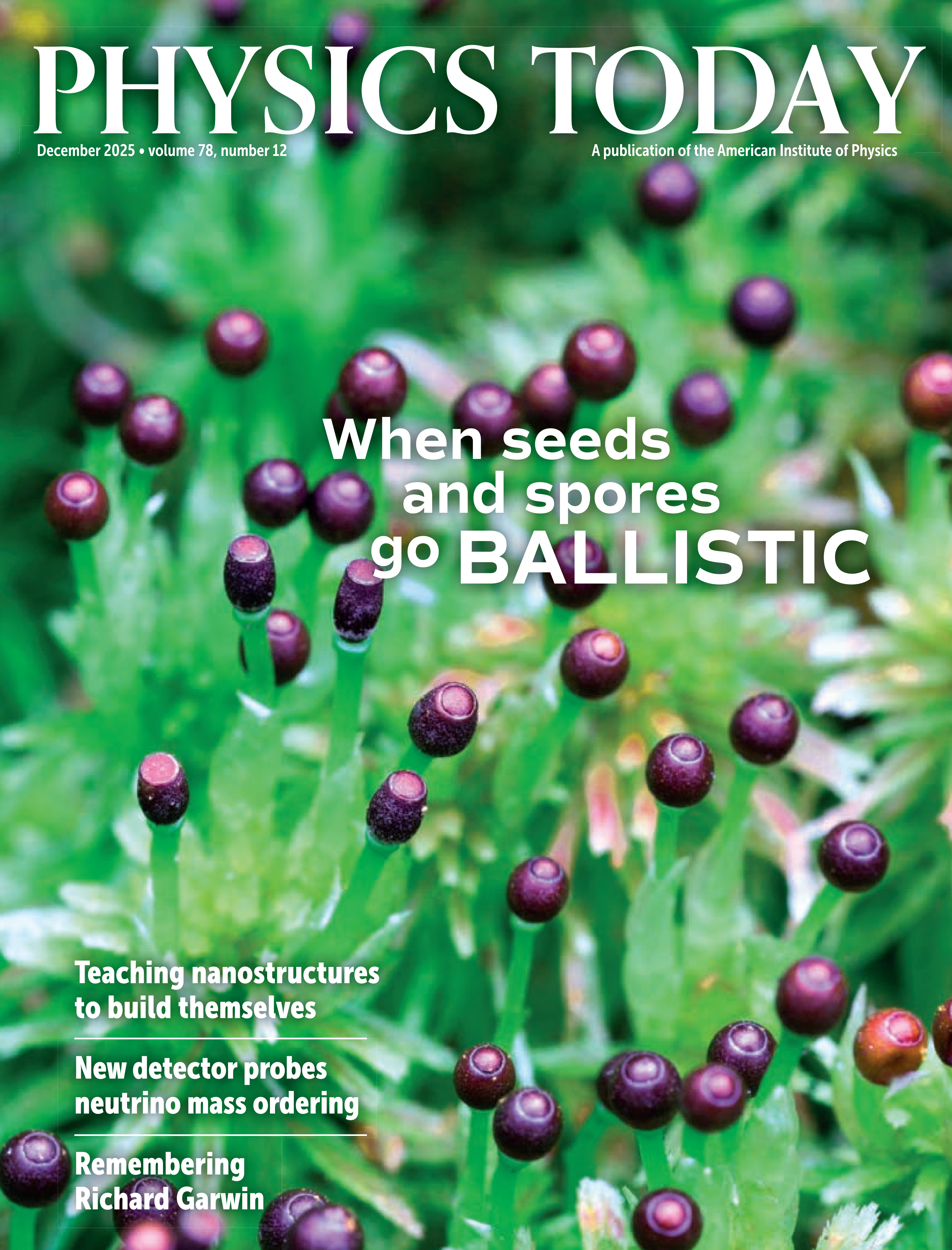

PHYSICS TODAY

December 2025 • volume 78, number 12

A publication of the American Institute of Physics

When seeds and spores go BALLISTIC

Teaching nanostructures to build themselves

New detector probes neutrino mass ordering

Remembering Richard Garwin

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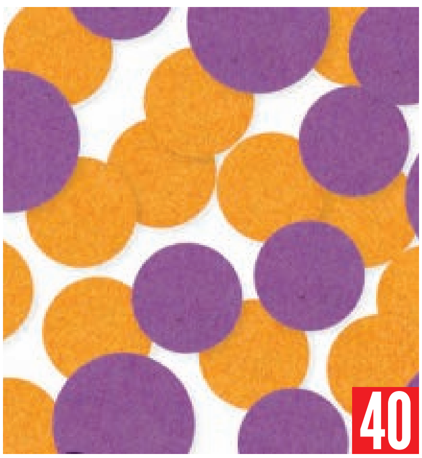

FEATURES

ON THE COVER: Like all mosses, the peat moss shown here lacks a vascular system, so it can't grow tall enough for the wind to carry its spores. But it elevates its spores a different way. As its spore capsules dry over time, they collapse. The rising gas pressure inside the capsule blows the lid off and thrusts the spores high enough to be transported by air currents. To learn more about ballistic spore and seed dispersal, turn to the Quick Study by Dwight Whitaker on **page 54**. (Image by Esa Ervasti/Alamy.)

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AIP

From the Niels Bohr Library & Archives: Victor Weisskopf, Maria Goeppert Mayer and Max Born

Sea-level reconstruction offers new interpretation of Pleistocene climate

Researchers find that large changes in global sea level occurred throughout the last ice age, rather than just toward the end of the period.

At the onset of the Pleistocene Epoch about 2.6 million years ago, global temperature fell, polar ice sheets grew, and sea level dropped. Another big switch occurred 1.2 million years ago in the middle of the Pleistocene: Sea-level fluctuations that had been recurring every 41 000 years became larger and started happening every 100 000 years. Since the Mid-Pleistocene Transition was first identified more than 40 years ago, researchers have predominantly interpreted the decreased frequency as a response to the ice sheets' increasingly large variations in size.

A new reconstruction of sea level challenges that interpretation. Peter Clark of Oregon State University and colleagues show, using geological archives spanning the past 4.5 million years, that global ice sheets experienced large changes in size throughout the Pleistocene.[1] The results, which are contrary to those from previous studies, indicate that the Mid-Pleistocene Transition was a switch only in the frequency of sea-level changes.

Many records of ocean temperature and sea level come from the relative amounts of oxygen-18 and oxygen-16 that are found in the fossil shells of foraminifera, microscopic organisms that have lived in the ocean, often at the bottom, for hundreds of millions of years. The isotope ratios reflect the environmental conditions in which the organisms lived, specifically ocean temperature and ice volume—and thus sea level.

That relatively simple picture, which has been used in many previous reconstructions of sea level, assumes that the relationship between sea level and the oxygen isotope composition of seawater is constant over time. But that's not entirely accurate. The ocean had more ^{18}O relative to ^{16}O during periods when the poles were warmer than during periods when the poles were cooler.

Clark and colleagues developed their picture of the climate by first reconstructing ocean temperature over the past 4.5 million years—a result they published in a paper earlier this year. To yield the oxygen isotope composition of seawater and thus the sea level, they combined the temperature results, which were inferred from oxygen isotope measurements, with the foraminifera isotope measurements.

Clark and colleagues discovered that in the early Pleistocene, when the temperature was higher than it was in the

DATA FROM THE GREENLAND ICE SHEET and other large bodies of ice were used with geological isotope data by researchers to reconstruct changes in global sea level over the past 4.5 million years. (Photo by NASA, courtesy of the US Geological Survey.)

middle to late Pleistocene, Earth experienced sea-level changes that were similar in magnitude to those in the middle to late Pleistocene. The researchers hypothesize that the long-term cooling, which they reported in 2024, caused the Southern Ocean to become more stratified, which would have resulted in atmospheric carbon being stored in deep water for long periods of time. As glaciation intensified, sea level dropped precipitously and reached as low as 150 m below today's sea level multiple times throughout the Pleistocene, including about 21 000 years ago, during the Last Glacial Maximum.

Alex Lopatka

Reference

1. P. U. Clark et al., *Science* **390**, eadv8389, 2025.

Micron-sized wave pools offer insights into nonlinear wave dynamics

Superfluid helium flowing on a silicon wave flume operates in a regime of nonlinear hydrodynamics that conventional fluid experiments can't access.

Nonlinear wave dynamics are challenging to model computationally. To validate theoretical models, researchers often rely on the results of experiments done with wave flumes—long channels filled with water, much like the Scottish canal where, in 1834, John Scott Russell first observed long-lived solitary waves, now commonly known as solitons (see the 2012 Physics Today story "Interacting solitary waves"). Flumes are used to study nonlinear hydrodynamics that emerge in shallow-water waves, like tsunamis, tidal bores, and turbulence. But even the largest constructed wave flume, the 300-m-long Delta Flume in Delft, the Netherlands, can't replicate the degree of nonlinearity observed in some natural settings.

Now researchers at the University of Queensland, led by Warwick Bowen and Christopher Baker, have found a way to access hydrodynamic nonlinearity beyond even the most extreme terrestrial examples.[1] They did it by going small: The team built a silicon wave flume just 100 μm long, about the width of a human hair, that guides waves of superfluid helium, as shown in figure 1. "What we've been able to do is to re-create, on a chip, nonlinear physics that is even more extreme than what can be modeled in these huge wave flumes," Baker says.

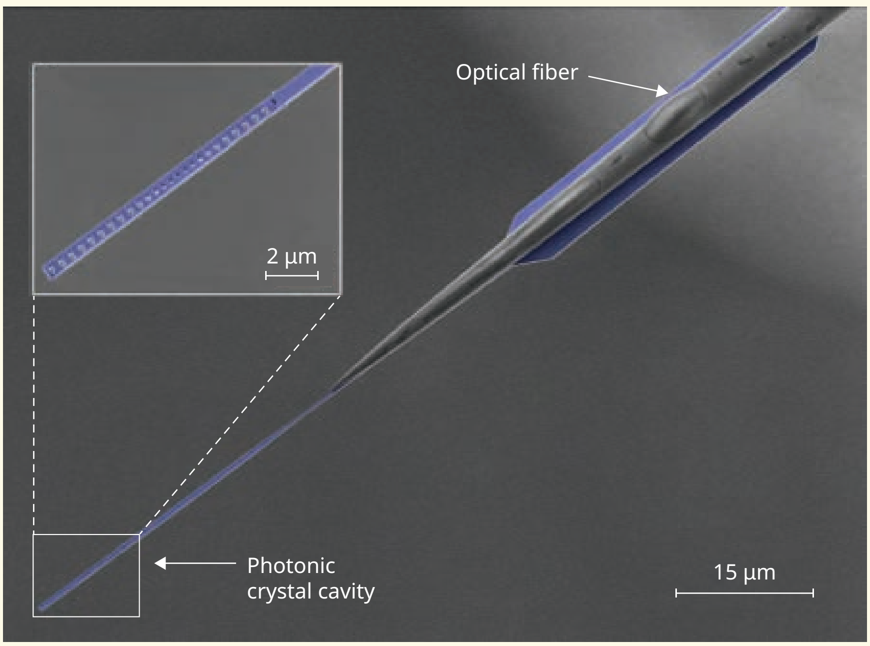


FIGURE 1. A 100-μm-LONG WAVE FLUME is used to observe nonlinear wave dynamics in superfluid helium. To induce waves in the channel of helium (shaded purple), an optical fiber delivers light to a photonic crystal cavity, shown in the inset, at one end of the flume. First, heat from laser pulses generates waves. Then, as freely evolving waves pass over the crystal cavity, its resonance frequency shifts in proportion to the wave height, which enables readout of the wave activity through the optical fiber. (Figure adapted from ref. 1.)

The team built the tiny flume using lithography, a standard semiconductor manufacturing technique. The device is glued to a tapered optical fiber that delivers laser light to a photonic crystal cavity at one end of the flume. Pulses of heat from the cavity start helium waves, and subsequent flow is measured by changes to the resonance of the cavity as waves pass over it. The advantage of using superfluid helium to observe fluid behavior at small scales is that unlike water, it has no viscosity and so can host waves in just nanometers of fluid. In a film of superfluid helium, it's the van der Waals force, not gravity, that provides the restoring force.

Nonlinearity in shallow waves is quantified by the Ursell number, which reflects wave height, wavelength, and fluid depth, as shown in figure 2. The shallow 6.7 nm depth of the superfluid helium allowed the researchers to access nonlinearities that were five orders of magnitude higher than what can be achieved in conventional experiments. They observed wave steepening—much like at the beach when waves steepen and break as they come to shore, but with a twist: The waves steepen on their back side, away from their direction of travel. The researchers also saw soliton fission, a process in which shock fronts evolve into a train of solitons. But unlike the solitons observed in macroscale fluids, the waves move as a depression, not a hill, in the fluid.

The research team plans to continue exploring wave dynamics with the new

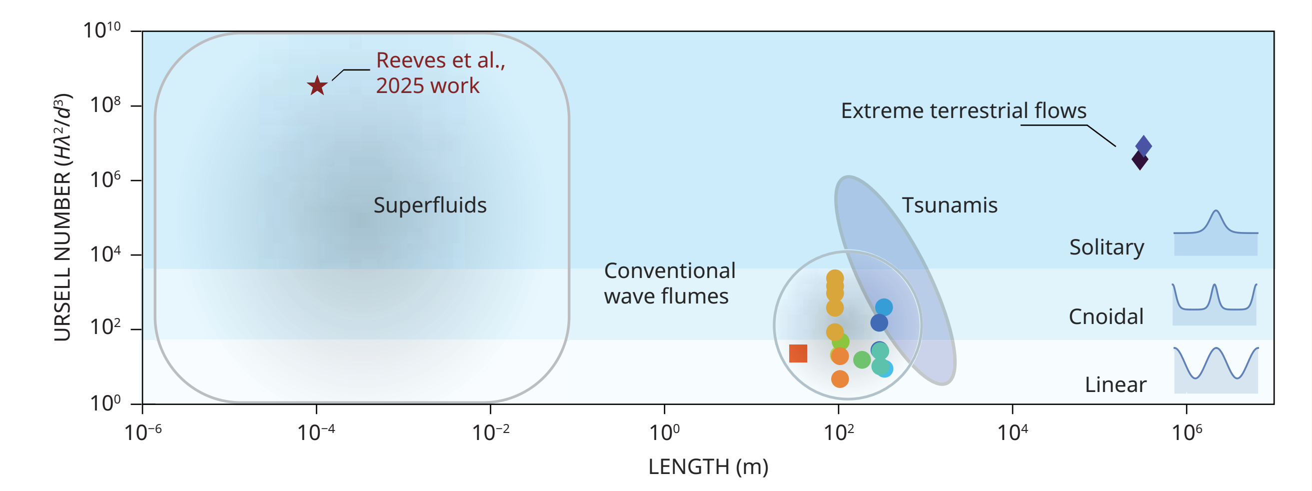


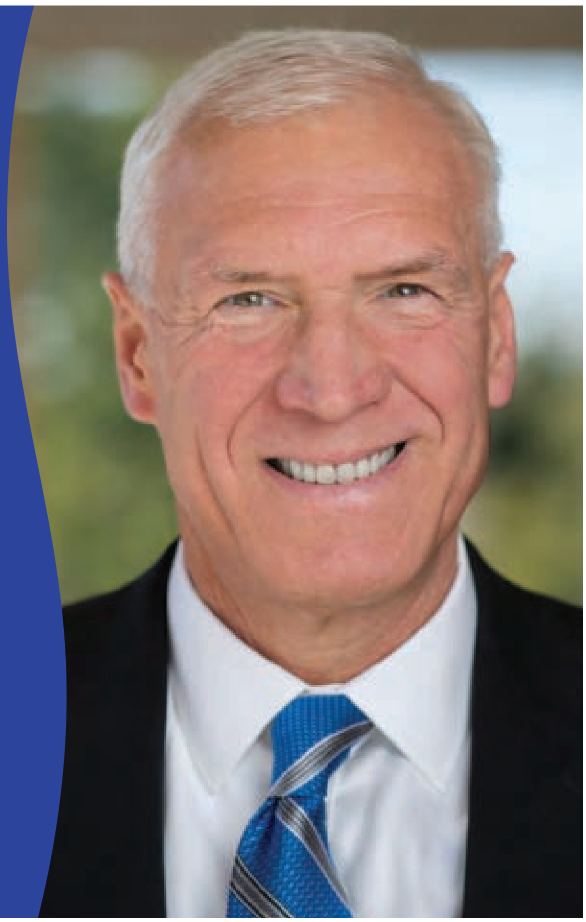
FIGURE 2. THE NONLINEARITY OF SHALLOW-WATER WAVES can be quantified through the Ursell number, which is described by the relationship between the wavelength λ and height H of a wave and the water depth d. The degree of nonlinearity determines whether waves operate in linear-, cnoidal-, or solitary-wave regimes. Small experiments that access a more extreme degree of nonlinearity open a path to new insights about nonlinear wave phenomena like turbulence. (Figure adapted from ref. 1.)

platform. It is much easier to create different shapes and lengths with the nanoscale flumes than with their macroscale counterparts. The researchers' simulations suggest that in future experiments, the system could generate what's known as a soliton gas—a random collection of hundreds of interacting solitons. "What soliton gas portends is the possibility of a turbulence theory, a statistical theory of nonlinear wave interactions, that could be solvable," says Mark Hoefer, an applied mathematician at the University of Colorado Boulder. "To be able to see it in this fluid system would be very exciting."

Laura Fattaruso

Reference

1. M. T. Reeves et al., *Science* **390**, 371 (2025). PT



Equation changes for international STEM scholars deciding whether to come to US

Even as funding cuts, visa issues, border fears, and other hurdles detract from US attractiveness, some scholars still come.

For STEM scholars from around the world, time at a US university or research institution—as a PhD student, postdoc, or visiting professor, for example—has long been a sought-after stepping stone on the academic career path. "A BTA—'been to America'—provides a leg up in getting a faculty job at world-leading institutions," says James Fraser, a physicist at Queen's University in Kingston, Ontario, and director of science policy and advocacy with the Canadian Association of Physicists.

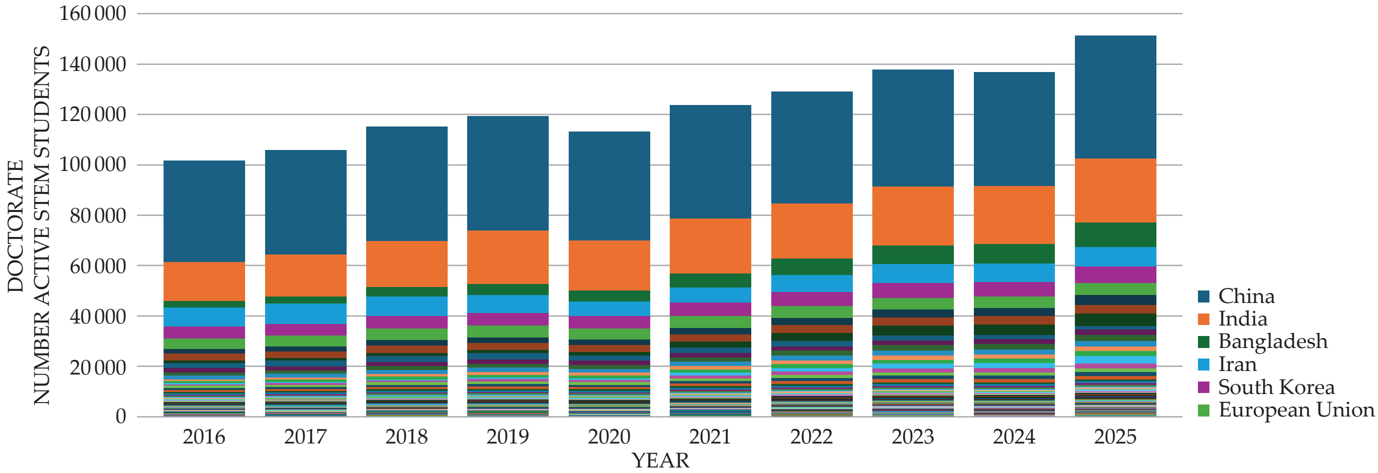
But changes in US politics and research funding in recent years have shifted how scholars weigh whether to come to, or remain in, the US. And anecdotally, at least, hesitance has ramped up in 2025.

