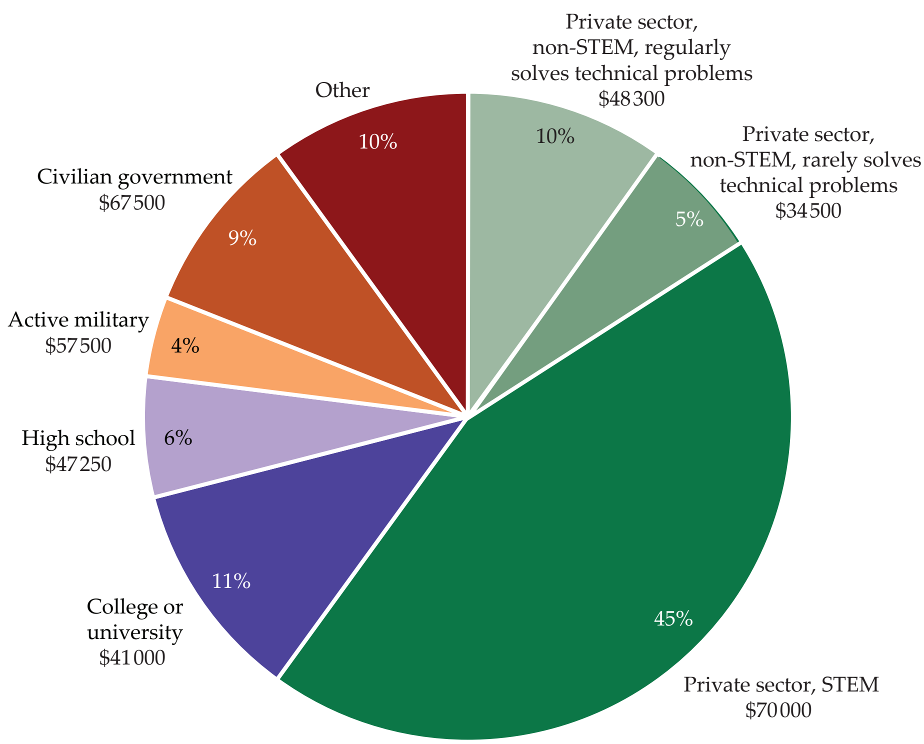
PT: What are you working on now?

CLOSE: I just sent in a proposal about Abdus Salam and John Ward. Their work on unifying the weak force and quantum electrodynamics is well known. How Ward missed a share of Salam's Nobel Prize is a question to be resolved. But how their covert lives—Ward's as the father of the hydrogen bomb in the UK and Salam's to be revealed in the book—got entangled is all in there. I am gathering the material and waiting for the protagonists, who both died more than 20 years ago, to tell me in my subliminal slumbers what their story will be. One of the great adventures is never quite knowing where a narrative is going to lead you.

Toni Feder

Physics bachelor's holders find jobs in many sectors

Just shy of half of US physics bachelor's degree recipients from the 2021–22 academic year entered the workforce within a year of earning their degree. The other half were enrolled in graduate studies in physics or astronomy (30%), were enrolled in another field (17%), or were seeking employment (4%). The percentage of physics bachelor's degree earners who enter the workforce immediately after graduating has been trending upward since 2009. Those and related data are available in a report published in January by the statistical research team of the American Institute of Physics (publisher of Physics Today.)



(Figure adapted from J. Pold, P. J. Mulvey, *Physics Bachelor's Initial Employment: Academic Years 2020–21 and 2021–22*, AIP Research, 2025.)

In the combined graduating classes of 2021 and 2022, 60% of physics bachelor's holders were in the private sector; 11%, in colleges and universities; 9%, in civilian government (including national laboratories); 6%, in high schools; 4%, in the military; and 10%, in other areas (see the chart).

In those employment sectors, new degree recipients worked in engineering (27%), computer software (16%), physics or astronomy (11%), and other fields. Starting salaries vary significantly both between and within sectors. The median salary for new physics bachelor's earners working in the private sector in STEM fields was $70 000; some individuals reported a starting salary of more than $120 000. The median starting salaries for those who work in civilian government was $67 500 and in colleges and universities, $41 000.

The full report, which includes details on salary ranges, job satisfaction, and skills used, can be found at https://ww2.aip.org/statistics/physics-bachelors-initial-employment-booklet-academic-years-2020-21-and-2021-22.

Tonya Gary

US science leaders offer blueprint for maintaining global leadership in STEM

A new report on how the US can realize its potential in STEM warns that China is pulling ahead.

SUDIP PARIKH (right), CEO of the American Association for the Advancement of Science, speaks about the Vision for American Science and Technology report on 25 February. (Photo by Lindsay McKenzie/FYI.)

The US could soon lose its position of global leadership in STEM without urgent action, according to a report released in February by prominent figures in the US science enterprise. The report warns that the country is at risk of falling behind competitors, particularly China, in terms of talent, infrastructure, and capital investment.

The Vision for American Science and Technology (VAST) report represents contributions from the VAST Task Force, comprising more than 70 leaders from nonprofit organizations, government, academia, and industry. (Michael Moloney, CEO of the American Institute of Physics, which publishes Physics Today, is a member of the task force.)

The report calls for increasing public and private investment in science, increasing the involvement of local leaders in regional STEM job creation, reinvigorating K–12 STEM education, strengthening public–private partnerships, attracting and retaining both US- and foreign-born workers, and increasing research security in order to protect scientific discoveries from foreign adversaries.

Among its funding recommendations, the report suggests creating a "recurring national priority-setting process to confirm areas of research that are foundational to national competitiveness and security." It also proposes "aggressively" increasing spending on AI, materials science, quantum computing, biotechnology, and "technologies for a resilient energy future" as well as using tax credits to incentivize private sector investment.

Sudip Parikh, CEO of the American Association for the Advancement of Science and chair of the VAST Task Force, acknowledged during the February AAAS meeting in Boston that the report comes at a time when many scientists are worried about the future of US science, particularly given recent layoffs at federal science agencies.

"There is uncertainty, there is anxiety, and it is rightfully so," Parikh said during a plenary session on the work of the VAST Task Force. He said that the task force debated how to "react to the current moment" and decided that their report is relevant as it provides a long-term "aspiration for the future that is saying, 'Here is what we must do.'"

Parikh argued that the US should look to the ambitions for federally funded basic research that emerged in the immediate aftermath of World War II. "We are standing on the shoulders of an 80-year-old vision, which is wonderful and thoughtful and amazing," he said. "Shouldn't this generation do something like that?"

The report highlights a proposal, put forward by National Science Board leaders, for the US to pursue an updated version of the National Defense Education Act of 1958 that would boost US STEM education, training, and job opportunities. Via email, Parikh said that the potential for an NDEA 2.0 is still present but that it is "not a one-year discussion." He added, "We must build momentum, but the building blocks and potential congressional champions are there."

During an Axios event in late February, Parikh again made the case for the government supporting basic research, stating that developments in fundamental science drive investment from the private sector.

"The United States government invests about $200 billion a year in science and technology. The private sector—industry and philanthropy—invests almost $800 billion a year in science and technology. But the $200 billion in basic research and other investments done by the federal government are critical. They actually enable all the rest of it," Parikh said. "The more dollars we put in from the feds, the more investment comes in from industry, and we get job growth, we get economic success, and we get national security out of it. What a deal."

Lindsay McKenzie

FYI SCIENCE POLICY BRIEFS

Congress plans to update small business R&D programs

Two federal programs that provide technology maturation grants to small businesses are set to expire at the end of the fiscal year on 30 September. The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs together allocate around $5 billion annually and are broadly popular, but they have been authorized for only a few years at a time; Congress has had to repeatedly extend them. Lawmakers have begun discussing potential reforms, including expanding research security measures and prioritizing funding for new applicants.

Protecting small business R&D from foreign exploitation, particularly by the Chinese government, was a central theme in a hearing held by the House Small Business Committee in late February. Shortly before the hearing took place, Republican lawmakers sent letters to the 11 federal agencies that administer SBIR and STTR grants to request that they examine the programs' potential vulnerabilities.

The Senate Small Business and Entrepreneurship Committee also discussed potential reforms to the programs during a hearing in early March. Committee Chair Joni Ernst (R-IA) has proposed legislation that would give the programs the ability to claw back funds from businesses that expose intellectual property to adversaries. The legislation would also set aside a large fraction of the SBIR budget for awards to new applicants, among other measures designed to reduce funding for companies that continually receive awards.

—LM

Staffing losses roil federal science agencies

Since President Trump took office in January, federal science agencies are down thousands of employees due to a combination of layoffs of probationary employees, deferred resignation offers, and reductions in force (RIFs). Some of the probationary employee layoffs have been challenged in court, and some have been reversed, but the same employees may ultimately be subject to RIFs, which are less open to legal challenges.

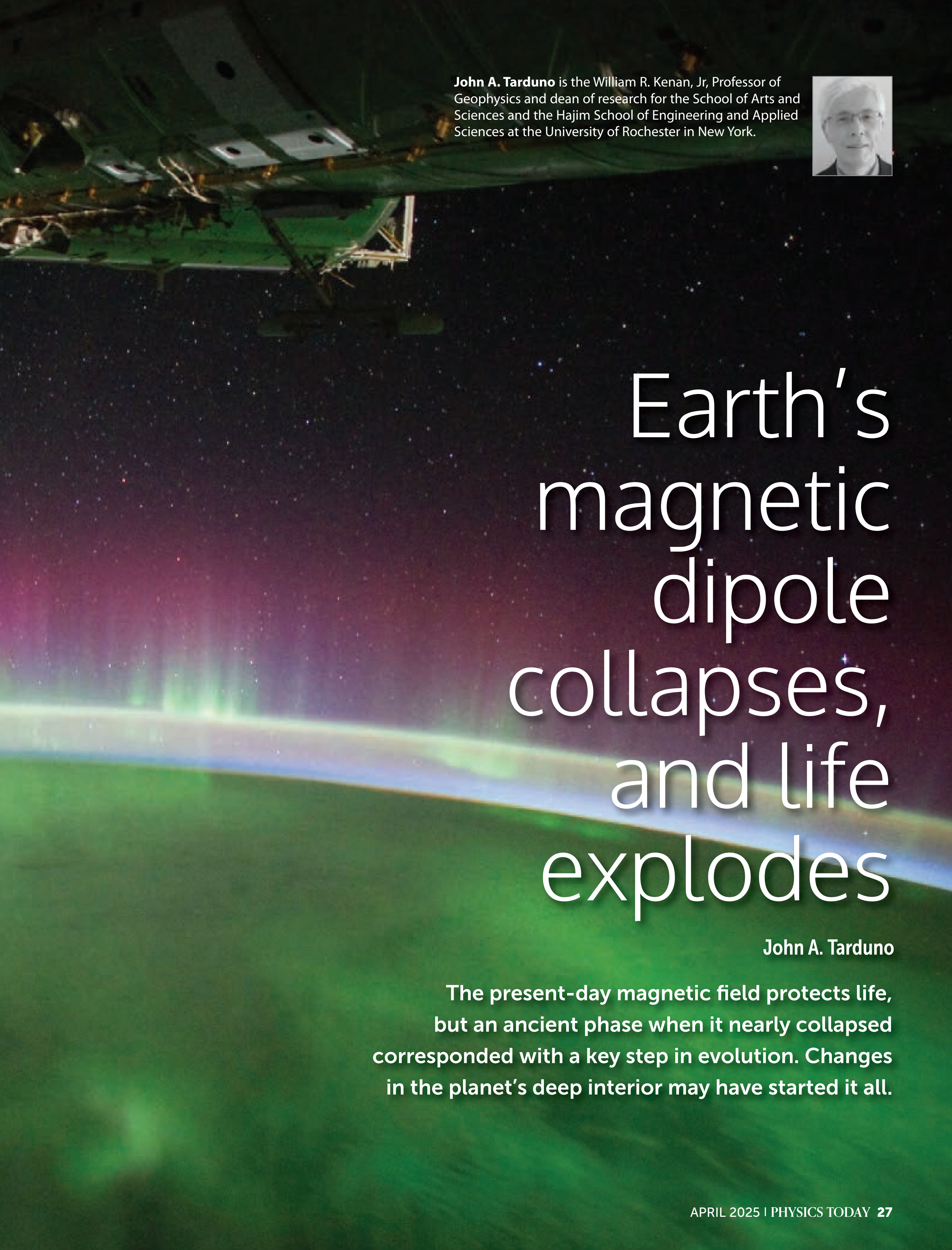
The exact size of the staffing cutbacks at science agencies remains unclear. As Physics Today went to press in mid-March, the losses included more than 2500 people at the Department of Energy, NOAA, and the National Institutes of Health. NSF fired more than 80 probationary employees but was in the process of rehiring most of them, and NIST fired around 70 probationary employees.

