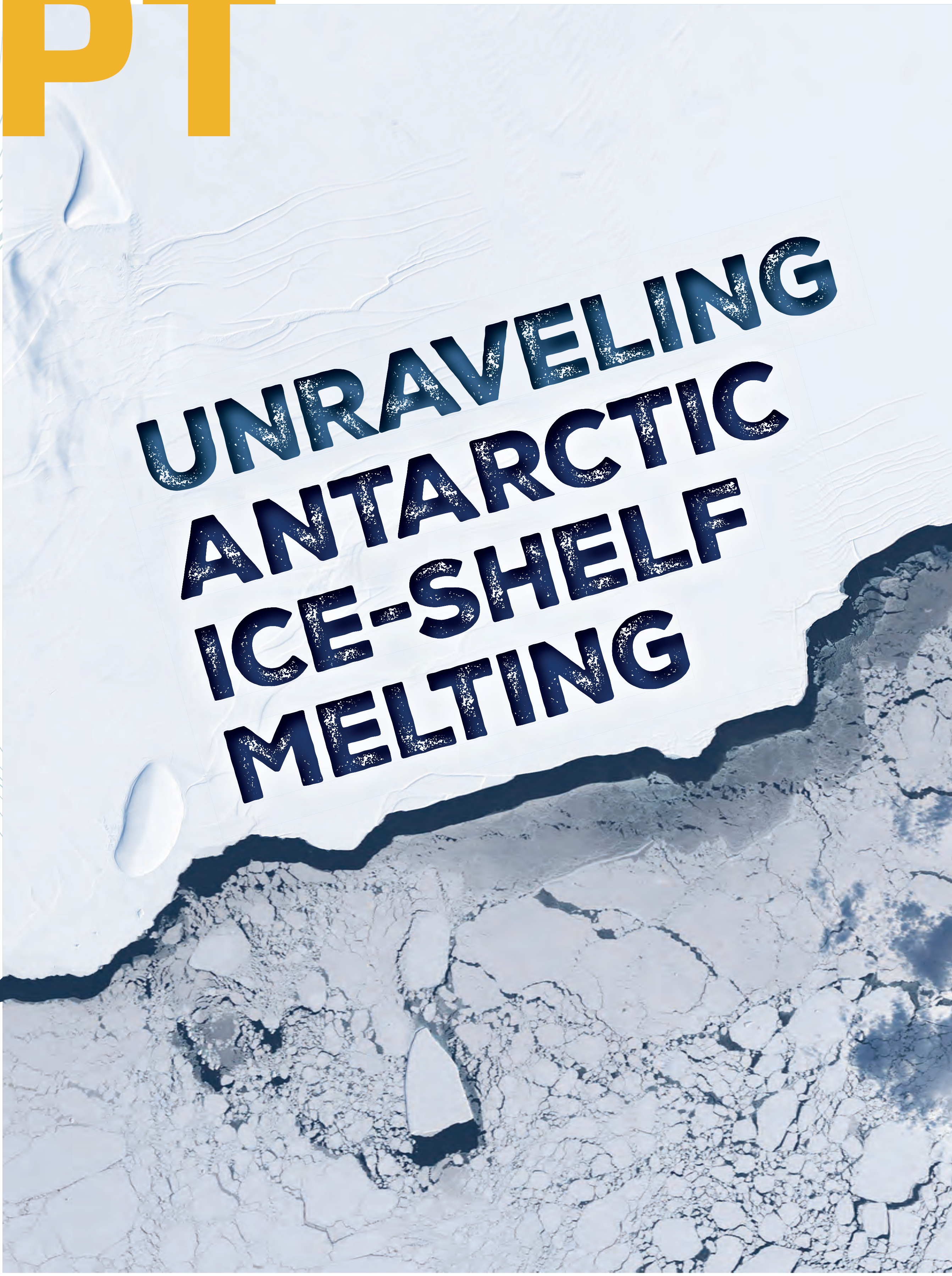
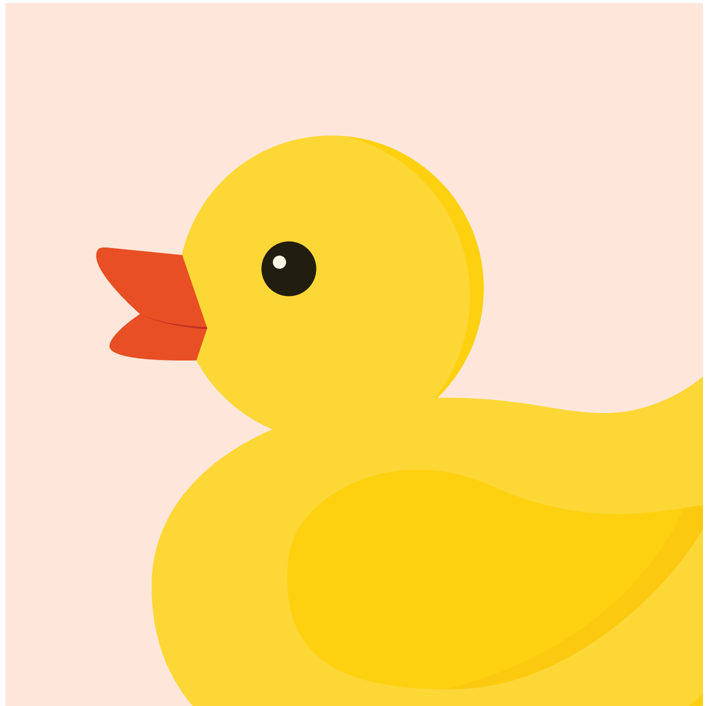
PT PHYSICS TODAY
FEBRUARY 2026 VOLUME 79 NUMBER 02



UNRAVELING ANTARCTIC ICE-SHELF MELTING

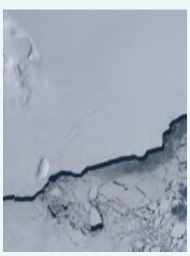
AIP

FEATURES



Physics Today (ISSN 0031-9228, coden PHTOAD) volume 79, number 2. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to *Physics Today*, American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300.

DEPARTMENTS



ON THE COVER

This image, based on satellite observations from September 2016, shows the edge of the Larsen C Ice Shelf in Antarctica, in the region from which an iceberg larger than Delaware would calve in July 2017. Although calving is more dramatic, ice shelves also lose a significant amount of mass through melting from below. To learn more about Antarctic ice-shelf melting, turn to the article by Catherine A. Vreugdenhil and Bishakhdatta Gayen on **page 42**.

(Observational data courtesy of NASA's *Landsat 8* and USGS; data processed by Paul Quast/CC BY 2.0; border art adapted from iStock.com/marukopum.)

Scan for the latest content

PT PHYSICS TODAY

TO READ ABOUT NASA'S NEXT SPACE TELESCOPE, TURN TO PAGE 14

Ultra-stable *DC Voltage Source*

DC205 ... $2995 (U.S. list)

- ±100 VDC range
- True 6-digit resolution
- 1 ppm/°C stability
- 0.0025 % accuracy (1 yr)
- Triggerable voltage scans
- Low-noise design
- Linear power supply

When you need a quiet, stable, high-resolution bias voltage, the DC205 is the right tool. Its bipolar, four-quadrant output delivers up to 100 volts with microvolt resolution and up to 50 mA of current. In 4-wire mode (remote sense), the instrument corrects for lead resistance delivering accurate potential to your load. The DC205's output stability is a remarkable ±1 ppm over 24 hours. With its linear power supply, there is no need to worry about high-frequency noise.

The DC205 can generate triggerable scans when voltage ramping is required. It is also fully programmable over RS-232 and USB, and there's a fiber optic interface for use with the SX199 Optical Interface Controller.

thinkSRS.com/DC205

SRS Stanford Research Systems
Tel: (408)744-9040 • www.thinkSRS.com

A fundamental limit to how fast coherence can spread

An ultracold atomic gas can sync into a single quantum state. Researchers uncovered a speed limit for the process that has implications for quantum computing and the evolution of the early universe.

By Laura Fattaruso

The transition of a system from a nonequilibrium to an equilibrium state is of interest across a broad range of research areas. Relevant questions include not only how the transition proceeds but also how long it takes.

Zoran Hadzibabic and his team at the University of Cambridge's Cavendish Laboratory have been studying that transition in a confined cloud of weakly interacting potassium-39 atoms using the setup shown in figure 1. Cooled to temperatures that are orders of magnitude colder than the vacuum of space, the atoms condense into a single, quantum state known as a Bose–Einstein condensate (BEC).

Starting with that equilibrium state, the Cavendish team pushed the atoms into a low-energy incoherent state far from equilibrium and then observed how they condensed back into the coherent ground state. When he examined the results, Gevorg Martirosyan, a PhD student at the time, found something surprising: Regardless of the initial nonequilibrium state, the clouds of atoms would reach a common intermediate state, as shown in figure 2, and then evolve in the same exact way toward the condensed equilibrium state.

Taking the observations a step further, the group used magnetic fields to tweak the strength of interactions between the particles. Common sense dictates that particles with stronger interactions evolve toward equilibrium faster. And to a certain extent, observations bore that out, but only until the cloud of atoms reached that common intermediate state. After that, systems with comparatively weak and strong particle interactions evolved the same way. "We realized the strength of interactions is just a detail," says Hadzibabic.

The researchers had found a universal speed limit for the spread of coherence as the atoms condensed into the BEC ground state.[1] The limit depends on just the ratio of two fundamental parameters—the reduced Planck's constant $\hbar$ divided by particle mass m—multiplied by a factor of 3.4. And the underlying physics should apply to fields well beyond cold-atom experiments, including high-energy physics and cosmology.

A long ride

A rough analogy can be drawn between the speed limit on the spread of coherence and the speed limit when traveling by car. Over short distances, like a morning commute, various factors, such as local traffic and the performance of your vehicle, can have a large impact on your arrival time. If you embark on a long journey—such as a cross-country trip across the US—those factors become less important, and the speed limits of the highway exert greater control over your travel time.

Similarly, the initial conditions of the atom clouds affect how quickly they reach the maximum speed for the spreading of coherence, but they all reach the same maximum speed limit that exerts control over how fast they can condense. Measuring the spread of coherence, though, poses a greater challenge than estimating your travel time from Washington, DC, to Santa Barbara, California.

One key breakthrough enabling the Cavendish experiment was the development of the box trap. For almost two decades, from the first demonstration of ideal-gas BECs in 1995 (see the *PT* story "Gaseous Bose–Einstein condensate finally observed") until 2013, the traps used to isolate and cool atoms to form BECs had harmonic-shaped potential-energy wells. That trap shape, unsurprisingly, produces a corresponding harmonic distribution of particle positions and energies that obscures observation of homogeneous-system behavior. In 2013, Hadzibabic and colleagues in the Cavendish Lab announced that they had developed a cylindrical optical trap that could confine a BEC in a region with nearly uniform potential in all directions,[2]

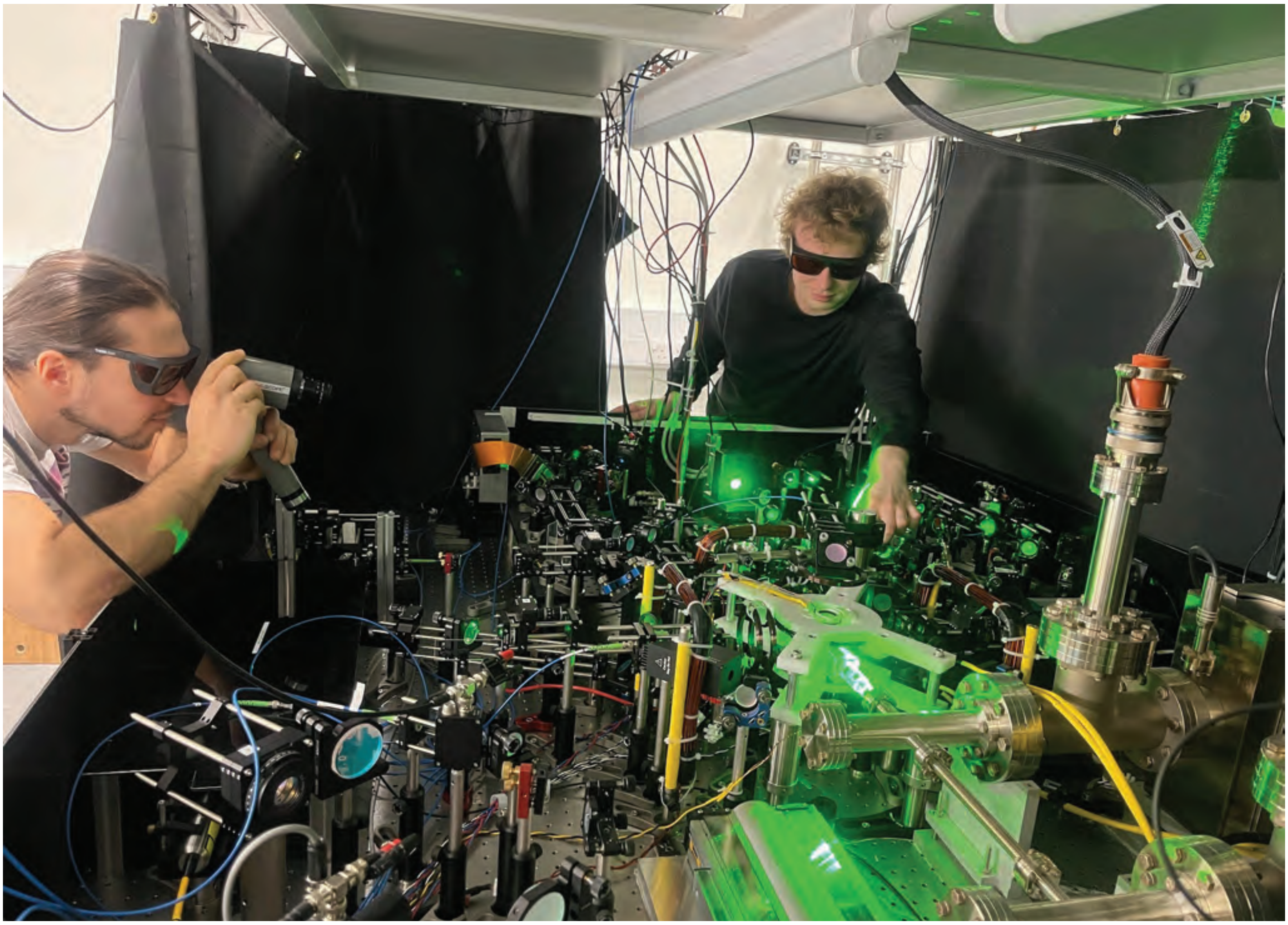


Figure 1. Gevorg Martirosyan (left) and Martin Gazo (right) make adjustments to the tabletop apparatus they use to make and measure Bose–Einstein condensates of potassium-39 atoms. Tens of thousands of experiments lasting about 30 seconds each led to the finding that there is a universal speed limit on the spreading of coherence and the formation of the condensates. (Photo courtesy of Simon Fischer.)

akin to the textbook example of putting a particle in a box. That set the stage for producing nearly uniform BECs that are much more theoretically tractable.