Alán Aspuru-Guzik grew up in Mexico and moved to the US for graduate studies in physical chemistry. In 2018, spurred by Donald Trump's first term as president, Aspuru-Guzik left his tenured position at Harvard University for a post at the University of Toronto. The new normal for scholars is, he says, "I will not go to the US for a postdoc or faculty position."

Nearly a year after applying for a tenure-track position in the US, a physicist on the verge of accepting the job decided at the last minute in August to stay in Germany. According to the chair of the department that the scientist would have joined, the candidate had been enthusiastic about the position and had wanted to get involved in NASA-funded projects. (The chair requested anonymity to protect the identity of the candidate.) But by spring 2025, the academic landscape looked different than when they had applied.

Three factors led the candidate to turn down the job, says the chair: With federal funding for science threatened, the candidate was worried about get-

ALÁN ASPURU-GUZIK (center, with hat) with the large, multidisciplinary group he leads at the University of Toronto in both theoretical and experimental research on quantum computer algorithms, molecular discovery, and more. He moved there from Harvard University in 2018 out of concerns regarding the direction President Trump was taking the US during his first term. Those concerns have escalated, he says, and his students and postdocs look outside the US for their next steps. (Photo by Sean Caffrey.)



THE TOTAL NUMBER OF VISAS for doctoral students enrolled in US STEM programs is up this year, despite a trend to look elsewhere that is fueled by tightening purse strings and policies that have US universities on edge. The data are for active visas to people from about 200 countries in the fall of each year shown. (Data compiled from the US government's Student and Exchange Visitor Information System and analyzed by Michael Marder.)

ting research grants; they wondered about the security of tenure in the US; and they feared that the US may no longer be safe for their spouse, who is not white.

"It used to be typical to go to the US" as part of one's training, says German native Jannis Necker, who began a postdoc at Leiden Observatory in the Netherlands this past April. "It was a way to get your foot in the door of international projects." But already during Trump's first term, he says, "the political climate looked restrictive." Now, he says, the US has lost appeal for him and many of his peers because of both the politics and uncertainty in funding. "The perceived value of going to the US has decreased," he says.

Alexandra Trettin earned her PhD in her native Germany and is currently a postdoc in neutrino physics in the UK. "For me, the political situation, and in particular, the attacks on LGBT rights, made it completely unattractive to go to the US," she says. "I had an offer in Texas," she continues. "But as a trans woman, I didn't feel I could live in the US safely, especially not in Texas." Trettin says she avoids the US—she won't go even for a conference out of fear of being hassled at the border—and that doing so comes with costs to her career. "It makes it harder to network."

With the introduction of new visa hurdles, attacks on diversity, threats to research funding, and other US political developments, the academic community has widely expected the appeal of the US—and consequently, international enrollment—to fall. Despite such prognostications, international enrollment in US master's and doctoral programs in STEM fields is up this year, according to data from the Student and Exchange Visitor Information System (SEVIS), which is under the US Department of Homeland Security. Data for postdocs and faculty are not available. Michael Marder, a physicist at the University of Texas at Austin, crunched the SEVIS enrollment data. "So far," he says, "the evidence doesn't bear out a drop in students coming to the US from abroad." Those data are from before the government proposed a four-year limit on student visas, which, if enacted, could start to squeeze STEM scholars out.

The US remains a top choice for early-career scientists from lower-income countries. "They still want to come," says a US-based physics professor who, as an immigrant from Pakistan, requested anonymity. But, says the professor, with many scholars experiencing visa issues, faculty members may not want to risk delays in the arrival of their graduate students or postdocs. "It's a simple equation: If you have [grant] money, you have to deliver. If someone can't come, take someone local, even if you sacrifice quality." Another US-based physics professor who didn't want to be identified notes that many students are coming from India (where the professor is from), but says, "Their parents don't want them to. They are scared."

For many years, "the US was the crown jewel for science," says a researcher who came to the US from the UK in 2011 to do their PhD in ocean science and engineering. Their mentors advised them that in the US they'd have better funding and more freedom as a PhD student to develop their own research. In 2018, when it came time to seek a faculty position, the researcher turned down offers in the UK in favor of a tenure-track job at a top-tier US university, where they work on glacier and ice-sheet dynamics. (The researcher is in the process of getting a green card and requested anonymity to avoid calling attention to themselves.)

These days, says the researcher, international undergraduate and graduate students who are based in the US express doubts about staying in the country because of funding uncertainties. American students and postdocs, the researcher adds, are increasingly looking to leave academia and, sometimes, science. The researcher's response? "Most of the time, I ask them if they are super passionate about science. And I help them focus on skills that they can transfer from their academic research to other workforce sectors."

Toni Feder

Next-generation underground neutrino detector in China up and running

JUNO seeks to answer a fundamental question about the elusive particles. So do two competing experiments coming on line in the next decade.

The Jiangmen Underground Neutrino Observatory (JUNO) achieved a major milestone in August, after 10 years of construction, when it began collecting data. More than 700 scientists from 17 countries are contributing to the facility, which is the largest liquid-scintillator detector in the world. Its primary goal is to determine the ordering of the neutrino masses.

Located 700 meters underground near China's south coast, JUNO measures electron antineutrinos arriving from two nuclear power plants, each about 50 kilometers from the detector. JUNO uses similar technology to China's Daya Bay Reactor Neutrino Experiment, which ran from 2011 to 2020, but the new, roughly $350 million facility operates on a much larger scale, says J. Pedro Ochoa-Ricoux, a professor of physics and astronomy at the University of California, Irvine, and a member of the JUNO experiment.

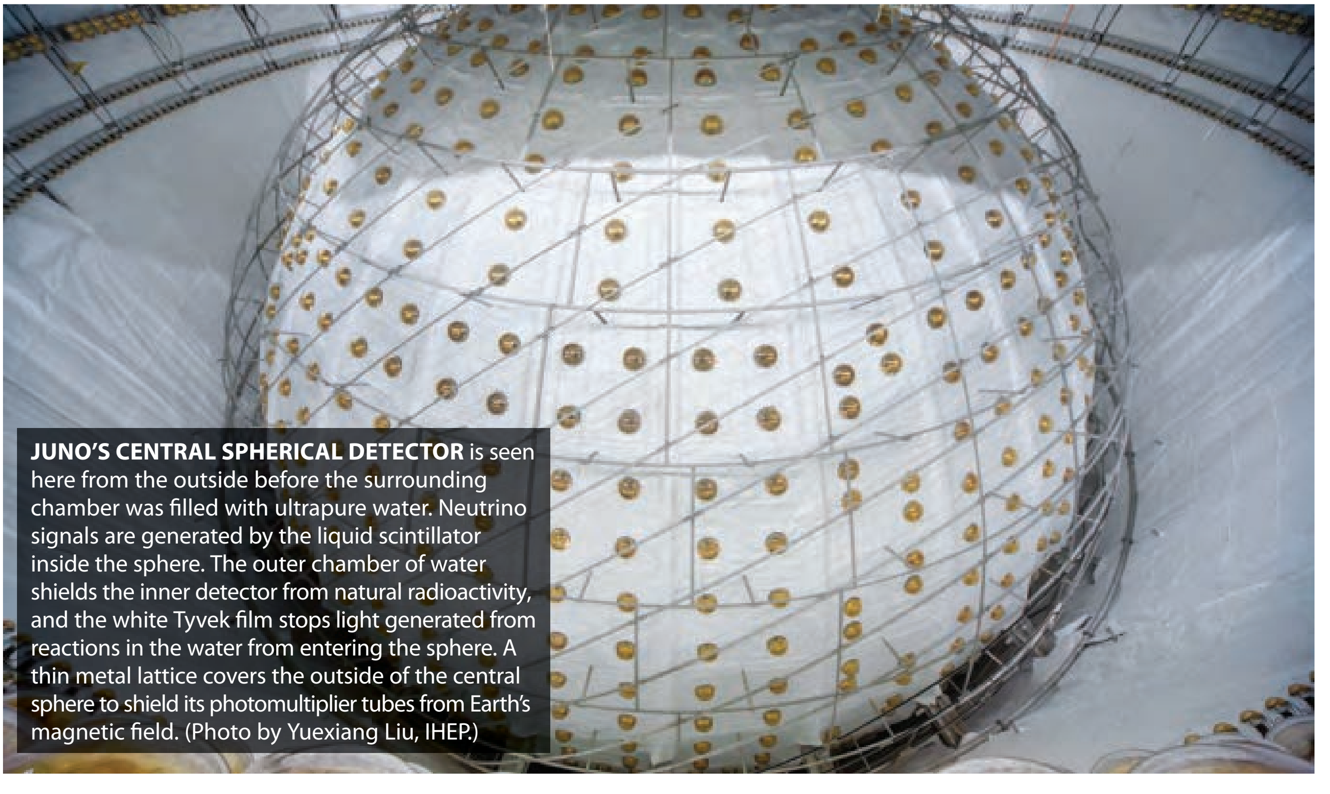
JUNO is the first of the three new large neutrino detectors under construction around the world to begin operations. Japan's new detector, Hyper-Kamiokande (Hyper-K), is slated to begin in 2028. The US's Deep Underground Neutrino Experiment (DUNE) is not scheduled to launch until at least the late 2020s. (See Physics Today's 2018 story "Japan's next neutrino detector to have huge tanks, bright beam" to learn more about Hyper-K and the 2022 article "Building a ship in a bottle for neutrino science," by Anne Heavey, to read more about DUNE.)

Like JUNO, Hyper-K and DUNE are designed to determine the neutrino mass ordering, also known as the neutrino mass hierarchy, and other neutrino characteristics. The JUNO team feels pressure to be the first with mass-ordering results, says physicist Yifang Wang, who is leading the JUNO experiment at China's Institute of High Energy Physics (IHEP). About 45 reactor antineutrinos will be observed per day in the detector. "After about six years of data collection, we should be able to determine the mass hierarchy up to the level of three sigma," Wang says.

Kam-Biu Luk, a coleader of the Daya Bay experiment, says the new detectors are the natural next step for the field. "After Daya Bay conclusively showed that θ_{13} is nonzero, a new generation of neutrino-oscillation experiments were initiated for tackling the remaining questions which are central for completing our understanding of neutrino mixing," says Luk, a physics professor at the Hong Kong University of Science and Technology and the University of California, Berkeley. The angle θ_{13} is one of the three parameters describing the superposition or mixing of neutrino mass states that's at the heart of neutrino oscillations from one flavor to another. (See Physics Today's 2012 story "Reactor experiment reveals neutrino oscillation's third mixing angle.")

Getting the mass in order

Determining the neutrino mass ordering is central to updating the standard model of particle physics. The model does not account for nonzero neutrino



JUNO'S CENTRAL SPHERICAL DETECTOR is seen here from the outside before the surrounding chamber was filled with ultrapure water. Neutrino signals are generated by the liquid scintillator inside the sphere. The outer chamber of water shields the inner detector from natural radioactivity, and the white Tyvek film stops light generated from reactions in the water from entering the sphere. A thin metal lattice covers the outside of the central sphere to shield its photomultiplier tubes from Earth's magnetic field. (Photo by Yuexiang Liu, IHEP.)

mass, and resolving the mass ordering will be key to developing a theoretical understanding of the origin of lepton masses and mixings. The mass ordering has implications for, among other things, cosmology and our understanding of the evolution of the universe's large-scale structure.

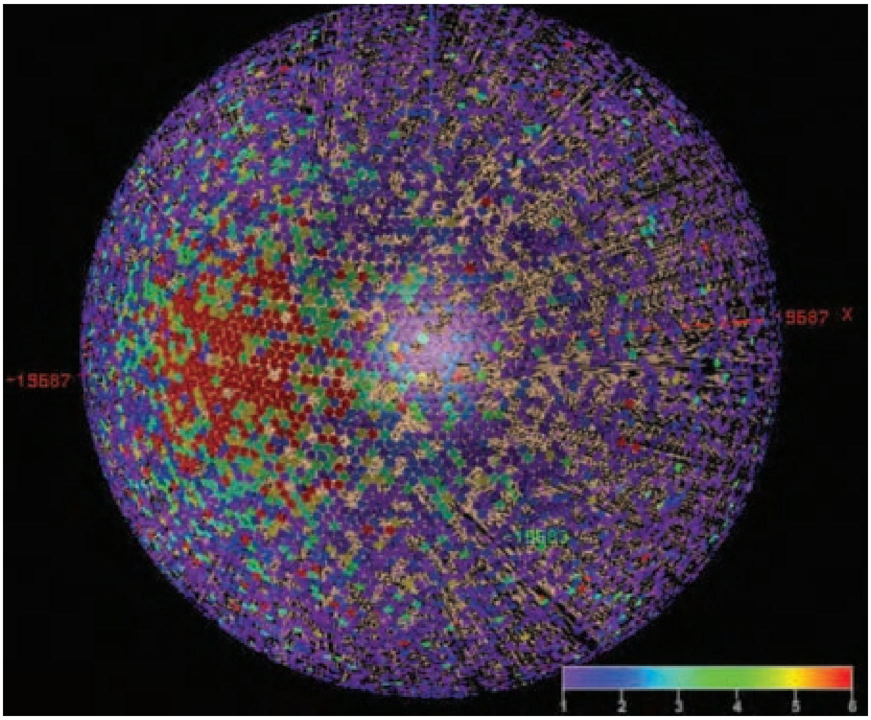
The three neutrino flavor eigenstates—electron, muon, and tau—are quantum superpositions of different neutrino mass eigenstates. The relative sizes of the three neutrino masses m_1, m_2, and m_3 is the mass-ordering question. Masses m_1 and m_2 are the closest in size, with m_1 the smaller of the two. Mass m_3 could obey normal ordering, given by $m_1 < m_2 < m_3$. Alternatively, neutrinos could obey inverted ordering, with $m_3 < m_1 < m_2$.

The previous generation of neutrino experiments, Japan's Super-Kamiokande detector and the US-based NOνA (NuMI Off-axis ν_e Appearance), has tried to determine the ordering, but the signals are subtle, says Duke University physics professor Kate Scholberg, a member of DUNE. The determination hinges on teasing out distortions in the oscillation pattern of electron and muon neutrinos. The current generation of detectors hasn't come up with a definitive answer yet, so it's up to the next generation of very large detectors to find it, she says.

JUNO's detector measures antineutrino interactions with protons, called inverse beta-decay reactions. It precisely measures the two components in the energy spectrum that are caused by oscillations. The low-frequency component of the energy spectrum comes from the oscillation of the neutrino mixing angle θ_{12} and the mass-squared difference Δm^2_{21}. The high-frequency component is controlled by the oscillation resulting from θ_{13} and Δm^2_{31}.

The team can fit the experimental data to the equation for the survival probability of reactor antineutrinos. That will help the researchers determine the four parameters and the ordering of the neutrino masses, which is indicated by the sign of the remaining mass-squared difference, Δm^2_{32}. The sign of Δm^2_{32} will be positive if mass ordering is normal or negative if it is inverted.

"Mass ordering is the gateway for the ultimate question," says Sam Zeller, deputy project director of the DUNE detector at Fermilab. It will allow scientists to determine the extent to which neutrinos violate *CP* (the combination of charge conjugation and parity) symmetry, which has implications for the matter–antimatter imbalance in the universe (see the 2020 Physics Today story "Accelerator experiments are closing in on neutrino *CP* violation"). "We'd all like to know why we're here, why we exist, and we're hoping that neutrinos hold that clue," Zeller says.



A NEUTRINO DETECTED BY JUNO on 24 August, as recorded by the experiment's approximately 43 000 photomultiplier tubes. (Image from the JUNO Collaboration.)

A knife's edge

Reactor antineutrinos have much lower energies than accelerator neutrinos: They are in the megaelectron-volt range rather than at accelerator neutrinos' gigaelectron-volt levels. "It's a very low-energy regime. There's a lot of radiological background," says Scholberg. The JUNO team, she says, "is drawing on a lot of past experience, but it's definitely a hard thing to do." But JUNO's approach has benefits too. Inverse beta-decay interactions are more well understood than higher-energy neutrino interactions and will give JUNO a cleaner reading of the energy spectrum.

The experiment will have to collect data with an energy resolution of at least 3% at 1 MeV, with an energy uncertainty lower than 1%. "There's not a lot of room for mistakes," says Ochoa-Ricoux.

JUNO's central detector is a 35.4-meter-diameter acrylic sphere filled with 20 000 tons of liquid scintillator. It is 20 times as massive as the world's next-largest liquid-scintillator detector, Japan's Kamioka Liquid Scintillator Anti-Neutrino Detector experiment, better known as KamLAND. JUNO's liquid scintillator is exceptionally clear; it has a light attenuation length of 20 meters, which is an 8-meter improvement over Daya Bay's attenuation length, Wang says.

More than three-quarters of the sphere's surface is covered in approximately 43 000 photomultiplier tubes. The PMTs capture the scintillation light from the inverse beta-decay reactions. Existing PMTs at the time of JUNO's planning phase were not sensitive enough to detect the small number of photons produced by the liquid scintillator, so the researchers made their own, says Wang. By changing the PMTs' electron amplification stages and improving their photocathode's quantum efficiency, the JUNO team increased their PMT photon-detection efficiency to double that of Super-Kamiokande's PMTs.

JUNO's central detector is suspended in a 44-meter-deep cylindrical water Cherenkov detector to shield it from cosmic rays and Earth's natural radioactivity. About 2400 additional PMTs point into the water Cherenkov detector to veto incoming cosmic rays. Those measures filter out background events to get a clean neutrino signal and improve the detector's energy resolution.

The project faced major engineering challenges, says Wang. Unlike the horizontal tunnel built for Hyper-K, he says, engineers had to dig a sloped tunnel going down into the mountain. "Building a detector with a 40-meter diameter underground with very limited space for people to work was hard because you just don't know where people can stand."

Friendly competition

DUNE and Hyper-K could independently determine mass ordering using different approaches than JUNO. Both are long-baseline accelerator experiments that examine the oscillation of muon neutrinos to electron neutrinos (and muon antineutrinos to electron antineutrinos).

DUNE will send a flow of neutrinos produced in Fermilab's Long-Baseline Neutrino Facility to a liquid-argon time-projection detector at the Sanford Underground Research Facility in South Dakota 1300 kilometers away. The experiment will use those accelerator neutrinos to determine the mass ordering.

Hyper-K will use a 71-meter-deep water Cherenkov detector in Kamioka to measure neutrinos from the Tokai-based Japan Proton Accelerator Research Complex (J-PARC) accelerator 295 kilometers away. The experiment will make use of atmospheric and accelerator neutrinos for the mass-ordering determination.

Once operational, DUNE would need only a few months of data to determine the mass ordering, says Zeller. She says it is the only experiment, either planned or current, that can measure the mass ordering at five sigma, the accepted threshold to be considered a discovery-level measurement. "From this regard, JUNO has to be faster, quicker. Otherwise, results will be quickly overwritten by DUNE," says Wang.

"JUNO will be really very complementary to the measurement that will happen with the long-baseline experiments," says Scholberg. For instance, the oscillations that JUNO observes are insensitive to neutrinos' interactions with matter and to the phase factor describing *CP* violation; accelerator experiments must take both into account.

"If our theories are correct, the experiments should, of course, get the same answer," says Zeller. "Determining neutrino mass ordering in completely different ways will be super interesting to see."

A WORKER PEERS INTO JUNO'S CENTRAL DETECTOR, a hollow sphere filled with 20 000 tons of liquid scintillator. (Photo by Yuexiang Liu, IHEP.)

Other applications

JUNO's operating timeline is 30 years. Wang says that after the experimental team determines the mass ordering, it plans on broadening its focus to research in astrophysics, cosmology, and geophysics.

"JUNO is going to be a major player in understanding supernovae through the detection of neutrinos," says Erin O'Sullivan, an associate professor of physics and astronomy at Uppsala University. JUNO could detect neutrinos that nearby supernovae emit even before they collapse; those neutrinos would provide early notice that an even larger burst of neutrinos is headed toward Earth imminently. The notice would give detector teams the opportunity to cancel any planned downtime and alert electromagnetic telescope operators.

William McDonough, a member of JUNO and an Earth sciences professor at Tohoku University and the University of Maryland, is looking forward to JUNO's geoneutrino measurements. (See the 2012 Physics Today article "The many uses of electron antineutrinos," by McDonough, John Learned, and Stephen Dye.) He anticipates that the first year of data will provide a significant advancement toward understanding the flux of geoneutrinos from Earth's crust and mantle and reveal important insights into the planet's energy balance.