—LM 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

(Image from NASA's Johnson Space Center.)



John A. Tarduno is the William R. Kenan, Jr, Professor of Geophysics and dean of research for the School of Arts and Sciences and the Hajim School of Engineering and Applied Sciences at the University of Rochester in New York.

Earth's magnetic dipole collapses, and life explodes

John A. Tarduno

The present-day magnetic field protects life, but an ancient phase when it nearly collapsed corresponded with a key step in evolution. Changes in the planet's deep interior may have started it all.

Is Earth's magnetic field crucial to the planet's habitability? Did it enable the evolution of life? Scientists have pondered those questions for at least 60 years.[1] The geomagnetic field shields our planet from solar and cosmic radiation that are harmful to life. The magnetosphere, illustrated in figure 1, can limit erosion of the atmosphere by solar winds. And it helps keep water, an essential ingredient for life as we know it, from escaping to space. Based on those facts, many scientists view evidence for the great antiquity of the geodynamo—which is thought to be more than 4 billion years old[2]—as consonant with a geomagnetic field that has helped preserve Earth's oceans and habitability. But those who study the core, dynamo, and magnetism have found questions about their relationship to life ever more intriguing as new findings have shifted our understanding of ancient Earth.

The magnetic field is generated by convection in Earth's liquid-iron outer core, as illustrated in figure 2, and it varies on time scales that range from less than a year to hundreds of millions of years. Paleomagnetists—geophysicists who study the ancient magnetic field recorded in rocks and sediments—have established that the field reverses polarity at irregular intervals and that during polarity reversals, the field decreases in strength. Polarity transitions take thousands of years, but they are just moments when viewed across the expanse of geologic time, across which there is a seemingly omnipresent magnetic field.

Until recently, no one had reason to suspect that the magnetic field in the past had nearly ceased for tens of millions of years. But with new data, paleomagnetists have found a prolonged near collapse of Earth's magnetic field, some 575–565 million years ago during what's known as the Avalon explosion, the dawn of macroscopic complex animal life. We now face the possibility of a new, unexpected twist in how life might relate to the magnetic field, a twist that could reach deep into Earth's inner core.

A field adrift

When, in the 1950s, Ted Irving and his contemporaries first used paleomagnetic data to quantify continental drift—the harbinger of plate tectonics—they assumed that Earth's magnetic field could be approximated as a dipole centered on the planet's axis of rotation.[3] Ever since, geologists and geophysicists have used paleomagnetic directions recorded in rocks to reconstruct the past positions of continents because those data tended to conform to the expected field morphology.[4] They met a profound obstacle, however, when studying the Ediacaran Period, between 635 and 541 million years ago, because rocks formed at that time recorded a myriad of peculiar magnetic directions.

Some suggested that the odd directions recorded true polar wander, a reorientation of the solid Earth relative to its spin axis, at rates so high—up to tens of degrees per million years—that the explanation violated limits imposed by the viscosity of the mantle. Others proposed that the odd directions recorded alternations between a geocentric axial north–south dipole and a geocentric axial equatorial dipole, but they offered no reason for those changes. Subsequent studies revealed more complex directions that were incongruent with an interchange of dipole axes.

As even more data were collected, several groups concluded that the Ediacaran magnetic field was reversing polarity at a hyperfrequent rate, greater than 10 reversals per million years. From investigations of the most recent reversal, which occurred about 800 000 years ago, paleomagnetists knew that

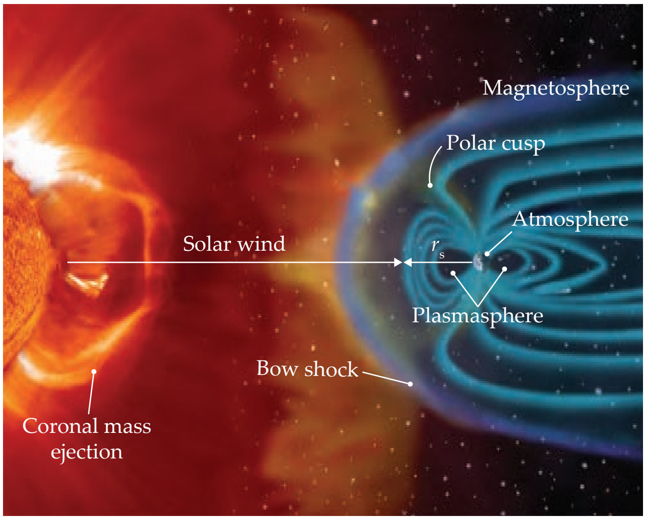


FIGURE 1. THE SIZE AND SHAPE OF THE MAGNETOSPHERE are controlled by interactions between the solar wind and Earth's magnetic field. A big-picture view of changes in magnetosphere size with time can be obtained by tracking the magnetopause standoff distance r_s, the point toward the Sun where the wind pressure is balanced by the magnetic field pressure. A typical standoff distance today is between 10 and 11 Earth radii. During solar storms—for example, the coronal mass ejection events and solar flares of May 2024 that produced auroras visible at low latitudes—the standoff can be compressed to half that distance, but only on hour time scales. The pressure balance between the solar wind and Earth's magnetic field can be calculated back in time to understand the ancient paleomagnetosphere.[2,7] (Image adapted from NASA's Goddard Space Flight Center.)

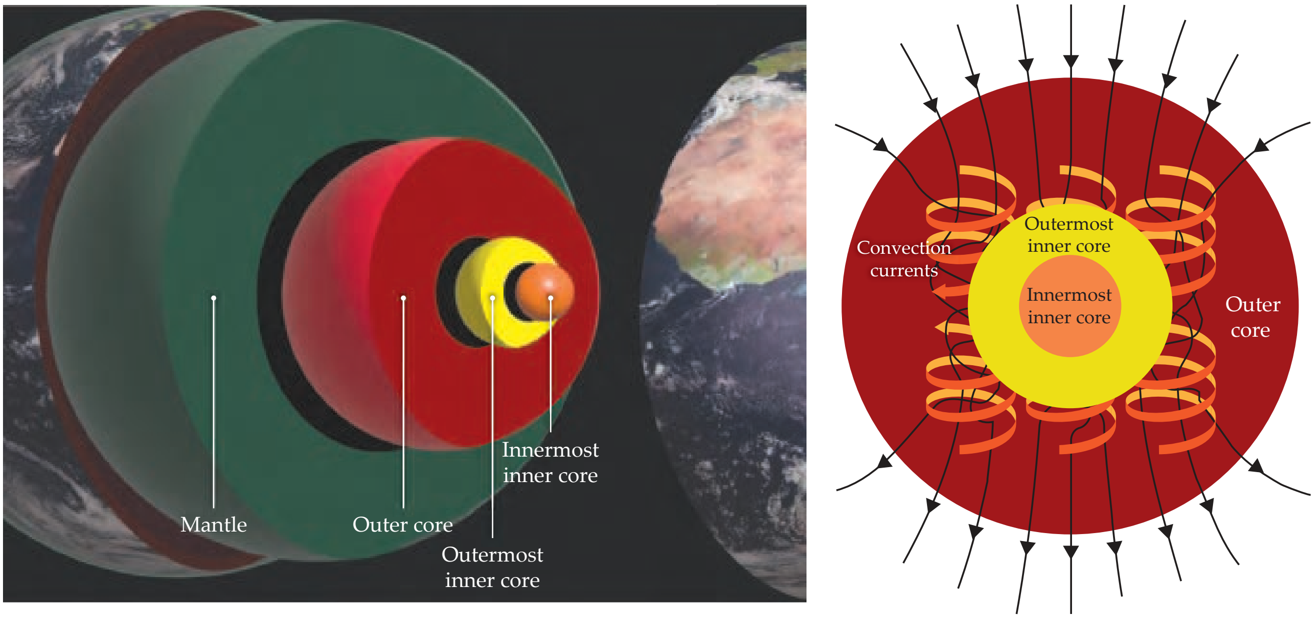


FIGURE 2. CHANGES DEEP INSIDE EARTH have affected the behavior of the geodynamo over time. In the fluid outer core, shown at right, convection currents (orange and yellow arrows and ribbons) form into rolls because of the Coriolis effect from the planet's rotation and generate Earth's magnetic field (black arrows). Structures in the mantle—for example, slabs of subducted oceanic crust, mantle plumes, and regions that are anomalously hot or dense—can affect the heat flow at the core–mantle boundary and, in turn, influence the efficiency of the geodynamo. As iron freezes onto the growing solid inner core, both latent heat of crystallization and composition buoyancy from release of light elements provide power to the geodynamo. (Left: Earth layers image adapted from Rory Cottrell, Earth surface image adapted from EUMETSAT/ESA; right: image adapted from Andrew Z. Colvin/CC BY-SA 4.0.)

the field could take on an unusual morphology during a polarity change. A few researchers recognized that frequent reversals pointed to nondipolar fields that could account for some of the seemingly erratic Ediacaran magnetizations. Other groups, however, stood by the idea of true polar wander and assimilated data into ever-changing models that raised the question, What was the principal physical process responsible for the strange magnetic directions?

Paleomagnetists had based their interpretations of the Ediacaran geomagnetic field on only magnetic directions because reliable data on the past strength of the field—paleointensity—had not yet been collected. The measurement of paleointensity is especially challenging because data are easily corrupted by alteration induced in the laboratory. The highest fidelity recording of paleointensity requires tiny magnetic grains, 50 to a few hundreds of nanometers in size. Those minute crystal grains hold a single domain, a region where the magnetization is in a uniform direction. The magnetization of an ensemble of single-domain grains provides a measure of the magnetic field strength at the time the grains cooled. But rocks with a dominance of such grains are rare in nature. (See the box on page 30 for more on single-crystal paleointensity measurements.)

In 2015, using the single-crystal paleointensity method, Richard Bono was the first to collect robust paleointensity data from the Ediacaran Period. His results—a geomagnetic field with a strength just one-tenth of the present-day field's—were startling.[5] Importantly, Bono and colleagues studied rocks that had cooled over at least many tens of thousands of years, so the readings were not just recording a geomagnetic reversal. Instead, they had measured the mean state of the past geodynamo. Bono and colleagues' study sites were in northern Quebec, on the ancient continent of Laurentia. Their results were soon reproduced by Valentina Shcherbakova and colleagues, who reported ultralow field values from rocks in Ukraine, part of the ancient continent of Baltica.

Shcherbakova and colleagues' results came from quickly cooled ancient lava flows, but their samples spanned a substantial time period, up to 20 million years long. Daniele Thallner, working with Shcherbakova, bolstered the results from Baltica and found tentative evidence for ultralow fields from dikes, quickly cooled igneous intrusions that formed in existing rocks, in Laurentia.[6] More recently, Wentao Huang used the single-crystal method to document ultralow field values from slowly cooled Ediacaran rocks from Brazil, part of the ancient continent Gondwana. Huang's data record the lowest time-averaged field found to date, one-thirtieth the strength of the present-day field. Together with the previous data, those results define an extraordinary ultralow time-averaged field interval, spanning at least 26 million years of the Ediacaran Period,[7] as shown in figure 3.

A new view of the inner core

Independent of the flurry of new paleointensity data, researchers, including theorists, mineral physicists, and geophysicists, had been reconsidering the evolution of Earth's thermal history and core evolution. In probing the details of the thermal history, those scientists raised the possibility that the thermal conductivity of Earth's core had been previously underestimated by as much as a factor of three. Stéphane Labrosse and Francis Nimmo both showed that if the core's conductivity was higher, the early core was also hotter. That suggested that Earth's solid inner core, illustrated in figure 2, was relatively young, with nucleation most likely commencing between about 600 and 500 million years ago.[8]

Mineral physicists have used high-pressure, high-temperature diamond anvil experiments to estimate conductivity values at core conditions, but those measurements are extraordinarily difficult. Recent experiments and analyses by several groups brought the initial high-conductivity estimates down, but the values are still higher than those based on classic assumptions. Measurements and debate are ongoing. Importantly, Peter Driscoll used a numerical model to predict that before inner-core nucleation, the geodynamo would approach the weak-field state, in which the kinetic energy of the fluid core exceeds the magnetic energy.[9]

Bono and colleagues considered the long-term history of the geomagnetic field and found that time-averaged paleointensity data show highs and lows on time scales of tens to hundreds of millions of years, as would be expected if the generating efficiency of the geodynamo reflects changes in the pattern of heat flux across the boundary between the core and the mantle. Such variations might be imparted by cold sinking slabs of tectonic plates or by hot rising mantle plumes.