Generally, when making a BEC, researchers rapidly cool atoms to very low temperatures using lasers and then evaporatively cool them down to the nanokelvin temperatures needed for the atoms to form a coherent quantum state. That works well for forming a condensate, but it doesn't provide ideal conditions for observing the transition from incoherent, nonequilibrium phases to coherent phases. By first forming a BEC and then using magnetic fields to manipulate it, the Cavendish researchers found that they could create low -energy, nonequilibrium states with varied momentum distributions,[3] such as the ones shown in figure 2. From there, they could quantitatively track the transition to a BEC.

A final crucial advance came from a study of 2D BECs earlier this year by Martin Gazo, Hadzibabic's PhD student, and colleagues. In that work, the researchers devised a way to separate out the initial state-dependent evolution of the trapped gas from the universal behavior that later emerged as it condensed into a BEC.[4]

Determining the speed limit of coherence in the quantum system required repeatedly returning to the same starting point and going a little bit further in time for each iteration. In the road trip analogy, figuring out your maximum speed on a trip from DC to Santa Barbara in a similar fashion would involve restarting the trip from DC for every time and distance measurement collected along the route—and doing so without knowing if a limit exists at all.

"It's a quantum system, so when we measure it, we destroy it," says postdoc Christoph Eigen, a coauthor on the new work. So, in the analogy, it's actually as though you are rebuilding the car for every measurement. Fortunately, each experimental run lasted about 30 seconds.

Driving forward

The universal nature of the speed limit means that it should have relevance across many fields—it's now in

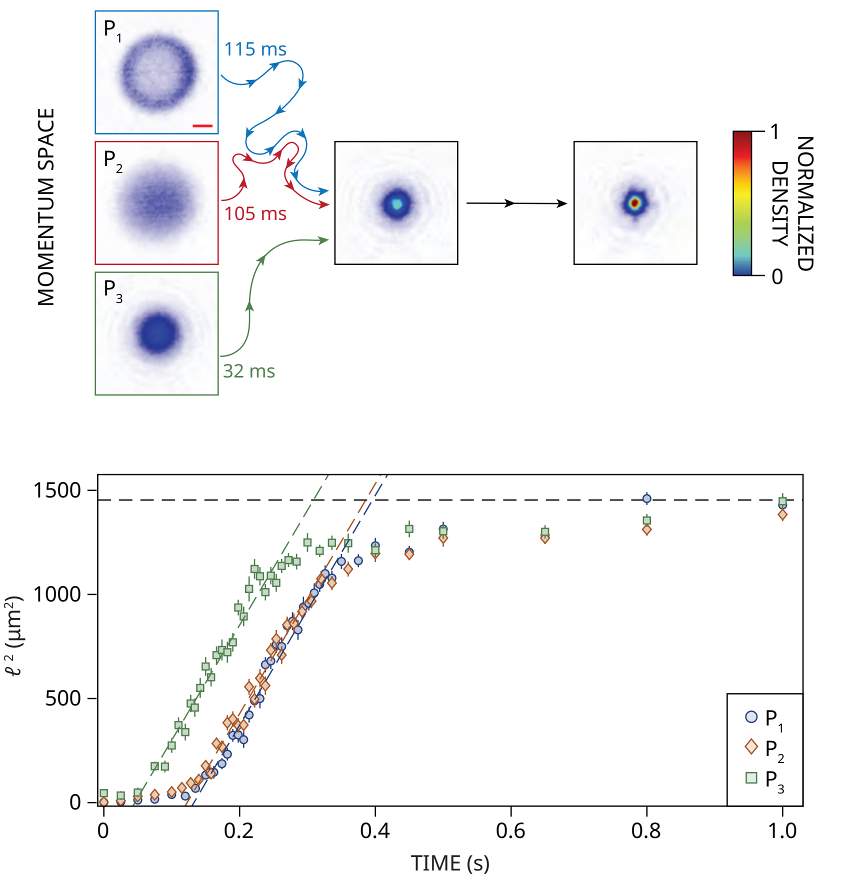


Figure 2. Researchers induced several distinct far-from-equilibrium states (P_1, P_2, P_3) in isolated atomic gases, each of which had a different momentum distribution, shown in the top left, but the same total energy. The red scale bar in the P_1 box corresponds to 1 μm^{-1}. Though the initial state affected the early stages of relaxation toward equilibrium, all systems eventually reached the same intermediate state. After reaching that state, the coherence length ℓ in all of the systems increased at the same maximum rate (indicated by the dashed lines on the graph), 3.4 $\hbar/m$, where m is the atomic mass. (Figure adapted from ref. 1.)

the hands of theorists to determine what the implications might be.

"The entire universe is, in principle, a closed quantum system," says Immanuel Bloch, scientific director at the Max Planck Institute of Quantum Optics. "So if you have the Big Bang and you ask how thermal equilibrium is established in parts of our universe, these are questions that pertain from very small to very large scales," he says. "To find universal behavior in relaxation dynamics is very important; I think it might help us find universal laws that govern out-of-equilibrium evolution."

The Cavendish team found the value of the speed limit to be surprisingly slow, which has possible implications for coherence in macroscopic systems: Calculations show that forming a BEC more than 1 cm across would take hours.

The finding also has implications for quantum computing. "There's a limitation imposed by the interactions of the system, and that's relevant now in an era of using and spreading quantum information," says Vanderlei Bagnato, a physicist at Texas A&M University and the University of São Paulo.

The ratio $\hbar/m$, which determines the coherence speed limit, also corresponds to the circulation of velocity around a quantum vortex. That similarity hints that vortices may play a role in the spreading of coherence. Simulations of low-energy atomic gases have suggested that ordering into a coherent BEC involves movement from a turbulent state to a spaghettilike tangle of vortices. "The ultimate process of ordering is about relaxing the tangle of vortices," says Boris Svistunov, a physicist at the University of Massachusetts Amherst. For the future, the researchers hope to use direct imaging to explore the roles of vortices and waves in the relaxation process. **PT**

References

1. G. Martirosyan et al., "A universal speed limit for spreading of coherence," *Nature* **647**, 608 (2025).
2. A. L. Gaunt et al., "Bose–Einstein condensation of atoms in a uniform potential," *Phys. Rev. Lett.* **110**, 200406 (2013).
3. G. Martirosyan et al., "Observation of subdiffusive dynamic scaling in a driven and disordered Bose gas," *Phys. Rev. Lett.* **132**, 113401 (2024).
4. M. Gazo et al., "Universal coarsening in a homogeneous two-dimensional Bose gas," *Science* **389**, 802 (2025).

Watching electrons in action: Still hard, but getting easier

In the closest thing yet obtained to a movie of a breaking chemical bond, there's a surprise ending.

By Johanna L. Miller

Electrons are the drivers of chemistry. They form the chemical bonds that connect atoms into complex molecules. When they move around, they break bonds, create new bonds, and transform molecules into different ones. When chemists hone their intuition for categorizing and predicting the results of chemical reactions (as described in the 2019 *PT* column "How to succeed in orgo without really trying"), most of what they ask themselves is, Where are the electrons inclined to go?

The chemist's mental picture is merely a heuristic. Experiments have never observed the real-time and real-space flow of electrons during a chemical reaction. But now researchers led by Dao Xiang, of Shanghai Jiao Tong University in China, have taken a step toward filming an electron reaction movie.[1] For their proof-of-principle experiment, they studied the photodissociation of ammonia, illustrated in figure 1: A laser pulse hits an NH_3 molecule and rips off one of its hydrogen atoms. The researchers probe the dissociating molecules with precisely timed blasts of electrons, which scatter off the molecular nuclei and electrons and give information about their whereabouts.

The result is still not a full 3D image of all the moving nuclei and electrons. Rather, as shown in figure 2, it's a measurement of the change in the charge-pair distribution function (CPDF), the electric-charge correlations at a particular distance. The CPDF is sensitive to all 14 particles—4 nuclei and 10 electrons—in the NH_3 molecule, and much of what it measures has nothing to do with electrons. For example, the blue (negative) streak that appears at 1 Å corresponds to the loss of one of the N–H nuclear pairs, which in the starting molecule are that distance apart.

But some of what's seen in the CPDF must be probing electron dynamics. The starting NH_3 molecule is only about 2 Å across, so any negative signals at larger distances than that can't correspond to the loss of nucleus–nucleus or electron–electron pairs. Rather, they must represent the formation of new electron–nucleus charge pairs. The diffuse, transient blue feature between 2 Å and 4 Å, which fades by about 300 fs,

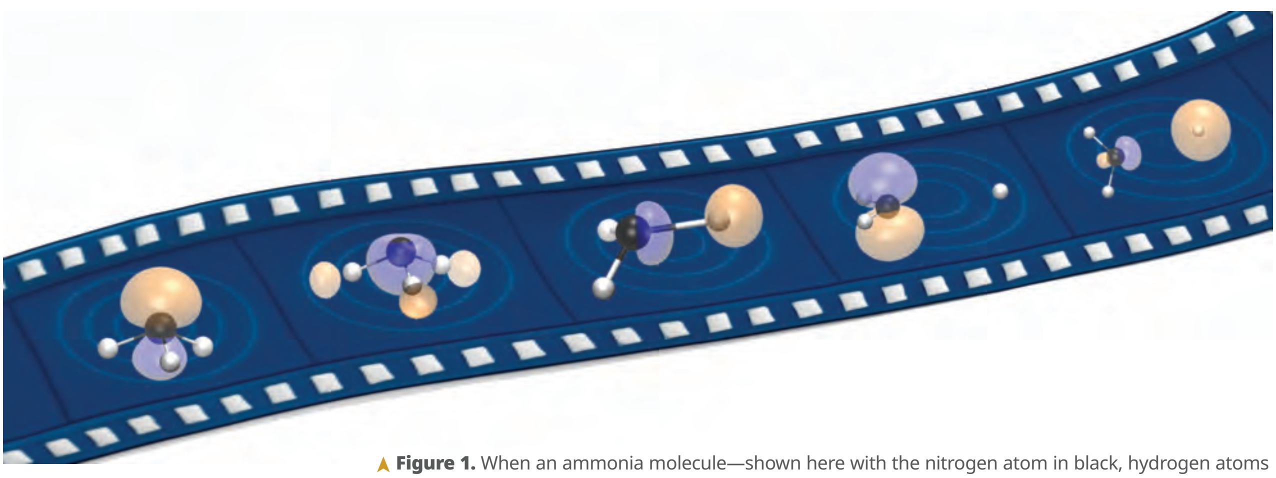


Figure 1. When an ammonia molecule—shown here with the nitrogen atom in black, hydrogen atoms in white, and representative electron orbitals as diffuse clouds—absorbs a UV photon, it loses one of its hydrogen atoms. Or does it? (Illustration courtesy of Hui Jiang/Shanghai Jiao Tong University.)

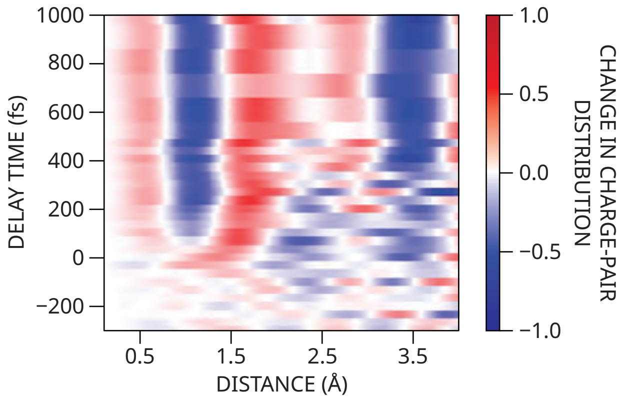


Figure 2. The experimentally obtained charge-pair distribution function shows how charge correlations change in space and time during the ammonia-dissociation reaction. Red (positive) signals can represent either the gain of nucleus–nucleus or electron–electron correlations or the loss of nucleus–electron correlations; blue (negative) signals represent the opposite. (Figure adapted from ref. 1.)

arises from the rearrangement of electrons during the molecular dissociation, and it's roughly in agreement with *ab initio* theory calculations.

The strong, steady blue feature at 3.5 Å—which doesn't appear in the *ab initio* calculations—is another story. It's not the hallmark of a molecule still undergoing a reaction. Rather, it suggests that at least some of the NH_3 molecules are returning to a relatively static structure. The researchers infer from it that many of the molecules use the laser energy not to dissociate but to vibrate: They remain intact, and they stretch their N–H bonds to uncharacteristically long distances. Theory had acknowledged that outcome as a possibility, but only for a much smaller fraction of the molecules. **PT**

Reference

1. T. Wang et al., "Probing valence electron and hydrogen dynamics using charge-pair imaging with ultrafast electron diffraction," *Phys. Rev. Lett*. **135**, 233002 (2025).

As satellite population surges, so does the impact on astronomy

Images captured by ground telescopes are getting contaminated by sunlight reflected off satellites. Space telescope data can get compromised too.

By Sarah Wells

Fewer than 2700 active satellites were orbiting Earth in early 2020. That number grew to more than 7500 by 2023, and today it stands at about 15 000. The sharp rise in the orbital population stems in part from the launches of telecommunications satellites by companies like SpaceX, OneWeb, Amazon, and Guowang. Aided by factors such as decreasing launch costs, the companies are rapidly sending up satellites and trying to sell internet access subscriptions to remote areas. The satellites can also be used for GPS navigation and for military intelligence collection. If companies follow through on the plans they have filed with the US Federal Communications Commission and the International Telecommunication Union, then half a million satellites or more could be orbiting Earth by 2040.