Wang says the long-term plan is to upgrade JUNO to become a detector for neutrinoless double-beta decay by loading candidate isotopes into its liquid scintillator. Searching for neutrinoless double-beta decay would help determine whether neutrinos are Majorana particles—that is, their own antiparticles—one of the highest-priority questions in particle physics. But the isotopes are radioactive and will lower the transparency of the liquid scintillator.

"We have to wait until the mass hierarchy has been determined or DUNE is on line and we are not able to compete anymore," says Wang. "Then we'll say, Let's forget about that, let's go do double-beta decay."

Jenessa Duncombe

Q&A: Henry Garcia built carbon nanotubes. Now he simulates big red curly hair

His work at Pixar on special effects and simulations blends physics and art.

HENRY GARCIA (Photo by Kris Campbell/Pixar.)

"If you are here because you want to work at Pixar, that's basically saying you want to be an NBA player. It's probably not going to happen." So said the teacher in a graphics course that Henry Garcia took as a sophomore at Sacramento State in California in 2001. Garcia decided to major in physics and computer science. He left graphics behind—at least for a while.

A few years later, when Garcia was a third-year PhD student, graphics—and Pixar—found him. He joined the company in 2008 and has worked in simulations and special effects ever since. *Toy Story 3* was the first movie he worked on, and he has been involved in *Toy Story 4* and *Toy Story 5* (scheduled to be released in 2026), *Brave*, *Elio*, *Luca*, *Dream Productions*, and more. These days, he works mostly as a simulation supervisor. His specialty is using motion to help tell a film's story.

"It's a work hard, play hard environment," says Garcia. "It's not uncommon during our busiest periods to work 50-hour weeks, several weeks in a row, or even in the 60s if it gets crazy. You've got to hit your deadlines."

Despite the pressures, says Garcia, he manages to balance work and life: "I have three kids. I have hobbies. I have a whole life outside of work. I am training as a meditation teacher in the Buddhist tradition."

PT: Describe your education path.

GARCIA: I come from humble beginnings. My neighborhood wasn't rough, but it was low socioeconomic status. I was the first in my family to graduate college. In high school, nobody was going to pick me as someone who was going somewhere. It wasn't until I got to college that I started to thrive.

I double majored in physics and computer science. Then I went to the University of California, Berkeley, for graduate school. Ironically, one of the reasons I pulled away from computer science and went into physics was that I didn't want to sit in front of a computer all day.

I originally wanted to get a PhD because I wanted to teach. I loved bringing my passion for math and science into the world, and I thought there was something I could offer people, especially at the high school and early college levels, where people get scared of those things.

At Berkeley, I worked in Alex Zettl's lab. I was working on constructing the most-robust, nicest-quality carbon nanotubes possible so that I could start playing around with shoving tiny diamonds into them for hydrogen storage. In the process, I created some wonderful nanotubes that others in the lab started using, and my name got on lots of publications.

I had just finished my coursework and was starting to get heavily involved in research when I left for Pixar.

PT: How did that happen?

GARCIA: I was enjoying my time in grad school, and I was succeeding. But I started to question whether I had the passion and drive for the next steps. I had about three years left on my PhD, then I'd have another two years in a postdoc, then I'd hopefully get started on a faculty position, and then, maybe, after six years I'd get tenure.

I felt I could be happy taking that path, but I asked myself, Is this really what I want to do? And what could I do now? Around that time, I got an email from DreamWorks Animation recruiting for internships. I could check off 8 of the 10 boxes of what they were looking for and thought, Maybe I could do this.

I swiped my laptop clean, put Linux on there with Windows, and started programming again. I hadn't really touched a computer in the three years since I started graduate school as an experimental physicist. I also audited a computer graphics course.

I applied to the residency program at Pixar Animation Studios. You get full salary, full benefits, and then after nine months, they either hire you or wrap you. The worst-case scenario was that I could have worked on a movie for a year and then gone back to graduate school to do what I loved there. Luckily it worked out, and I've been at Pixar since 2008.

PT: In what sense were you an atypical hire?

GARCIA: I came in without film or computer graphics experience, but the timing was good. Pixar was expanding from making one movie a year to three movies every two years, so the company was expanding its workforce and was willing to take a risk on somebody like me.

When I was applying for the residency, they asked me if I painted or was artistic. My answer was that I used to draw a lot in elementary school but hadn't done it since then. I said that my mom was a painter and I knew there is an artistic side inside of me that hadn't been brought out yet.

I've kind of pieced together what happened: Half the room was saying, What are we doing hiring this guy who doesn't know anything about how to make a film? The other half was like, He's a smart guy, he works hard, he'll pick it up. Luckily, somebody on that side was in charge of *Toy Story 3*, and he said, "I am hiring him, and he's coming on my team."

HENRY GARCIA TALKS WITH SIMULATION ARTISTS about how he created the weightless feel of the movie character Elio's cape and hair. (Photo by Emron Grover/Pixar.)

PT: What do you do at Pixar?

GARCIA: I am a simulation supervisor. I lead teams of 10 to 30 people to create and use technology to bring our characters and environments to life. My department specializes in clothing, hair, and vegetation. I tend to focus on motion, such as walking through grass, or if characters interact with ropes, or things like that. I have spent 25–30% of my career in the effects department, which also uses simulations, but it tends to do things more like water, and smoke and fire, and large destruction.

I always prefer to carve out about 15% of my time to get into the trenches with my team and help make the film. I think it makes me a better supervisor because I'm in there with my team doing it, seeing the pain points. I can relate to everybody and give better advice to my team. Every film involves creating new technology, so working directly on the film helps keep my skills up to date.

As a supervisor, I'm in charge of the budget. I work with producers to figure out how to get the film done. I partner with directors and production designers. During the first half of the filmmaking process, I try to learn what they want and work with my team to build the technology and assets needed for the film.

As we start getting into the second half of production, we use the technology we've built to start making the movie. During this part of production, the deadlines come quickly and there are hundreds of people working on the film. Part of me loves that pressure cooker.

PT: How does physics play into simulating characters?

GARCIA: My first lead role was on *Brave*. Merida is a character in the film who has big red curly hair. No one had done curly hair at the caliber we were trying to target. I worked with a team of engineers in the research department to develop a new simulator. My role was as a liaison between the artists making the film and the engineers developing the simulator. The engineers were talking about conservation of energy, damping and spring forces, and so on. I really got to see my physics side come out and become very useful.

PT: What were you trying to do with Merida's hair?

GARCIA: One of the issues was how her hair uncoiled as she moved. A lock of curly hair is like a spring. But when she would bounce or turn her head quickly, her hair would uncoil too much and stretch out really far. The director wanted a softness to her hair and to see S shapes in motion as she moved. How do we solve the problem of keeping the hair soft enough to create S shapes but not so soft that the locks could uncoil?

Sometimes the solution is very physics based, like changing damping in a spring model, and sometimes the fix is more of a hacky Band-Aid. For Merida's hair, we created nonlinear stiffness: If her hair was close to its default length, then the stiffness would be low enough to create the S shapes, and if the hair started to uncoil and lengthen, then the springs would strengthen automatically to reduce the uncoiling. It's not realistic, but it created the look the director wanted.

PT: What are some other examples of how physics comes into play for the characters you work on?

GARCIA: In the film *Luca*, which I was a supervisor on, the director and production designer wanted a stylized look for the shapes and motion of the clothing. The character Giulia had these baggy pants that create a triangle shape, and it was important that her silhouette was maintained. It had to be simple and clean. This required us to push the simulator in a nonphysical way.

There is a technical side of the job: understanding the existing technologies and the physics-based simulators that make things move. At the same time, the artistic side of my brain is challenged. I need to make sure that the physics we are applying is adding to the performance and overall storytelling, not subtracting or distracting from it.

Accuracy is not always the goal. We want fast, efficient, and beautiful, and it's not always physically based. A large percentage of my job is spent strongarming the physics into doing what I want it to do, as opposed to what it naturally would do. That was the case for *Luca*.

But in the movie *Soul*, for example, the physicality of all the details, all the wrinkles in Joe's sweater, were celebrated. The physics sung in that movie.

PT: How else do you use physics in your work?

GARCIA: The other way my physics comes in is as a soft skill—the ability not to shy away from a complicated problem and to break it down into manageable pieces. I use that all the time to tackle complex problems.

PT: What do you like most about your work?

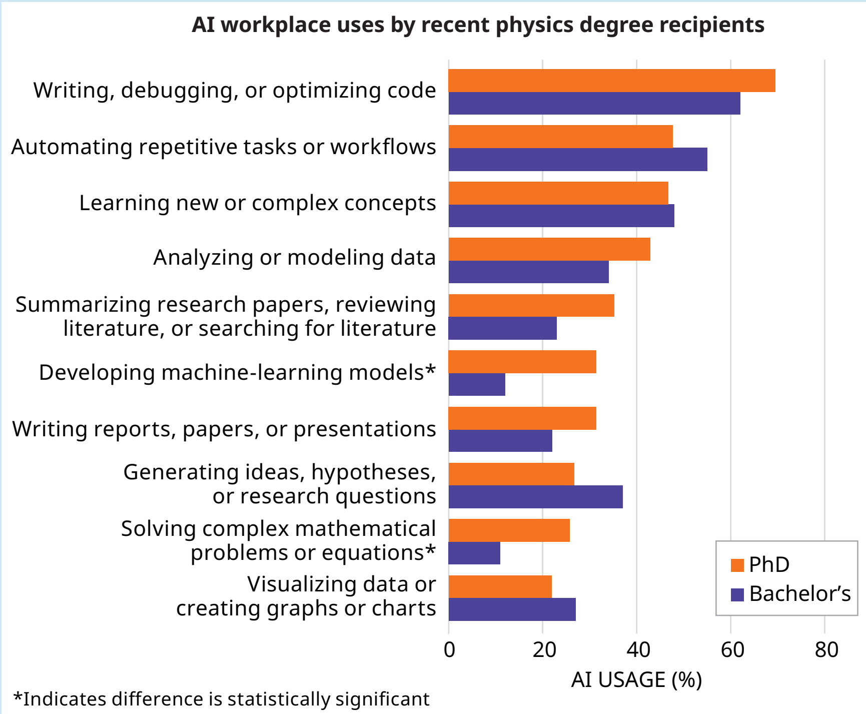
GARCIA: I love using physics to create something beautiful. That was something I had to learn. Sometimes it's an emotion or a tender moment. When I can use motion to convey emotion, it's very rewarding.

Toni Feder

Recent physics degree recipients use AI at work for coding, repetitive tasks, and more

Some 40% of newly minted physics PhDs who enter the workforce use AI tools routinely in their jobs, compared with about 23% of employed new physics bachelors. That's according to data gathered from a survey of people who received their physics degrees in the US in the 2023–24 academic year. The survey was conducted by the American Institute of Physics' (publisher of Physics Today) statistical research team, who for the first time included specific questions about AI usage in its annual degree-recipient follow-up survey.

The most common application of AI tools among the bachelor's and PhD recipients who reported using them routinely was writing, debugging, or optimizing code; other frequently reported uses of AI were automating repetitive tasks and learning new or complex concepts. The PhD respondents were more likely to report using AI tools for developing machine-learning models and solving complex mathematical problems or equations than the bachelor respondents were.



(Figure adapted from P. Mulvey, J. Pold, *AI use among physics degree recipients*, AIP Research, 2025.)

Those results and others regarding recent physics degree recipients' AI use at work can be found in the report at https://doi.org/10.1063/sr.f1815e968c. The report also breaks down data by STEM and non-STEM employment and includes specific responses from participants regarding their AI usage.

Tonya Gary

Archivists seek photos of today's physical scientists

The goal of a new crowdsourcing effort is to build a more contemporary and inclusive visual record of the physical sciences community.

The Emilio Segrè Visual Archives (ESVA) at the American Institute of Physics (AIP) hosts some 30 000 digital and physical images that showcase the personal and professional lives of physical scientists spanning nearly two centuries. For the first time, the repository is inviting scientists to submit their photos of everyday life to be added to AIP's permanent collection. (AIP publishes PHYSICS TODAY.)

"The more faces, places, and communities we have represented in our archives, the richer they become as authoritative research resources," says Trevor Owens , AIP's chief research officer.

In the past, the ESVA has largely relied on individual bulk donations, but that approach has led to a lag between its current holdings and the scientific work happening today. By accepting digital photos from across the community on a rolling basis, the ESVA seeks to build a more contemporary and inclusive record of the physical sciences community. "We can't wait for photos to pile up in someone's attic or scrapbooks like we could in the analog era," Owens says. "If we don't get your digital photos now, it may not be possible to get them decades from now."

The ESVA is the most widely used resource in AIP's Niels Bohr Library & Archives. Its photos, going back to the 1830s, are a mix of formal and candid shots of scientists at work, at home, and on their travels. They document, for example, professional triumphs, intimate moments with family, and long hours at the laboratory. Together, the photos show science as a human endeavor, one molded from many moments, stories, and communities.

The ESVA invites scientists at all career stages to share photos, including those taken on a smartphone, by using a one-page digital form. A submitted photo could be taken, for example, at a research meeting, classroom lecture, or conference presentation; at a dinner or on a group hike; or of a hobby or on a vacation with family. The form allows users to select how AIP and others can use their photos, such as requiring express permission or allowing use without restriction.

ASSORTED PHOTOS from the Emilio Segrè Visual Archives. Archivists at the American Institute of Physics' image repository are crowdsourcing photos to capture what it's like to be a scientist today. (Photos, clockwise from top left, courtesy of the AIP Emilio Segrè Visual Archives: Yukawa Collection; American Association of Physics Teachers; Ronald E. Mickens Collection; Duke University physics department; gift of Dr Sandra Faber/University of California, Santa Cruz; gift of Dr Ronald Mallett; American Association of Physics Teachers; gift of Dr Meg Urry; gift of Dr Wilhelm Tappe/Kohn Photo Collection.)

Historians, museum curators, book authors, scientists, and others use ESVA resources for their work. In a 2024 book, the repository's photos helped tell the story of four women physicists who escaped from Nazi Germany; other images appeared in the William Shatner television documentary series, *The UnXplained*. Since 2018, ESVA archivists have received some 2000 reference questions and usage requests, many of which have resulted in the images' publication.

Jenessa Duncombe

FYI SCIENCE POLICY BRIEFS

Commerce Department moves to take cut of research patent profits

Commerce Secretary Howard Lutnick says he wants the US to receive half the profits from university patents that are the result of federally funded research. In a September interview with *Axios*, Lutnick argues that every US university should be subject to such profit sharing, with "a few universities to start and then it'll become a master deal." But implementing such a policy would seemingly violate the Bayh–Dole Act, a 1980 law that allows universities full ownership of such patents.

In an August letter to Harvard University, Lutnick suggests that the Commerce Department would take ownership of the school's patents or grant patent licenses to third parties. He asserts that Harvard has failed to comply with regulations that mandate timely disclosure and election of title, preference for US industry, and "effective steps to achieve practical application of subject inventions."

The Commerce Department began implementing new patent-related policies soon after Lutnick's interview. For example, in a broad funding solicitation issued on 24 September, NIST states that awardees may be required to issue royalties or otherwise share revenue with the Commerce Department "to ensure a return on investment to the Government."

Responding to Lutnick's remarks, Stephen Ezell of the Information Technology and Innovation Foundation think tank writes that the federal government receives 20 times as much in annual tax revenues from university research parks as it would by taking half of annual university royalty revenues. The government, he says, also benefits from the "extensive innovations" produced and the tax revenue from "trillions in industrial output and millions of jobs created as a result of university tech transfer." —CZ

Multiple groups challenge new H-1B visa fee

The Trump administration is facing multiple legal challenges following its introduction of a $100 000 fee on new petitions for H-1B visas, the avenue through which many skilled workers from abroad are hired in the US.

The US Chamber of Commerce announced in mid-October that it is suing to block the new fee, which it argues is both unlawful and misguided. The Association of American Universities joined the lawsuit shortly after. A separate lawsuit was filed in early October by the American Association of University Professors (AAUP), labor unions, health-care providers, schools, and religious organizations.

Both lawsuits, which aim to block the 19 September presidential proclamation that is responsible for the increase, argue that the new fee is unlawful under the Immigration and Nationality Act and the Administrative Procedure Act. "The H-1B program has a carefully crafted fee and oversight system set by law," an AAUP press release says. "The president cannot rewrite it overnight or levy new taxes by proclamation."

The White House says the new fee, which went into effect on 21 September, is necessary to counter abuse of the H-1B visa program and to improve the job market for US workers. "The H-1B nonimmigrant visa program was created to bring temporary workers into the United States to perform additive, high-skilled functions, but it has been deliberately exploited to replace, rather than supplement, American workers with lower-paid, lower-skilled labor," the proclamation states. It also argues that abuses of the program threaten national security by both depressing wages and "discouraging Americans from pursuing careers in science and technology."

The White House initially said the fee would apply to nearly all H-1B visa applicants. US Citizenship and Immigration Services later clarified that the fee does not apply to certain applicants, such as those filing to move to the H-1B visa from another type—for example, an F-1 for international students in the US. —LM

Department of Energy consolidates advisory committees

The Department of Energy has replaced the six discipline-specific committees that advised the Office of Science with a single entity, the Office of Science Advisory Committee.

The consolidation of the previous committees into a single one was announced on 30 September, a few weeks after former National Science Board Chair Darío Gil was confirmed as DOE undersecretary for science.

The six terminated committees are DOE's Fusion Energy Sciences Advisory Committee, Biological and Environmental Research Advisory Committee, Basic Energy Sciences Advisory Committee, and Advanced Scientific Computing Advisory Committee and DOE and NSF's High Energy Physics Advisory Panel and Nuclear Science Advisory Committee.

In a DOE press release, Gil says that the new committee will "connect DOE with leaders from academia, industry, and National Laboratories and will inform exciting new paths to keep us at the forefront of research." Furthermore, according to the release, the committee will "adopt the core functions" of the six former advisory committees along with "any current charged responsibilities of these former committees." Gil will appoint the committee members.

A DOE spokesperson told *FYI* that the committee plans to hold its first meeting by April. —LM

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.

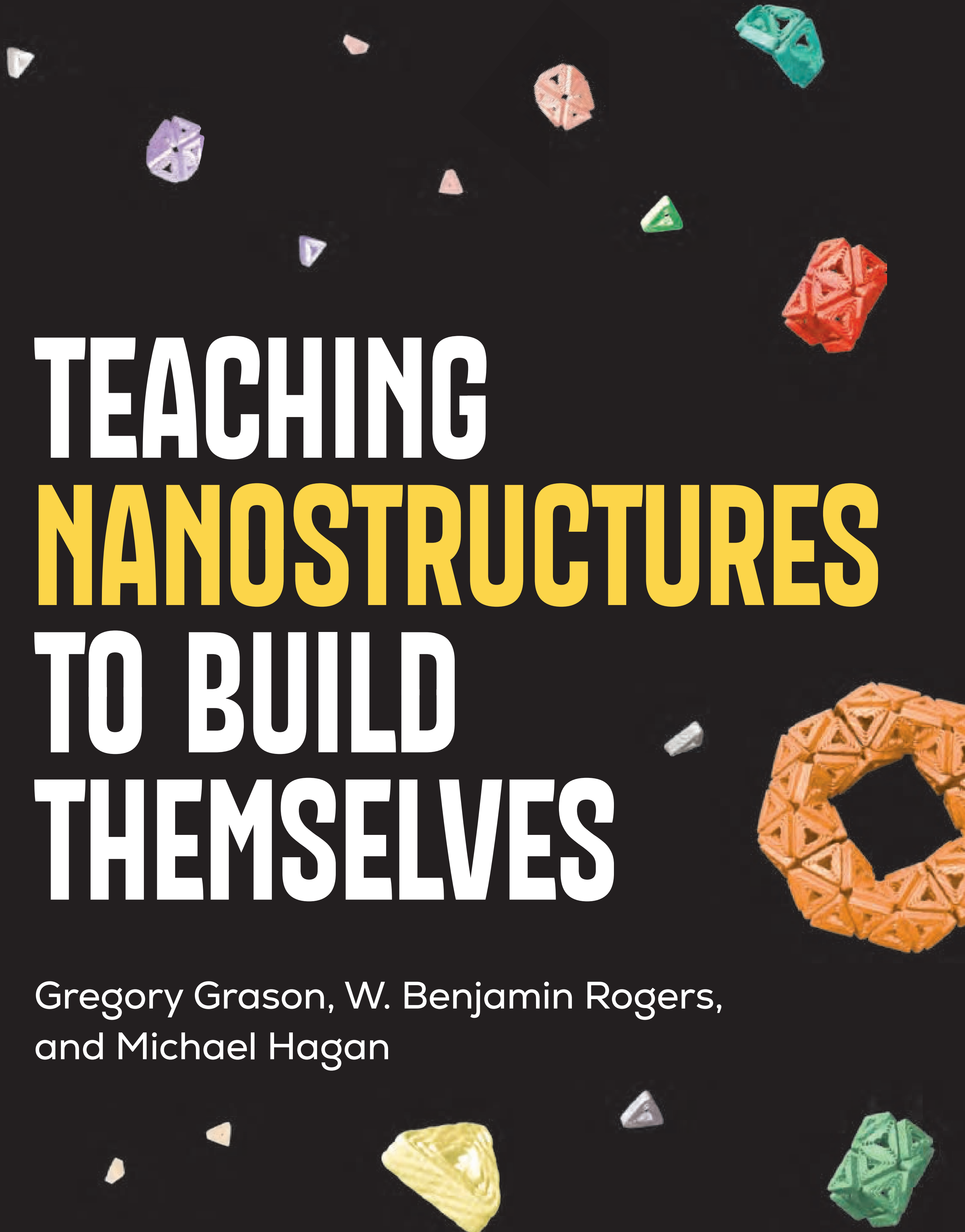
AIP | FYI

Corrections

September 2025, page 22 — The Deep Synoptic Array-2000 team is considering making the telescope's data freely available immediately, and it is discussing a collaboration with NANOGrav.