Yet behind those variations, the researchers also detected from 3.5 billion years ago a signal of an ever-decreasing dipole intensity leading into the field's near-collapse, now dated between 591 and 565 million years ago, as shown in figure 3. That decrease is consistent with waning core–mantle boundary heat flux before inner-core nucleation. Combining that observation with their ultralow field values and the model predictions, Bono and colleagues proposed an Ediacaran inner-core nucleation date.[5]

Models predict that the magnetic field would strengthen as soon as the inner core started to grow because energy from both latent heat of crystallization and composition buoyancy would supply new power to the dynamo. Seizing on that prediction, Tinghong Zhou and colleagues conducted single-crystal paleointensity analyses on slowly cooled igneous rocks of the earliest Cambrian Period, just after the Ediacaran Period. They found that the time-averaged field strength had almost tripled between 565 and 532 million years ago[10] (see the top graph of figure 3). Based on those results, they assigned a more precise age of 550 million years to the time of inner-core nucleation and recognized an opportunity to explore an even deeper issue of core science.

Since Inge Lehmann's discovery of the solid inner core in 1936, seismologists have used data from large earthquakes to probe its inner structure. In 2002, Miaki Ishii and Adam Dziewoński found evidence for an innermost inner core, as sketched in figure 2, from the distinct behavior of seismic waves traveling through that region of the core. Although model details differ, many seismologists have confirmed the existence of an innermost inner core,[11] but its origin remains a mystery.

Zhou and colleagues investigated the possibility that changes in the lower mantle's structure and heat flow could have influenced the pattern of iron crystallization that formed the inner core. Using their estimated age for the onset of inner-core nucleation and a model for its growth, they proposed that the boundary between the outermost and innermost inner core reflects a change in deep-mantle heat flow. In their model, the ancient deep mantle was dominated by one basal thermochemical structure until, some 450 million years ago, it was replaced with two structures—one beneath the Pacific Ocean and one beneath the Atlantic Ocean—by deep subduction of

Measuring the intensity of the ancient magnetosphere

The magnetization, or remanence, of magnetic minerals in cooling igneous rocks can record the strength and direction of Earth's magnetic field at the time the rock formed. Grains with a single magnetic domain are key to the collection of robust measurements of the past strength, or paleointensity, of Earth's field. The magnetic grain sizes in most rocks are large enough that individual crystal grains contain many domains. The propensity of domain walls in multidomain grains to move, especially during geologic reheating events that even the best-preserved ancient rocks have experienced, can call into question whether magnetization has been accurately retained.

The single-crystal paleointensity method was developed to overcome that field-recording challenge. Many rock-forming silicate minerals (such as feldspars, pyroxenes, and quartz) or accessory minerals (such as zircons) can contain minute magnetic single-domain inclusions, without the multidomain grains common in bulk rocks. Some slightly larger magnetic inclusions, including small grains with more complex structures that act like single domains (for example, pseudosingle domains and single-vortex states), can also preserve ancient magnetizations.

Magnetic grains with a single magnetic domain can retain their magnetic fields for billions of years.[18] Laboratory heating experiments can be used to recover the paleofield strength H_{paleo} using the relationship

$$H_{paleo} = (M_{NRM}/M_{TRM})H_{lab},$$

where M_{NRM} is the natural remanent magnetization (NRM) lost after heating over a given temperature range in no magnetic field, and M_{TRM} is the thermoremanent magnetization (TRM) gained after heating over the same temperature in a known applied lab field of strength H_{lab}. In practice, the experiment is conducted over heating steps spanning the range of temperatures at which a sample's magnetic minerals lock in their magnetizations.

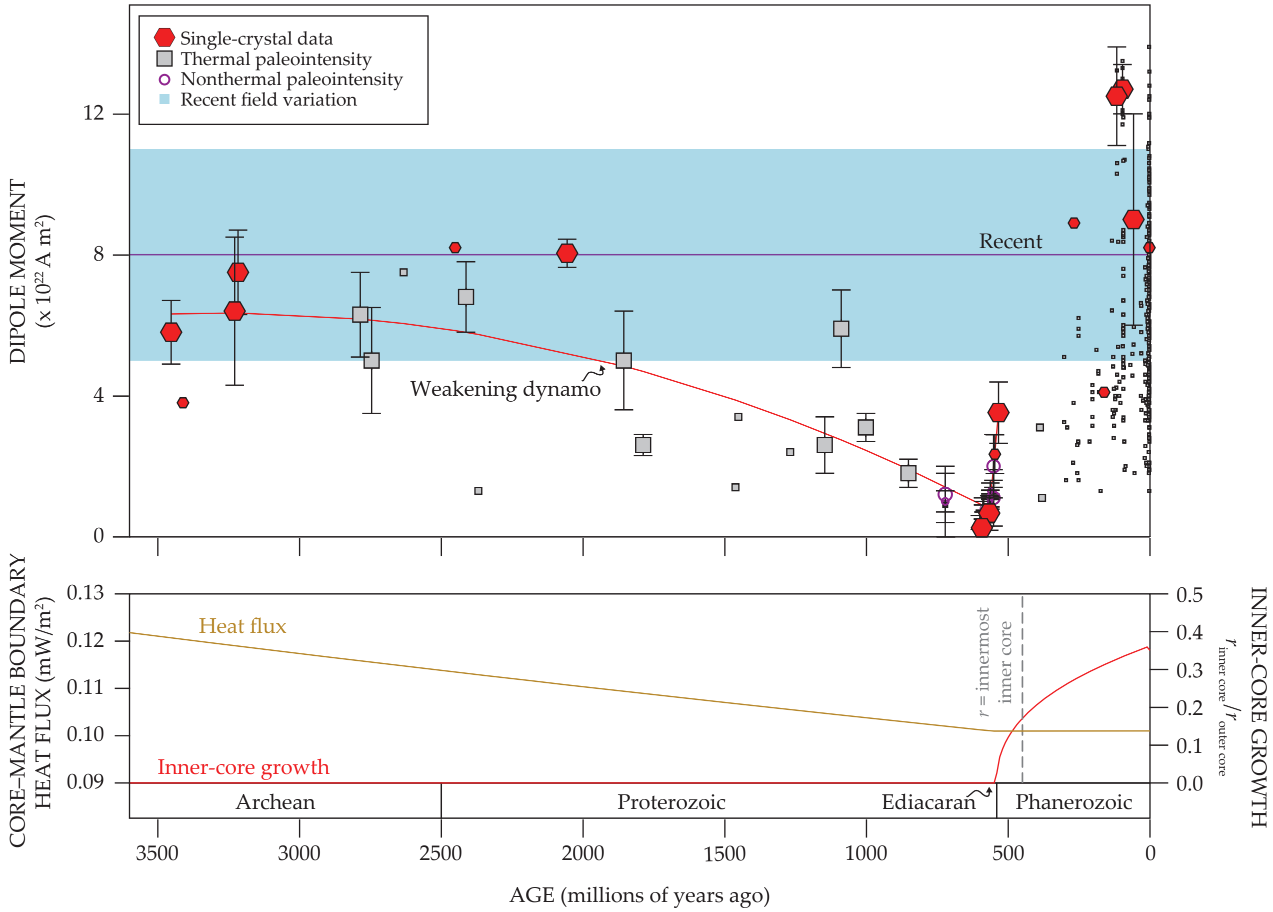


FIGURE 3. THE COLLAPSE OF EARTH'S MAGNETIC FIELD in the late Ediacaran Period corresponds with the formation of the inner core, based on geodynamic simulations of the planet's history. **(top)** Field strength (shown here as the strength of Earth's dipole moment) over time is constrained by select paleointensity analyses. Symbol sizes are larger for time-averaged values. **(bottom)** Geodynamic models are used to estimate changes in the heat flux at the core–mantle boundary[8] (gold) and corresponding estimates of inner-core nucleation and growth (red). The gray dashed line marks the time when the inner core was 50% of its current size. Some data analyses show a change in seismic anisotropy at that same radius, which is linked to the boundary between the innermost and outermost inner core,[11] shown in figure 2. (Figure adapted from refs. 5, 7, and 10.)

oceanic slabs (see the article by Ed Garnero and Claire Richardson, Physics Today, December 2024, page 36).

An explosion of animal life

Geophysicists and mineral physicists are approaching a consensus that could provide the key conceptual framework—the weak-field state before inner-core nucleation[5,9]—to understand why the Ediacaran geomagnetic field was so strange. Huang and colleagues also found a striking correlation between the evolutionary radiation (rapid increase in speciation) of animal life and the ultraweak field, and they took up anew the question of linkages with evolution.[7,12] Joseph Meert and colleagues had in 2016 suggested that a weaker field, which they inferred might be present from the apparent frequent geomagnetic reversals, was related to the explosion of complex life during the Cambrian Period, when nearly all modern animal phyla first appeared in the fossil record. (Although the Cambrian explosion of life has been recognized since the mid 20th century, the Avalon explosion of the preceding Ediacaran Period was discovered only in recent decades.)

In Meert and colleagues' model, a key agent driving the Cambrian explosion was a greater incidence of energetic solar protons.[13] Charles Jackman and colleagues had long advocated that a deeper penetration of energetic solar particles into the atmosphere during periods of weak geomagnetic field strength would lead to chemical reactions that produce nitrogen oxides, which in turn would deplete the ozone layer and lead to an increase in UV radiation. Meert and colleagues hypothesized that a higher UV-B flux would increase mutation rates and thereby stimulate evolutionary processes during the Cambrian.

But Manasvi Lingam questioned the linkage because the atmosphere and water shield much UV radiation, something Carl Sagan had highlighted some 60 years earlier.[14] Paleontologists infer that most new Ediacaran and Cambrian animal forms lived in the subsurface of oceans, which makes UV shielding particularly relevant. And Huang and colleagues emphasize that the correlation between the ultraweak field and evolution is a phenomenon of the Ediacaran Period and not the Cambrian Period (see figure 4).

Paleontologists have documented that eukaryotes (organisms with cell nuclei) were present before the Ediacaran Period, but they were almost exclusively microscopic in size. A dramatic increase in body size, however, occurred late in the Ediacaran Period—when mobile animals like the pancake-shaped *Dickinsonia* reached many decimeters in size[15]—and squarely within the time of ultraweak fields. Biologists generally associate larger body sizes and increased mobility with higher oxygen demands.

Is there evidence for increases in oxygenation during that spurt of evolution? Notwithstanding considerable ongoing debate associated with the difficulty of obtaining global oxygen signatures from measurements of ancient rocks, geochemists have found a wealth of data supporting an increase in oxygenation that coincides with the ultralow geomagnetic fields,[7,16] as shown in figure 4. Faced with a correlation between the ultraweak fields, oxygenation, and animal radiation, my group at the University of Rochester then asked the question, What might link these phenomena?

Eric Blackman, David Sibeck, and I have considered whether the linkage might be found in changes to the paleomagnetosphere. Records of the strength of the time-averaged field can be derived from paleomagnetism, whereas solar-wind pressure can be estimated using data from solar analogues of different ages. My research group and collaborators have traced the history of solar–terrestrial interactions in the past by calculating the magnetopause standoff distance, where the solar-wind pressure is balanced by the magnetic field pressure, shown in figure 1. We know that the ultralow geomagnetic fields 590 million years ago would have been associated with extraordinarily small standoff distances, some 4.2 Earth radii (today it is 10–11 Earth radii) and perhaps as low as 1.6 Earth radii during coronal mass ejection events.

Satellite and ground-based measurements have established that the area of the polar cap, the high-latitude region where atmosphere loss can be exacerbated, will increase at smaller magnetopause standoffs. In a now-classic work, George Siscoe and Chin-Kung Chen summarized standoff distances with respect to the plasmasphere,[17] the region in the magnetosphere beyond which plasma density drops by an order of magnitude (see figure 1). Because the plasmasphere is dominated by H^+, the small standoff distances my group has found highlight how hydrogen loss could have led to a net gain in oxygenation during the Ediacaran Period.

We are at an early stage in exploring exactly how much hydrogen could be lost, and available models yield different amounts, ranging from only modest increases in hydrogen escape to losses that produce oxygenation increases of a few percent. Together with our colleagues, we have proposed that the latter might represent the crossing of an oxygenation threshold and aided evolution of large, mobile Ediacaran animals like *Dickinsonia*.