The continuing crowding of space is rife with unintended consequences. (See, for example, *PT*'s 2022 news story "Ballooning satellite populations in low Earth orbit portend changes for science and society.") Ground-based telescopes that take long and wide exposures of the sky have already had their data affected by the trails of reflected sunlight from passing satellites. They can leave marks on telescope images and make some of the data unreadable. Although space telescopes orbit above some telecommunications satellites, as shown in figure 1, and generally have narrower fields of view than ground-based survey telescopes, they are not immune to image contamination from satellite trails. Alejandro Borlaff at NASA's Ames Research Center and colleagues explored how an increased number of satellites would affect four space-based missions: the *Hubble Space Telescope*, NASA's *SPHEREx*, and two still under development—the European Space Agency's *ARRAKIHS* and China's *Xuntian*.[1]

The researchers created a simulation in which four cameras—stand-ins for the space telescopes—orbit Earth. The team then intro-

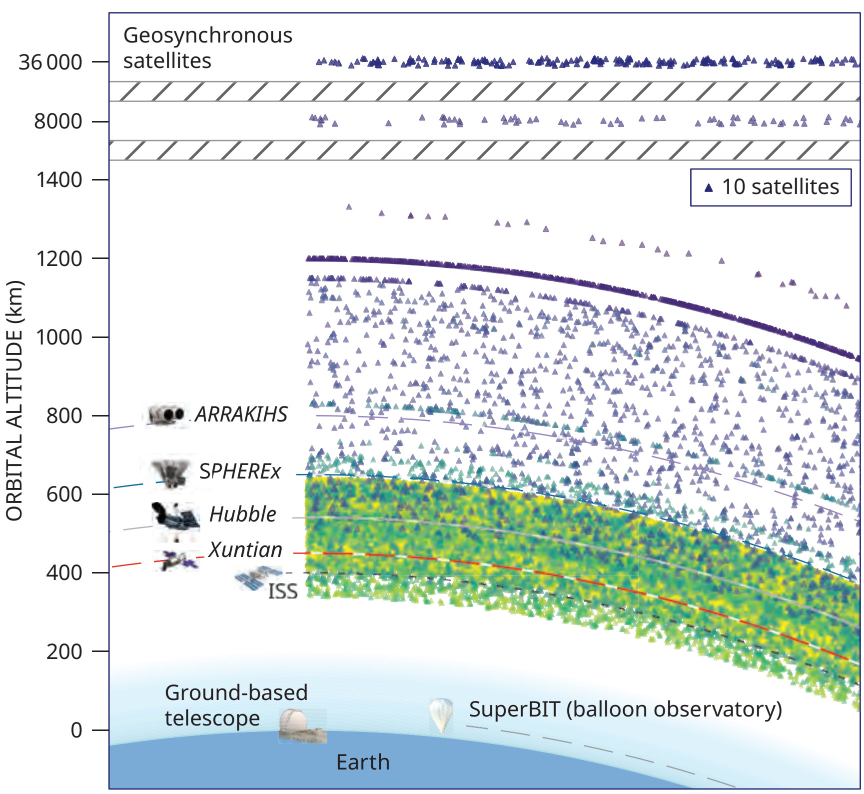


Figure 1. A visualization of the potential satellite population in 2040. Each triangle represents 10 satellites. Tens of thousands of telecommunications satellites could soon orbit at similar and even greater altitudes than those occupied by space telescopes. (Image adapted from NASA and ref. 1.)

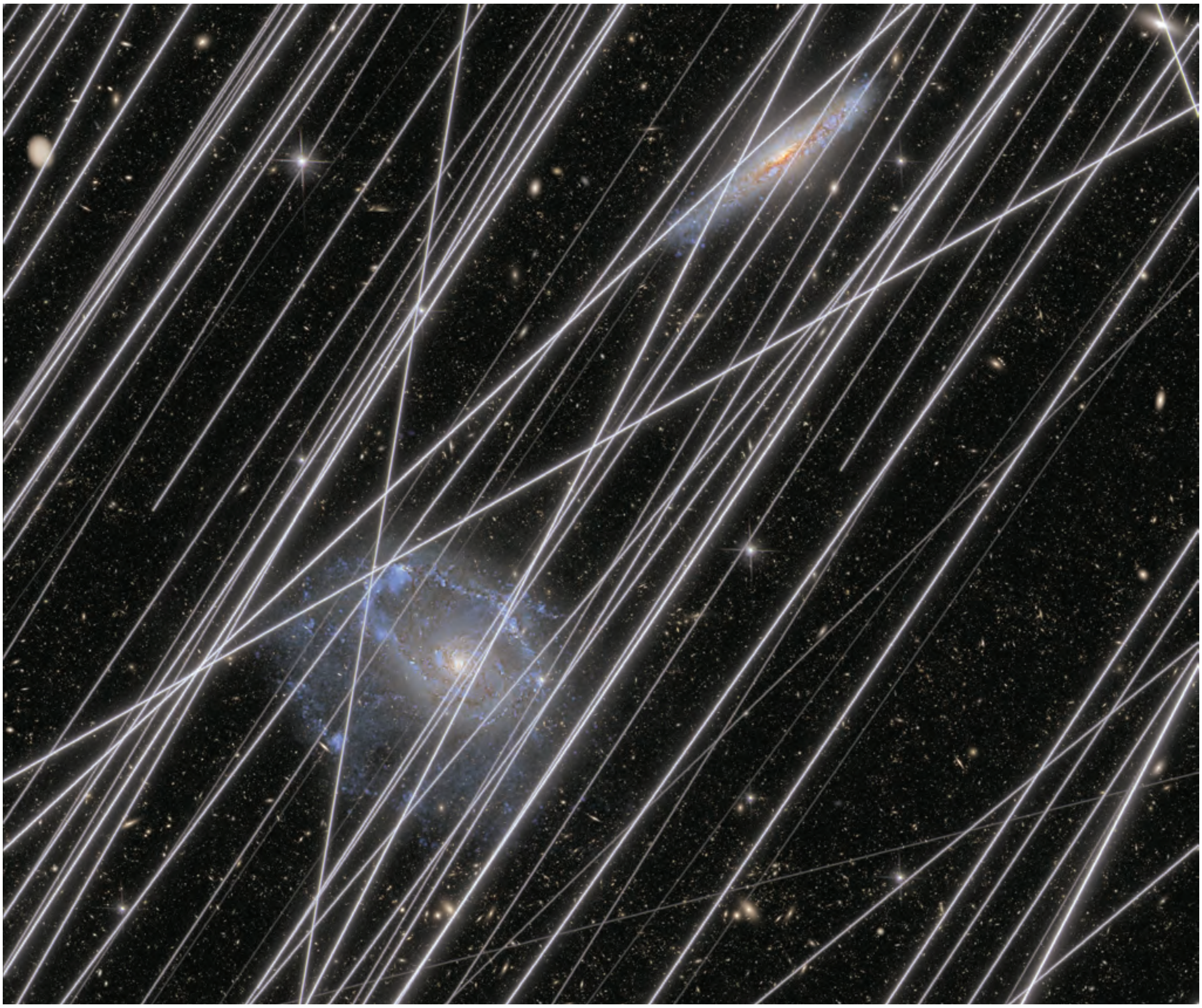


Figure 2. This simulated image for a spacecraft at *ARRAKIHS's* proposed altitude illustrates the potential effect of satellite light trails. Even a handful of streaks can result in the loss of important data. (Image from NASA and ref. 1.)

duced satellites as points of light and recorded how many times they passed each camera. The researchers found that if all the proposed satellites make it to orbit, then 30% of *Hubble*'s images and 96% of the images from the other three space-based observatories would contain at least one satellite trail. The differences between telescopes can be attributed mainly to *Hubble*'s smaller field of view. A simulated streak-filled exposure at the planned altitude of *ARRAKIHS* is shown in figure 2.

There's still a lot of uncertainty about how satellites will affect astronomical observations going forward. As examples of hard-to-predict factors, Borlaff cites how many of the proposed satellites will reach orbit, how effectively the satellites will reflect sunlight, and where the telescopes will be looking. If even a fraction of the predictions come true, however, it would still be a major blow. "The pixels themselves are lost," Borlaff says.

No single authority regulates the satellites in orbit around Earth. But that doesn't mean that nothing can be done. For example, astronomers are educating their industry partners on their work and needs. In 2024, the International Astronomical Union's Centre for the Protection of the Dark and Quiet Sky published a report with a list of recommendations, including launching satellites to lower-altitude orbits and limiting satellite reflectivity with techniques like applying light-absorbing coatings. PT

Reference

1. A. S. Borlaff, P. M. Marcum, S. B. Howell, "Satellite mega-constellations will threaten space-based astronomy," *Nature* **648**, 51 (2025).

SPECIAL OFFER

Post your REU at Physics Today Jobs Network for ***FREE***

Physics Today Jobs Network offers FREE postings to employers recruiting seasonal REUs and interns.

Your positions are redistributed across all relevant job boards in the Physics Today Jobs Network:

- Physics Today Jobs
- SPS Jobs
- AAPT Career Center
- AVS Career Center

Don't Miss Out!

Students are on the hunt for summer opportunities now.

GET STARTED NOW!

1. Visit employers.physicstodayjobsnetwork.org and select the 60- or 90-day free REU option at the bottom of the posting chart.
2. Create or login to your Physics Today Jobs Network account
3. Post Your REU

PLEASE NOTE: Valid intern-level opportunities are defined as limited-term (up to 12 weeks) employment for current undergraduates or recent Bachelor-degree recipients (within one year), with compensation in the form of a modest salary/stipend or academic credits.

PT PHYSICS TODAY JOBS NETWORK

AIP

NASA's next space telescope reaches assembly milestone

The *Nancy Grace Roman Space Telescope* will survey the sky for vestiges of the universe's expansion.

By Jenessa Duncombe

When the *Nancy Grace Roman Space Telescope*'s inner and outer portions were bolted together at NASA's Goddard Space Flight Center in Greenbelt, Maryland, last November, one might imagine a collective sigh of relief from everyone involved. In the five years since receiving a green light from NASA, the mission has navigated a pandemic, a US government shutdown, and threats of budget cuts. Now the telescope will undergo final tests before being shipped to NASA's Kennedy Space Center in Florida for launch as early as the fall.

The concept that led to *Roman* was recommended in the 2010 decadal survey of astronomy and astrophysics. A decade earlier, scientists had discovered dark energy, which putatively pervades all space and is the leading explanation for the accelerating expansion of the universe (see Saul Perlmutter's 2003 *PT* article on dark energy). The astronomical community was eager to develop a telescope that could further study the universe's expansion and probe the nature of dark energy. It was also keen to continue the exoplanet hunt of the *Kepler* space telescope, which was retired in 2018.

Over the next 15 years, teams at NASA created a space telescope that could tackle those two tasks. *Roman* was designed with a much larger field of view in the near-IR than any of the agency's previous large missions. And it was engineered to survey exoplanets that *Kepler* and other space-based technology could not detect.

Roman's distinctness comes from its massive surveying capacity. Whereas the *Hubble Space Telescope* and the *James Webb Space Telescope* excel at imaging an individual galaxy or single cosmic feature, *Roman* will image thousands of them at once. Using that wide lens, astronomers can study the brightness, distance, and distribution of supernovae, galaxy clusters, and other objects. The observa-

Technicians take in the completed *Nancy Grace Roman Space Telescope* in a clean room at NASA's Goddard Space Flight Center in November 2025. (Photo by NASA/Jolearra Tshiteya.)

tions will be relevant for answering many cosmological and astrophysical questions.

For instance, astronomers will use the survey data to further understand the nonuniformity of today's universe. Precision measurements of the cosmic microwave background suggest that the universe was almost perfectly uniform some 378 000 years after the Big Bang. Fast-forward more than 13 billion years: The universe has volumes of empty space interspersed with dense sheets and clumps of galaxies. Mapping how the large-scale structure evolved over time could provide insight into changes to dark energy.

Roman will fill a void in space-based exoplanet surveys as well. Other NASA missions, such as *Kepler* and the *Transiting Exoplanet Survey Satellite,* have identified exoplanets located one Earth's distance or less to their host star by detecting the signature of a planet transiting in front of its star. While powerful, the transit method has its limitations: If a telescope using the transit method peered at our solar system from far away, it would miss all the planets. In addition to spotting transits, *Roman* will use the microlensing method (see the 2009 *PT* article by Jonathan Lunine, Bruce Macintosh, and Stanton Peale about exoplanet detection techniques). That way, *Roman* will identify exoplanets that have orbital radii larger than Earth's distance to our Sun. Such planets are likely much more analogous with our solar system's planets.

Although most of *Roman*'s observing time will be dedicated to large surveys, the mission also will test a novel way to identify fainter exoplanets than even the most advanced telescopes today can detect. In addition to employing indirect exoplanet surveying methods such as transits and microlensing, *Roman* will attempt to take direct images of exoplanets. Direct images are much harder to capture because the light from the host star masks the faint presence of a planet. Ground and space telescopes have been able to directly image only about a dozen exoplanets, most of which are large, young, hot planets that glow brightly.

The coronagraph instrument that *Roman* will use to take direct images will be the first of its kind in space to use deformable mirrors and active wavefront control. Although it won't be sensitive enough to spot an Earth analogue, it could see the equivalent of our solar system's Jupiter in size, temperature, and orbiting distance to its host star.

A bumpy ride

The *Roman Space Telescope* has weathered numerous headwinds over its development. Shortly after the official go-ahead came from NASA in February 2020, the pandemic slowed its progress. Delays in hardware delivery, testing, and assembly caused the mission's budget to increase by nearly 10%, from about \$4 billion to \$4.3 billion, and pushed the launch date back by at least six months. The team later made up that time and is on track to meet its prepandemic launch goal. Half the mission's work was paused during last fall's government shutdown, but time-critical testing was allowed to continue. As a result, the launch date did not slip further.

So far, the mission has retained funding necessary to stay on schedule despite NASA's budget uncertainty last year. The annual appropriations bill to fund NASA this fiscal year has not been passed as of publication, but drafts of the House and Senate bills suggest *Roman* may avoid the deep cuts that were in the president's FY 2026 budget request and maintain what NASA has projected the mission will need. The funding level in a draft conference report released in early January should enable *Roman* to meet its projected launch date. **PT**

Q&A: Patricia Vader pivoted from astronomy to sculpture

She uses the same approach to problem-solving in her art as she did in her science.