October 2025, page 43 — The correct answer to the example question in the box is C, not A.

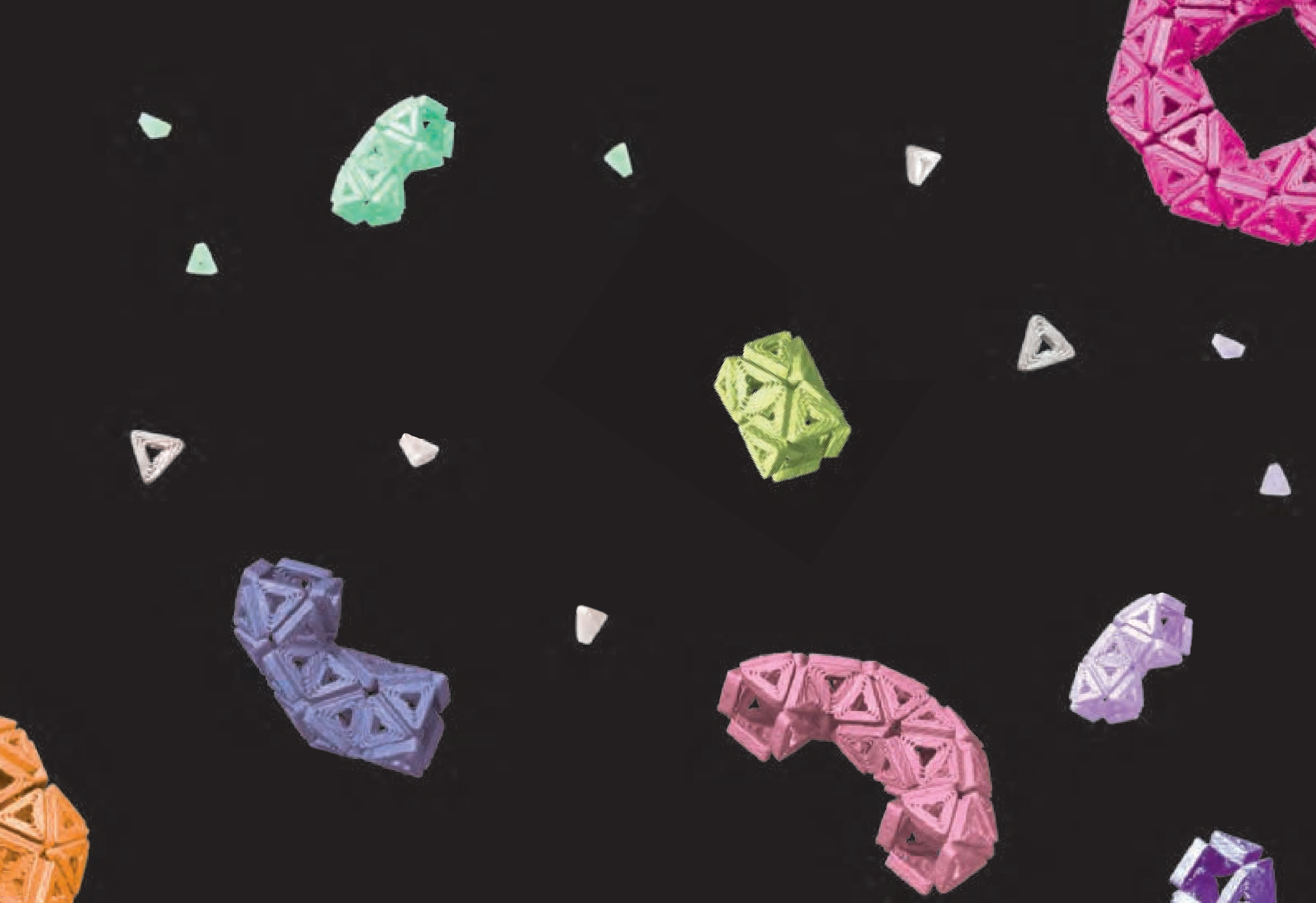
November 2025, page 41 — Jacob Lynn has interviewed, not hired, around 200 people for Booking.com. PT



TEACHING NANOSTRUCTURES TO BUILD THEMSELVES

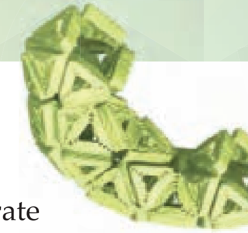
Gregory Grason, W. Benjamin Rogers, and Michael Hagan

Gregory Grason is a professor of polymer science and engineering at the University of Massachusetts Amherst. **W. Benjamin Rogers** and **Michael Hagan** are faculty of the Martin A. Fisher School of Physics at Brandeis University in Waltham, Massachusetts. The three authors are members of the NSF-funded Bioinspired Soft Materials Center.



Bottom-up self-assembly is a powerful approach to engineering at small scales. Special strategies are needed to formulate components that assemble into predetermined shapes with precise sizes.

(Design by Masie Chong with artwork adapted from Bella Aizenberg, Thomas Videbæk, and iStock.com artists Xansa Green and bgblue.)



Self-assembly is a widespread phenomenon in which multiple initially disparate building blocks spontaneously arrange into collective multiunit structures. To the materials scientist, self-assembly offers an attractive paradigm to build useful superstructures at especially small size scales purely through the careful design and synthesis of the building blocks. Bottom-up, molecule-by-molecule fabrication enables structural complexity and functional utility that can otherwise be achieved only at larger scales through top-down fabrication methods, like lithography and 3D printing. The approach has already been used to build simple yet useful nanostructures, like spherical shells that can engulf pathogenic viruses. As the ability to define and control the final structure matures, one can envision future applications of self-assembly to build far more complex architectures, like 3D integrated circuitry.

Nature uses self-assembly to build the functional elements of cells and tissues of living organisms in the form of multiprotein superstructures. Those structures include shells, plates, filaments, tubules, ropelike fibers, and nanoporous material networks;[1] two such structures are shown in figure 1. For many biological assemblies, their tightly controlled, finite size is critical to their function. For example, a virus's protein shell, or capsid, must be sufficiently large to enclose the virus's genome but small enough to gain entry to the cells that the virus infects. Photonic nanostructures in the feathers and scales of animals are composed of multiprotein domains whose sizes directly control what colors they give off.

Self-limiting assemblies in biology exhibit well-controlled structures that are much larger than their components. Proteins that are only a few nanometers in size cooperatively assemble to build structures 10–100 times as large, and they somehow achieve the same finite size from structure to structure, notwithstanding the strong effects of randomness at the nanoscale.

Though self-assembly processes that autonomously terminate at a finite, predetermined size are especially

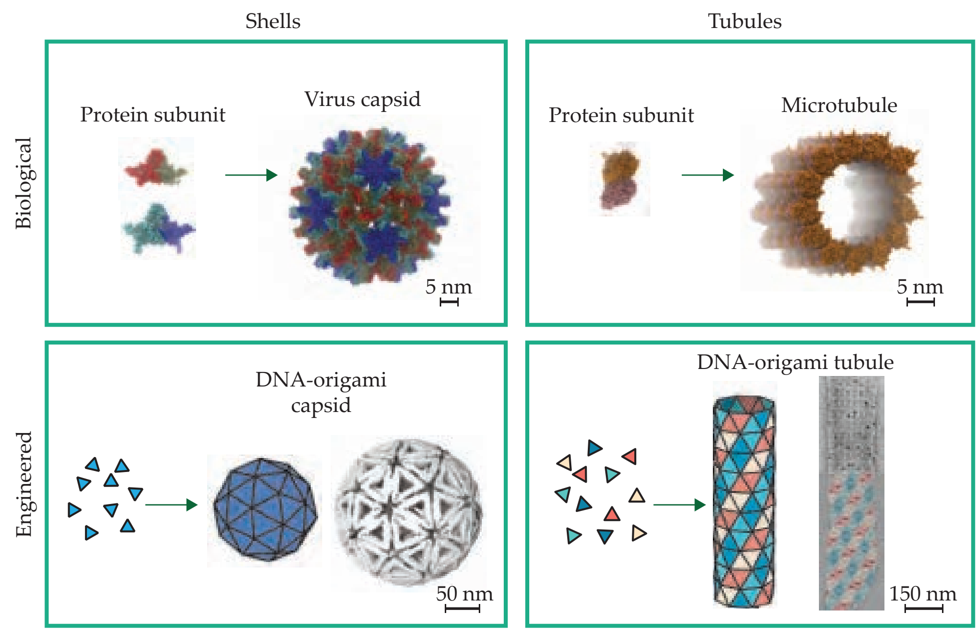


FIGURE 1. SELF-LIMITING ASSEMBLIES observed in biological systems have served as inspiration for synthetically engineered nanostructures. Triangles of folded DNA are particularly useful for building engineered structures because their edges can be designed to form specific bonds that shape the design of the final structure. For the examples of engineered nanostructures, models of self-assembly components and target structures are shown next to micrograph images of self-assembled 3D nanostructures. (Figure adapted from ref. 10 and ref. 17, with contributions from Thomas Videbæk and Layne Frechette.)

attractive to materials scientists, in synthetic self-assembly they are the exception rather than the rule.[2] That's because self-assembly of nanoscopic subunits is driven toward thermal equilibrium, and for most engineered systems, the cohesive forces that bring subunits together also favor forming spatially unbounded assemblies. As depicted in figure 2, unbounded sizes minimize the energy cost of open boundaries at the exterior of assemblies, where the subunits have fewer or weaker cohesive bonds than in the interior.

Because such equilibrium assemblies are driven to arbitrarily large sizes, many synthetic approaches for making size-controlled structures, such as uniformly sized nanoparticles and colloids, rely on nonequilibrium processes.[3] Those approaches might be viewed as supervised assembly because they require the adjustment of parameters like temperature and concentration in a particular temporal sequence to turn assembly processes on and off and trap the aggregating structures at finite and well-defined sizes. Of course, those strategies can't be used where the assembly environment is not under global control, such as in the biological milieu.

For unsupervised self-assembly, in contrast, all the information needed to dictate the assembly pathways and terminate growth must be encoded in the subunits themselves. But what physical mechanisms can tell unsupervised self-assembly when to stop at a particular size—that is, to self-limit? And how much bigger can a self-limiting assembly be than the subunits from which it forms? In this article, we summarize recent efforts to understand the mechanisms of self-limiting assembly, principles for encoding information about finite-size assembly into subunits, and ways in which those principles can inform efforts to engineer new classes of synthetic, biologically inspired nanomaterials with programmable self-limiting structures.

Costs of fitting in

In some scenarios, the size of an assembly is intrinsically limited by the size of its constituents. A classic example is soap. Soap molecules are composed of oily chains with hydrophilic chemical groups at their ends. Toss them into water and they ball up into a sphere, called a micelle, with their hydrophobic ends buried in the middle, shrouded by the water-loving ends of the molecules.[4] The radius of the sphere is limited by the length of the soap molecules. And just as there is room for only a certain number of players' hands in the middle of a sports team huddle, there is room for only a certain number of molecules to reach the center. As the micelle reaches capacity, attempts to

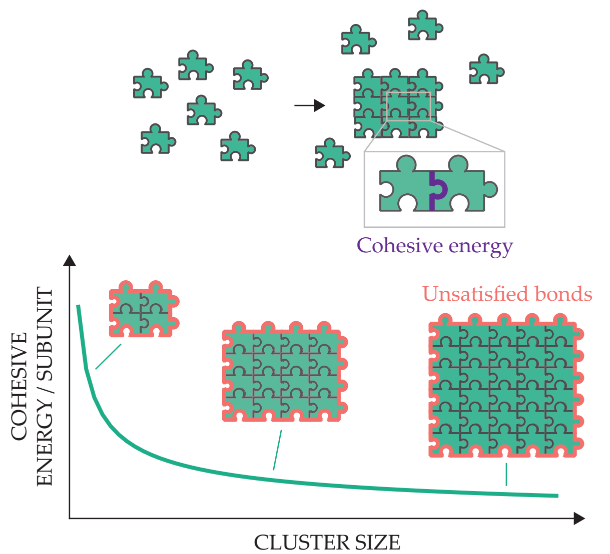


FIGURE 2. UNLIMITED SELF-ASSEMBLY is driven by interparticle physical attraction, such as electrostatic forces, van der Waals forces, or hydrogen bonding. Starting from a disassembled state, a system of particles (each puzzle piece represents a particle) moves to a lower energy state by forming cohesive interparticle bonds (represented as fitted edges) and reducing the proportion of unsatisfied bonds. The energetic benefit of increasing the cluster size makes arbitrarily large clusters thermodynamically favored.

squeeze in more molecules or extend the radius strain the components, leading to an added energy cost.

Such excess energy costs depend superextensively on size—the energy cost per subunit increases with additional subunits—and they push back against the generic tendency of cohesion to drive assemblies to unlimited size. Under certain conditions, those superextensive energy costs can result in finite, self-limiting assembly. As shown in figure 3, the increase of excess cost with size can counterbalance cohesive forces to produce a specific assemblage size that, being at an energy minimum, is thermodynamically favored.

But can an assembly limit its finite size at length scales that exceed subunits and the range of their interunit forces? And if so, how could a subunit at the open boundary of such an assembly sense the finite size and determine whether to bind to it? Answering those questions would open up attractive possibilities of designing and synthesizing mixtures of nanoscopic self-assembling building blocks that can be programmed to sense and limit their finite assembly size at microscopic or even millimeter dimensions.

Such seemingly paradoxical thermodynamic action at a distance is possible via geometrically frustrated assembly. Geometric frustration broadly refers to scenarios in which a locally favored packing arrangement cannot be extended uniformly in an ordered system. In the context of assembly, the scenario is illustrated by self-assembling building blocks that are misshapen, like the warped puzzle pieces in figure 3, such that formation of interunit bonds requires distortion of the subunits.

If the multiunit assembly is soft enough, the degree of misfit and its energetic costs will accumulate with size, leading to the type of superextensive costs that restrain self-limiting assembly. The thermodynamic sensitivity at large, multiunit aggregate sizes derives from self-organized strain gradients that extend through the structure: The degree of misfit is higher for the highly constrained and stressed subunits at the core of clusters than for those at the open boundary, where they have fewer bound neighbors and are relatively freer.

That basic paradigm of frustration-limited assembly has been used to explain self-limiting dimensions of a range of biological and synthetic systems,[5] including twisted bundles of protein filaments, liquid-crystalline membranes, and 2D crystals growing on spherical surfaces. An emerging and open area of research is exploring avenues to rationally design and engineer frustrated building blocks for the purposes of programming their self-limiting size.[6] Those efforts rely on state-of-the-art techniques for synthesizing colloids or nanoparticles with defined anisotropic shapes and programmable flexibility and interparticle interactions,[7] as well as on critical breakthroughs that use AI for design of *de novo* proteins tailored for an increasing number of assembly shapes.[8]

The ability to fabricate particles of essentially arbitrary 3D shapes raises some basic unsolved questions about the physical principles underlying frustrated self-assembly. Chief among those questions is, Given an arbitrarily misfitting particle design, is it possible to predict the thermodynamic accumulation of misfit cost at the multi-subunit scale? What are the fundamental limits for the maximum size range a frustrated assembly can sense? And under what circumstances do systems escape frustration by forming defective assemblies of unbounded size?

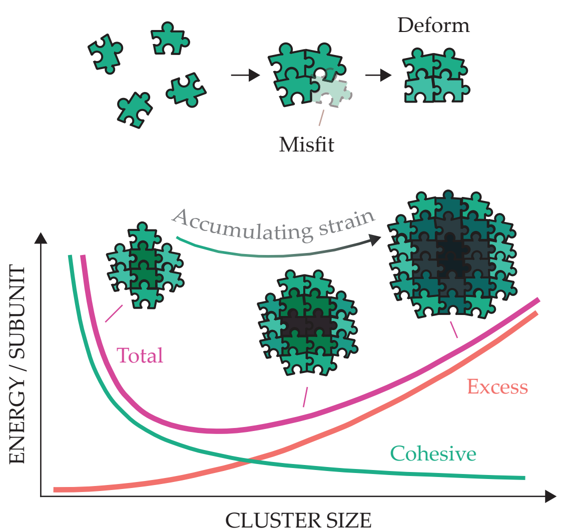


FIGURE 3. GEOMETRICALLY FRUSTRATED ASSEMBLIES accumulate strain as cluster size increases. The excess energy cost of assembly limits the cluster size. Particles (depicted as warped puzzle pieces) must elastically distort (indicated by darker shading) to form interparticle bonds. In addition to geometric frustration, excess energies may also arise from long-range interactions, such as electrostatic or magnetic repulsion.

Closing the loop

Another strategy for restraining the effects of open boundaries in cohesive assemblies is to eliminate open boundaries from the target structure. That is the approach used for self-closing assemblies, in which interactions between neighboring subunits are slightly rotated from one to the next. Interunit rotation produces curvature with a preferred radius and can eventually lead the assembly to close upon itself with a finite size larger than the single subunit, as shown in figure 4.

Self-closing assembly is widely employed in multiprotein structures in biology, including cylindrical tubules, which are closed in one dimension, and spherical shells and capsules, which are doubly closed.[9] The ability to target a particular self-closing size relies on careful control of the relative angles between bound subunits, which biology achieves via precise taper of protein subunits.

Recent advances in the design of shape-programmed particles make use of a technique known as DNA origami to achieve an analogous level of curvature-controlled assembly.[10,11] DNA origami exploits the genetic code to fold long loops of single-stranded DNA into essentially arbitrary 3D shapes. (See, for example, Physics Today's 2021 article "DNA assembles nano-objects," by Oleg Gang.) To target a range of self-closing assemblies, researchers begin with triangular DNA particles (those forming the white capsid in figure 1 are 50 nm on a side) whose attractive interedge binding promotes a 2D lattice-like assembly. The subunit edges are beveled so that neighbors bind at controlled angles, thereby driving the assemblies to roll up in specific directions.