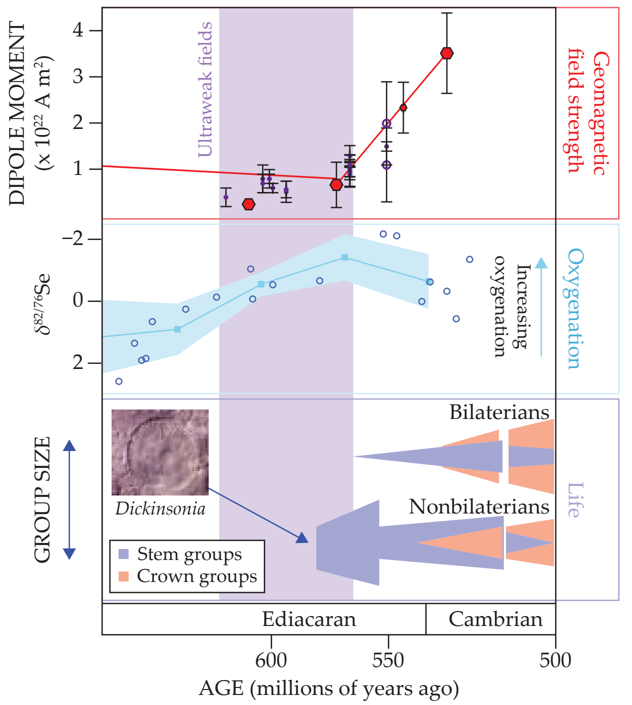


FIGURE 4. POTENTIAL CONNECTIONS between Earth's magnetic field, oxygenation, and the evolution of life. **(top)** Geomagnetic field strength, shown here as the strength of Earth's dipole moment, hit an all-time low (violet shading) in the late Ediacaran Period, followed by a rapid rise into the Cambrian Period, likely caused by the nucleation of Earth's inner core. **(middle)** Atmospheric oxygen fluctuations over that period can be interpreted from relative variations in selenium isotopic ratios, $\delta^{82/76}$Se (open symbols, shown with a 25-million-year window mean and an error of one standard deviation).[16] **(bottom)** Evolutionary radiation of animal life, both with and without bilateral symmetry, increased in the Ediacaran and into the Cambrian.[12] Stem groups are those that have gone extinct, whereas crown groups include modern animals and their evolutionary ancestors. (Figure adapted from ref. 7; image of *Dickinsonia* fossil courtesy of Mary Droser/UCR.)

Today, hydrogen supply to the plasmasphere and stratosphere is diffusion limited, so for hydrogen loss to be important, there needs to be an extra source of free hydrogen. We envision that source being tied to the increase in energetic solar particles, creation of nitrogen oxides, and destruction of the ozone layer, the process that Jackman, Meert, and others had contemplated. But we believe that the principal Ediacaran influence of increased UV radiation would be in increasing photodissociation of water and liberation of hydrogen that could ultimately escape to space.

New directions

In the past 12 years, paleomagnetists have found ultraweak magnetic fields for an interval that extended for tens of millions of years during the Ediacaran Period. They have demonstrated the reproducibility of that finding, and by sampling rocks from different ancient geologic regions, they have also provided strong evidence for the global nature of the ultraweak field. My colleagues and I interpret the weak field in the Ediacaran Period, followed by the increase in strength during the late Ediacaran and early Cambrian Periods, as marking the onset of inner-core nucleation.

That view is consistent with numerous models of Earth's thermal history and geodynamo models, but the sparseness of the database of robust paleointensity values, uncertainties in the core's thermal conductivity, and limitations of models in reaching parameters representing the core still allow for alternative models and interpretations. Addressing those uncertainties will enable the exploration of related fundamental questions, including whether the innermost inner core preserves a signal of an ancient mantle structure.

The correlation between the ultralow time-averaged Ediacaran field and evolutionary radiation of animal life is independent of uncertainties in the timing of inner-core nucleation. Many geologists and geochemists have produced data that show a concomitant increase in oxygenation, but the difficulties of isolating unambiguous global signals remain. Many biologists would regard an increase in oxygenation as a plausible factor aiding the evolution of larger, mobile Ediacaran animals. Our hypothesis of hydrogen loss provides a mechanism to link the ultralow fields, oxygenation, and animal radiation.

Scientists studying the Earth system, from surface to magnetosphere, will need to test the viability of that idea and other potential linkages that might explain the data and correlations. If our hypothesis is correct, we will have flipped the classic idea that magnetic shielding of atmospheric loss was most important for life, at least during the Ediacaran Period: The prolonged interlude when the field almost vanished was a critical spark that accelerated evolution.

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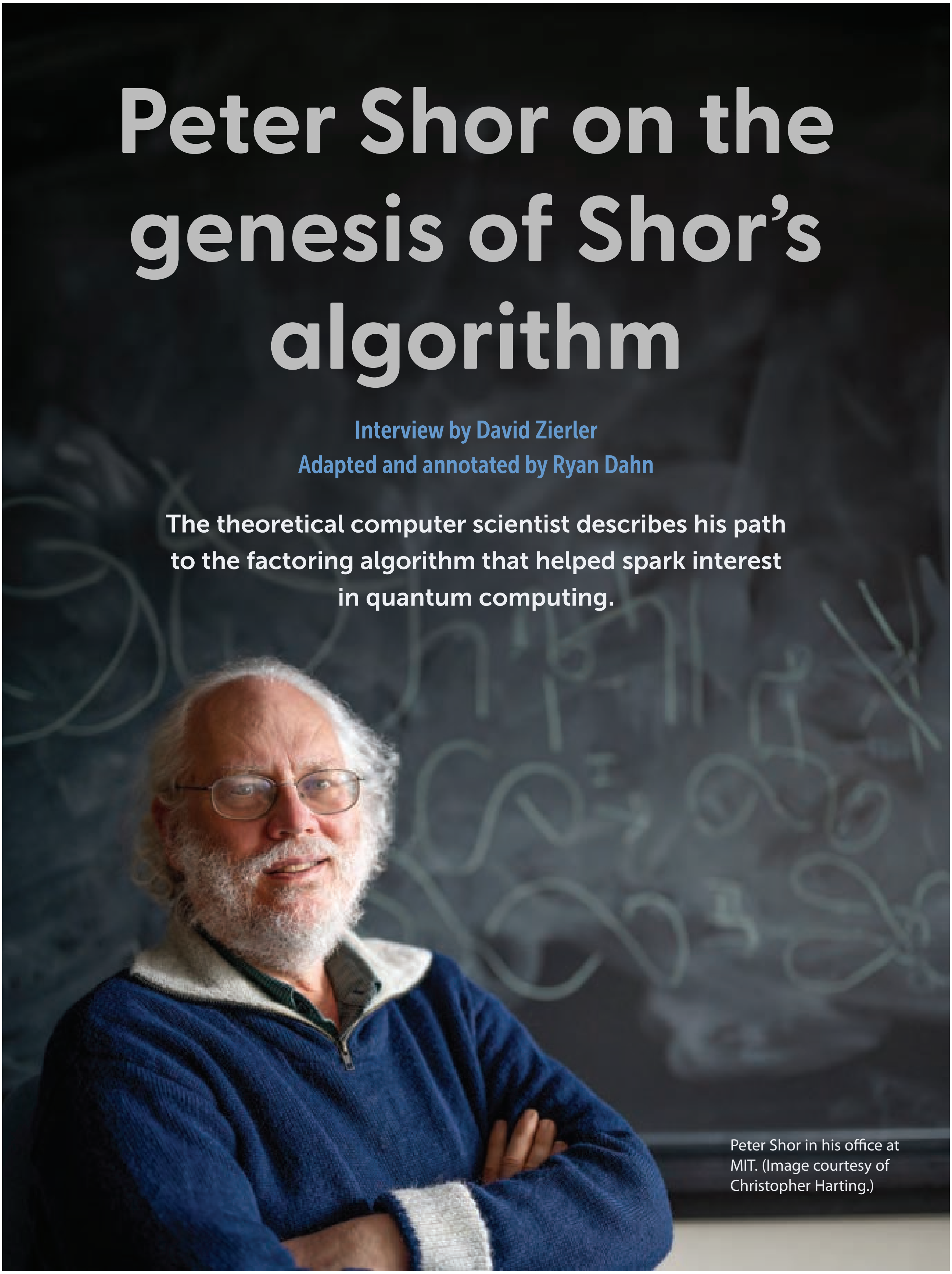
Peter Shor on the genesis of Shor's algorithm

Interview by David Zierler
Adapted and annotated by Ryan Dahn

The theoretical computer scientist describes his path to the factoring algorithm that helped spark interest in quantum computing.



Peter Shor in his office at MIT. (Image courtesy of Christopher Harting.)

David Zierler is the Ronald and Maxine Linde Director of the Caltech Heritage Project. When he conducted this interview, he was the oral historian at the American Institute of Physics. **Ryan Dahn** is a senior associate editor at PHYSICS TODAY and a historian of science.

In the early 1990s, the field now known as quantum information science was a minor subdiscipline comprising a handful of theoretical physicists, mathematicians, and computer scientists. It was often viewed as an esoteric backwater with no real-world applications because no one had demonstrated a scenario in which quantum computers—which at that time were purely theoretical—would be markedly more efficient than their classical counterparts.

INTERNATIONAL YEAR OF
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That all changed in 1994, when Peter Shor outlined one of the first algorithms that could make a problem that rapidly became intractable on a classical computer practical on a quantum one. The algorithm attracted extra attention because it found the prime factors of large numbers and so had serious implications for information security: A crucial assumption underlying several important digital cryptography schemes, many of which are still in use today, was that factoring large numbers on a computer would take an unfeasibly long time.

Shor's paper kicked off a wave of interest in quantum computing from both scientists and policymakers. Today, universities, governments, and private corporations have invested billions of dollars in the sprawling field of quantum information science.

Shor sat for an oral history with David Zierler of the American Institute of Physics (which publishes PHYSICS TODAY) in 2020. The following is an abridged, annotated, and lightly edited excerpt from the transcript.

ZIERLER: What are the origins of Shor's algorithm? What were you working on that led you to realize you had come upon this?

SHOR: Theoretical computer science in the US had, and I guess still has, two main conferences. They're called STOC [Symposium on Theory of Computing], which happens in the spring, and FOCS [Symposium on Foundations of Computer Science], which happens in the fall. In those days, these were really the *Physical Review Letters* of people in theoretical computer science. It was really very good for your career to get lots of papers into STOC and FOCS.

So, before the program committee[s] met [to select papers for the conferences], people went around the country giving talks on their results. Umesh Vazirani had a paper in STOC in spring of 1993.[1] He came and gave a talk at Bell Labs sometime before that conference, so it must have been late fall or early winter of 1992. I saw that talk, and I thought it sounded really interesting.

So, after he left, I started thinking about this, and I went to the Bell Labs library and looked up a lot of early papers on quantum computing, like [Richard] Feynman's, and [David] Deutsch's, and Deutsch and [Richard] Jozsa's. There were not that many.

Anyway, I read them, and I started thinking about what a quantum computer would be good for. Of course, this was such a crazy, far-out idea, I didn't tell anybody about it.

So, for the next STOC, I happened to be on the program committee, and Dan Simon had submitted a paper on what is now known as Simon's algorithm.[2] That was really a very good paper, but the STOC committee rejected it.

1. Umesh Vazirani, currently the University of California, Berkeley's Roger A. Strauch Chair of Electrical Engineering and Computer Sciences, authored a 1993 paper with then-student Ethan Bernstein that introduced the concept of quantum complexity theory and laid the mathematical foundations of quantum computation. They also proposed a specific problem that a quantum computer could accomplish much faster than a classical one.

2. Daniel Simon is a principal security engineer at Amazon Web Services. In 1994, while a postdoc at the University of Montreal, he published a paper outlining his now-famous algorithm that would run faster on a quantum computer than on a classical one.

> “I started thinking about what a quantum computer would be good for. Of course, this was such a crazy, far-out idea, I didn’t tell anybody about it.”

ZIERLER: What was their reasoning? Why did the committee reject it?

SHOR: It was an incremental improvement on [Ethan] Bernstein and Vazirani, and do we really want another of these crazy quantum computing papers in our conference?

ZIERLER: Crazy, meaning what? Why would they be labeled as crazy?

SHOR: They’re far out. They’re completely impractical. It’s a completely theoretical model which has nothing to do with real life, and nobody understood it. I always regret not bringing it up and jumping up and down and saying, “We have to take this.” But I didn’t. I should have, obviously.

Anyway, we rejected it. So, I started thinking about the paper, and this paper uses periodicity to find an algorithm to solve Simon’s problem much faster than a classical computer could. I knew that periodicity was very important for the discrete log problem,[3] and periodicity was used in Simon’s algorithm. So, I started thinking about this, and I came up with a quantum Fourier transform that I thought could be used for discrete log, and I solved a special case of the discrete log, which was actually doable in polynomial time[4] on a regular computer, which I thought showed real promise. Then, I eventually got to the real discrete log problem.

ZIERLER: How far developed was quantum computing at this point? When you’re talking about things that could not be accomplished on a classical computer, how far along was quantum computing where you know that this would be doable?

SHOR: We didn’t know this was doable. For the first few years after the factoring algorithm, everybody was completely convinced that it was not doable. Anyway, I managed to get a discrete log algorithm in polynomial time.

At first, I didn’t tell very many people about it. I told Jeff Lagarias, and he found a minor bug, which I fixed in my paper. Then I told my boss David Johnson and a couple other colleagues, and then I gave a talk in Henry Landau’s seminar on a Tuesday [in April 1994]. That weekend, I was at home with a cold, and I got a call from Vazirani saying, “I heard you know how to factor on a quantum computer. Tell me about it.”