By Toni Feder

"I was passionate about science as long as I did it," says Patricia Vader, who earned her PhD in mathematics and natural sciences in 1981 at the University of Amsterdam. Her astronomy career took her to Yale University, the Carnegie Observatories, and the Space Telescope Science Institute. Among other highlights, she and a colleague discovered a quasar. Eventually, though, she felt that it was time to do something else to keep herself "amused and interested and excited."

Since 2001, Vader has been a sculptor. Many of her works are large public sculptures with moving parts—on view in cities in California, Colorado, New York, Texas, and other states. (Photographs and more can be found on Vader's website, https://patriciavader.com.)

Patricia Vader (Photo courtesy of Patricia Vader.)

What drew you to science?

As a teenager, I read Sigmund Freud and Carl Jung, and I thought I would become a psychiatrist. But I was turned off by the prospect of 13 years of studies. It's a good thing because I don't think I would have done well. One of my grandfathers was a mathematician who had wanted to become an astronomer. I still have his thesis, so maybe he was an inspiration. And my father, who was an engineer, pushed me to go into the physical sciences.

I ended up in astronomy because the classes, departments, and research groups in physics were so large. It was intimidating. Astronomy seemed more accessible and a field where it would be possible to have real connections with people. And astronomy is fascinating.

Describe your educational and career paths.

From age eight, I went to school in France and for a time in Algeria. For college, I decided to return to the Netherlands, where I was born. The Netherlands had a better reputation in astronomy than France.

While I was working on my PhD, Jerry Ostriker from Princeton University and Beatrice Tinsley from Yale visited. I talked to them about my work, and they both encouraged me to visit. I spent about three months at Princeton, and then I visited Tinsley. She was a famous astronomer and the first

Wheely Whirly Peacock was Patricia Vader's first public artwork. It was commissioned by the City of Orinda in California and has stood outside the public library since 2009. (Photo courtesy of Patricia Vader.)

woman hired in astronomy at Yale. She invited me to stay with her, and we discussed all kinds of things, including music.

When I finished my PhD thesis, I spent another year in Amsterdam. I then got a job as an assistant professor at Yale. I moved to the US in 1982. Besides its excellence in science, Yale has a wonderful cultural environment, with theater and music. I was very happy there.

I started out as a theorist. But at Yale, I got involved in some observational work. I traveled to the Cerro Tololo observatories in Chile; the observatories in Tucson, Arizona; and a few other places. After Yale, from 1991, I worked at the Carnegie Observatories in Pasadena and then the Space Telescope Science Institute, where I stayed until 1994.

What made you take the leap from science to art?

While I was at Yale, I began to realize that I would rather be on the side of the performers than that of the audience. I also felt the academic

Patricia Vader's sculpture *Sunflower* was purchased by the City of Livermore in California in 2018. (Photo courtesy of Patricia Vader.)

workload was impacting my private life.

All that was in the back of my mind while I pursued my scientific career. I enjoyed working with students and going to observatories. Computers became too prominent for my taste and changed the way people worked. It became possible to observe remotely. I was not too happy about it.

Later, the Space Telescope Science Institute was not a positive experience for me. It felt more like a business than a university. When budget cuts demanded a reduction in staff and an attractive financial bonus was offered for voluntary leave, I took it.

Was it a difficult decision to go into art?

It's odd to say, but it's true: My father died while I was at Yale, and I'm not sure I would have had the courage to tell him that I was leaving science. When your parents die, you don't have their constraints anymore. That kind of facilitated this step. And I was aware of that.

Did it feel financially risky?

Yes, it was risky. But you know, Yale didn't pay much either. The first time I got any real money was at the Space Telescope Science Institute. I didn't do any of it for money—as long as I had enough to get by on, that was okay.

Have you missed science?

No. I really felt that I had done everything in science that I wanted. I had explored the venues that I wanted to explore. And I had a good life doing it. It was a busy life. When I read now what I did, I don't know how I managed it all: the traveling, the meetings, the exchanges. I had done all that, and it was all wonderful. And I think the prospect for me of doing the same thing for another 30 years was not appealing. I wanted to get out of it.

How did you go about shifting careers?

Not having ever had any training in art, I wanted to enroll in an art school. I spent a few years taking various classes and building up the required portfolio. I was admitted to the California College of the Arts in San Francisco as a graduate student in painting. After a few months, I realized I was not learning much, and I lost interest in the format. I had started doing some 3D work and decided I would learn more if I went into the sculpture program. I had to convince the school to let me. It meant an extra year of school, but I didn't mind. I found sculpture really exhilarating.

Tell me about your sculptures.

After graduating in 2001, I moved to a large property that was formerly ranchland. I still look out at cows grazing in the field. The move changed the scale of things I made because I could work outside.

The first summers on this prop-

Sky Ride, Patricia Vader's 2023 sculpture in Cass Park in Ithaca, New York, was commissioned by the local Community Arts Partnership. (Photo courtesy of Patricia Vader.)

erty were very windy, suggesting kinetics. With a bicycle wheel at hand and a tin full of thin stainless steel disks, I made my first windmill mounted on a rotating bicycle fork. It still spins and rotates and has never had to be regreased. From there, I proceeded to larger kinetic sculptures, relying on an innate sense of balance and aesthetics.

A landscaping friend of mine, who saw my work and sat on the Orinda, California, Art in Public Places Committee, asked if I would be willing to make a sculpture for her hometown.

I had dreamed of a sculpture with a large number of windmills for some time, a giant peacock. I made the peacock. In 2009, it was installed in front of the library in Orinda. It's still there. That was my first public artwork. It was gigantic and well received. That set me on the course of public art.

There are all kinds of legal liability issues at stake with public art. Making big things is challenging. The artist is responsible if something fails or goes beyond budget. I used certified welders, engineers, and contractors for public art projects. I bought a pickup truck to transport the sculptures and took my large German shepherd for company and safety on many long trips across the country. I did public art for about 15 years, and I loved it.

I still deliver large sculptures on loan to cities.

What do you want people to take from your public art works?

I create figurative work in a contemporary style that speaks of my passion for life. My art is tinged with elements of levity, whimsy, and humor. My objective in public art always is to lift people's spirits with an engaging surprise, which naturally flows out of my own desire and need to keep myself challenged, amused, and excited by what I do.

Have you been able to make a living as an artist?

Not really. I had other support. I have sold roughly one big sculpture a year—either on loan or commissioned. That's pretty good.

Does your physics background feed into your work as a sculptor?

It's the way of thinking and approaching problems. You use the same brain training in science and in art. At least I do. Basically, it's problem-solving. In art, you envision a sculpture and then figure out how to do it in all facets, practically and aesthetically and with the motion. It involves the same abilities as in science to think things through—for example, calculating wind load—and get a result. PT

The arXiv server to require English version with submissions

The availability of free translation software clinched the decision for the new policy. To some researchers, it's anathema.

By Toni Feder

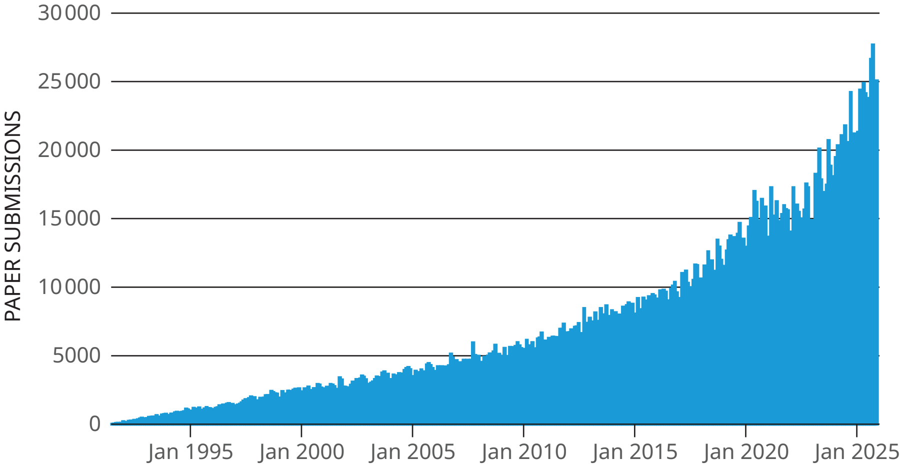
Effective 11 February, the arXiv preprint server is requiring authors to submit papers in English or with a full English translation. Within several weeks of publication, the November arXiv blog post announcing the change received more than 45 comments opposing the new rule. The administrators of the server say that is record pushback from the science community. "It was not a 100% comfortable decision," says Ralph Wijers, an astrophysicist at the University of Amsterdam and chair of the arXiv Editorial Advisory Council. Two issues, he says, held sway: Moderators can't judge the appropriateness of submissions in languages they can't read, and papers in English can reach a broader audience.

Researchers in physics, astronomy, quantitative biology, economics, and other fields use arXiv. The server hosts nearly 3 million preprints and receives, on average, roughly 24 000 submissions and tens of millions of downloads per month. (To read about the origins of the server, see the 2021 *PT* story "Joanne Cohn and the email list that led to arXiv.") The number of submissions per month is growing, in part because of AI-written papers. Non-English papers make up about 1% of the submissions, according to arXiv administrators. A 2005 French-language algebraic geometry paper with, according to Google Scholar, 1212 citations is an example of an influential one.

Until now, authors had to include an English abstract, but their papers could be in any language. Under the new policy, authors can still submit in other languages, but they have to include an English translation of the full paper.

The arXiv editorial board had been talking for several years about requiring that papers be submitted in English, Wijers says. The triggers were the growth in submissions and the availability of free, adequate translation software, he says. "We want to be fair to moderators and give the papers the widest reach."

Although preprints published on arXiv are not peer reviewed, moderators look them over to make sure they are suitable. Some 300 experts around the world volunteer to make sure submissions are "not AI slop, not all false, and are in fact scientific papers," says Licia Verde, a Catalan Institution for Research and Advanced Studies professor of theoretical physics at the University of Barcelona and the chair of the arXiv Science Advisory Council. "It needs to be something that an editor of a journal would send to a referee."



▲ The numbers of preprints submitted monthly to arXiv has steadily grown in the past three decades. (Graph data from arXiv.org monthly submissions page.)

Having authors submit translations reduces the burden on the moderators, notes Wijers. When he previously moderated submissions in high-energy astrophysics, he says, he spent about 30 seconds on each paper. “I couldn’t afford to spend more than half an hour per day.”

Much of the online opposition to the new policy comes from French mathematicians. Among the objections they and others raise (not all of which were posted in English) are that “putting English first as this policy does treats the hundreds of non-English human languages as second-class participants in the global conversation” and the policy “raises further barriers to participation in science and mathematics.” Another poster wrote that “important articles will be read in any language.” Several people posted that they might or would stop using arXiv because of the policy, and others offered their services as moderators in various languages.

Jean-Pierre Bourguignon is a former president of the European Research Council who is now an honorary professor at the IHES (Institut des Hautes Études Scientifiques) outside of Paris. He notes that arXiv plays a “key role” for mathematicians, physicists, and computer scientists worldwide. The move, he says, caught him by surprise and “is certainly not going to be a solution” that contributes to making arXiv more international.

Several posters noted that the moderators could translate submissions as needed. But, says Verde, it’s better for authors to retain control over their own work and how it is presented. Wijers notes that leading scientists worldwide must have decent passive knowledge of English.

Steinn Sigurðsson, an astrophysicist at the Pennsylvania State University and arXiv’s scientific director, says that “the intent is to encourage more foreign-language papers,” rather than to squeeze out submissions in other languages. The server will be able to accept a lot more foreign-language papers under the new policy, he says, because the moderators “will be able to curate the content from the translated version.”

Wijers says that arXiv will revisit the issue in a couple of years. “I don’t expect this to be permanent,” he says. In five or so years, he says, translation software may be good enough that arXiv could include an option on its website to translate on the spot. **PT**

NSF changes grant review requirements

By Lindsay McKenzie

NSF is reducing the number of external reviewers required for evaluating its grant proposals. Previous guidance required a minimum of three external reviewers for most grants. But a new policy, according to a 1 December memo to agency staff and obtained by *Science*, drops that requirement to two reviewers, and in some cases only one needs to come from outside the foundation. That and other changes to the agency's grant review process were also mentioned in a policy notice issued on 8 December.

According to the staff memo, the policy changes are intended to reduce the burden of the grant review process on NSF's staff. But some critics say the changes may reduce the agency's ability to select the best proposals.

The National Science Board, which oversees NSF, released a report around the same time that proposes multiple updates to NSF's grant review policy. The report's recommendations include aligning NSF's award portfolio with national priorities and inviting expert reviewers from a broader swath of industries, research institutions, and regions of the country. The board also recommends renaming the "broader impacts" criterion for grants as "societal benefits." The broader impacts review criterion is required by statute and includes diversity objectives.

Annual defense law includes research security measures

By Lindsay McKenzie

Signed by President Trump in December, the 2026 National Defense Authorization Act (NDAA) includes several research-related provisions.

The law includes the Senate-proposed BIOSECURE Act, which bars agencies from contracting with or making grants to biotechnology companies from "foreign adversary" nations, notably China. It also includes the 2026 Intelligence Authorization Act, which covers intelligence agencies and contains provisions relating to AI and biotechnology.

The NDAA also includes the Comprehensive Outbound Investment National Security Act, which calls for sanctions and regulations aimed at prohibiting investment in and private deals with Chinese, Cuban, Iranian, North Korean, Russian, and Venezuelan entities that are engaged in developing dual-use strategic technologies. The law lists semiconductors, AI, high-performance computing, and quantum information and hypersonic systems, and it allows for other technologies to be added in the future.

The NDAA features various provisions for nuclear energy and weapons, including one that calls for the creation of an advanced nuclear transition working group. Its goal is to advance the priorities laid out in a May executive order that aims to drive research into new reactor concepts for energy applications and to increase the deployment of reactors for both civilian and military uses.

The law also directs the Defense Department to produce reports and briefings on projects related to Trump's Golden Dome missile defense program. The architecture would consist of a vast array of ground- and space-based sensors and interceptors capable of protecting the entirety of US territory. The NDAA prohibits the department from developing Golden Dome capabilities that are not owned and operated by the armed forces.

Several notable proposals failed to make it into the law's final text. The SAFE Research Act, a research security bill in the House version of the NDAA, was not included. It would have prohibited federal grants to any researchers and institutions that have broadly defined affiliations with "hostile foreign entities."