The simplest example of that type of curvature control comes from triangular DNA

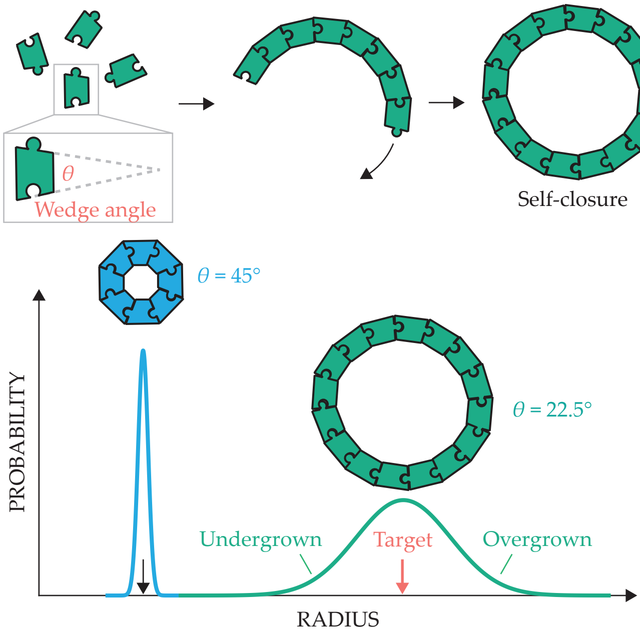


FIGURE 4. SELF-CLOSING ASSEMBLY of a ring is controlled by the wedge angle of its constituents. The radius of the designed target structure depends on the wedge angle. Structures built from more subunits are susceptible to greater deviation from a target size because of propagation of a larger number of small errors in the angles between neighbors.

subunits that curve in one direction to make self-closing cylindrical tubules, as shown in the bottom right of figure 1. In principle, one can target tubules of increasingly large but still finite diameter by redesigning the intertriangle bevel angles to be progressively shallower. In practice, curvature-controlled assembly faces a fundamental limitation because of inevitable fluctuations in the interparticle angle θ. While the particle shape sets a preferred angle, thermal fluctuations generically lead to finite angular deviations away from that target value. Since the angle between particles determines the preferred radius, imprecision in that angle is directly correlated with imprecision in the radius.

No matter how precisely angles between neighbors are defined, the more subunits a structure contains, the more likely imprecision in the self-closing radius becomes (a concept shown schematically in figure 4). A preferred curvature's diminishing power to target ever-larger self-closing assemblies also generalizes to other shapes, such as shells; it was first theoretically predicted by Wolfgang Helfrich in the context of spherical vesicles and microemulsions.[12] That effect of imprecision increasing with size was recently directly measured for assemblies of self-closed tubules of DNA-origami particles.[11] As we describe in the next section, however, one can rescue target fidelity from the increasing imprecision of curvature fluctuations at large scales by increasing the design complexity of self-closing assemblies.

Every subunit in its place

In the examples above, the assemblies can be formed from many copies of a single species of subunits. A different strategy for targeting finite-size equilibrium structures, often called addressable assembly,[13] relies on multiple species of subunits combined with species-specific interactions. The mechanism of assembly takes inspiration from multiprotein complexes in biology, in which several distinct protein subunits bind together in a specific arrangement to form a 3D functional structure, such as a ribosome. Materials scientists have developed several ways to mimic the approach synthetically.

One example is coating colloidal spheres with dangling single-stranded DNA molecules, whose sequence-specific interactions drive self-assembly.[14] In that approach, an assembly may be designed on the basis of multiple particle species A, B, C, and so on. Interactions can be designed so that specific pairs of particle species bind to one another, as illustrated in figure 5. For example, A is not attracted to A but strongly binds to B, while B may bind to both A and itself. The scheme can be described by an interaction matrix. With a sufficiently large number of possible interactions, one can design a multispecies mixture that assembles into a specified structure. If the interaction types are sufficiently complex, there is ideally only a single 3D structure that can self-assemble from that mixture. Since only favorable bonds are formed in the target, it is preferred in thermodynamic equilibrium.

Taking advantage of recent advances in DNA nanotechnology, researchers have been remarkably successful in using that approach to design synthetic assemblies with previously unimaginable complexity, including nanomachine elements and nanobeams of DNA with size-controlled cross sections.[15] In the context of self-limiting assembly, however, addressable assemblies face a particular

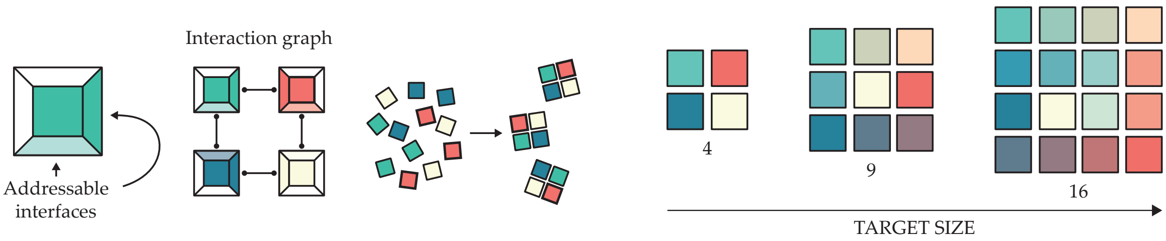


FIGURE 5. PROGRAMMABLE BONDING SITES enable detailed control of self-assembled structures in a technique known as addressable assembly. The technique relies on the ability to configure the subunits' binding sites to interact only with other specific subunit species. The interaction graph shows what the preferred interactions are for this model system; that set of interactions yields specific subunit arrangements. Though the technique provides exquisite control over a final product, the number of unique components needed to build a specific structure increases rapidly as the size of the target structure increases.

challenge: The number of distinct species and interaction types needed to target a structure often grows very rapidly as the desired finite size increases.[14] The larger the finite-size structure is, the higher the costs become in terms of both the expense of synthesizing the species and the time to form the assembly. The time it takes each particle to find its correct position grows with the size of the target structure.

The costs of complexity associated with increasing target size raise general questions about strategies for optimizing the economy of design in addressable assembly: Given a target assembly, what is the minimal complexity of a multispecies mixture needed to robustly achieve it? And how does the minimal complexity grow with increasing finite size?

One approach to answering those questions is to look to biological assemblies, which are subject to evolutionary pressure toward optimized assembly strategies. The quasispherical capsids (see figure 1) that enclose many viruses arguably constitute a case of optimization.

As structural biologists Donald Caspar and Aaron Klug describe, a large family of viral capsids adopt icosahedral symmetry, with protein subunits in a triangular arrangement that is related to the spherical fullerene structure.[16] They argue that the high-symmetry icosahedral arrangement minimizes the number of inequivalent protein conformations needed to form the shell. Therefore, shells composed of a large number of proteins can be built from multiple copies of a much smaller number (by a factor of 60) of distinct species. The genome that is enclosed in the capsid thus only needs to encode for one or a few distinct capsid proteins.

Combining self-closure and high symmetry with addressable assembly provides at least one strategy to mitigate the growth of complexity cost with size. The design paradigm from Caspar and Klug has been directly implemented using DNA origami,[10] which combines both the careful design of bevels that program the spherical curvature and the selective interactions between distinct edges of triangles. Through that strategy, Christian Sigl and coworkers achieved high-yield shell assemblies with modular sizes of 20 to 180 particles per shell (see the example in the bottom left of figure 1).[10]

Though symmetry is a blessing in terms of the economy of addressable assemblies, it can also be curse for self-closing assemblies. That is evidenced by the ability of tubules composed of a single particle type to close at off-target radii: The edge-matching rules of a single species enable the assembling sheet to roll up into many different tubules with similar bending energies. Those results reveal a generic trade-off in self-assembly—increasing assembly economy tends to reduce fidelity.

Thomas Videbæk and coworkers recently explored the optimal balance between maximal economy (one subunit species) and complete specificity (full addressability) in the context of self-closing tubules like that in the bottom right of figure 1.[17] Those experiments indicate that there is a minimum amount of complexity needed to prune away off-target, misassembled states that are accessible through thermal fluctuations and to guarantee nearly 100% yield of the target tubule geometry. Such examples of self-closing assemblies with just enough addressability illustrate that optimal strategies for achieving self-limiting assemblies, a central concern for synthetic efforts, likely require a measured blend of different physical size-control paradigms.

Beyond equilibrium

In many cases, equilibrium processes of assembly are not necessarily sufficient, nor are they the best way to achieve size-regulating nanostructures. Self-assembly is notoriously prone to getting stuck in kinetic traps: Misassembled states rapidly form and then take prohibitively long times to rearrange into their proper target geometries. A key focus of research in the engineering of synthetic assembly systems is the development of nonequilibrium strategies to coax assembling systems toward self-limited structures or other desired end states.

One strategy takes advantage of the programmability of subunits in order to devise time-varying environmental conditions that steer interactions toward target shapes more robustly than can be achieved in passive self-assembly. Another frontier direction is inspired by subunits found in biology that actively consume chemical fuel during assembly and thereby break the rules of equilibrium physics to enable exotic size-regulated assemblies with persistent motion. In such treadmilling assemblies, like cytoskeletal filaments, subunits are constantly binding to one end of a structure and simultaneously unbinding from the other to maintain a fixed and controllable average size.[18]

Though many of the basic paradigms for those classes of nonequilibrium assembly have been studied theoretically, a frontier question remains of how to encode and engineer the necessarily dynamic features into the subunits to achieve assemblies that are far out of equilibrium but remain under control.

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Richard Garwin receiving the Presidential Medal of Freedom from President Barack Obama on 22 November 2016.

(Photo by Pat Benic/UPI/Alamy.)





John Holdren is a research professor of environmental policy at Harvard University's Kennedy School of Government in Cambridge, Massachusetts. He was President Barack Obama's science adviser from 2009 to 2017 and chaired the National Academies' Committee on International Security and Arms Control (CISAC) from 1994 to 2005. **Raymond Jeanloz** is a professor of Earth and planetary science and of astronomy at the University of California, Berkeley, and chaired CISAC from 2005 to 2025. **Frank von Hippel** is a senior research physicist and emeritus professor of public and international affairs in the Program on Science and Global Security at Princeton University in New Jersey.

Remembering RICHARD GARWIN physicist and science adviser

The polymath scientist leaves behind a monumental legacy in both the scientific and political realms.

John P. Holdren, Raymond Jeanloz, and Frank N. von Hippel

The US physics community lost one of its most esteemed members, Richard Garwin, on 13 May 2025 at the age of 97. Known as Dick to friends and colleagues, Garwin made contributions to the development of thermonuclear weapons, reconnaissance satellites, medical and information technologies, energy technology and policy, and many areas of fundamental physics, including nonconservation of parity and gravitational waves.

One of the smartest, most diversely creative, and most productive scientists of his era, Garwin was relentlessly candid as a researcher and governmental adviser. Even if the recipients of his advice did not always love what Garwin told them, they knew it was virtually certain to be technically impeccable. During his long tenure as a senior science adviser to seven US presidents, he became famous for his willingness to go public with his advice when he thought the government was ignoring relevant scientific evidence.

Garwin also worked extensively with national and international nongovernmental organizations that address global security, nuclear arms control and nonproliferation, nuclear and nonnuclear energy options, and international cooperation in science and technology (S&T). In this remembrance for Physics Today, we offer a brief glimpse into his life's work and legacy.

The hydrogen bomb

Garwin was born in 1928, and his interest in S&T was apparent early on: As a boy in Cleveland, Ohio, he helped build and repair audio amplifiers and movie projection equipment that his father sold, serviced, and operated. After studying physics as an undergraduate at Case Institute of Technology (now Case Western Reserve University), he went to the University of Chicago, where in 1949, at age 21, he completed his PhD thesis under the supervision of Enrico Fermi. He then joined the university's physics department as an assistant professor.

Fermi invited Garwin the following year to accompany him on his annual summer consultancy at what is now Los Alamos National Laboratory, which had just been ordered by President Harry Truman to develop a hydrogen bomb. Garwin immersed himself in bomb physics and quickly mastered its intricacies. The next summer, he was asked by Edward Teller to devise an experiment showing that thermal x rays generated by a fission explosion could be used to compress deuterium fuel to a supercritical mass and induce a fusion reaction.[1] Garwin's design centered on a huge dewar containing liquid deuterium. The resulting test detonation on 1 November 1952, code-named Ivy Mike, released the energy equivalent of 10 million tons of TNT—700 times the power of the Hiroshima atomic bomb—and turned the island of Elugelab in Enewetak Atoll in the western Pacific Ocean into a crater. The test device was far too bulky to be deliverable by a bomber, but it served as a proof of concept.

The development of thermonuclear weapons was still being discussed when, in 1949, Fermi declared that they would be "an evil thing considered in any light."[2] Garwin's view was more nuanced. "I think it would be a better world if the hydrogen bomb had never existed," he said in a 1984 *Esquire* article. "But I knew the bombs would be used for deterrence."[3] Nevertheless, he was appalled by the enormity of the nuclear buildup during the Cold War, and he worked to achieve deep cuts in the US and Soviet nuclear arsenals.

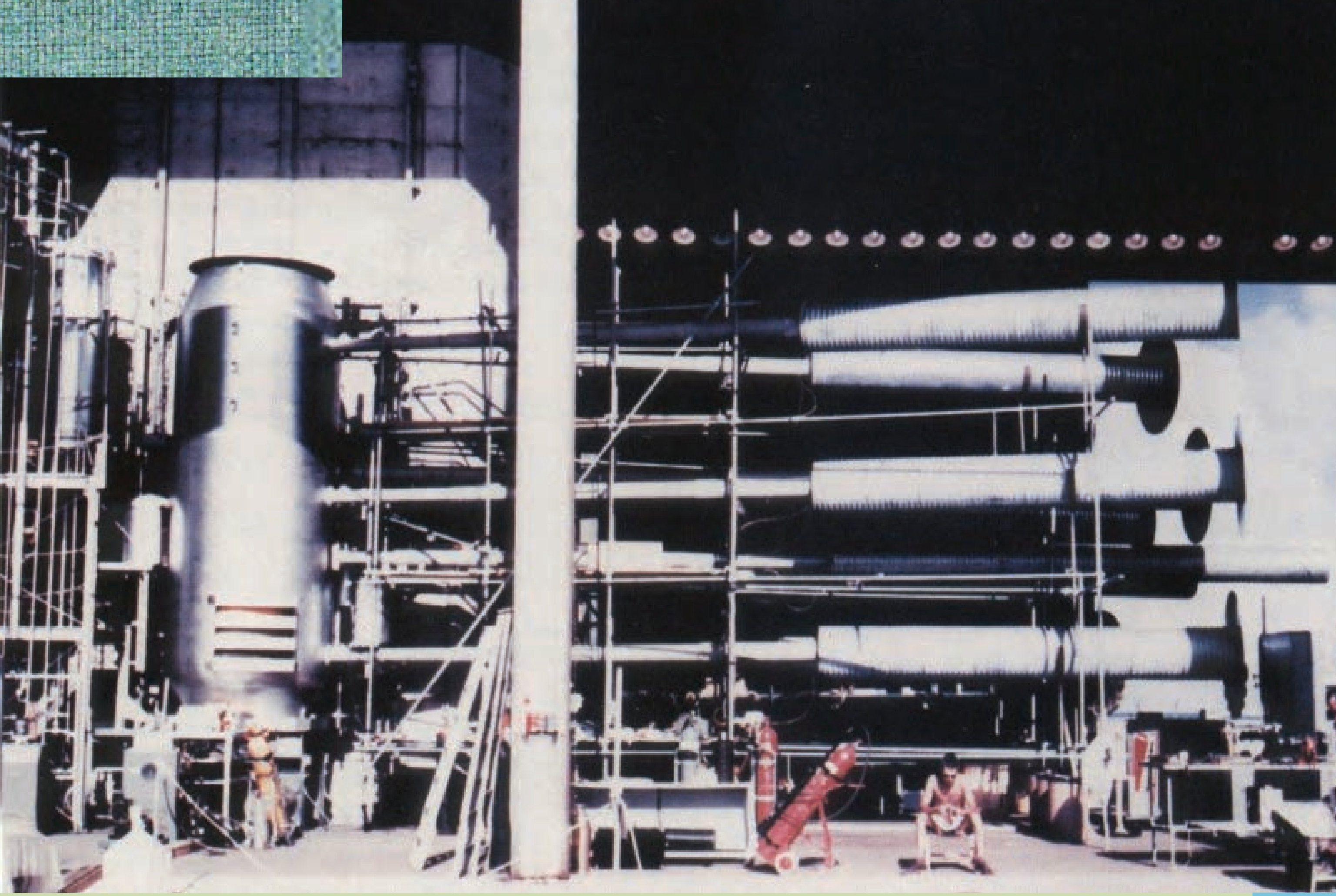
IBM

Garwin joined IBM in 1952 and would spend most of the rest of his career there. Originally at IBM's Watson Laboratory at Columbia University, he moved to the Thomas J. Watson Research Center in Yorktown Heights, New York, when it opened in 1961. In addition to being a world-class physicist, Garwin was a remarkably talented engineer, and IBM gave him the opportunity to contribute to the development of modern information technologies at a time when the company led the field. Part of Garwin's agreement with IBM stated that he could spend up to a third of his time advising the government. IBM insisted that he not inform the company about what he was working on or testifying about for the government so that the company would not be blamed for the outside work.[4]

Even though he was not a full-time employee, Garwin made many major contributions at IBM. He helped to advance the fast-Fourier-transform algorithm, which is central to the digital signal processing at the heart of modern telecommunications, music streaming, and the internet. He helped develop magnetic-core memory devices, laser printers, touch screens, and GPS. During his 41 years at IBM, he was awarded 47 patents, published more than 500 research papers, and variously served as Watson Laboratory's head at Columbia University and director of applied research at Yorktown Heights and as a member of the corporate technical committee.[5]

The joy of physics

Perhaps Garwin's most significant physics experiment was done over a long weekend in 1956 at Columbia's Nevis Laboratories cyclotron in Irvington, New York. There, he helped Leon Lederman and Marcel Weinrich establish the parity violation in muon decays, which had been postulated the year



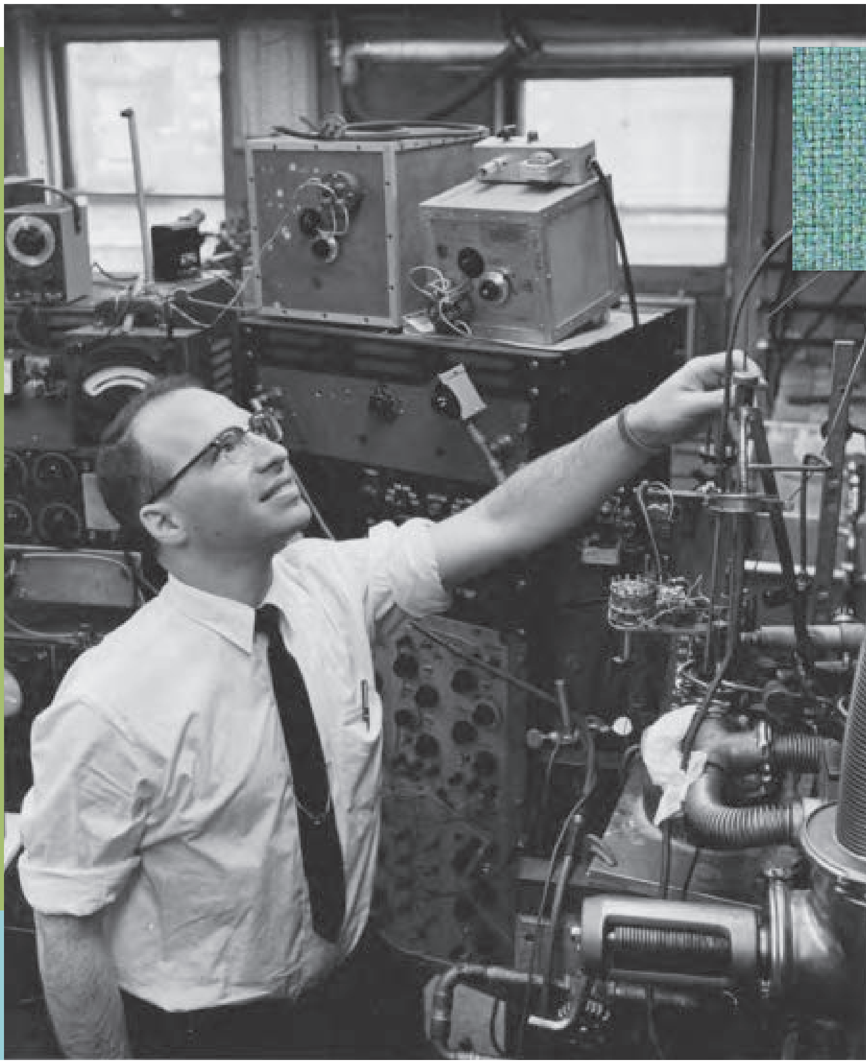
THE EXPERIMENTAL THERMONUCLEAR EXPLOSIVE designed by Garwin and assembled on Enewetak Atoll. A dewar holding the liquified deuterium was located inside the cylindrical structure on the left, which also contained the primary fission stage of the bomb. The cylinder itself reflected the x rays from the primary stage's explosion onto the dewar, where they compressed the deuterium and initiated fusion. The pipes going off to the right transmitted x rays to sensors before the explosion destroyed the structure. The seated man at the bottom right provides scale. (Image from the US Department of Energy/Wikimedia Commons.)

before by Tsung-Dao Lee and Chen Ning Yang.[6] Garwin, Lederman, and Weinrich's article was published back-to-back in *Physical Review* with Chien-Shiung Wu's paper outlining her experiment demonstrating parity violation in cobalt-60 decay (for more on that work, see the 2024 Physics Today article "Chien-Shiung Wu's trailblazing experiments in particle physics," by Chon-Fai Kam, Cheng-Ning Zhang, and Da Hsuan Feng). The two articles resulted in Lee and Yang receiving the 1957 Nobel Prize in Physics. Lederman, responding to a question on Garwin's contribution to the experiment, reportedly said, "If he hadn't been involved, it would have been a 43-day experiment rather than a 43-hour experiment."[7]

Periodically thereafter, Garwin would weigh in on controversies in fundamental physics—perhaps, most notably, claims that gravitational waves had been detected. In 1974, on the basis of his own work and that of others, he showed that a claim of the frequent detection of gravitational waves through coincidences of vibrations in two suspended bars at two widely separated locations was probably due to an error in analysis.[8] Later, Garwin helped vet plans for the Laser Interferometry Gravitational-Wave Observatory, which in 2015 ultimately detected gravitational waves from the merging of two black holes (see Physics Today's 2016 story "LIGO detects gravitational waves"). Three of the main contributors to the observatory—Rainer Weiss, Barry Barish, and Kip Thorne—were awarded the Nobel Prize in Physics in 2017 for their work.[9]

Governmental science adviser

Garwin spent a large fraction of his time serving on governmental science advisory committees. He rose quickly to the top of the establishment, serving as a consultant to the President's Science Advisory Committee (PSAC) under Dwight D. Eisenhower and then two terms as a member of the committee: 1962–65 under John F. Kennedy and Lyndon Johnson and 1969–72 under Richard Nixon. He was one of the longest-standing members of the JASON group, which provides independent technical advice to all parts of the US government, and he interacted with foreign counterparts through the National Academy of Sciences' Committee on International Security and Arms Control (CISAC).