ZIERLER: Where would he have heard this news?

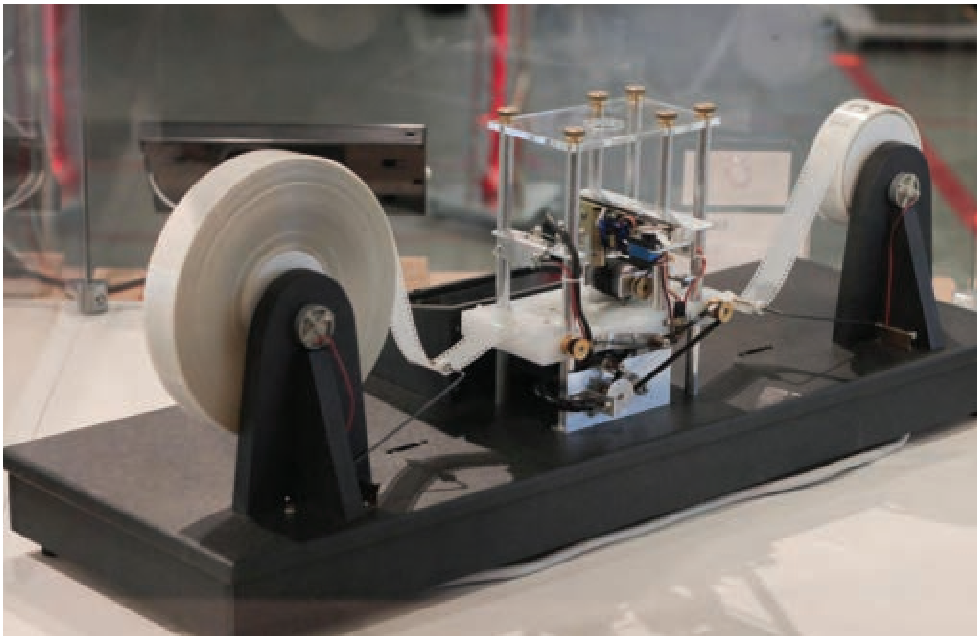
SHOR: Well, this is a game of telephone. I gave a talk on Tuesday about how to solve the discrete log problem, because I had not figured out how to factor yet. So, somebody at the talk told somebody else, who told somebody else, who told Umesh Vazirani that I knew how to factor on a quantum computer. So, if you look at discrete log and factoring, they’re similar problems, and they’re both used for public key crypto systems. Anytime someone has found an algorithm for factoring, there is a parallel algorithm for discrete log, and vice versa. So when I announced that I had an algorithm for discrete log and explained it at the Tuesday talk, somebody told somebody told somebody told Umesh that I had an algorithm for factoring.

I explained the factoring algorithm to Umesh over the telephone, and then I was invited to give a talk at the Algorithmic Number Theory Symposium at Cornell University in early May. I guess I was invited about a week before it happened, so that was the very end of April, and I flew up and gave a talk. And then, later, Santa Fe Institute had a conference on quantum computing. For some reason, I couldn’t go, so [Umesh] gave a talk on it there. At some point, the science writers started hearing about it, and the news spread very rapidly.

ZIERLER: From your vantage point, what was so exciting about this? Why were people paying attention? What were the promises being offered by this breakthrough?

3. Discrete logarithms (or discrete logs, for short) broaden the logarithm concept to operate over mathematical groups instead of real numbers; the discrete logarithm problem involves finding specific integers that satisfy an exponential relation. The problem is an exceedingly time-consuming one for conventional computers to solve, which is why it is used as the foundation of many well-known digital cryptography schemes.

4. An algorithm is said to run in polynomial time if its running time is bounded by a polynomial function that can be expressed in terms of the size of the input. Those algorithms are typically considered to be efficient because the time to execute the algorithm grows relatively slowly as the size of the input increases. They are typically contrasted with algorithms whose running time is bounded by an exponential function and are thus far less efficient.



A FUNCTIONAL TURING MACHINE displayed at Harvard University in 2012. (Image by Rocky Acosta/CC BY 3.0.)

SHOR: I guess before this, computer scientists were absolutely convinced of the extended Church–Turing thesis, which says, basically, anything any computer can do in polynomial time, a Turing machine[5] can do in polynomial time. This showed that it might not be true. So, this really shook the very foundations of computer science. Of course, it doesn't affect any of the real work in computer science going on right now, but computer scientists thought it was interesting for that reason. I guess physicists thought it was interesting because now quantum mechanics might have yet another application. Cryptographers thought it was interesting because factoring is the basis of all the security on the internet, and if somebody can break it, we're going to have to scramble and replace all these cryptographic protocols.

ZIERLER: What new applications were there for quantum mechanics? Can you explain that a little more?

SHOR: Well, computing. I mean, if using quantum mechanics, you can build a computer that can do things that classical computers cannot. That's a very important application of quantum mechanics.

ZIERLER: To what extent has that excitement been realized?

> "This really shook the very foundations of computer science."

SHOR: I guess people are still very excited about quantum computers. I mean, there are not that many problems that can be solved by quantum computers that can't be solved by classical computers. At least, we haven't discovered that many yet, but there do seem to be a few—I mean, for molecules, materials design, and actual computing properties of systems that are actually quantum mechanical, they really seem like they're going to work better once we build larger machines. If you look at what fraction of the world's computing power the pharmaceutical industry uses in simulating molecules—which the big difficulty of simulating molecules is they obey the rules of quantum mechanics—it's a fairly large fraction of all the computer power used in the world today. So, if you're able to do better with quantum computers, then you have a huge market. PT

5. The simple computing device theorized by Alan Turing in 1936 can manipulate mathematical symbols (drawn from a finite set) on a strip of tape of infinite length. Turing machines can carry out any computation that a real computer can do, albeit on a longer time scale. The extended Church–Turing thesis essentially asserts that if the running time of an algorithm on a Turing machine is described by an exponential function, then so is the running time on any other computer. Shor's algorithm appears to refute that thesis.

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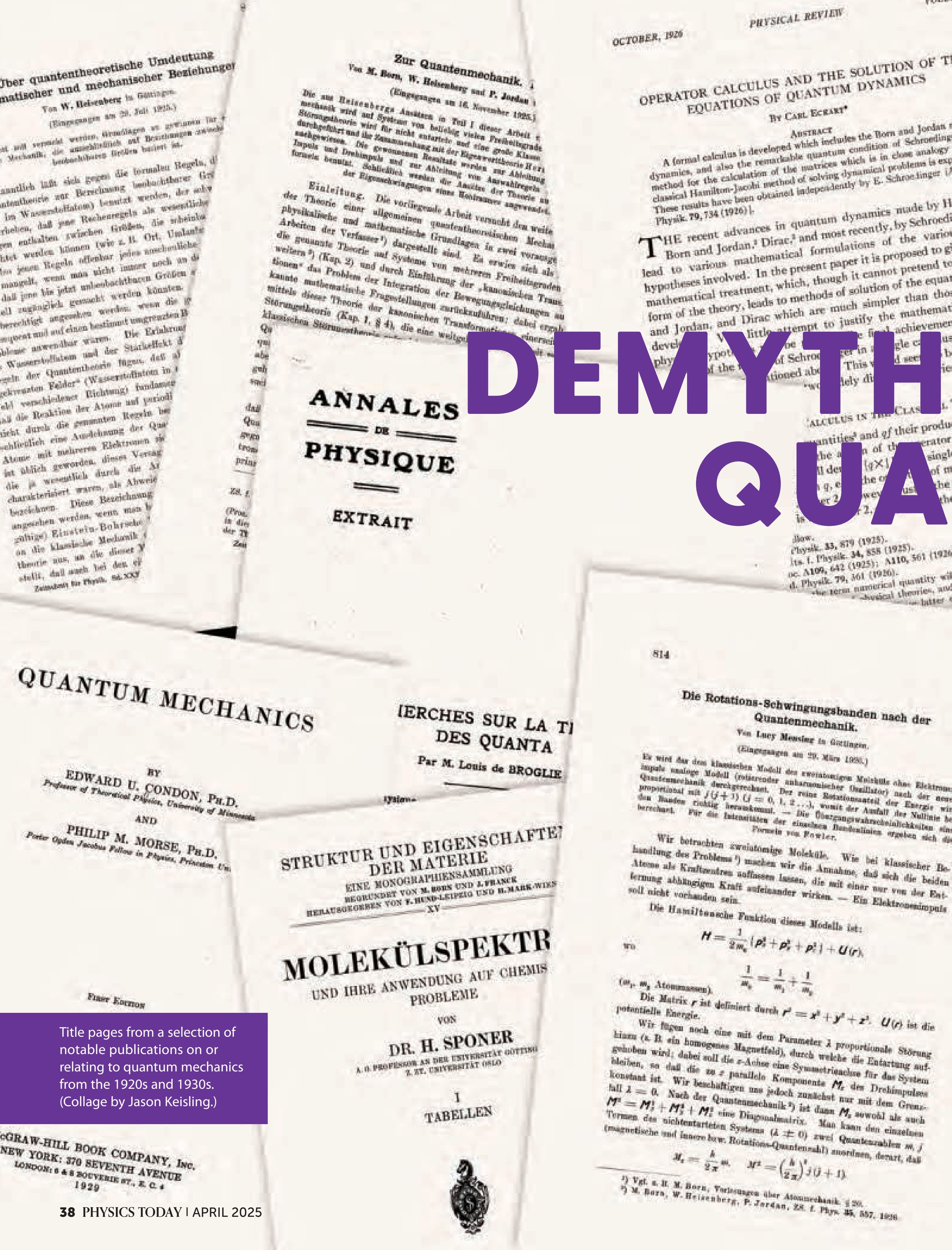


Title pages from a selection of notable publications on or relating to quantum mechanics from the 1920s and 1930s. (Collage by Jason Keisling.)

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

INTERNATIONAL YEAR OF
Quantum Science and Technology

OLOGIZING NTUM HISTORY

Ryan Dahn

Celebrating the 100th anniversary of quantum mechanics in 2025 without providing appropriate context risks reinforcing a long legacy of hagiography and hero worship.

The United Nations has proclaimed this year the International Year of Quantum Science and Technology. Official pronouncements about the IYQ tend to emphasize forward-looking technological applications of quantum science, such as computing and cryptography. They nod only obliquely to the reason why 2025 was chosen as the IYQ: that this year is, allegedly, the centennial of the development of quantum mechanics. The UN resolution proclaiming the IYQ, for example, notes that 2025 “coincides” with the anniversary, and the official IYQ website mentions “100 years of quantum mechanics.”

But is 2025 really the 100th anniversary of quantum mechanics? It depends on whom you ask. According to the standard textbook narrative, it was in 1900 that Max Planck proposed the quantum hypothesis—that the magnitude of a physical property was not continuous but a set of discrete, countable units, or quanta. Several publications celebrated the 100th anniversary in 2000.[1] But Planck did not use the term “quantum” in 1900, and most historians now argue that he did not quantize anything that year. Other milestone years include 1905, when Albert Einstein introduced the quantum theory of light to explain the photoelectric effect, and 1913, when Niels Bohr debuted his solar-system model of the atom, in which electrons revolve around a nucleus in a set of discrete, quantized orbits.

That said, 1925 was, by any estimation, a pivotal year in the development of quantum mechanics. By that time, the deficiencies of what historians now term the old quantum theory were apparent. Based on Bohr’s atomic model, which was refined by Arnold Sommerfeld and others, the old theory could not accurately model the spectra of anything heavier than ionized helium. But 1925 marked the turning point toward the quantum mechanics we know today—a theory that remains part of the backbone of our understanding of the universe.

So it does make sense to celebrate this year. The trouble lies with the lack of clarity about what happened 100 years ago. Because most people aren’t familiar with the historical details, the IYQ threatens to fuel popular portrayals of Werner Heisenberg as the lone genius who initiated the quantum

ARNOLD SOMMERFELD (left) **AND NIELS BOHR** (right) pictured in 1919. The two physicists were key contributors to the so-called old quantum theory, which assumed that electrons orbited a nucleus like a miniature solar system. (Photo from the AIP Emilio Segrè Visual Archives, Margrethe Bohr Collection.)

revolution. A closer examination of what happened in 1925 reveals that the development of quantum mechanics was a collaborative process from the start. It also serves as an example of how simplistic narratives of scientific discovery tend to perpetuate hero worship and omit other important contributors.

A satisfying story propagates

Despite efforts from historians to tell a nuanced story about the birth of modern quantum mechanics, the tale that's seeped into the popular consciousness seems to stem from Heisenberg himself. As the German physicist related on several occasions, most notably in his 1969 memoirs, he had reached an impasse in his investigations of several problems in the old quantum theory in June 1925 when he was stricken by a bad bout of seasonal allergies. Seeking relief, Heisenberg decamped from his position at the University of Göttingen in Germany to the nearly pollenless island of Helgoland in the North Sea. Free from distractions and fortified by long walks and swims, Heisenberg devoted himself to his work attacking the inconsistencies in the old theory. One evening, he made the crucial breakthrough: Energy conservation had to hold true in his new quantum theory just as it did in classical physics. After working through the night carrying out calculations, he was quickly able to finish drafting a paper upon returning home.