A White House–backed proposal to block states from regulating AI also did not make it into the NDAA. Trump preemptively signed an executive order in December that aims to create a similar prohibition. **PT**

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


aip.org
FYI: Science Policy News
from AIP
35+ years of authoritative US science policy news and analysis.
Trusted by policymakers and scientists nationwide.
Subscribe to get FREE
access to policy tracking tools and timely news.
AIP

Celebrations of the international quantum year

Toni Feder

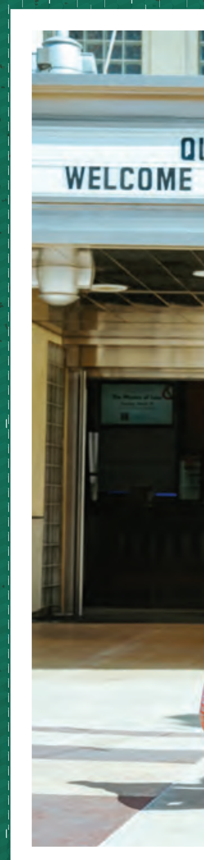
Events held around the world have recognized the past, present, and future of quantum science and technology.

Between the kickoff for the International Year of Quantum Science and Technology (IYQ) in February 2025 at UNESCO headquarters in Paris and the closing event this month in Ghana, more than 1000 quantum-related activities large and small have taken place around the globe. They have included conferences, public lectures, hackathons, theatrical performances, art exhibitions, and poetry and photo contests.

The goal of the IYQ was to create awareness and get the gears turning for building a more inclusive and responsible quantum ecosystem, says Claudia Fracchiolla, head of public engagement at the American Physical Society. "I think it's achieved that."

The following photos provide a taste of the activities that scientists, institutions, governments, and others organized over the past year.

Toni Feder is a senior editor at *Physics Today*.



The public Quantum Jubilee kicked off a weeklong festival that took place during the American Physical Society's Global Physics Summit in Anaheim, California, in March 2025. The performances included *Quantum Voyages*, an original piece by Smitha Vishveshwara and Latrelle Bright that follows the adventures of two explorers in the quantum realm: In one scene (top left), they find themselves inside a minuscule metallic crystal and battling a Fermi sea of electrons. (Photo by James Gross.) In another (top right), the spirit of Erwin Schrödinger shares the conundrum of his dead-and-alive cat. (Photo by Trity Pourbahrami.) In a performance by Le Petit Cirque (bottom right), acrobats engage in a dance of merging black holes while below them physicists on stage discuss astrophysical discoveries. (Photo by Katie Clark.) At bottom left, Le Petit Cirque artists perform at the theater entrance. (Photo by James Gross.)

(Design by Masie Chong with artwork adapted from iStock.com artists desifoto, Mironov Konstantin and Ardkyuu.)

A model of the IBM Quantum System One computer is on display at Chicago's O'Hare International Airport. Installed in September, it will remain for at least a year. The Scientists, Technologists, and Artists Generating Exploration Center at the University of Chicago created the exhibit in collaboration with IBM and United Airlines. (Photo by Anne Ryan.)

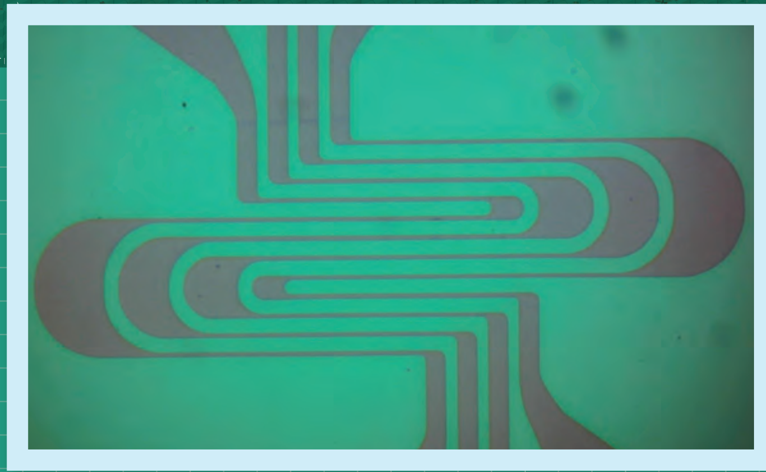
Wave and light experiments were on show at a festival in October at the National Autonomous University of Mexico. (Photo by Evelyn Ayala.)

A debate on quantum mechanics and society held in May was popular with the public in Trieste, Italy. (Photo courtesy of Elisabetta Gregoric, Trieste International Foundation.)

Researchers from Koforidua Technical University in Ghana receive the first-place prize in a contest for quantum innovation. The award was presented in August at the 2025 Africa Regional Conference on Education and Skills Development. (Photo courtesy of ESDEV Foundation Africa.)

Peter Knight, quantum optics and information scientist, looks back on 100 years of quantum science in a keynote talk at the UK Royal Society IYQ opening event in February 2025. (Photo by Louis Barson/Institute of Physics.)

A suitcase carrying a single-photon-emitting artificial atom, during a stop at the Eiffel Tower in Paris (photo by Hêlio Huet) and changing hands in Rome (photo by Fabrizio Mercoli). On its journey, known as QuanTour, the suitcase visited laboratories and tourist sights across Europe.



Star Trails (left) juxtaposes a fixed bicycle with streaks of starlight to represent movement in space and time. It took first place in the At a Glance category of a quantum-themed photo contest organized by the International Union of Pure and Applied Physics. (Photo by Vishwesh Tiwari.) To represent progress for photon-based quantum technologies, *A Microscopic Detector Toward Quantum Innovation* (above) depicts a superconducting microstrip detector. It took third place in the category Beyond Our Eyes. (Photo by Pasquale Ercolano.)

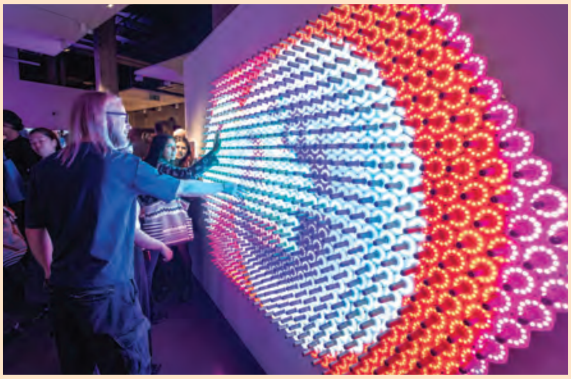
Rajamani Vijayaraghavan (seated) receives the Pancharatnam Prize for Excellence in Quantum Science and Technology at an IYQ event in Bengaluru, India, last summer. (Photo courtesy of Quantum India Bengaluru Secretariat, Department of S&T, GoK.)

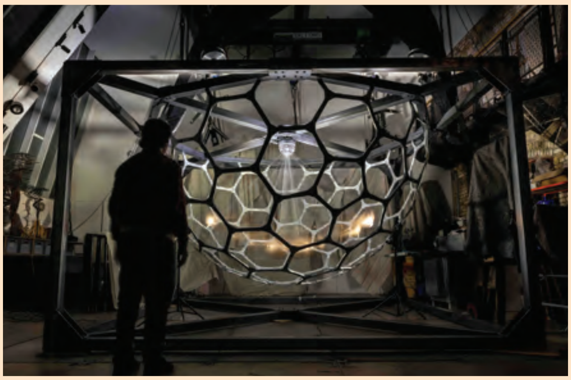
Panelists at a discussion for the public on quantum science and technology in April. The event was organized by the Nepal Physical Society and Rajarshi Janak University and hosted by the Monastic College of Management and Technology in Janakpur, Nepal. (Photo by Hari Shankar Mallik.)

Quantum Unplugged hosted members of Geneva's diplomatic community at CERN in May. The initiative explored quantum mechanics and quantum computing. (Photo courtesy of the Open Quantum Institute.)

A consortium that includes the University of Geneva, CERN, and Rolex launches the Geneva Quantum Network on Quantum Industry Day in October. (Photo by Louis Nausch.)

Undergraduate physics student Aya Abdel-Hayy presents her painting, *Savoring the Universe—Can the Infinite Be Contained Within the Finite?*, at Mind-Blowing Physics, a day of hands-on activities celebrating IYQ and the International Day of Light at the University of Jordan in July. (Photo courtesy of the LAMBDA Physics Group/University of Jordan.)





The art exhibition *Quantum Untangled* at Science Gallery London runs through late March 2026. It includes (from top) *Quantum Jungle*, by Robin Baumgarten (photo by George Torode) and *The Blind Proliferation* and *Ringdown*, both by Conrad Shawcross (photos, courtesy of the University of Nottingham, by Nick Dunmur and Richard Ivey, respectively).

In honor of IYQ, MIT undergraduate Marc Vidal aims to levitate a person with a device he is building using superconductors and magnets on a track. As of press time, he had levitated a 4.6 kg block of copper with a prototype device. (Photo by David Fischer, MIT.)

Physics Nobel laureates Frank Wilczek (left) and Duncan Haldane (right) and IYQ steering committee member Smitha Vishveshwara (center) cut quantum-themed cakes at the Quantum Connections summer school in Högberga Gård near Stockholm. (Photo by Antti Niemi.) School activities also included summer solstice festivities. (Photo by Smitha Vishveshwara.)

At a quantum science slam in Berlin on World Quantum Day in April, participants gave short, entertaining synopses of their work. (Photo by Mauro Franceschetti, courtesy of the Deutsche Physikalische Gesellschaft and Humboldt Innovation.)

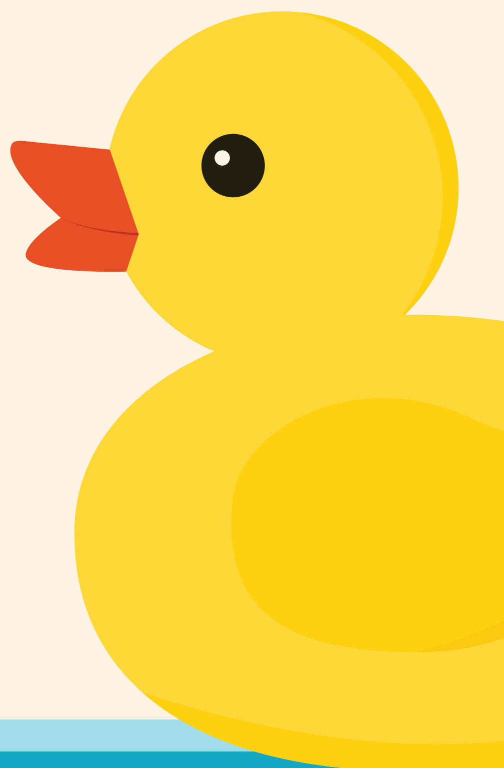
Artists, engineers, policymakers, and cultural leaders gathered in Dunedin, New Zealand, for a global IYQ event in July that focused on the intersection of art and quantum science and technology. The event kicked off with a Maori ceremony welcoming participants to the ancestral land of the Kāi Tahu tribe. Participants went through a traditional gateway (left, photo by Omar Costa Hamido) and convened in the tribal meeting house (right, photo by Jessa Barder). The hybrid event included talks, a roundtable discussion, and a presentation on the synergies between local indigenous knowledge and quantum theory.

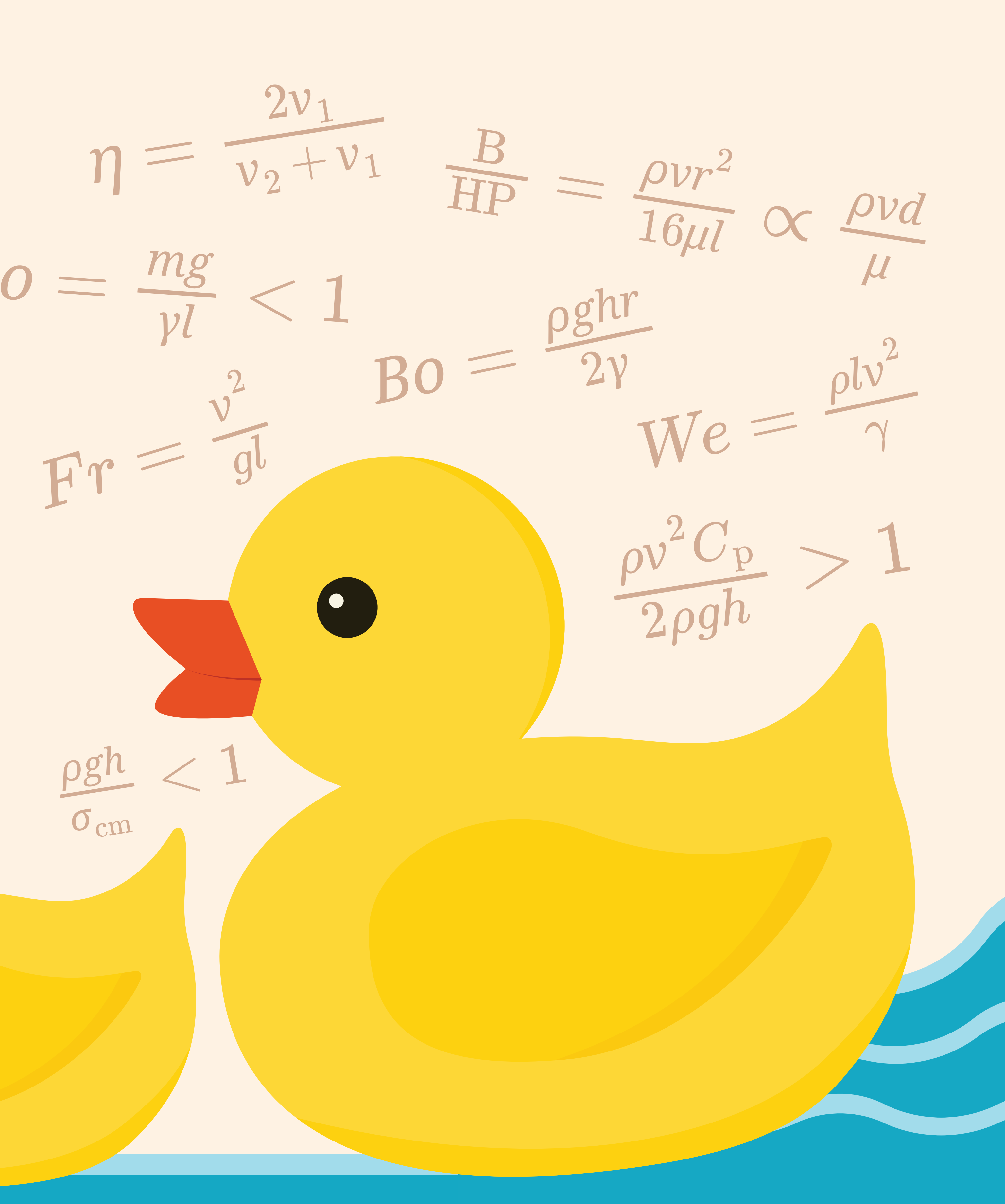
FROM THE ARCHIVES
November 1998

Exposing life's limits with dimensionless numbers

Steven Vogel

A crude device for quantification shows how diverse aspects of distantly related organisms reflect the interplay of the same underlying physical factors.