GARWIN WORKING ON A SPIN-ECHO MAGNETIC SYSTEM at IBM in an undated photo. His research into magnetic resonance helped lead to the development of commercial MRI machines. (Photo courtesy of IBM.)

He also felt a responsibility to inform Congress, the wider S&T community, and the public of his views on policy matters of importance relating to S&T. During his long career, Garwin disclosed his opinions in books, lectures, op-eds, and congressional testimony, and he was always careful to say that he was speaking as an individual, not on behalf of the groups with which he was affiliated. When he gave testimony to Congress in 1970 and 1972 on topics on which PSAC had advised Nixon, it became clear that his views conflicted with the president's. For example, Garwin saw ballistic-missile defense as easy to defeat and likely to provoke a Soviet offensive buildup,[10] and he had chaired a PSAC review that concluded correctly that the supersonic passenger transport project would be both uneconomic and a public nuisance because of its takeoff noise and sonic boom.[11]

In a 1970 *Saturday Review* article,[12] Garwin explained how he dealt with the responsibilities of being both a presidential adviser and a public citizen:

> I'm not a full-time member of the administration, and I feel myself in the same position as a lawyer who has many clients. The fact that he deals with one doesn't prevent him from dealing with another so long as he doesn't use the information he obtains from the first in dealing with the second. Since there are so few people familiar with these programs, it is important for me to give the Congress, as well as the administration, the benefit of my experience.

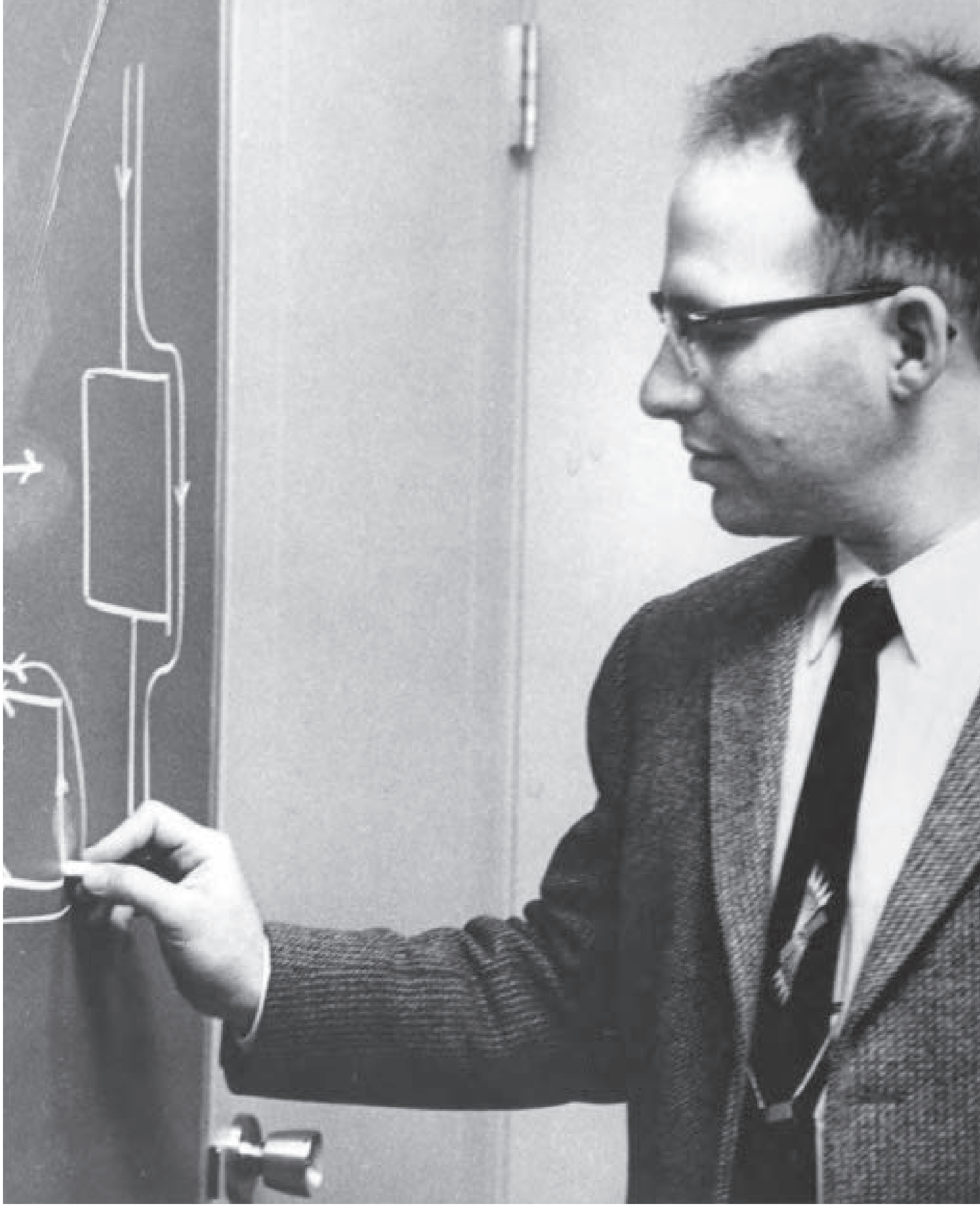
Nixon did not see it that way: Immediately after his second inauguration in January 1973, he abolished PSAC and dismantled the White House Office of Science and Technology (OST).[13]

In 1996, US President Bill Clinton and Russian President Boris Yeltsin agreed at a summit to create a bilateral panel that would advise both leaders on how to reconcile the US and Russian positions on managing the surplus plutonium left by nuclear weapons reductions on both sides. Clinton appointed Garwin as one of the five members on the US side; the Russian chair, Evgeny Velikhov, was one of Garwin's longtime collaborators in arms control efforts. Velikhov and the Russian team trusted Garwin deeply, which helped the two sides reach an agreement in June 1997 on eight of the nine points at issue.

During the Obama administration, one of us (Holdren) served as Obama's science adviser. Garwin offered to serve as a pro bono consultant to the White House Office of Science and Technology Policy (the successor to the OST). Garwin spent every other Friday in the OSTP's White House offices, offering the benefit of his unparalleled experience and deep knowledge on the technical dimensions of matters relating to defense and intelligence. For those visits, the OSTP's senior staff saved up the S&T questions that arose during the preceding two weeks that no one had been able to resolve. Garwin usually was able to answer them all in an afternoon.

Other advisory committees

Garwin served as a member on the Department of Defense's Defense Science Board under presidents Johnson and Nixon, as chair of the Arms Control and Nonproliferation Advisory Board (now the International Security Advisory Board) of the State Department, and as a member of



GARWIN AT A BLACKBOARD in an undated photo. (Photo courtesy of IBM.)

CISAC from its inception in 1980 to 2023. Two of us (Holdren and Jeanloz) served as CISAC chair during Garwin's 43 years on the committee.

During Holdren's term, Garwin was instrumental in drafting several major reports that the committee produced for the federal government, including *Management and Disposition of Excess Weapons Plutonium* (1994) and *The Future of U.S. Nuclear Weapons Policy* (1997). Garwin had an immense influence on those studies because of both his deep familiarity with every aspect of the relevant S&T and his ability to clearly convey what mattered with impeccable logic. Both studies' recommendations influenced how US and foreign policymakers managed the massive reductions of Russian and US warheads after the end of the Cold War. The studies proved influential not least because of Garwin's energetic advocacy of the findings among his extensive network of contacts, which included top US and foreign officials and their science advisers.

Garwin also served, with great effect, on a separate National Academies committee that delved into technical issues that had been advanced as objections to US ratification of the Comprehensive Nuclear-Test-Ban Treaty after it was signed by Bill Clinton in 1996. The committee's report, published in 2002, concluded that the supposed objections were unpersuasive. Those conclusions were reexamined and reaffirmed in yet another National Academies report in 2012, which Garwin was also involved in drafting. Although the Senate has not ratified the treaty, all countries except for North Korea have abided by it since 1998.

Over the past 20 years, Garwin was particularly engaged in dialogues with Russian and Chinese arms control counterparts. Having first traveled to China in the 1970s, Garwin had a long-standing interest in the country's scientific community. He was a key advocate for development of the 2008 *English–Chinese Chinese–English Nuclear Security Glossary*, which was jointly authored by US and Chinese experts to facilitate diplomatic and technical discussions about nuclear weapons. That project helped inspire the creation of the *P5 Glossary of Key Nuclear Terms*, a similar 2015 English-Chinese-French-Russian dictionary compiled by experts from the US, the UK, China, France, and Russia.

As a member of the JASON group from 1966 to 2025, Garwin contributed to innumerable studies bearing on technical

RICHARD GARWIN (center) **SPEAKS ABOUT THE PROBLEMS** with President Ronald Reagan's proposed space-based ballistic-missile defense system at a March 1984 press conference organized by the Union of Concerned Scientists. At left is Hans Bethe, and at right is Henry Kendall. (Photo by Dave MacKenzie/CC BY-NC 2.0/Flickr.)

questions of interest across the entire US government, including the census, counterterrorism efforts, nuclear security, and public health. He helped to generate experimental measurements and numerical simulations as readily as he communicated results and their implications. By taking a hands-on role in drafting reports, Garwin led by example: No matter how expertly generated, results do not exist until they are documented in writing.

After his retirement from IBM in 1993, Garwin began engaging full-time in JASON studies during the summers, when the bulk of the group's work is done.[14] Under his guidance, younger generations of scientists and engineers received a deep and rapid education in policy-relevant technical matters. He also provided a unique form of institutional memory by encouraging different parts of the government to communicate with each other and learn from past experiences.

Pugwash conferences

Starting in 1961, Garwin served for many years as an active member of the Pugwash Conferences on Science and World Affairs. The Pugwash organization's international, invitation-only annual conferences and other meetings provide venues for off-the-record discussions among senior scientists and public figures from across the world. The organization's initial focus at its founding in 1957—reducing the dangers from nuclear weapons and armed conflict—has remained its central preoccupation, but it has also addressed several other topics relating to science and security, including chemical and biological weapons, nuclear energy, and climate change.

Garwin attended many Pugwash meetings and served for some years on both the international Pugwash Council and the US Pugwash Committee at the American Academy of Arts and Sciences. In a tribute to Garwin in the *Bulletin of the Atomic Scientists*,[15] Holdren writes,

> What struck me immediately about Dick's role in Pugwash meetings was the extraordinary respect the most senior participants on all sides gave to his interventions. When Dick made a statement about the technical realities around an issue, it was generally taken as definitive on that topic. If, after hearing someone else's presentation, he commented "I didn't understand your argument," all present (usually including the presenter) knew this meant the argument had not made sense to the smartest person in the room.

Garwin accomplished far more during his long and distinguished career than we could address in the space available for this appreciation. In addition to the roles mentioned here, he served at different times as an adjunct research fellow and as a professor of public policy at Harvard University's Kennedy School of Government, an adjunct professor of physics

GARWIN (center) **IN A DISCUSSION WITH PARTICIPANTS** of a 2011 Vienna conference convened by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization. (Photo by Marianne Weiss, the Official CTBTO Photostream/CC BY 2.0.)

at Columbia, and the Philip D. Reed Senior Fellow in Science and Technology at the Council on Foreign Relations. He also lectured widely and coauthored a number of important books on the relationship between science and society. Among his many honors are the National Medal of Science, awarded in 2002 by President George W. Bush, and the Presidential Medal of Freedom, awarded in 2016 by Obama. He was the loving husband of Lois Garwin for 70 years, until her death in 2018, and father to three children.

One of his legacies is the Garwin Archive (https://rlg.fas.org), a collection of his writings hosted on the website of the Federation of American Scientists. He wanted his work to remain easily accessible to others concerned about the problems to which he devoted his life. In a time when the world appears to be on the verge of a renewed, three-way arms race between the US, Russia, and China, his extensive work on arms control issues might be one particularly relevant place to start.

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SOLID-STATE

HYPE, HOPES, AND HURDLES

As conventional lithium-ion battery technology approaches its theoretical limits, researchers are studying alternative architectures with solid electrolytes.

Sokseiha Muy, Kelsey Hatzell, Shirley Meng, and Yang Shao-Horn

   

Sokseiha Muy is a research scientist at the Massachusetts Institute of Technology in Cambridge. **Kelsey Hatzell** is an associate professor of mechanical and aerospace engineering at Princeton University in New Jersey. **Shirley Meng** is a professor in the Pritzker School of Molecular Engineering at the University of Chicago. **Yang Shao-Horn** is a professor of mechanical engineering and materials science at the Massachusetts Institute of Technology.

BATTERIES

(Design by Three Ring Studio.)

The cornerstone technology that powers smartphones, electric vehicles (EVs), and various other modern devices is the lithium-ion battery (LIB). The widespread adoption of LIBs reflects their efficiency, scalability, and versatility. In its *World Energy Outlook* 2022 report, the International Energy Agency identified LIBs as the fastest growing storage technology in the world.

To reach global net-zero carbon emissions by 2050, the report says that annual battery demand for EVs would need to grow from 0.16 TWh in 2020 to 14 TWh by 2050. Meeting that demand is critical to decarbonizing transportation and mitigating climate change. Major automakers have committed billions of dollars to embrace EVs and meet net-zero emissions goals. The switch away from internal combustion engines would comply with policies such as the European Union's plan to ban gasoline-powered vehicle sales by 2035.

Despite the widespread use and undeniable advantages of LIBs, they have several limitations. Safety is a perennial concern because short circuits can lead to fires. Conventional LIB technologies, moreover, are approaching theoretical energy limits. Such constraints underscore the need for innovations that meet the demands of automakers and deliver higher energy densities and faster charging speeds than today's LIBs.

Some automakers have EV models with battery packs that can provide roughly 600 km of range on a single charge.[1] But car buyers' range anxiety—the fear of running out of battery power while driving—is still one of the most significant barriers to EV adoption. Further increasing the driving range may not be feasible with conventional LIB technology. Figure 1 shows that approximately 20 kWh of energy is needed to drive an EV 100 km. Given that conventional LIBs with graphite anodes have energy densities of about 250 Wh/kg and that the ideal battery weight is below 500 kg, the farthest an EV can travel with an LIB is around 600 km.

Another drawback of EVs is the time it takes to recharge their batteries. Recently, some eye-catching claims have promised that certain vehicle models with new battery designs could recharge in about 10 minutes.[2] Such capability, however, comes with an important caveat: A full charge to 100% would require about a megawatt of power (see figure 1), which is comparable to the output of a small power plant.

Researchers are pursuing various battery architectures to replace or improve LIBs. Some work, for example, has focused on replacing lithium's graphite anode with lithium metal or a lithium–silicon mixture. A compelling next-generation solution for delivering high energy and high-power density with improved safety is the solid-state battery (SSB).[3] The technology has drawn interest from established companies, such as Toyota and Samsung, and has spurred a wave of innovations among startups, including QuantumScape and Solid Power. They all have recently developed SSB prototypes that demonstrate encouraging performance metrics (see box 1 for metric definitions), and Toyota has claimed that SSBs could be commercialized as early as 2027. The developments suggest that SSB technology could be a promising alternative to LIBs.[4]

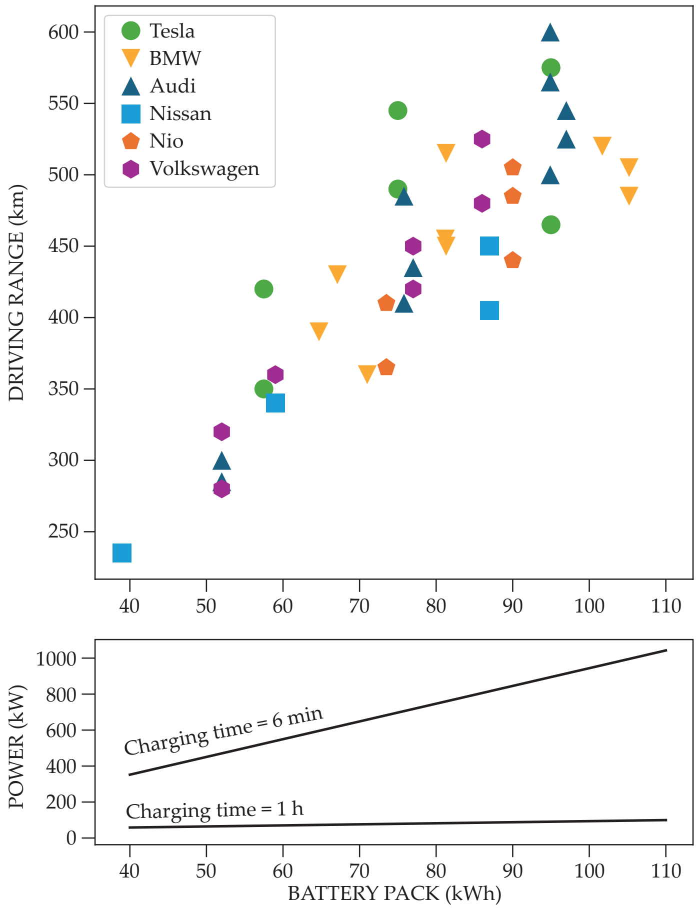

FIGURE 1. ELECTRIC VEHICLES (EVs) can currently drive 600 km or less **(top)** on a single charge.[2] To extend the vehicles' driving range with conventional lithium-ion technology, a battery pack would need to provide more than 110 kWh of energy, which would make it prohibitively heavy. Many EVs take at least an hour to charge **(bottom)** but require no more than about 100 kW of power. To charge a vehicle in just a few minutes requires 4–10 times as much power. (Figure adapted from ref. 1.)

Unpacking battery basics

A battery consists of three main components: a cathode, an anode, and an electrolyte. The cathode, or positive electrode, is typically made from layered transition-metal oxides that contain nickel, manganese, and cobalt. Lithium ions slip in and out of the oxides' crystal structure during charging and discharging.

On the opposite side of the cathode is the anode, or negative electrode, which is commonly made of graphite with a honeycomb lattice structure. It has tightly spaced layers that can host lithium ions.