On 29 July, Heisenberg submitted his paper,[2] whose title translates as "On a quantum theoretical reinterpretation of kinematic and mechanical relations," to the *Zeitschrift für Physik*, a relatively new German journal that had gained a reputation for publishing cutting-edge research. In the popular narrative, the *Umdeutung* ("reinterpretation") paper, as it's typically referred to after its original German title, birthed the matrix formulation of quantum mechanics and almost single-handedly initiated a dynamic period of feverish work that culminated in the creation of modern quantum theory in an astonishingly short amount of time. By 1927, it was mature enough that Bohr and Einstein were debating its philosophical implications at the Fifth Solvay Conference on Physics. And a few years later, Heisenberg would receive the 1932 Nobel Prize in Physics "for the creation of quantum mechanics."

It's not surprising that Heisenberg's narrative took off. After all, what could be more poetic than a sensitive, Nobel-winning savant who, paralyzed by mere allergies, sought refuge on a remote, beautiful island, where he had a stroke of genius? The Helgoland story now permeates popular writing on the quantum revolution of the 1920s. "If there is any moment that marks the birth of quantum mechanics," wrote Steven Weinberg in 1994, "it would be a vacation taken by the young Werner Heisenberg in 1925. . . . On Helgoland [he] made a fresh start."[3]

Inadvertently or advertently, the IYQ organizers are contributing to the Heisenberg hagiography: One of the most prominent meetings will be held on Helgoland this June. The workshop features many distinguished members of the field, including 2022 Nobel laureates Alain Aspect, John Clauser, and Anton Zeilinger, and focuses on the future of quantum science and technology. But its website perpetuates the heroic version of quantum history by asserting that Heisenberg "developed Matrix Mechanics, the first formulation of Quantum Theory" during his 1925 trip to the island.

The Helgoland myth

The veracity of the Helgoland story is dubious at best. It has its roots in Heisenberg's memoirs, *Der Teil und das Ganze*, which were published in English in 1971 under the title of *Physics and Beyond*. But memory is notoriously unreliable. Heisenberg admitted in the book's preface that it wasn't a "historically accurate retelling of all the various events in every detail" and that he only intended to depict the "broader picture."[4] Far too many writers have taken his account as gospel.

Contemporary evidence confirms that Heisenberg spent about 10 days on Helgoland in June 1925. It's not clear how much he accomplished there: As Anthony Duncan and Michel Janssen note in their magisterial history of the 1920s quantum revolution, Heisenberg probably did much of the work on the Umdeutung paper before and after his brief visit to Helgoland.[5] Moreover, as they point out, several letters he wrote to Wolfgang Pauli in June and July of that year indicate that Heisenberg was not confident in his theory at first. He was so unsure of his results that he gave his finished manuscript to

THE LUMMENFELSEN CLIFFS on the German island of Helgoland in the North Sea. Werner Heisenberg spent about 10 days on the island during an oft-mythologized visit in June 1925, during which he allegedly made a breakthrough in the development of the matrix formulation of quantum mechanics. (Photo by BraunGregor, Wikimedia Commons/CC BY 4.0.)

Max Born, who supervised his 1924 *habilitation* at the University of Göttingen, to look over and decide whether it was worth submitting. That's not exactly what you'd expect from someone who allegedly had a eureka moment.

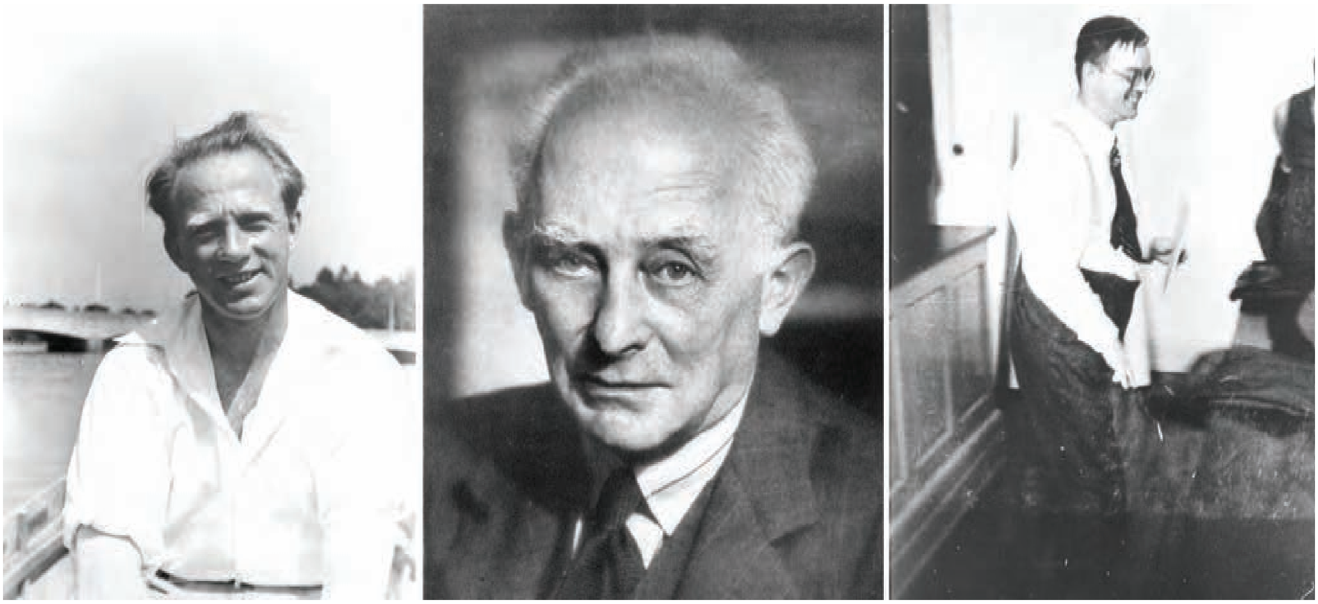
Moreover, the Umdeutung paper is notoriously obscure. In the same book in which he propagated the Helgoland myth, Weinberg went on to confess that he had "never understood Heisenberg's motivations for the mathematical steps in his paper" and that he believed the article to be "pure magic."[6] He is not the only one who has been baffled by the Umdeutung paper over the years: Something of a cottage industry among technically oriented historians of physics has developed that attempts to explain both the content of the paper and its intellectual backstory. Tellingly, the various exegeses of the Umdeutung paper invariably dwarf the slender 15-page original: An early and widely cited 1977 article on the topic by historian and philosopher Edward MacKinnon, for example, runs to 52 pages, while Duncan and Janssen devote an entire 46-page chapter of their 2023 book to it.[7]

It was only after other researchers recognized that Heisenberg's clunky calculations could be elegantly rewritten using the mathematical language of matrices—a formalism unknown at the time to nearly all physicists, including Heisenberg—that his work began to assume the form in which it is taught today. Born was immediately captivated on reading Heisenberg's Umdeutung paper, and he soon roped the mathematically talented Pascual Jordan—one of his former doctoral students—into a collaboration. They submitted their paper on the topic, whose title translates as "On quantum mechanics," to the *Zeitschrift für Physik* on 27 September 1925. It was only in that article that matrix mechanics started to resemble something that today's physicists are likely to understand.[8]

Even before finalizing the paper, Born and Jordan began collaborating with Heisenberg on a follow-up article that was submitted to the *Zeitschrift für Physik* on 16 November that same year.[9] Often referred to as the "three-man paper," it was arguably the most crucial milestone of that year: Historian of science Max Jammer termed it the "first comprehensive exposition of the foundations of modern quantum mechanics in its matrix formulation."[10] Heisenberg admitted that the Royal Swedish Academy of Sciences should have split the 1932 Nobel Prize: After receiving the news about the award, he wrote separately to Born and Jordan stating that he was sorry the three had not shared it.[11]

An important lesson

Although textbooks and popular articles alike continue to repeat the Helgoland myth and perpetuate hero worship, the

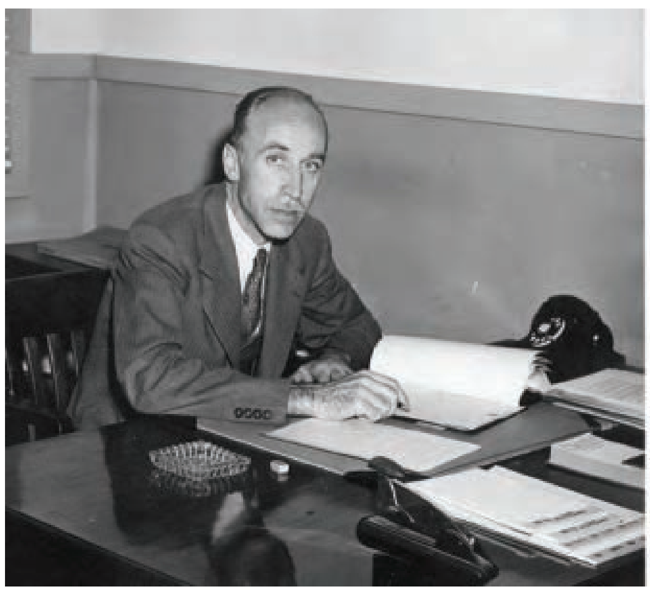


WERNER HEISENBERG, MAX BORN, AND PASCUAL JORDAN (from left to right). Although Heisenberg typically receives the lion's share of the credit for the development of the matrix formulation of quantum mechanics in late 1925, Born's and Jordan's contributions were equally pivotal. With their mathematical backgrounds, the two realized that Heisenberg's clunky equations could be elegantly rewritten using the mathematical language of matrices. (Photo of Heisenberg from the Max Planck Institute, courtesy of the AIP Emilio Segrè Visual Archives; photo of Born from the AIP Emilio Segrè Visual Archives, gift of Maria Goeppert Mayer; photo of Jordan from the Niels Bohr Archive, B526, Copenhagen, courtesy of the AIP Emilo Segrè Visual Archives.)

real story of the genesis of matrix mechanics in 1925 was one of collaboration and teamwork between Heisenberg, Born, Jordan, and even Pauli. That lesson holds true for the history of quantum mechanics writ large. Historians estimate that between 1925 and 1927, almost 200 papers were published—many of which were authored by long-forgotten individuals—that advanced the new theory and applied it to various problems in atomic dynamics.

One prominent example is US physicist Carl Eckart, who asserted the equivalence of the matrix and wave formulations of quantum mechanics independently of Erwin Schrödinger. Working in California, Eckart submitted his paper in June 1926 to a then-obscure journal called *Physical Review*, some three months after Schrödinger sent off his famous equivalency paper to the *Annalen der Physik* in Germany. Although Eckart did not receive priority for the discovery—in a note added on 2 September, when the article went to press, he lamented that Schrödinger had already "published all the essential results contained in the above paper"[12]—his contribution was nevertheless important. Eckart used matrix mechanics as his starting point and then attempted to demonstrate its equivalence to the wave formulation; Schrödinger's proof worked the other way around. Ironically, most scholars now agree that both Eckart and Schrödinger's proofs were incomplete and that it was actually John von Neumann, building on their and others' work, who conclusively showed in a series

CARL ECKART, LUCY MENSING, AND HERTHA SPONER are among the early contributors to quantum mechanics whose names do not usually appear in physics textbooks. Eckart (portrait at left) asserted the equivalence of the matrix and wave formulations of quantum mechanics in 1926 independently of Erwin Schrödinger. That same year, Mensing (third from left in the middle photo) was one of the first to apply the new quantum theory to diatomic molecules. Sponer (photo at right) conducted early spectroscopic work in the 1920s and 1930s that experimentally confirmed the predictions of quantum mechanics. (Photo of Eckart from the AIP Emilio Segrè Visual Archives; photo of Mensing from the AIP Emilio Segrè Visual Archives, Landé Collection; photo of Sponer from the AIP Emilio Segrè Visual Archives, Lisa Lisco, gift of Jost Lemmerich.)



of publications in the late 1920s and early 1930s that the two formulations were equivalent.[13]

Lucy Mensing, who was working in Göttingen when Heisenberg, Born, and Jordan made their breakthrough in 1925, quickly became acquainted with the new quantum mechanics and may have been the first individual to apply the theory to diatomic molecules.[14] Mensing followed up her pathbreaking article by collaborating with Pauli—who had supervised her dissertation in Hamburg—on presenting a quantum understanding of the electric polarizability of those molecules. Physicist Gernot Münster terms the article a "milestone in applied quantum mechanics."[15] Although little primary documentation about her career survives, Mensing seems to have gradually withdrawn from the field in the late 1920s in part because she was put off by the highly competitive academic culture of the era. Her last scientific publication appeared in 1930, although she apparently continued to assist her husband, fellow physicist Wilhelm Schütz, with his work afterward.[16]

Another physicist working in Göttingen during the quantum revolution of the mid 1920s was Hertha Sponer. She went on to publish a number of works, including an influential two-volume set on spectroscopy in 1935–36 that experimentally confirmed predictions of quantum mechanics.[17] Unlike Mensing, Sponer remained in academia for the long haul. As a woman in Nazi-ruled Germany, she had little hope of obtaining an academic position, so she ended up emigrating, first to Norway in 1934 and then in 1936 to the US, where she received a tenured position at Duke University.[18]

Eckart, Mensing, and Sponer are just the tip of the iceberg: There are many other early quantum innovators who aren't part of the standard canon. If we're going to recognize the 100th anniversary of quantum mechanics this year, let's broaden the scope of our celebration. Despite their vague rhetoric about what happened in 1925, even the IYQ organizers seem to be cognizant of the dangers of hagiography: In their mission statement, they urge participants to "foreground honesty about the past and future of quantum science and technology." At the very least, let's avoid the type of hero worship emblematized by the Helgoland myth.