(Design by Masie Chong with artwork adapted from iStock.com artists IRYNA NASKOVA and Giorgi Gogitidze.)

The impressive performance of evolution as a design mechanism needs no belaboring. Physics, though, constitutes a larger reality that evolution can no more transcend than a cow can jump upward at escape velocity. Enzymes cannot act as Maxwellian demons, nor can birds turn off gravity. Physics limits life's designs no less rigidly than it constrains our own technology.

But how, in practice, can we locate the limits that the physical context sets on life? At least for understanding its macroscopic, mechanical aspects, a device long used by engineers in particular proves to be useful. Surprisingly often, boundaries get set by the interplay of two competing factors, and their ratio, expressed in dimensionless terms, provides us with at least heuristic guidance.

As a simple if fanciful example, consider the limits to stacking. The ratio of the stress on the pile's base to the compressive strength of the blocks' material cannot exceed one. Or,

$$\frac{\rho g h}{\sigma_{\rm cm}} < 1,$$

where ρ is the density of the material, g is the strength of gravity, h is the height and $\sigma_{\rm cm}$ is the material's ultimate compressive stress or crushing strength. Inserting values, we find that ordinary bricks run into trouble at a height of less than 400 meters, but granite can be piled to nearly 5000 meters; bone and wood do better, and a pile of either could exceed 8000 meters. So simple gravitational loading imposes no serious design limitation. Doing the same thing for tensile loading gives the length at which a cable breaks from self-loading alone. It exposes the impossibility of lowering a rope to Earth's surface from a satellite in geosynchronous orbit, a notion both raised and shot down back in 1966 by a group at the Woods Hole Oceanographic Institute.[1]

Dimensionless numbers are usually offshoots of their parent subject, dimensional analysis, and hundreds have been defined and named.[2,3] Most consist of the ratio of two forces, such as viscous and gravitational. But they can be contrived without formal analyses, with just an eye to practical utility. They typically permit simple but still quantitative views of complicated physical phenomena. Biology, cursed by complicated phenomena, needs even such relatively crude tools.

Dimensionlessness holds an additional appeal for biologists. It can keep size from confusing an analysis, which is no small matter for a field whose subjects encompass lengths spanning eight orders of magnitude. For instance, the ratio of surface area to volume is important when looking at the sizes of cells, at swimming speeds and at metabolic rates, but its values reflect both size and shape. If something (sinking rates of plankton, let's say) varies with surface-to-volume ratio, either shape or size may be responsible. A dimensionless version, such as the ratio of surface cubed to volume squared, depends on shape alone. Something shape dependent will vary with this cubed/squared ratio, while a purely size-dependent phenomenon won't.

Swimming, gas extraction, gait changes

William Froude (1810–79) first devised a useful way to extrapolate performance data from small model ships moving slowly to full-size ships at their intended speeds. We now use a scaling parameter that bears his name for a lot more than ensuring dynamic similarity between model and ship. One way to get the Froude number is by taking the ratio of the inertial force that keeps the water within a wave moving to the gravitational force that prefers the water's surface to be flat. Thus,

$$Fr = \frac{v^2}{gl},$$

where v is the speed at which the waves move across the water's surface and l is the distance between adjacent crests. (Sometimes the square root of the relationship is used as the Froude number.) Waves move at a specific Froude number. So longer waves travel faster than shorter ones, at least in the range (lengths greater than a few centimeters) where inertial and gravitational forces are what matter.

A surface ship with an ordinary water-displacing hull creates waves as it moves. In particular, it makes a bow wave in front and additional waves along its length and at its stern. At full ("hull") speed, it's left with a bow wave and a stern wave, the two separated by the length of the ship's hull. All is well as long as the ship doesn't exceed the speed that waves of that length will travel. Going faster than the critical Froude number of about 0.16 requires that the ship leave its

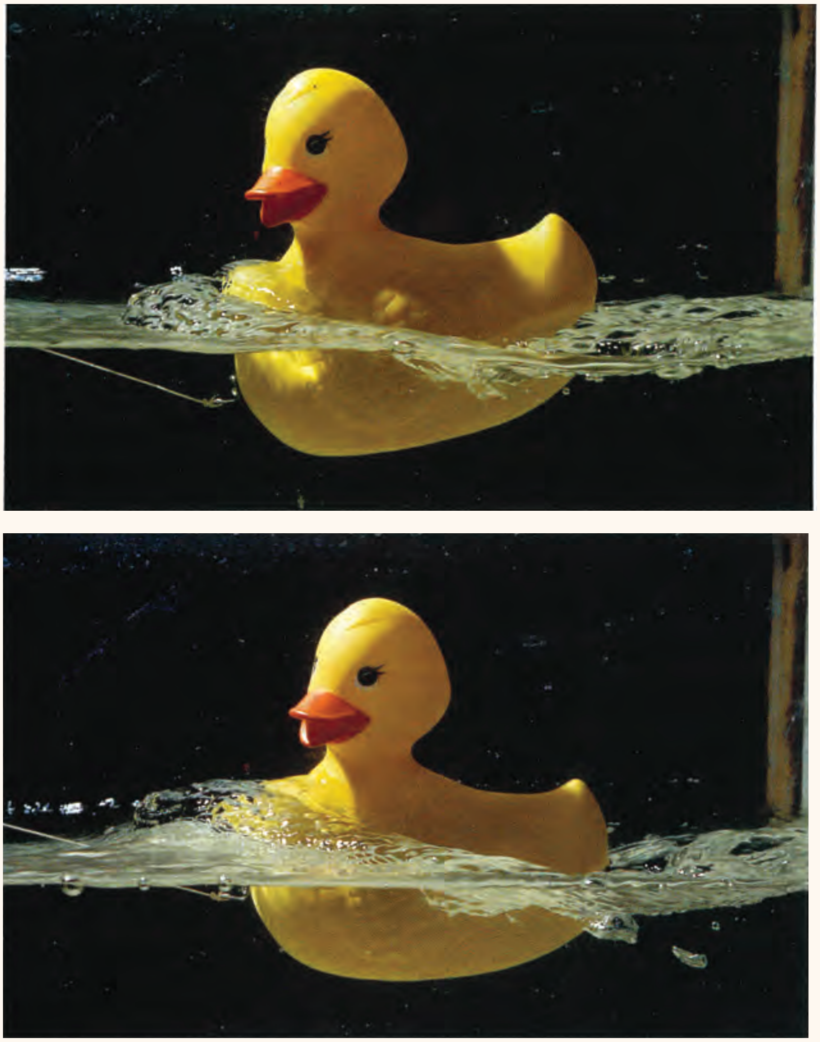


Figure 1. Rubber ducky being towed in a flow tank just under **(top)** and just over **(bottom)** its hull speed. Notice that at the higher speed this small surface ship tips upward and its stern wave disappears.

beneficent stern wave astern and try to cut through or climb up its bow wave. That's why getting ahead becomes an uphill battle, as the small ship of figure 1 discovers. Crucial here is the longer-is-faster rule, which permits the longer ship to go faster before reaching the point at which its power requirement rises steeply.

Surface ships are practical, in short, when they're long. A 100 m long ship reaches hull speed at about 13 m/s, or 28 mph, whereas a 10 m long ship can do only 4 m/s, or 8 mph—or just a little more with a clever hull design. That's why animals find that swimming with a displacement hull on the surface is such a bad deal relative to swimming fully submerged. A duck, with a hull length of about a third of a meter, hits hull speed at 0.7 m/s, or 1.6 mph. Fully submerged, it can swim several times as fast.[4] Terrie Williams of the University of California, Santa Cruz found that above hull speed, mink towed along the surface had up to ten times as much drag as they did when fully submerged.[5]

The value of that critical Froude number shows why decent surface speeds are off-limits for the sizes of most of nature's craft, why even its air breathers mostly swim submerged. An occasional animal porpoises up and down through the interface or planes on the surface, but only a large whale could consider migrating as a surface ship. Snorkeling is rare, perhaps because swimming deep enough to keep wave drag low requires breathing against too much hydrostatic pressure—an argument originally raised by Knut Schmidt-Nielsen of Duke University for why long-necked dinosaurs couldn't have walked around largely submerged.[6]

Mention of hydrostatic pressure brings up another limit for which the Froude number provides insight. Consider an organism attached to a rock beneath flowing water while it manages to hold on to a bubble of air. The flow of water, by Bernoulli's principle—that a fluid's velocity and static pressure vary inversely—will reduce the pressure in the bubble. So while the very front of the bubble may be subjected to an inward dynamic pressure, the rest will be drawn outward. If sufficient air is dissolved in the water, oxygen and nitrogen will diffuse into the bubble, which could act as a permanent lung. And the water of rapid streams is usually equilibrated with the atmospheric air above. But the subambient pressure in the bubble isn't necessarily subatmospheric, for ambient pressure increases hydrostatically with depth. Pressure reduction in the bubble follows Bernoulli's principle, so it depends on the square of the flow speed. For the bubble to provide a permanent lung, the ratio of the flow-induced pressure decrease to the hydrostatic pressure increase (inertial and gravitational forces, again) must exceed one, or,

$$\frac{\rho v^2 C_\mathrm{p}}{2\rho g h} > 1,$$

where h is the depth and C_p is an empirically determined pressure coefficient.[7]

For small bubbles, C_p will be about 0.2, so the critical depth can be expressed as a Froude number v^2/gh of about 10, with h now indicating depth. That's a severe constraint: For a brisk water speed of a meter per second, the lung will persist only down to a depth of a centimeter. To go down a full meter would require a 10 m/s flow, a speed encountered only in waterfalls and large, breaking waves. At least a few organisms do use the device—a West African beetle that dives into shallow, rapid streams and grazes on the algae on their rocky floors, and the pupae of some midges (figure 2) attached to rocks in torrential streams.[8,9] But we're no longer surprised by the rarity of the scheme.

An application of the Froude number both more general and closer to home was pointed out by R. McNeill Alexander of Leeds University.[10] He noted that in a walking gait, an animal uses gravitational energy storage in pendulum fashion to reduce the work of repeatedly accelerating inertial legs. Animals of all sizes should walk in a dynamically similar manner at a given Froude number, when length in the formula is redefined as the hip-to-ground distance. To keep storing energy as they walk faster, animals increase amplitude, or stride length, rather than frequency. Dynamic similarity implies that all will reach the practical amplitude maximum at about the same Froude number, which turns out to be between 0.5 and 0.6. At that point, animals ranging from small insects to large mammals shift to a trot or some other gait that uses elastic energy storage (mainly in tendons) instead of

Figure 2. Pupa of a midge with a bubble between its gills, together with several larvae of the same species—*Neocurupira chiltoni* (in the blepharocerid family). The bubble acts as a permanent lung, with air diffusing into it from the flowing water. (Photo courtesy of Douglas Craig, University of Alberta.)

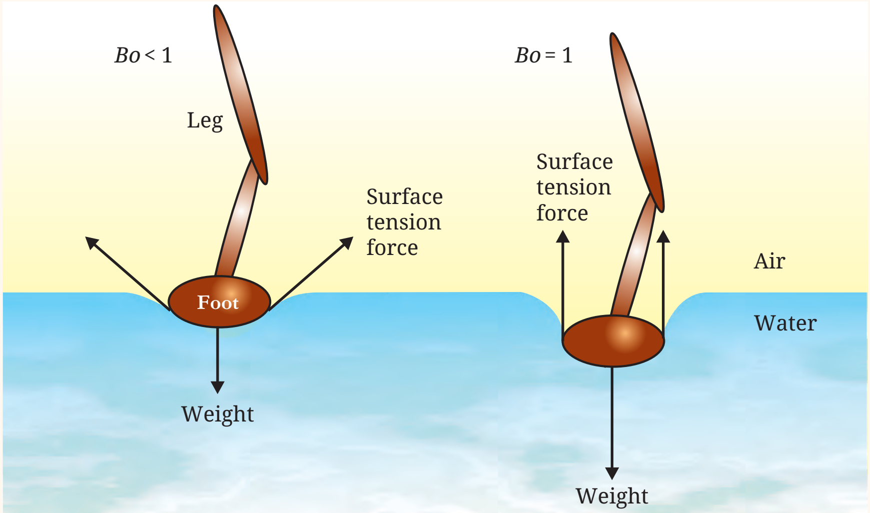


Figure 3. Walking on water. The schematic diagram shows legs pressing on the air–water interface where surface tension is more than adequate for support (Bond number *Bo* < 1), and where the weight of the animal just reaches the force that can be sustained by surface tension (*Bo* = 1).

gravitational storage. The transition point, of course, is size dependent. You can walk comfortably while the youngster holding your hand prefers to jog. For a typical adult, the gait transition happens at about the expected 5 mph—try it. Recently, Rodger Kram and his coworkers at the University of California, Berkeley found that the transition happens at the same Froude number even when the value of gravitational acceleration is altered.[11]

Alexander noted as well that the trot-to-gallop transition for quadrupeds occurs at Froude numbers between 2 and 4, still a fairly specific transition point considering the size range involved. This is puzzling, because neither gait involves gravitational energy storage. The explanation may turn not on the upper speed limit of trotting but on the lower limit of galloping—an animal is in free fall for a time within each stride, and it ought to tolerate a fall of a fixed fraction of leg length. So gravity can reasonably reenter the picture. If the period of falling is a fixed fraction of stride duration and if running speed at transition varies with leg length times stride frequency (which is supported by observations),[12] then the Froude number ought to set that transition point.

Walking on water, getting sap up the tree

For us, water's high surface tension is a mild nuisance ordinarily mitigated by a dose of detergent. For other organisms, typically smaller than we, it can be a major player in their physical world. Quite a few creatures can walk on water, pressing legs into the interface and using the upward component of surface tension for support. But they are mainly insects and spiders that span a narrow size range of about a millimeter to a centimeter or two in length. A pair of dimensionless numbers sheds some light on the bounds of their window of opportunity.