Between the two electrodes is the electrolyte, which allows lithium ions, but not electrons, to shuttle to and from the electrodes. In conventional LIBs, electrolytes consist of organic solvents such as ethylene carbonate and dimethyl carbonate. Those materials present a safety risk because of their high flammability.

SSBs have a similar architecture, but a solid material replaces the liquid electrolyte, as shown in figure 2. Solid electrolytes are nonflammable; allow for battery components to be more tightly packed, which can increase energy density; and permit the anode to be made from lithium metal, which has a higher energy density than graphite. To realize all the benefits, however, solid electrolytes must enable lithium ions to move at room temperature at least as fast as they do in liquid electrolytes.[5]

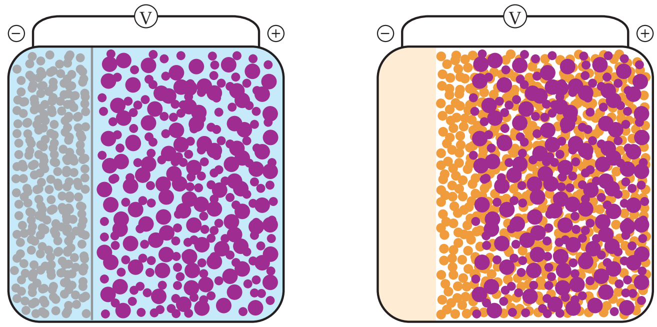

FIGURE 2. BATTERY SCHEMATICS. A conventional lithium-ion battery (LIB; **left**) consists of a graphite anode (gray particles), transition-metal oxide cathode (purple particles), and liquid electrolyte (blue background). During the discharge phase, positively charged lithium ions move through the electrolyte from the anode to the cathode while the electrons flow through the external circuit to power a device. During the charging phase, the sequence is reversed. A safer alternative to a liquid electrolyte is a solid-state one. By using a solid electrolyte (orange particles) and replacing the graphite anode with a lithium-metal one (light yellow), a solid-state battery **(right)** can provide approximately 40% higher energy density per weight than an LIB and 70% higher energy density per unit volume. (Figure adapted from ref. 16.)

Quest for new solid electrolytes

The conventional thinking is that ions diffuse through liquid electrolytes faster than they do through solid ones. Yet lithium ions seem to defy that expectation in certain solid materials, known as superionic conductors.[6] Inelastic neutron scattering studies have revealed that the energy of some crystal-lattice vibrations in those materials can be unusually low, which is associated with the high ionic mobility and liquid-like behavior of the mobile-ion sublattice.

Ion mobility can also be affected by crystal structure. As lithium ions diffuse through the electrolyte, they eventually encounter bottlenecks, which are regions where the diffusion pathway narrows and creates an energetic barrier to ion transport. To minimize the barrier, researchers have designed solid-electrolyte materials that have a large diffusion pathway. In addition, they can encourage ion mobility by minimizing the crystal structure's change in the coordination environment, which is a measure of the number of atoms in the vicinity of the mobile ions.

In recent decades, researchers have identified and studied many solid-state superionic materials. Figure 3 shows a timeline of the discoveries of three families of ceramic lithium-ion conductors. A breakthrough came in 2011 with the discovery of lithium germanium thiophosphate (LGPS).[7] It has a room-temperature ionic conductivity of 12 mS/cm—many liquid electrolytes' conductivity is on the order of 10 mS/cm.

Since LGPS's discovery, even more conductive materials have emerged. Earlier this year, researchers made a lithium-strontium-antimony compound with an ionic conductivity of 42 mS/cm, which is higher than that of any other lithium-ion conductor.[8]

So, considering their measured conductivities, are solid electrolytes suitable alternatives to liquid electrolytes? The answer is complicated. In conventional LIBs, the liquid

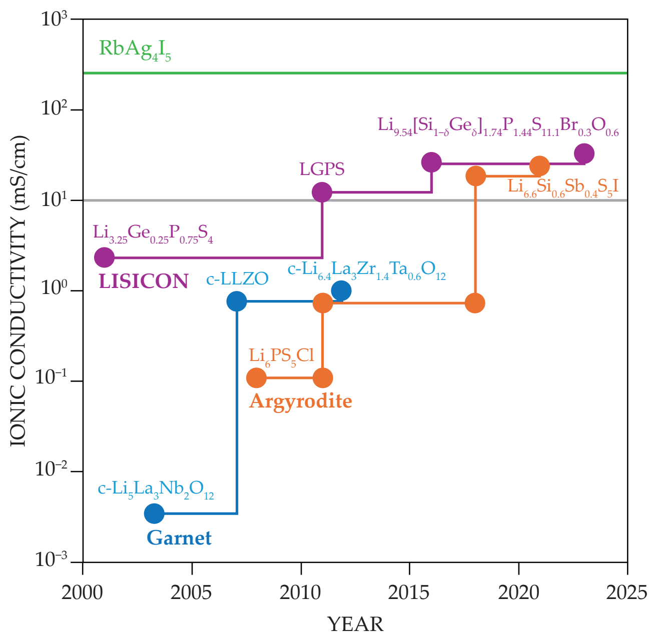

FIGURE 3. THREE FAMILIES of lithium-based materials—argyrodite, garnet, and LISICON, or lithium superionic conductor—that could be used as electrolytes in solid-state batteries have been discovered over the past century. The gray line shows the ionic conductivity of lithium in the liquid electrolytes that are used in conventional lithium-ion batteries; the green line indicates the conductivity of rubidium silver iodide, which was discovered in 1967 and has the highest known ionic conductivity of any material. LGPS is lithium germanium thiophosphate, and LLZO is lithium lanthanum zirconium oxide.

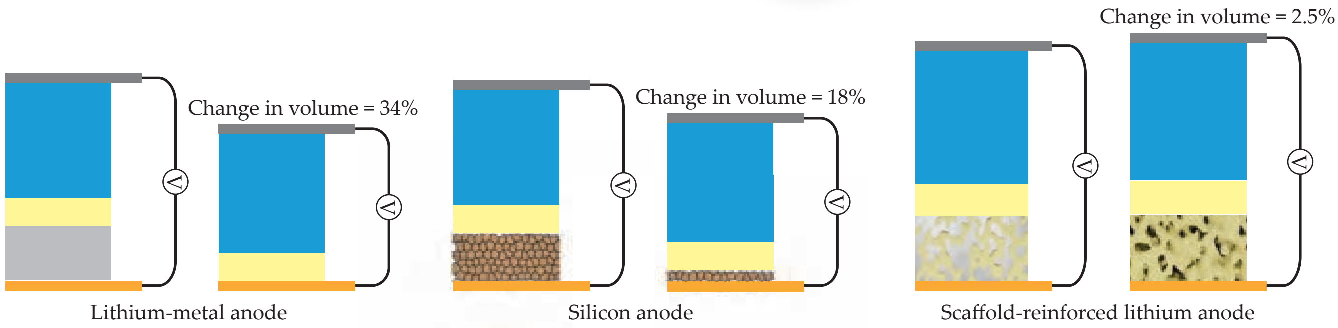

FIGURE 4. VOLUME CHANGES that occur during the charging and discharging of solid-state batteries (SSBs) degrade battery performance and reliability. The three types of SSBs shown here have the same cathode (blue) and solid electrolyte (yellow), but they have different anodes: **(left)** lithium metal, **(middle)** silicon, and **(right)** scaffold-reinforced lithium. The calculations assume that the cathode is made of entirely active material, the scaffold has a porosity of 70%, and the amount of charge per unit area of the batteries is 8 mAh/cm^2.

electrolyte can percolate through the porous cathode, which enables efficient ion transport and the full utilization of the cathode active material, the compound that produces the battery's electrical energy through chemical reactions. Compared with the electrodes in conventional LIBs, the ones in SSBs have higher tortuosity—a measure of the complexity of the ion's path—and other resistive heterogeneities, such as grain boundaries, which lead to lower ionic conductivities in real-world applications.

Those factors can significantly hinder the formation of a robust ion-conduction network, especially when the fraction of solid electrolyte in the electrode is low. To ensure effective ion transport, researchers must meticulously control the microstructures of both the solid electrolyte and the cathode-particle mixture.[5] If SSBs are to compete with LIBs in terms of performance metrics such as areal loading and current density, they need to have an effective ionic conductivity—which takes tortuosity into account—of at least 10 mS/cm.

Although a few solid electrolytes, such as lithium argyrodites and LGPS derivatives, meet the ionic-conductivity benchmark, solid electrolytes fall short in other performance metrics, such as the electrochemical stability of the high-voltage cathodes and lithium-metal anodes. The search, therefore, continues for new lithium superionic conductors with high lithium-ion conductivity, chemical stability, and optimized solid-electrolyte composites that balance ionic and electronic conductivity, stability, and mechanical integrity.[5]

Energy density of solid-state batteries

Although solid electrolytes can significantly boost a battery's energy density by minimizing the battery's volume, the greatest gains come from replacing conventional graphite anodes with higher-capacity, low-electric-potential alternatives. Some candidates, such as lithium metal and silicon-based materials, offer dramatically higher capacities than graphite (see box 2). But they also introduce substantial challenges.

One major issue is the pronounced volume changes, plotted in figure 4, that the candidate materials undergo during charging and discharging. Lithium-metal anodes, for example, expand and contract by 15–30%, whereas cathodes typically exhibit volume changes of 1–5%. Volume change creates significant mechanical strains at the interfaces between the active materials and the solid electrolyte. Those strains can lead to a loss of contact between the electrolyte and the cathode and to the cathode fracturing and fatiguing. Such failures can cascade to further issues, including microcracking, dendrite growth, and electrical shorting, all of which compromise the battery's performance and lifetime.

A promising approach to mitigating volume change of lithium-metal anodes involves the use of scaffolds. They provide a rigid framework for lithium ions to attach to the anode and strip evenly from it. The risk of dendrites plummets, and battery performance and reliability improves. Various startup companies are developing scaffold designs that enable stable lithium uptake and release.

Researchers have demonstrated continuous lithium-metal cycling at extremely high current density without dendrite formation in a symmetric battery cell, in which both the cathode and anode are made of a porous LLZO (lithium lanthanum zirconium oxide) scaffold that's separated by a dense LLZO layer. But the scaffold doesn't lead to much higher energy density compared with that of the scaffold-free battery. The scaffold is an inactive material that takes up precious space in the battery that would otherwise be used for materials that increase the battery's capacity.[9]

The problems of contact loss and particle fracture created by volume change could be alleviated by zero-strain cathode materials. They experience minimal structural changes during lithium insertion and removal and, in theory, could alleviate contact loss and particle fracture. Some researchers are encouraged by approaches to control volume change, but more work is needed to evaluate whether zero-strain cathode materials and novel battery architectures are viable pathways toward high-energy density SSBs.

An alternative to a lithium-metal anode is one made of silicon. It offers exceptional theoretical specific capacity—about 10 times as much as that of graphite—but during lithiation, silicon also undergoes significant volume expansion, which leads to

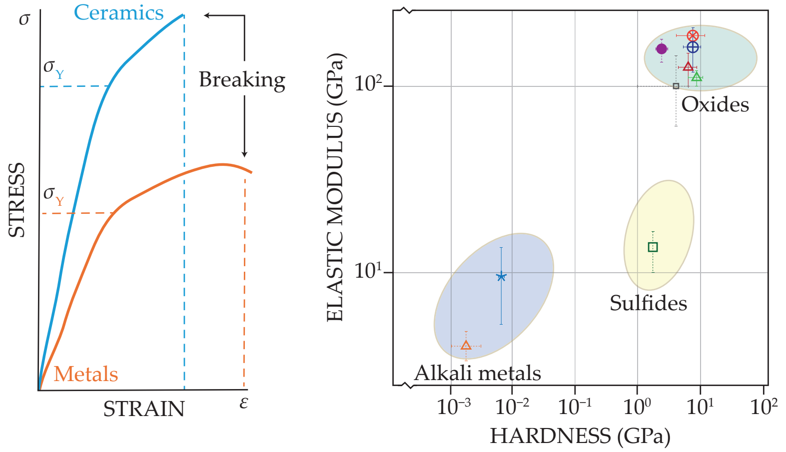

FIGURE 5. THE CONSTITUENT MATERIALS in solid-state batteries (SSBs) respond differently to applied pressure. **(left)** The horizontal lines correspond to the stress level in ceramics and metals as they enter the plastic regime, and the vertical lines correspond to each material's breaking point. The differences affect how readily the materials can stay in contact with one another and thus the battery's operation and reliability. **(right)** When choosing a solid electrolyte, researchers must balance a material's mechanical trade-offs. Oxide-based materials have a high elastic modulus and fracture toughness, which help them resist crack propagation. But those properties make it harder for the electrolyte to remain in contact with the alkali-metal cathode. More ductile materials, such as sulfide-based argyrodites, can deform plastically during electrode volume changes, which helps the electrolyte to maintain contact with the battery's active materials.

mechanical stress on the anode and other parts of the battery and to capacity fading (see figure 4). Companies such as Sila Nanotechnologies are advancing commercial solutions by introducing engineered silicon particles as partial or full replacements for graphite. Silicon-enhanced anodes reportedly are 20% of the weight of graphite and are 50% of its volume.[10]

Mechanical properties of solid electrolytes

The performance and durability of SSBs depend on the interfaces between ceramic particles, cathode active materials, and the lithium-metal anode. The interfaces are influenced by the materials' mechanical properties, including brittleness, ductility, and plasticity. Brittle materials break easily, ductile materials deform elastically, and plastic materials deform readily without hardening. To classify a material, researchers measure its stress–strain curve, which describes the material's deformation under stress. Some example curves are shown in figure 5.

Oxide-based electrolytes such as LLZO, for example, exhibit higher elastic moduli, hardness, and fracture toughness than do sulfide-based electrolytes. That means that the ceramic LLZO struggles to maintain contact with the cathode particles during battery cycling. Softer materials such as argyrodites deform plastically during volume changes, which helps the active materials maintain better contact with the electrolyte. Ceramic and glass electrolytes, however, often suffer from low fracture toughness, and their pairing with lithium metal in high-rate applications is limited.

The use of a lithium-metal anode in SSBs is hindered by filament growth and fractures caused by stress gradients and defects. In addition, battery cycling at high charge rates for long lifetimes remains challenging. Deformable solid electrolytes that ensure continuous contact during operation are preferred because they prevent mechanical failures, including crack formation, crack propagation, and filament growth.[11] Researchers have also proposed pressure control to maintain contact at interfaces, but that approach has been challenging to implement.

Box 1. Battery performance metrics

- **Specific energy (Wh/kg):** the amount of energy a battery can store per unit mass, either of the active material or of the entire battery cell.
- **Energy density (Wh/L):** the amount of energy that a battery can store per unit volume.
- **Specific capacity (mAh/g):** the amount of electric charge that a battery can deliver per unit mass of the active material in the electrodes. Specific capacity is related to specific energy: specific energy (Wh/kg) = specific capacity (mAh/g) × voltage (V).
- **Power density (W/L):** the amount of power a battery can deliver per unit volume. It indicates how quickly a battery can be charged or discharged.
- **Areal density or loading (mAh/cm^2):** the amount of charge per unit area of the electrode. The higher the areal density, the higher the battery's specific capacity, but such a battery will require higher ionic and electronic conductivity to sustain its high charge and discharge currents.
- **C-rate:** a measure of how quickly a battery is charged or discharged relative to its capacity. Rates of 0.5 C, 1 C, and 2 C mean that the battery is fully charged or discharged in two hours, one hour, and half an hour, respectively.

Box 2. Anode comparison: Graphite and lithium

The theoretical capacity of graphite, the most commonly used anode material in lithium-ion batteries, can be calculated according to the intercalation of lithium into graphite. It proceeds via the equation $Li^+ + e^- + C_6 \rightarrow LiC_6$. Each unit of graphite (C_6) can accommodate one lithium ion (Li^+). The molar mass of graphite C_6 is 12 g/mol × 6 = 72 g/mol. One mole of lithium corresponds to one mole of electrons, which equals 96 485 C/mol (Faraday's constant). Each mole of graphite, therefore, can store 96 485 C. Normalized by the molar weight, graphite's specific capacity is

$$96\,485/72\ \text{C/g} = 96\,485/72 \times 1000/3600\ \text{mAh/g} = 372\ \text{mAh/g}.$$

With the same steps, the theoretical specific capacity of lithium metal can be calculated. The only difference is that the corresponding reaction is $Li^+ + e^- \rightarrow Li$. Each lithium atom contributes one electron. The molar mass of lithium is 6.94 g/mol. The specific capacity of a lithium-metal anode, therefore, is

$$96\,485/6.94\ \text{C/g} = 96\,485/6.94 \times 1000/3600\ \text{mAh/g} = 3860\ \text{mAh/g}.$$

That capacity is about 10 times as large as graphite's capacity.

Exploring alternatives

Much of the focus of this article has been on ceramic electrolytes, but they're not the only option for SSBs. Polymer electrolytes made of materials in the polyethylene oxide family, for example, have been extensively studied and commercialized in certain applications.[12]

The company Blue Solutions has developed SSBs that capitalize on polymer electrolytes' unique advantages, including the ease with which they are processed and their excellent contact with cathode particles, which helps to reduce interfacial resistance. Polymer electrolytes, however, still face limitations. Their low ionic conductivity necessitates elevated operating temperatures—typically around 80 °C—for adequate performance.

A persistent challenge for all types of solid electrolytes is their chemical stability when they're paired with advanced electrode materials. As with liquid electrolytes, the wide number of possible next-generation anodes and cathodes creates compatibility issues. LGPS, for example, offers high ionic conductivity but suffers from chemical instability and reacts with cathodes and anodes to form interphases that degrade performance over time. Even LLZO, which is known for its superior chemical stability, faces challenges such as forming reliable interfaces.

An intriguing approach to overcoming chemical instability is the use of dual, or bilayer, electrolyte systems. In those configurations, solid electrolytes are tailored to stabilize their respective interfaces, and each layer plays a specialized role to enhance the overall electrochemical stability of the battery cell. Although promising, that strategy has its own set of challenges, including maintaining adequate ion transport and chemo-mechanical stability at the layer interfaces.

Looking ahead, advances in AI offer exciting opportunities to accelerate the discovery of new battery materials. By learning from vast datasets of known compounds, AI models can predict promising candidates with chemical stability and tailored ionic conductivity. Landmark efforts such as Google DeepMind's discovery of more than 2 million new crystal structures[13] and Microsoft Research's development of a generative AI capable of proposing materials with targeted properties[14] mark significant strides toward truly AI-driven materials discovery.

AI models, however, are not yet able to reliably handle structures with compositional disorder or partial occupancies. As a result, the models may incorrectly identify compounds with the same structure but different arrangements of atoms as distinct "new" materials, when, in fact, the compounds all correspond to the same experimentally determined structure with partial occupancy. In addition, AI-based algorithms for automatic identification of new compounds from x-ray diffraction analysis still require further refinement to unambiguously distinguish novel phases.[15]

The integration of AI with multiscale modeling and experimental data is paving the way for digital twins—virtual replicas of batteries that can simulate electrochemical behavior in diverse conditions. AI-enhanced digital twins not only enable optimization of battery design and operation but also offer promising strategies for addressing challenges such as maintaining robust electrolyte–electrode interfaces without the need for external pressure. As the field advances, such data-driven approaches may be critical to unlocking the full potential of solid-state batteries.

Sokseiha Muy and Yang Shao-Horn have a research collaboration with Toyota.