Thanks to Michel Janssen for providing helpful comments that prevented the inadvertent propagation of several quantum myths.

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NEW PRODUCTS

Focus on software, data acquisition, and instrumentation

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

Andreas Mandelis

Compact hexapod for photonics and optics alignment

The H-811.S2iHP compact hexapod for photonics and optics alignment from PI uses six low-friction, long-life actuators and 12 precision Cardan joints with offset axes to enhance stiffness. The actuators provide a resolution of 1.4 nm; the platform delivers in-position stability of 3 nm. With a linear velocity of 20 mm/s, a rotary velocity of 28°/s, a load capacity of 5.5 lbs, and fast acceleration, the hexapod is suitable for automating tasks such as alignment, testing, and assembly of high-resolution miniature lenses and photonics components. It offers linear travel ranges of up to 34 mm in XYZ and rotary motions (pitch, yaw, and roll) of up to 42°. A user-programmable pivot point further facilitates the alignment of lenses, fiber optics, and photonics systems. Low-friction precision ball screws, precision joints, and long-life brushless motors ensure reliability and durability. A powerful hexapod controller for the H-811.S2iHP features advanced multi-axis alignment routines that enable tasks such as optimization, tracking, array alignment, and first light detection. ***PI (Physik Instrumente) LP****, 16 Albert St, Auburn, MA 01501, www.pi-usa.us*

Mathematical programming software

Mathworks' Release 2024b, a new addition to its MATLAB and Simulink software, introduces updates designed to scale, automate, and streamline user workflows for wireless communications systems, control systems, and digital signal processing applications. The 5G Toolbox now enables the exploration of 6G waveform generation and signal-quality assessments of 5G waveforms. The DSP HDL Toolbox (DSP denotes digital signal processing, and HDL, hardware description language) currently provides hardware-ready Simulink blocks and subsystems for developing signal processing applications. Release 2024b adds an interactive DSP HDL internet protocol Designer app for configuring DSP algorithms and generating HDL code and verification components. A hardware support package is also now available for the Qualcomm Hexagon Neural Processing Unit, the technology embedded within the Qualcomm Snapdragon family of processors. It leverages Simulink and model-based design to deploy production-quality C code across various Snapdragon processors for DSP applications. ***The MathWorks Inc****, 1 Apple Hill Dr, Natick, MA 01760, www.mathworks.com* PT

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INTERNATIONAL YEAR OF Quantum Science and Technology

The no-cloning theorem

William K. Wootters and Wojciech H. Zurek

People gather, copy, and distribute information all the time. But in the quantum world, the laws of physics impose a severe restriction on copying: It is impossible to make a perfect copy of an unknown state.

The principle of superposition is a cornerstone of quantum mechanics. It says that when two evolving states solve the Schrödinger equation, any linear combination of the two is also a solution. For that reason, waves from the two slits in the double-slit experiment simply add together to create the familiar interference pattern. As it happens, the superposition principle also prohibits the arbitrary copying of quantum states.

Linearity, unitarity, and cloning

To see why, imagine a machine that copies the state of a photon or an electron. When the original enters, two copies come out, each having the same state as the original. If such a machine were successful, it would convert the state $|\diamondsuit\rangle$ to $|\diamondsuit\diamondsuit\rangle$ and $|\heartsuit\rangle$ to $|\heartsuit\heartsuit\rangle$, where the fanciful symbols $|\diamondsuit\rangle$ and $|\heartsuit\rangle$ represent arbitrary states. The problem arises when we send a linear combination, $|s\rangle = a|\diamondsuit\rangle + b|\heartsuit\rangle$, through the hypothetical cloner. If $|\diamondsuit\rangle$ and $|\heartsuit\rangle$ are cloned correctly, then because of the linearity of quantum mechanics, the output for their superposition must be the superposition of the outputs, $|e\rangle = a|\diamondsuit\diamondsuit\rangle + b|\heartsuit\heartsuit\rangle$. But we want $|s\rangle|s\rangle = (a|\diamondsuit\rangle + b|\heartsuit\rangle)(a|\diamondsuit\rangle + b|\heartsuit\rangle)$, the original and a copy of $|s\rangle$. That is not the state $|e\rangle$ we get! The figure illustrates the general argument with a specific example.

The difficulty stems from the inherent nonlinearity of copying: When one asks for "two of the same," a square $|s\rangle|s\rangle$ of the original $|s\rangle$ is requested. The desire for a squared state is in conflict with the strict linearity of quantum theory. As a result, a single cloner cannot make a perfect copy of every quantum state. So what states can it clone?

Thus far, we have considered the linearity of quantum mechanics. But quantum evolutions preserve probability. The norm $\langle e|e\rangle$ of the state emerging from the copier must be the same as $\langle s|s\rangle$ of the original. The only difference between the two norms, expressed in terms of $|\diamondsuit\rangle$ and $|\heartsuit\rangle$, is in the cross term. Thus the equation $\langle\heartsuit|\diamondsuit\rangle = \langle\heartsuit|\diamondsuit\rangle^2$ must be satisfied by any two states that are perfectly copied. That simple equation has profound consequences: It shows that a quantum copier can work only when the possibilities for the original are orthogonal—that is, the scalar product $\langle\heartsuit|\diamondsuit\rangle$ vanishes.

One reaches the same conclusion after recognizing that quantum evolutions are unitary—they preserve the scalar product of any two states. So for states that can be copied, one again gets $\langle\heartsuit|\diamondsuit\rangle = \langle\heartsuit|\diamondsuit\rangle^2$. That is no surprise; unitarity follows from linearity and preservation of the norm.

Quantum evolutions are reversible, so one can imagine running the copier in reverse to delete the extra copy in states such as $|\diamondsuit\diamondsuit\rangle$ or $|\heartsuit\heartsuit\rangle$. Since uncopying also preserves the scalar product, it follows that perfect copying or deleting is possible only for sets of states that are orthogonal.

The optimistic assumption that a copier will work according to specs for the arbitrary states $|\diamondsuit\rangle$ and $|\heartsuit\rangle$ was naive. Perfect copying can be achieved only when the two states are orthogonal, and even then one can copy those two states (or perhaps a larger collection of mutually orthogonal states) only with a copier specifically built for that set of states. Thus, for example, one can design a copier for any orthogonal pair of polarization states of a photon, but a copier that works for $\{|\updownarrow\rangle, |\leftrightarrow\rangle\}$ will fail for $\{|⤢\rangle, |⤡\rangle\}$, and vice versa.

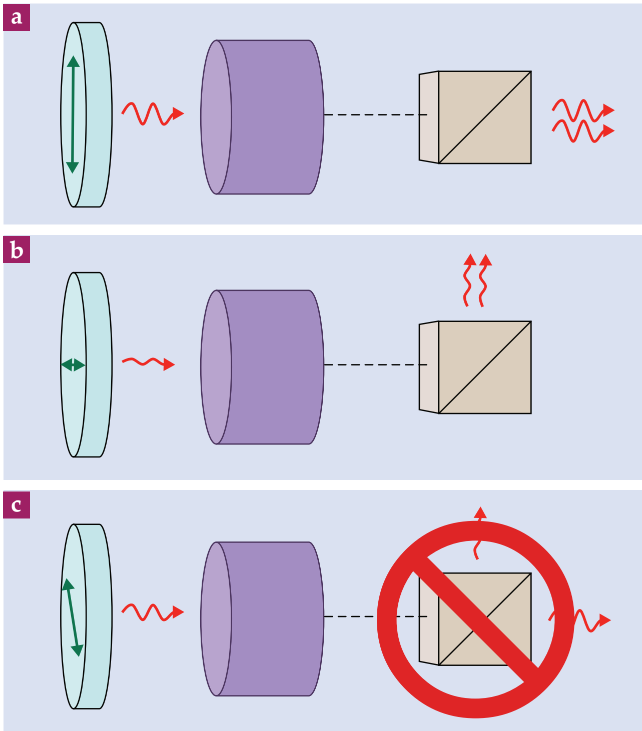
In sum, one cannot make a perfect copy of an unknown quantum state, since, without prior knowledge, it is impossible to select the right copier for the job. That formulation is one common way of stating the no-cloning theorem.

Quantum cryptography

The impossibility of cloning may seem at first an annoying restriction, but it can also be used to one's advantage—for instance, in a quantum key distribution scheme devised by Charles Bennett and Gilles Brassard in 1984. The idea is for the sender, Alice, to transmit many photons to the receiver, Bob, with the aim of ultimately creating a shared, secret, random string of zeros and ones. Such a random string can later be used as a key for encrypting and decrypting messages. For example, armed with a coded binary message and the key, Bob can decode the message by reversing the binary ciphers in all the positions where the key has a "1."

In the Bennett–Brassard scheme, each of Alice's photons is prepared at random in one of four possible polarization states: $|\updownarrow\rangle$, $|\leftrightarrow\rangle$, $|⤢\rangle$, or $|⤡\rangle$. An eavesdropper, Eve, would like to get a copy of each photon for herself, but she also wants to pass an accurate copy on to Bob, or else her presence will be detected later when Alice and Bob check a random sample to see if Eve has disturbed their signals. Notice, though, that because of the no-cloning theorem, Eve cannot succeed in her task. As discussed earlier, if her cloning device can successfully copy the vertical and horizontal polarizations, it will fail to copy faithfully either of the two diagonal polarizations. Thus the prohibition against cloning helps preserve privacy.

Although Eve cannot perfectly copy the photons Alice sends to Bob, she can, in fact, do a pretty good job of approximately cloning Alice's transmission. Indeed, optimal approximate cloning is, in principle, one of the best methods Eve can use against quantum cryptography. Fortunately for Alice and Bob, it is possible to place strict theoretical limits on the fidelity



THERE IS NO PERFECT QUANTUM COPIER. Imagine a device that could clone an arbitrary quantum state. **(a)** A vertically polarized photon would yield two vertically polarized photons, both of which make the "vertical" choice at a polarizing beamsplitter. **(b)** A horizontally polarized photon would yield two horizontally polarized photons, both of which make the "horizontal" choice. **(c)** Because quantum mechanics is linear, a diagonal polarization—a superposition of vertical and horizontal—can produce only the measurement outcomes represented in panels a and b; it could not produce the outcome shown. But such an outcome would be possible if the diagonal polarization were cloned correctly. The linearity of quantum mechanics thus prohibits the cloning of arbitrary states.

of any such copying scheme. The study of approximate cloning is currently an active area of both theoretical and experimental research and is discussed in detail in the additional resources provided at the end of this Quick Study.

Causality, copying, and collapse

If cloning *were* possible, one could communicate instantaneously over a distance. Suppose Alice and Bob share two photons in the entangled polarization state, $|\zeta\rangle = (|\leftrightarrow\updownarrow\rangle - |\updownarrow\leftrightarrow\rangle)/\sqrt{2}$. The state $|\zeta\rangle$ can be expressed in any orthogonal basis with the paired polarization states always oriented along perpendicular axes; for example, $|\zeta\rangle = (|\nearrow\nwarrow\rangle - |\nwarrow\nearrow\rangle)/\sqrt{2}$. So to send information to Bob, Alice might measure her photon in one of two bases, $\{|\updownarrow\rangle, |\leftrightarrow\rangle\}$ or $\{|\nearrow\rangle, |\nwarrow\rangle\}$, her choice of basis encoding "0" or "1." Alice's measurement collapses $|\zeta\rangle$ into an eigenstate of the polarization she measures. If she chooses "0," Bob's photon will end up either $|\leftrightarrow\rangle$ or $|\updownarrow\rangle$, whereas "1" prepares it in one of the diagonal states.