The upper size limit ought to involve, as competing factors, the upward force of surface tension and the downward force of gravity. If the animal isn't to fall through, the ratio of gravitational force to surface tension force, the Bond number, should be less than one:

$$Bo = \frac{mg}{\gamma l} < 1,$$

where γ is the surface tension and l is the wetted perimeter, which is the length of the air-water-leg interface (figure 3). Assuming unpolluted water, a human wearing my size 9C sandals could weigh no more than 10 grams to stand or 5 grams (one leg supporting) to walk. But an insect weighing a tenth of a gram needn't be bizarrely shaped—1.3 mm will do for a perimeter, which a water strider, for instance, can divide among four contacting legs. A fringe of hydrophobic foot hairs gives it lots of leeway. For that matter, some creatures can jump vertically from the surface, which demands support by an upward force an order of magnitude greater. Ignoring shape and substituting density times length cubed for mass shows that the Bond number varies with length squared. So larger is very much worse.[13]

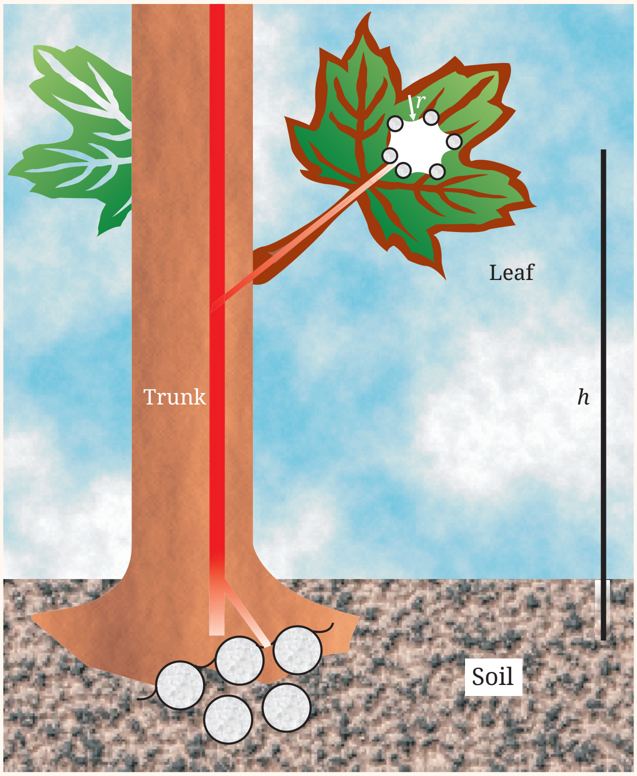


Figure 4. Continuous columns of liquid sap, nearly pure water, run up a tree and connect the water between soil particles with the wet walls of the cells within the leaves that contact the air. Supporting the columns of height h, as well as offsetting the pressure losses due to flow and capillary forces within the soil, requires that the radius of curvature r of the final air–water interfaces be very small.

What about the lower size limit? Here the problem isn't support but locomotion. The water's surface tension will pull against an animal whichever way it tries to move. Can it get enough inertial force to offset the force of surface tension? Put another way, it needs a sufficiently high value of the ratio of those forces, given by the Weber number,

$$We = \frac{\rho l v^2}{\gamma},$$

not to find the surface a fatal trap. So the animal has to be sufficiently large and fast; because size and speed are ordinarily correlated, that makes real trouble for really tiny creatures. As D'Arcy Thompson, the greatest prose artist among biologists, put it, "A water beetle finds the surface of a pool a matter of life and death, a perilous entanglement or an indispensable support."[14]

The interplay of gravity and surface tension may be still more important in quite a different biological context. The columns of liquid sap within even the tallest tree extend, uninterrupted by gas, from roots to leaves. Could capillary rise account for the ascent of sap? Assuming perfect wetting of the walls of the conduits, the upward pressure will be twice the surface tension divided by conduit radius, so we can write that Bond number as

$$Bo = \frac{\rho g h r}{2\gamma}.$$

For the Bond number not to exceed one with a typical conduit radius of a twentieth of a millimeter, the rise h must remain below about 3 m. That wouldn't be much of a tree; capillary rise simply won't do the job.

In the generally accepted picture, columns of sap are maintained by the considerable internal cohesion of water, in essence hanging from the tops of trees and drawn up by evaporative water loss from the leaves, as in figure 4.[15] Putting aside the matter of cohesion, we can ask how the columns can remain open to the air at the top. Put another way, we can ask why, since water vapor quite clearly leaves the leaves, air doesn't enter. Here the relevant interfacial radius is much smaller, about a ten-thousandth of a millimeter for the pores in the walls of cells within the leaves. With this radius, the Bond number won't rise above one and air won't be pulled in by gravity until a tree exceeds 1500 meters in height—over an order of magnitude higher than any tree ever known. So trees are not limited in height on this account, and they have lots of margin for pressure losses from flow in the conduits and from extracting water from soil.

Two matters of circulation

Perhaps nowhere does physics so strongly constrain the arrangements of organisms as in their systems for moving fluids through themselves. Surface tension may play a much smaller role in animals than we noted in plants, but gravity matters as much to a large, terrestrial animal as to a tree. And sucking with subambient pressures is a game played largely by plants, with their noncollapsible piping; siphoning has been persuasively excluded even for giraffes and thus most likely for dinosaurs. So, lacking much in the way of auxiliary pumps, we need hearts that can pump blood up to our heads with enough pressure left to drive blood through arterioles and capillaries. (See the article by George J. Hademenos on the physics of cerebral aneurysms, *Physics Today*, February 1995, page 24.)

Trouble ensues if an animal has a height, expressed in units of blood pressure, that exceeds its systolic blood pressure, the peak output of the left ventricle. That's a rough-and-ready criterion: On the one hand, one's heart isn't in one's feet, and so body height overstates the hill to be climbed, while on the other hand, systolic pressure overstates the pressure drop available to supply the brain. Still, we can define what we could call "circulatory hazard" as the ratio of manometric height (blood density times gravity times height) to systolic pressure, and assert that it ought to stay below one.

What happens in mammals proves intriguing. Most mammals have about the same resting systolic pressure as we humans—120 mm of mercury, corresponding to a manometric height of about 1.7 m or between 5 and 6 feet. That works for cat, dog or human, but species much taller than we increasingly depart from the typical mammalian pressure. Horses run about 180 mm Hg at rest, and giraffes get as high as 300.[16] So humans are near the inflection point where a plot of manometric height against blood pressure, as in figure 5, begins to slope upward—as necessary to keep the circulatory hazard below one. If I stand up suddenly after sleeping horizontally, I get a bit dizzy, which I'm told indicates that I'm not hypertensive. Our cat should have no such problem.

For aquatic animals, living in a medium near blood density, height and posture are of little concern, so whales have normal mammalian pressure and sea snakes have the normal reptilian pressure of around 40 mm Hg. A terrestrial snake is okay on the ground, but how can it climb a tree without passing out? Tree-climbing snakes keep their circulatory hazard under control by a heroic adjustment—their hearts are located considerably nearer their front ends. One wonders about long-necked dinosaurs; they must have had the fully separate systemic and pulmonary circulations of present birds (and humans), together with the high pressures of giraffes.[17] Physics, again, doesn't bend for evolution.

Physiology textbooks often begin their section on circulatory systems by talking about Bernoulli's principle. Only a few ever mention Bernoulli again—probably a good thing, as we'll see. Consider what should happen if a fluid pulses through a pipe with a flexible wall. Bernoulli's principle implies lower pressures with faster flow, so the pipe ought to constrict as the flow speeds up. Another rule, the Hagen–Poiseuille equation, predicts the opposite. It describes the pressure necessary to force a laminar flow through a pipe whose walls exert some resistance, and it makes clear

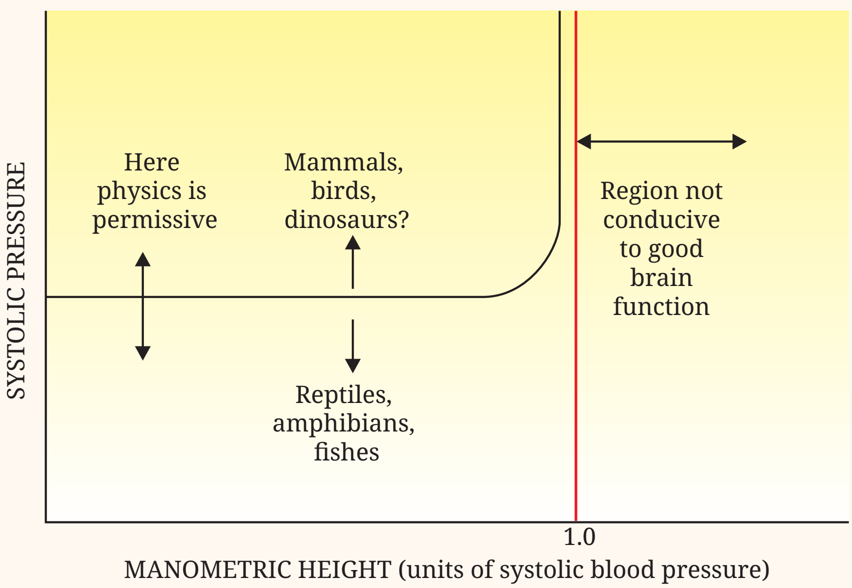


Figure 5. Systolic blood pressure as a function of animal height. The pressure shows little regular variation among small- and medium-sized mammals. But it must (and does) rise in large mammals so that it remains at least as great as manometric height (the product of blood density, gravitational field strength and the animal's height).

that faster flow requires higher pressure. Is a given flow Bernoulli dominated or Hagen–Poiseuille dominated? We need do no more than look at their ratio (using dynamic pressure $\rho v^2/2$ for the former),

$$\frac{\mathrm{B}}{\mathrm{HP}} = \frac{\rho v r^2}{16\mu l} \propto \frac{\rho v d}{\mu},$$

where μ and ρ are the dynamic viscosity and density of blood, respectively.

For a pipe 100 mm long and 1 mm in diameter carrying blood at 100 mm/s, the ratio has a value of about 0.01, indicating that Hagen–Poiseuille is in charge and Bernoulli has little to say.[7] Because circulatory systems have their pipes serially arrayed, the effective lengths are in practice even longer. In circulatory systems, Bernoulli's principle finds use only around heart valves, at pathological stenoses and in a few other places. That one's pulse is felt as an arterial expansion rather than constriction ought to make the point. Bernoulli does better in turbulent flow or where (as in carburetors) the ratio of pipe radius to length is high. Maybe the terminal ends of the urethras of large animals are braced, like vacuum-cleaner hoses, against collapse.

Incidentally, the relationship in the equation above turns out to be a version of the Reynolds number, the ratio of inertial to viscous forces and the most famous of all dimensionless numbers in fluid mechanics.

Jets, propellers and wings

Efficiencies are dimensionless indices that establish limits, usually by setting an ideal of 100%. Perhaps of more biological interest are places where low values preclude the use of certain devices. Thus the maximum thermal efficiency of an engine with a heat source at 40 °C and a sink at 0 °C—a range that a wet, proteinaceous organism may achieve—is less than 13%. That nature lacks heat engines should thus be no surprise.

Consider a device, such as a propeller, that provides thrust by speeding up a fluid flowing through it from v_1, the craft's speed, to v_2, some output speed. The device's thrust is the product of the mass it processes per unit time and the increase in speed ($v_2 - v_1$) it imparts. Its power output is that thrust times the craft's speed. Its power input is kinetic energy per unit time, or half that mass per unit time multiplied by the difference in the squares of the speed of its output and the craft's speed $v_2^2 - v_1^2$. So efficiency, usually called the Froude propulsion efficiency, is simply[7]

$$\eta = \frac{2v_1}{v_2 + v_1}.$$

Now v_2 has to be at least a bit above v_1 if any thrust is to be generated, and so 100% efficiency can't be reached. But making v_2 approach v_1 means processing the largest possible volume of fluid and giving it the least increase in speed. That's a bad indictment of jets relative to paddles or propellers—a jet ordinarily gives a smaller mass flux a higher incremental speed. In this light, it's understandable that neither Hero's jet engine of the first century nor James Rumsey's pulse-jet steamboat of 1787 led anywhere.[17]

But nature makes quite a few jet engines—in jellyfish, salps, frogfish, dragonfly nymphs, squid, scallops and others. They're probably easy to achieve given that organisms often push water through themselves to filter food or gain oxygen, often make one-way valves, and often wrap muscle around soft tubes. Aside from squid, though, nature's large, fast swimmers—fish, penguins, seals, whales and such—all use some form of propeller, like our propellers except for being oscillatory rather than rotational. Jets lose when competition between fins or flukes and jets turns on Froude propulsion efficiency. Squid can go fast—8 m/s is impressive for foot-long swimmers. But they do so only briefly, to escape predators or lunge at prey, when efficiency must matter little, and they use their fins for steady traveling.[7]

We have a similarly equivocal attitude toward jets. No commercially produced cars or motorcycles and only a few boats use jet engines. We usually reserve them for high-speed applications since, when push comes to shove, the jet's output speed has to be high enough to exceed the craft's speed. An exception, the Harrier jet, a small military aircraft that can take off vertically and hover, consumes fuel at a notoriously high rate. One can imagine a birdlike creature that uses its chest muscles and a pair of one-way valves to run a pulse-jet engine that provides thrust and respiratory gas exchange at the same time. Birds, in fact, do pump air through their lungs unidirectionally. But even the fastest known avian flyer, a falcon diving at a little over 60 m/s, or 130 mph, is surely too slow to make good use of the scheme.[18]

Froude propulsion efficiency exposes yet another limit, although this one matters mostly for human technology. Our earliest successful aircraft (ignoring lighter-than-air fliers) and most of our present ones get lift from fixed wings and forward propulsion from propellers or jets. That combination is almost unknown among birds, bats and insects, which get both lift and propulsion from pointing a single thruster in the appropriate direction. The helicopter, our analog of nature's fliers, wins no prizes for either fuel economy or range. Are nature's fliers as bad?