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NEW PRODUCTS

Focus on cryogenics, vacuum equipment, materials, and semiconductors

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

Cryocooler for quantum research

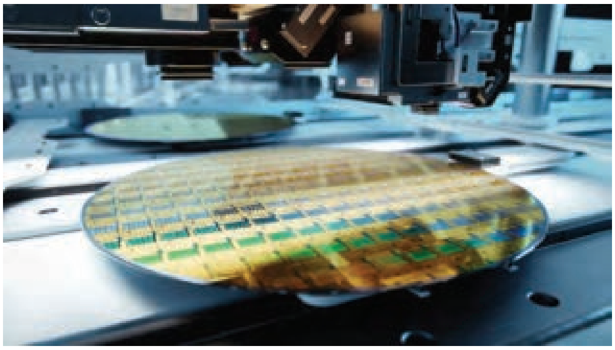
Bluefors' Cryomech PT205, a two-stage pulse tube cryocooler, supports advanced scientific applications and superconducting technologies. The lack of moving parts in its design provides for reliability, longevity, and low-vibration operation, which is particularly crucial in applications in which even the smallest of vibrations can disrupt sensitive equipment or measurements. For example, the cryocooler can be used with superconducting nanowire single-photon detectors, which are indispensable in quantum optics, communications, and other applications that require precise photon detection. The PT205 provides substantial cooling power at low temperatures, ensuring reliable performance in demanding environments. It consumes only 1.3 kW of power at 60 Hz and delivers more than 10 mW of cooling power in the 2.5 K range, which makes it energy efficient and cost-effective for long-term operation. ***Bluefors Oy**, Arinatie 10, 00370 Helsinki, Finland, https://bluefors.com*

Liquid diaphragm pump

KNF has launched its FP 1.70 liquid diaphragm pump for high-pressure and low-pulsation applications. As the high-pressure version of the FP 70 model, the FP 1.70 offers state-of-the-art diaphragm pump technology for demanding applications such as fuel-cell and 3D-printing technology. Depending on the configuration, it delivers a flow rate from 70 to 800 mL/min at a maximum pressure of 6 bar (relative). The self-priming and dry-run-safe pump offers a suction height of at least 3 mH_2O. (Suction height is the vertical distance between the pump's inlet and media source.) The FP 1.70 not only delivers a smooth flow similar to that of pump technologies known for their low pulsation, such as gear pumps and circular pumps, but it also offers the advantages of a diaphragm pump. Those include clean and gentle media handling, oil-free operation, high chemical compatibility, and reliability. Users can choose among various elastomer materials for maximum chemical compatibility and motor options, including a lower-cost brushed 12 V or 24 V DC motor and an advanced 12 V, 24 V, or 10–28 V brushless DC motor. ***KNF Neuberger Inc**, 2 Black Forest Rd, Trenton, NJ 08691, https://knf.com*

Vacuum gauges

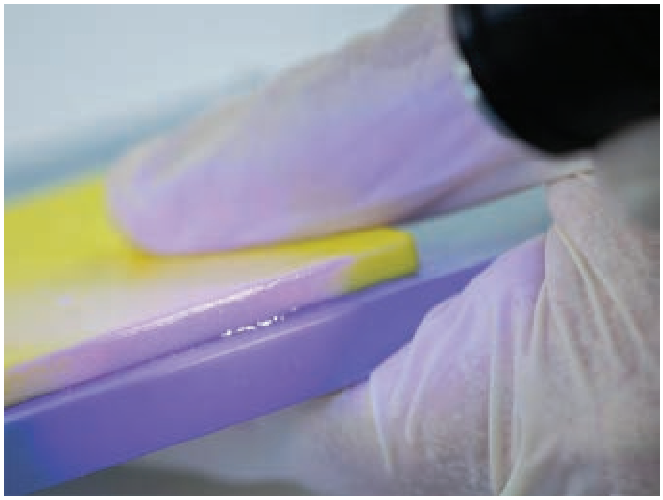
Pfeiffer Vacuum+Fab Solutions has expanded its CenterLine family of vacuum gauges by adding the CNR series of analog capacitive vacuum gauges, which can measure over four decades in the full scale between 0.1 and 1000 Torr. They deliver reliable measurements even under harsh operating conditions. Ideally used in combination with pressure-control valves, CNR gauges can be used for many applications in the semiconductor industry, such as chemical-vapor and atomic-layer deposition and dry etching, R&D and analytics, and other fields. Five versions provide options for processes at different temperatures. The 36x, an unheated variant for measurements at ambient temperatures, has an accuracy of 0.2%. Self-heating versions are available at 45, 100, 160, and 200 °C. With an accuracy of 0.15%, the 45 °C variant is suitable for calibration laboratories and high-quality control. The other self-heating versions allow for a higher accuracy of readings, at 0.4%, in high-temperature or hot-gas processes than comparable gauges, according to the company. ***Pfeiffer Vacuum Inc**, 24 Trafalgar Sq, Nashua, NH 03063, www.pfeiffer-vacuum.com*



Semiconductor etch end-point optimization

Hiden Analytical has released its EP-Replayer, a software tool for optimizing end-point (EP) detection in semiconductor etch processes. Built with real-time data replay and advanced simulation capabilities, the EP-Replayer enables fine-tuning of semiconductor etch recipes without the need for repeated wafer consumption. Designed for seamless use with Hiden's HAL10 IMP-EPD ion-beam etch monitoring systems, the EP-Replayer lets users replay previous etch data, enabling predictive EP development and recipe refinement. With the algorithmic recipe template, users can define and adjust parameters to simulate EP behavior. Like live data acquisition, the EP-Replayer offers complete tracking of time stamps, state transitions, and key-count rates through the events log. The chart marker graph simultaneously displays the EP progression, thus allowing users to visualize outcomes. By helping to streamline processes, the EP-Replayer saves time and reduces material waste. ***Hiden Analytical Ltd**, 420 Europa Blvd, Gemini Business Park, Warrington WA5 7UN, UK, https://www.hidenanalytical.com*

Nanosilica-filled adhesive



Master Bond LED422DC90 is a one-component, nanosilica-filled, dual-cure adhesive system designed for the precise, high-speed fixturing and bonding of opaque substrates and heat-sensitive components. Its side-bonding capability allows for rapid polymerization up to 3–4 mm in depth. The adhesive is first exposed to 405 nm of LED light from an angle, then the cure is completed by heating it to 90–95 °C for 30–45 min. LED422DC90 provides good dimensional stability and a relatively low coefficient of thermal expansion for a dual-cure LED product, at 30–40 × 10^{-6} inches/°C. It is optically clear and has a refractive index of 1.49, a Shore D hardness of 85–90, and an elongation of 1–3%. The system has a tensile strength of 6000–7000 psi and a tensile modulus of 475 000–575 000 psi. It is a reliable electrical insulator with a volume resistivity greater than 10^{14} Ω-cm. LED422DC90 meets NASA's low-outgassing standards; bonds well to various substrates, including plastics, glass, and metals; and is suitable for use in the electronics, optics, and aerospace industries. ***Master Bond Inc**, 154 Hobart St, Hackensack, NJ 07601, www.masterbond.com*

Accessories for broadband vector network analysis

Keysight has introduced vector network analyzer (VNA) accessories to help accelerate the design and validation of 1.6 and 3.2 Tb/s components and next-generation semiconductors. There are two millimeter-wave frequency extender modules—the NA5305A, up to 170 GHz, and the NA5307A, up to 250 GHz—and the 85065A 0.5 mm coaxial precision calibration kit. When used with Keysight's PNA and PNA-X VNAs and N5292A test-set controller, the new accessories enable users to achieve fully calibrated single-sweep broadband S-parameter measurements from 100 kHz or 10 MHz to 170 or 250 GHz. The broadband VNA accessories simplify test setups and reduce the lengthy design and verification cycles needed to characterize subterahertz on-wafer or packaged components such as optical RF drivers, transimpedance amplifiers, printed circuit boards, cables, packages, and passive devices. The accessories achieve the system dynamic range of 105 dB at 170 GHz to accommodate various measurements, lossy passive component testing, high rejection filters, and active devices testing under various power levels. ***Keysight Technologies Inc***, *1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Upgraded digital vacuum transducers

Thyracont has announced that its Smartline digital vacuum transducers are being equipped with an upgraded EtherCAT module. The Smartline transducers enable accurate measurements across a wide range of demanding environments, including rough and high vacuum ones, to ensure reliable control of industrial vacuum processes. The enhancement, beginning with models from serial number 25004917, provides expanded functionality and a more user-friendly experience in day-to-day operation. Full support for the Thyracont Communication Protocol V2 provides additional diagnostic and maintenance features, including the ability to read out sensor wear parameters, which is an advantage for predictive maintenance. Firmware updates can now be conveniently installed via the EtherCAT interface without having to remove the device or use external programming hardware, which saves time, reduces maintenance costs, and increases system reliability. ***Thyracont Vacuum Instruments GmbH***, *Max-Emanuel-Str 10, 94036 Passau, Germany, https://thyracont-vacuum.com* PT

QUICK STUDY

Dwight Whitaker is a professor of physics and astronomy at Pomona College and a research associate at the California Botanic Garden in Claremont.

How plant seeds fly

Dwight Whitaker

Although plants often rely on wind and water to carry their seeds and spores, some have evolved extraordinary launch mechanisms to disperse them.

Without the ability to move from one location to another, plants must disperse their spores and seeds for their offspring to reap the benefits of locomotion, such as finding nutrients, escaping predators, and avoiding diseases. Through natural selection, various dispersal mechanisms have evolved to efficiently scatter seeds and spores—often called by their technical term diaspores by researchers.

The most effective and familiar dispersal strategy of plants is fluid-aided transport, in which the lift, drag, and buoyancy of seeds and spores are exploited so that they can move far away from the host plant. A buoyant coconut, for example, can ride the ocean's currents for thousands of kilometers before washing up on a beach and growing into a palm tree. The fluffy pappi of dandelion fruits utilize their high drag coefficients to stay aloft and sow their seeds in grassy fields (see the 2019 Physics Today article "Dandelion seeds are optimized for wind-based travel").

Other fruits, like the autorotating samara of a maple tree, provide lift, similar to that produced by a helicopter blade, to stay aloft. The various mechanisms that keep spores and seeds suspended have evolved convergently across multiple taxa.

In contrast to fluid-aided transport, a more dynamic way that plants have evolved to disperse seeds and spores is to launch them as projectiles. That approach means that some plants can scatter seeds even if they aren't tall enough to have the seeds carried by wind or close enough to water or animals that can carry the seeds.

Rapid release

Plants that swiftly propel their seeds or spores utilize a collection of rapid motions called latch-mediated spring actuation. The process begins with a slow buildup of energy followed by a sudden release of the energy to create a powerful launch. A familiar example happens with a bow and arrow: An archer slowly loads tension into the bow, and when the bowstring is released, the stored energy is rapidly converted into kinetic energy in the arrow. Similarly, plants can slowly load stress into tissue through growing, desiccating, and increasing the pressure inside cells. Then the stresses are released rapidly through the explosive rupture of tissue.

Some flowers launch their diaspores at extraordinary speeds, which lead to impressive dispersal distances. The stamens of bunchberry flowers, for example, are unable to grow straight because the petal tips fuse together and restrain them. Consequently, elastic energy increases as the growing stamens bend, much like what happens when a loaded catapult bends its launch arm. Eventually, the petals quickly break apart so that the straightening stamens can launch the pollen like a trebuchet. The pollen travels several centimeters, which is enough for them to reach air currents. The elastic energy in the stamens is released in about 0.5 ms, which makes the bunchberry the fastest-blooming flower on Earth.

Fruits use similar mechanisms to disperse seeds. The fruits of touch-me-nots, for example, have valves, which can be thought of as spring-loaded banana peels, that are fused along their seams. The valves grow straight despite the internal stresses that act to curl them inward. A slight disturbance—even a breeze—breaks the valves apart and, as they curl up, they launch seeds at speeds of up to 4 m/s.

Flight dynamics

Fluid-aided diaspores are shaped to match their motion to the surrounding fluid. But ballistic projectiles need to reduce their drag as much as possible to best utilize the kinetic energy they acquire during launch. The drag force on rapidly moving projectiles depends primarily on inertial drag, whose magnitude is given by the equation $F_D = \frac{1}{2} C_D \rho A v^2$, where C_D is the drag coefficient, ρ is the density of air, A is the frontal area of the projectile, and v is its speed.

The drag force does not tell the whole story. A Ping-Pong ball and a golf ball, for example, have approximately the same area and drag coefficient, but with the same launch velocity,

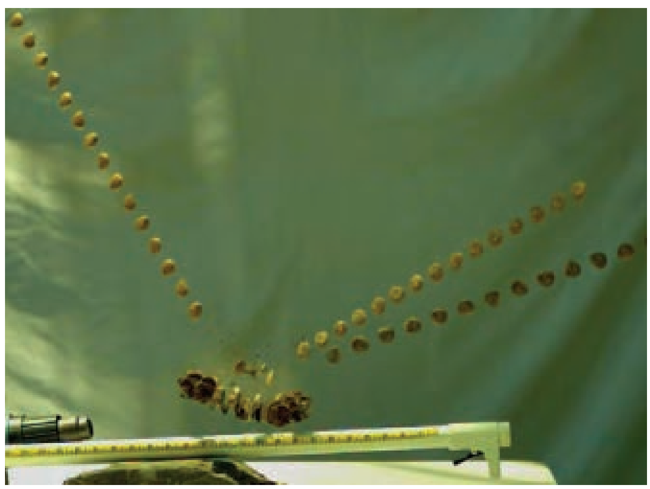


FIGURE 1. THE HAIRYFLOWER WILD PETUNIA launches its disk-shaped seeds with a backspin. This composite photo is made of several images; successive frames were taken 0.5 ms apart. The seeds, spinning at about 1200 Hz, are the fastest-rotating natural things on Earth. (Image courtesy of Dwight Whitaker.)

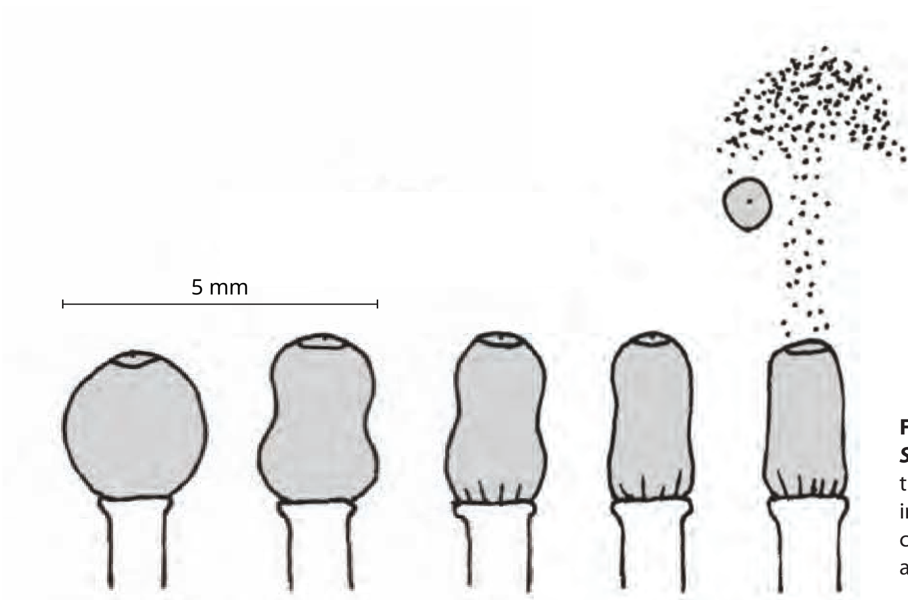


FIGURE 2. THE EXPLOSION OF A *SPHAGNUM PALUSTRE* SPORE CAPSULE. As the capsule loses water and shrinks, pressure increases and internal stress builds until the cap is blown off the capsule, and the spores are ejected. (Image courtesy of Emily Chang.)

the golf ball will fly significantly farther. That's because the same drag force induces a larger deceleration on the lighter Ping-Pong ball than it does on the heavier golf ball. A projectile's deceleration because of drag can be quantified by dividing the drag force by the projectile mass m, such that $a_D = F_D/m = \frac{1}{2} b\rho v^2$, where $b = C_D A/m$ is the ballistic parameter, which should be minimized to maximize launch distance.

Given that the mass of an object increases with an increase in its volume faster than with an increase in its area, one might conclude that larger seeds make better projectiles. A heavier seed, however, requires a commensurately more powerful launch than a lighter seed does to achieve the same velocity. The trade-off between launch speed and ballistic parameter means that for a diaspore of a given size, the plant will usually maximize range by reducing the projectile's frontal area, its drag coefficient, or both.

Figure 1 shows one example of drag minimization. The seeds of a hairyflower wild petunia are small disks that are approximately 2.5 mm in diameter with a thickness of 0.5 mm, and the plant's fruits can launch them 7 m. The shape of the confetti-like seeds means that the seeds' orientation has an enormous effect on their drag force as they fly through the air.

Compared with a disk traveling edge on, one that's traveling with its axis of symmetry aligned with its velocity has an area five times as large and a significantly higher drag coefficient. Because of the torques that are applied on a disk as it moves through a fluid, the most stable orientation is the one with maximum drag. To maintain the drag-minimizing and edge-on orientation and thus achieve greater distances, the plant launches its seeds at about 10 m/s with a backspin of more than 1200 Hz. That frequency makes hairyflower wild petunia seeds the fastest-rotating natural thing on Earth.

The angular momentum from such tremendous spin gyroscopically stabilizes the seeds in their backspin orientation and minimizes their drag. Hairyflower wild petunia seeds that are launched with a backspin travel 60% farther than a sphere of equivalent volume and roughly twice as far as nonspinning seeds.

Vortex-induced dispersal

Peat moss, also known as sphagnum, uses aerodynamics to great effect to discharge its spores. Mosses lack a vascular system, so they can't grow tall enough to where the wind can easily carry their spores. Furthermore, the dust-sized spores can't be launched any significant distance because of their low mass and subsequently high ballistic parameter. Instead, a sphagnum spore capsule creates its own fluid flow to launch its spores efficiently into the turbulent boundary layer, where wind can carry them indefinitely.

On a warm summer day, the peppercorn-sized spore capsules, which are perched a couple centimeters above the bog's mat, desiccate and collapse. The pressure inside the capsules increases. Eventually, the strain from the collapsing capsule is strong enough to suddenly eject the capsule's lid, which releases pressurized gas—as shown in the illustration in figure 2. A vortex ring that emerges upward from the capsule can carry the spores to a height of about 10 cm, where they can be transported by air currents.

The vortex ring of peat moss is the only one known to be produced in the plant kingdom. The process combines both the projectile and fluid-aided dispersal strategies: The vortex ring provides a low-drag means of transporting the high-drag spores until they reach a height where wind dispersal then carries them over enormous distances. Once brought into the jet stream, the spores can be carried around the world.

The aforementioned adaptations are a small sample of the multitude of ways that plants efficiently transport their diaspores in the fluid that surrounds them. By studying the aerodynamics of seed and spore dispersal, physicists and engineers can learn from adaptations that evolved over millions of years and develop bioinspired engineering designs.

Additional resources

- M. Ilton et al., "The principles of cascading power limits in small, fast biological and engineered systems," *Science* **360**, 397 (2018).
- E. S. Cooper et al., "Gyroscopic stabilization minimizes drag on *Ruellia ciliatiflora* seeds," *J. R. Soc. Interface* **15**, 20170901 (2018).
- D. L. Whitaker, J. Edwards, "*Sphagnum* moss disperses spores with vortex rings," *Science* **329**, 406 (2010).
- A. Sakes et al., "Shooting mechanisms in nature: A systematic review," *PLOS One* **11**, e0158277 (2016).

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A comet's ghost tail

If you looked up at the night sky in fall 2024, you may have seen comet C/2023 A3. This image of it was taken by Binyu Wang, a student at Anhui Jieshou No. 1 Middle School in Jieshou, China. He and his teacher Li Shen won first place in the Natural category of the 2025 American Association of Physics Teachers' High School Physics Photo Contest. Their caption, lightly edited, is below.

> C/2023 A3 (Tsuchinshan–ATLAS) is one of the greatest comets in recent years and was discovered by the Tsuchinshan Observatory in China and ATLAS in South Africa. The comet peaked in brightness around 9 October 2024, shortly after passing perihelion on 27 September, and could easily be seen by the naked eye. So I rushed to go to Inner Mongolia, where you can find one of the greatest dark-sky conditions in China, to capture such an amazing astronomy phenomenon. Then I was shocked when the comet appeared out of the twilight in the western sky. When I looked through the camera screen to see the long-exposure single image of the comet, I found something much more incredible! The comet not only showed a bright tail but also a distinct, faint, downward or Sun-directed tail pointing in nearly the opposite direction, which is called the anti-tail. That is because Earth was crossing the comet's orbital plane, where the comet left its dust that reflected sunlight, which means it is an optical illusion. After my initial excitement, I began trying to just enjoy this beautiful scene: The huge comet hung on the sky, while the moonlight bathed the grassland and river. As the comet faded beyond the edge of the horizon, it was time to say goodbye to Comet Tsuchinshan–ATLAS. Perhaps you'll vanish like the river water—flow away and never return.

—AL

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