In view of the collapse induced by Alice's measurement, Bob's photon, in a sense, gets the message. But Bob doesn't. He cannot simply ask his photon, "What's your state?" A quantum measurement is a multiple-choice test. It poses questions such as, "Are you $|\updownarrow\rangle$ or $|\leftrightarrow\rangle$?" Eigenstates of the measured observable are the only legal answers. If he wrongly measures in the basis complementary to that selected by Alice, Bob will randomize the state of his photon and, in effect, erase Alice's message. And to choose correctly, he needs to know the message. That's the proverbial catch-22.

Direct measurement fails, but what if Bob were able to clone his photon first? Copying $|\updownarrow\rangle$ or $|\nearrow\rangle$ into $|\updownarrow\updownarrow\updownarrow\ldots\rangle$ or $|\nearrow\nearrow\nearrow\ldots\rangle$ would introduce valuable redundancy. Even a "wrong measurement" on some of the copies would not erase Alice's message, as other copies would remain for Bob to query with complementary questions. And the right question would lead to a consensus; all copies would give the same answer in the multiple-choice test. Many copies of his photon would thus allow Bob to find out the state and thereby read Alice's message. But as noted earlier, amplification requires a copier tailored to the right basis. So the superluminal communication-via-cloning scheme is foiled by the no-cloning theorem.

What if Bob uses a copier for, say, just the basis $\{|\updownarrow\rangle, |\leftrightarrow\rangle\}$? If Alice sends "0," the copier works. But for the diagonal input states $(|\updownarrow\rangle \pm |\leftrightarrow\rangle)/\sqrt{2}$, it produces $(|\updownarrow\updownarrow\updownarrow\ldots\rangle \pm |\leftrightarrow\leftrightarrow\leftrightarrow\ldots\rangle)/\sqrt{2}$. The two multiphoton states are equally probable and determined by the measurement at Alice's end. That state of affairs is indistinguishable from what happens when Alice sends "0" and Bob's properly working copier is equally likely to generate $|\updownarrow\updownarrow\updownarrow\ldots\rangle$ or $|\leftrightarrow\leftrightarrow\leftrightarrow\ldots\rangle$. The bottom line is that Bob's basis-specific copier is of no use for communication.

Nevertheless, the redundancy in states like $(|\updownarrow\updownarrow\updownarrow\ldots\rangle \pm |\leftrightarrow\leftrightarrow\leftrightarrow\ldots\rangle)/\sqrt{2}$ is of interest, as it sheds light on the origin of the "collapse" in quantum measurements. Each such state looks, to the casual observer, like many copies of just one preferred polarization. For example, $(|\updownarrow\updownarrow\updownarrow\ldots\rangle + |\leftrightarrow\leftrightarrow\leftrightarrow\ldots\rangle)/\sqrt{2}$ is a superposition of many copies of two polarizations. Yet if Bob detects any one of the photons in, say, the state $|\leftrightarrow\rangle$, all the other photons will agree, just as when Alice sends a "0." The branch $|\updownarrow\updownarrow\updownarrow\ldots\rangle$ then becomes inaccessible, and all further data will point to the single remaining possibility. This consistency—this agreement among the photons—looks like a collapse. Such considerations suggest a strong affinity between a copier and a measuring apparatus. Both impose their choice of preferred states. Only states that respect the "symmetry breaking" can be found out or copied. Other states are converted into superpositions of redundant branches that collapse into a single option when probed by an initially ignorant observer.

Phrases like "Bob's photon gets the message" or "Bob erases the message" suggest that a definite underlying pure state of Bob's unobserved photon exists as soon as Alice makes her measurement. Such language is natural in that it provides a convenient picture that agrees with experimental results. However, the fact that an unknown quantum state cannot be discovered by a measurement or revealed by cloning suggests that not only is it unknown, but it does not even exist in the usual sense. Indeed, the nature of a quantum state is still the subject of lively debate, and the restriction on copying expressed by the no-cloning theorem is an important part of the discussion.

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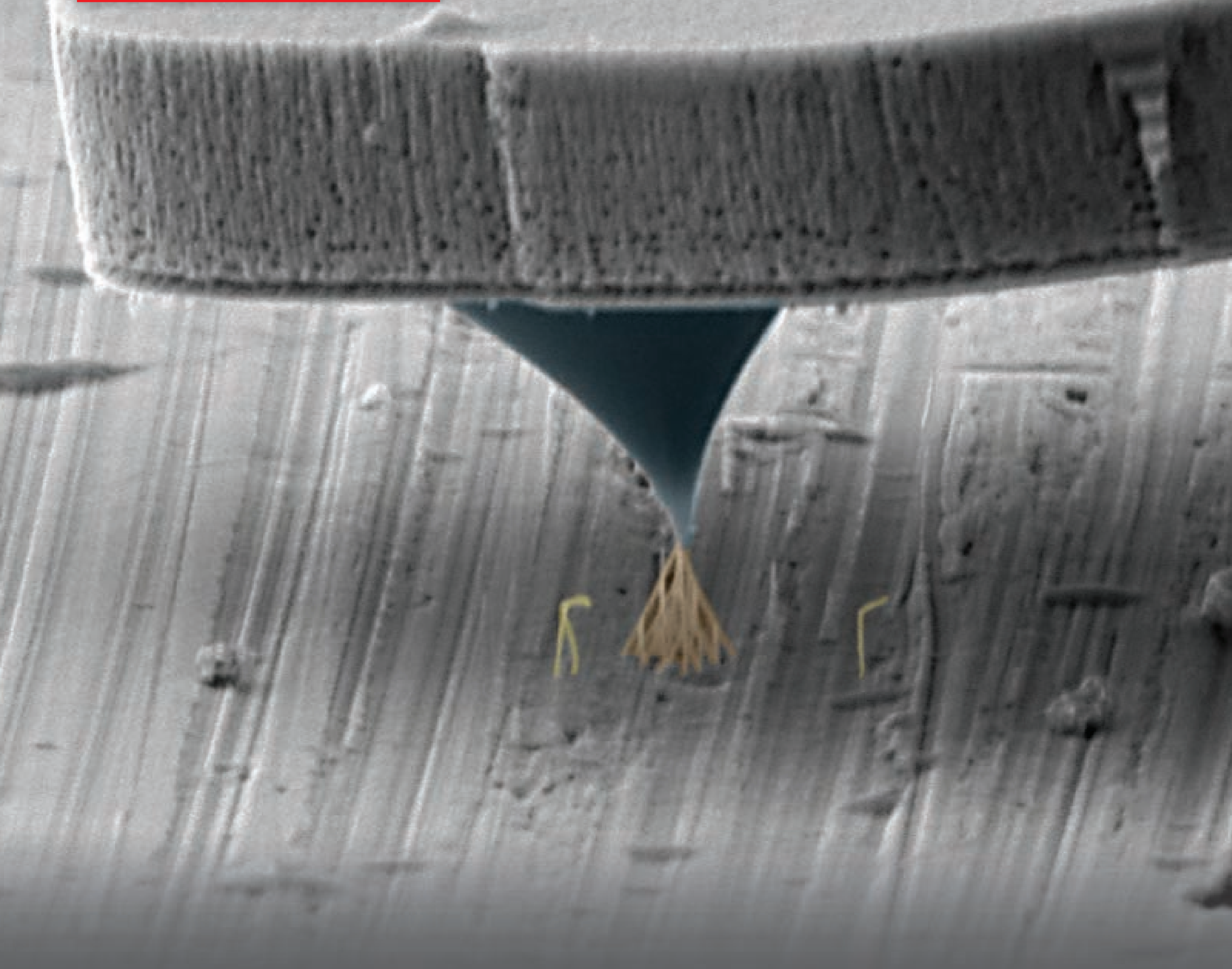
BACK SCATTER



Nanoscale 3D printing

Focused electron beam–induced deposition (FEBID) is a 3D nanoprinting technique capable of producing intricate metal-based nanostructures with exceptional design flexibility. All that's needed are a conventional scanning electron microscope (SEM) and a continuous source of gaseous precursor molecules, typically metal–organic compounds.

In the SEM, the molecules spread out over the surface of the fabrication substrate, and those in the focus of the electron beam become dissociated. Although volatile fragments quickly dissipate, nonvolatile components, including the metal constituents, will stick. A stationary SEM beam will make a vertical pillar of deposits, and a slowly moving beam will generate a sloped one. By controlling the motion of the beam and the angle of the substrate, one can create a vast array of complex 3D nanostructures with features as small as 10 nm. The technique, which can be applied to arbitrarily shaped substrates, has diverse applications in nano-optics, nanomagnetism, scanning probe microscopy, particle trapping, and more.

This SEM image shows an atomic force microscope (AFM) cantilever with its tip hovering over a 2-μm-tall platinum structure (highlighted in light orange) inspired by the Louvre Pyramid. The structure was built from a mesh of 100 nm nanowires printed in the SEM with FEBID. The AFM probe serves as a sensitive force sensor for analyzing the mechanical properties of such nanostructures. (A. Alipour et al., *Microsc. Today* **31**(6), 17, 2023; image submitted by Stefano Spagna.) —RJF

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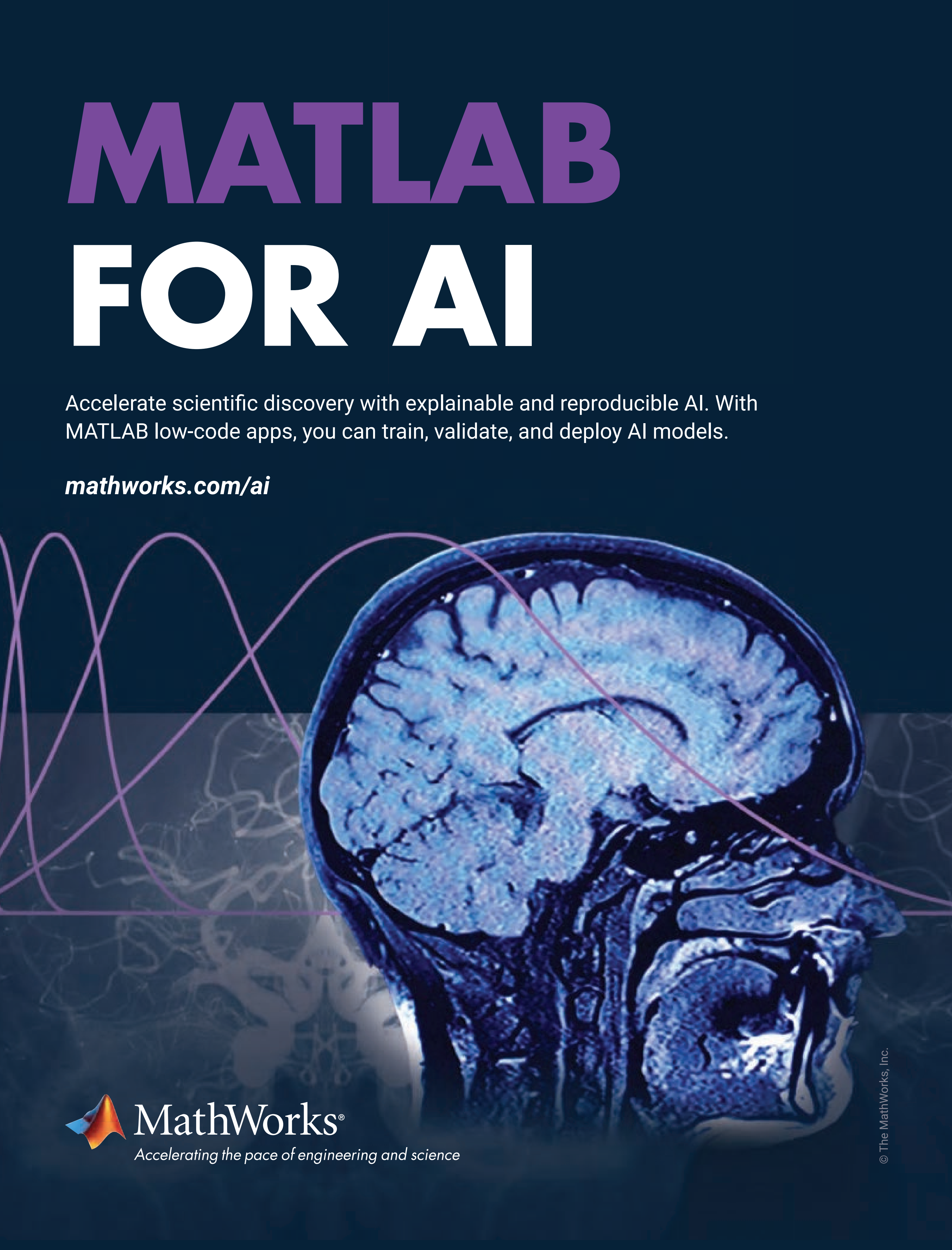
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