The utility of fixed wings turns out to depend on size. The lift of a wing varies with its area, while the weight of craft to be lifted varies with its volume. Larger thus means relatively lift-deprived unless wings are disproportionately large—or unless the flying machine goes faster. A faster v_1 demands a greater v_2 to generate forward thrust. Lift, of course, comes from downward thrust, and that's the crux of the problem. The vertical speed of an airplane is trivial, so the downward component of v_1 is negligible. If the propeller or jet is simply reaimed to get some downward momentum flux, then $v_{2\text{down}} - v_{1\text{down}}$ will be great and the efficiency low. A fixed wing acts as a transformer, converting some of the high-speed, low-volume rearward flow from propeller or jet into a low-speed, high-volume downward flow behind the wing, and thereby creating lift efficiently.

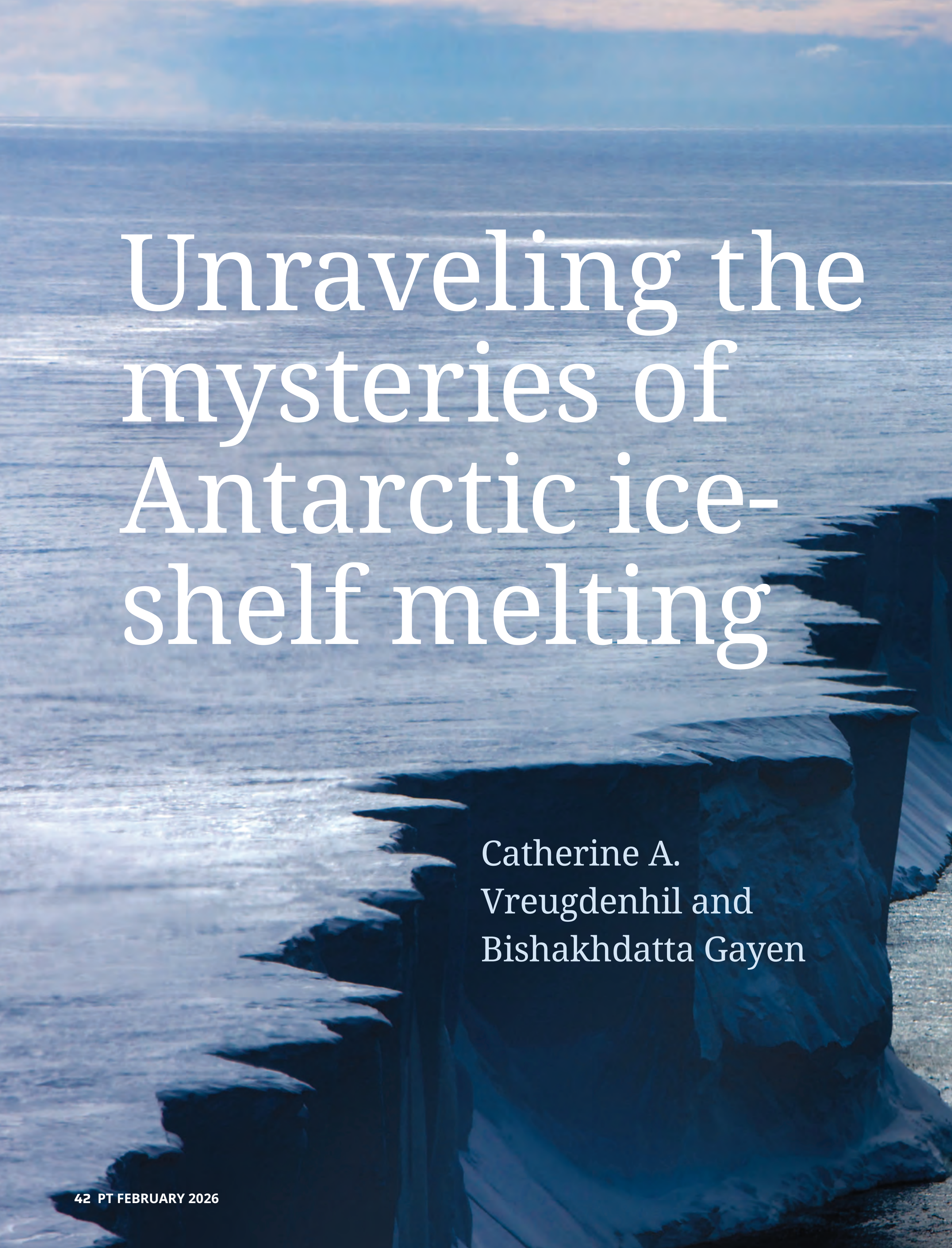
Nature's fliers go much more slowly—a bird that flies horizontally at 30 m/s is remarkable, while an airplane that flies that slowly is equally special. So flying animals can achieve adequately high propulsion efficiencies without resorting to separate fixed wings and propellers. Or mostly so, since the inner portions of the wings of large birds operate nearly as fixed, horizontal airfoils. The relatively large wings of nature's small fliers permit low speeds. Thus, very small birds can hover steadily, medium-sized ones can hover only momentarily and large birds can't hover at all. The advent of hovering aircraft awaited engines of very high power-to-weight ratios, and the very slow human-powered aircraft have gigantic wings.

Dimensionless numbers find use in many other biological or at least biomechanical situations. Some are well-established in the physical sciences, where they get used in much the same fashion; others have their variables redefined for biological purposes; still others have been especially contrived. Some set specific boundaries for the possible; others provide scaling rules that show how the desirable slopes off toward the impractical. Some answer specific questions; others just head us in some useful direction. Most, though, involve more complicated stories than those just related, which merely give the flavor of the game. PT

References

1. J. D. Isaacs, A. C. Vine, H. Bradner, G. E. Bachus, *Science* 151, 682 (1966).
2. R. C. Pankhurst, *Dimensional Analysis and Scale Factors*, Chapman and Hall, London (1964).
3. N. S. Land, *A Compilation of Dimensionless Numbers*, NASA, Washington, DC (1972).
4. H. D. Prange, K. Schmidt-Nielsen, *J. Exp. Biol.* 53, 763 (1970).
5. T. M. Williams, *J. Exp. Biol.* 103, 155 (1983).
6. K. Schmidt-Nielsen, in *Scale Effects in Animal Locomotion*, T. J. Pedley, ed., London, Academic Press (1977), p. 3.
7. S. Vogel, *Life in Moving Fluids*, 2d ed., Princeton U. P., Princeton, N.J. (1994).
8. G. O. Stride, *Ann. Entomol. Soc. Am.* 48, 344 (1955).
9. G. D. W. Pommen, D. A. Craig, *Can. J. Zool.* 73, 373 (1995).
10. R. M. Alexander, *Am. Sci.* 72, 348 (1984).
11. R. Kram, A. Domingo, D. P. Ferris, *J. Exp. Biol.* 200, 821 (1997).
12. N. C. Heglund, C. R. Taylor, *J. Exp. Biol.* 138, 301 (1988).
13. S. Vogel, *Life's Devices: The Physical World of Animals and Plants*, Princeton U. P., Princeton, N.J. (1988).
14. D. A. Thompson, *On Growth and Form*, 2d ed., Cambridge U. P., Cambridge, England (1942), p. 77.
15. M. H. Zimmermann, *Xylem Structure and the Ascent of Sap*, Springer-Verlag, Berlin (1983).
16. S. Vogel, *Vital Circuits: On Pumps, Pipes, and the Workings of Circulatory Systems*, Oxford U. P., New York (1992).
17. S. Vogel, *Cats' Paws and Catapults: Mechanical Worlds of Nature and People*, W. W. Norton, New York (1998).
18. V. A. Tucker, T. J. Cade, A. E. Tucker, *J. Exp. Biol.* 201, 2061 (1998).

Steven Vogel (1940–2015) was a James B. Duke Professor in the zoology department at Duke University in Durham, North Carolina.



Unraveling the mysteries of Antarctic ice-shelf melting

Catherine A. Vreugdenhil and Bishakhdatta Gayen

Beneath the ice shelves of the frozen continent, a hidden boundary layer of turbulent ocean is determining Antarctica's fate.

An aerial view of the edge of the Ross Ice Shelf. (Photo by Andy Myatt/Alamy.)

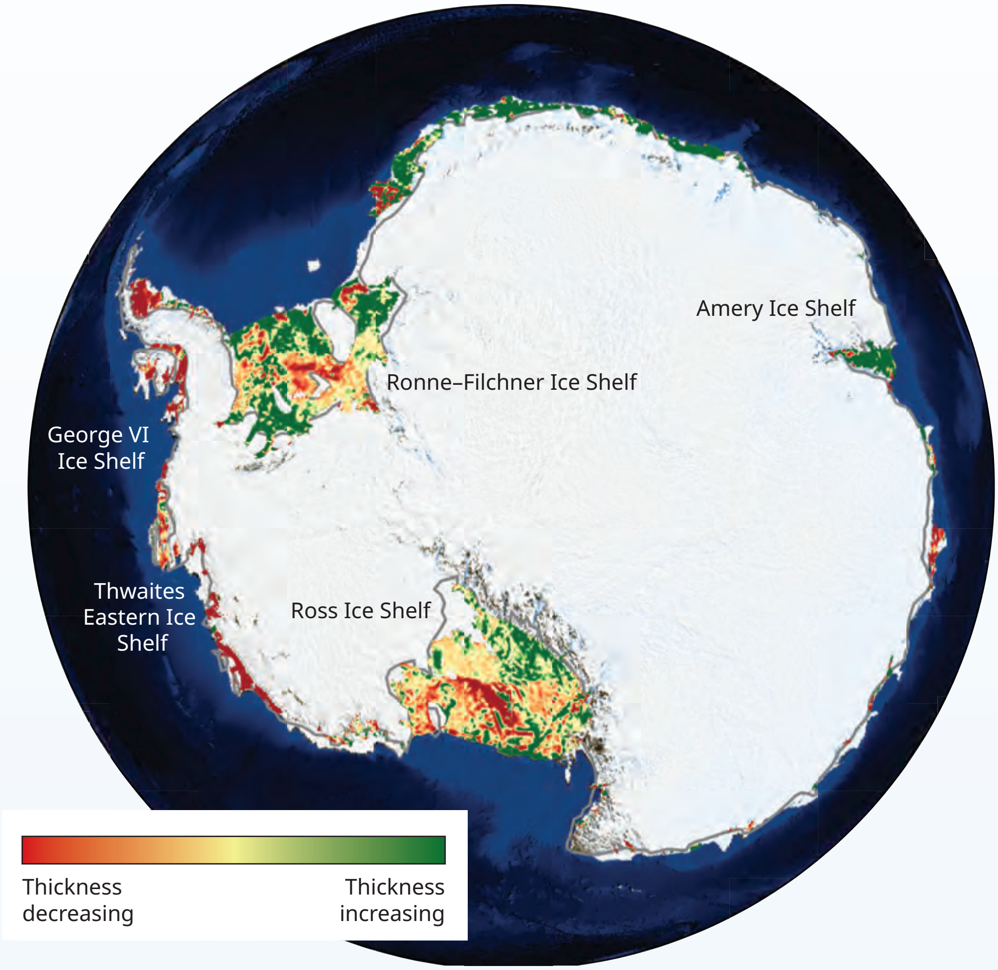


Figure 1. Major ice shelves on the Antarctic coastline. Regions in red are decreasing in thickness; regions in green are increasing.

Antarctica remains one of Earth's great enigmas: a frozen continent whose vast white expanse hides many secrets of our planet's climate. At the continent's fringes lie the ice shelves, immense floating extensions of the Antarctic Ice Sheet. Those shelves, mapped in figure 1, act as natural buttresses that hold back the massive inland ice sheets and slow their flow into the ocean. If the entire Antarctic Ice Sheet were to melt, global sea level would rise by about 58 meters[1] and inundate coastlines worldwide. Despite decades of research and exploration, the stability of ice shelves remains uncertain.[2,3] Scientists are still grappling with a central question: What controls the rate at which ice shelves melt?

Although the southernmost continent's ice shelves are colossal—they can stretch across hundreds of kilometers and plunge several kilometers deep—they are thinning and retreating in many locations. They lose mass both by calving icebergs and, more insidiously, by melting from below.[4] That basal melting occurs in the hidden ocean cavities beneath the ice shelves, where glacial ice meets seawater that is warm and salty enough to erode it. The interactions there between the ice and seawater generate complex, turbulent boundary layers that control the flow of heat and salt. The cavities are some of the most intriguing frontiers in polar science and are only now beginning to yield their secrets.

When ice shelves melt from below, as seen in figure 2, they cool and freshen the ocean—that is, make it less salty. The buoyant meltwater plays a far-reaching role in shaping the Southern Ocean and, ultimately, the global climate. As it spreads outward, it alters the ocean's temperature, salinity, and density and modifies circulation patterns that extend thousands of kilometers away from Antarctica. Recent studies have assessed how much melting is already unavoidable because of warming caused by past greenhouse gas emissions.[5] But projections of ice-shelf mass loss and meltwater remain highly uncertain: They are hindered by our limited knowledge of the ice–ocean boundary layer, where ocean turbulence and density stratification govern the pace of melting and ultimately affect the fate of rising seas.

The ocean beneath ice shelves

The fate of Antarctic ice is determined not just by large-scale climate forcing but by what happens in a much narrower area within boundary layers typically just several millimeters to a few centimeters thick beneath the ice shelves.[6,7] In those boundary layers, temperature and salinity gradients regulate how heat and salt diffuse and are exchanged between the ocean and the ice. The transfer of saltier water toward the base of an ice shelf causes melting to occur more rapidly; the presence of salt decreases the temperature at which ice melts, so saltwater is warmer relative to its freezing point than is freshwater at the same temperature. Because heat diffuses roughly 100 times as fast as salt, their gradients are markedly different: A thicker thermal boundary layer overlies a thinner salinity boundary layer just beneath the base of an ice shelf. That asymmetry establishes strong buoyancy gradients that determine whether the local stratification—the natural separation of seawater into layers of differing density—is stable or unstable.

Boundary-layer turbulence is governed by the buoyancy differences in seawater, which arise from variations in temperature and salinity and generate or suppress motion depending on the stability of the stratification. An unstable buoyancy profile, in which denser fluid lies above lighter fluid, drives overturning motion and forms turbulent convective plumes that vigorously mix the surrounding water. But a stable buoyancy profile, in which lighter water overlies denser water, resists vertical motion and suppresses turbulence. The shifting balance between buoyancy-driven convection and buoyancy-suppressed turbulence in the water beneath an Antarctic ice shelf dictates how effectively heat is carried to the ice shelf's base and, ultimately, how fast the ice melts.

The velocity boundary layer impacts the local generation or suppression of turbulence in the ocean flow. Immediately beneath the ice, the ocean flow experiences the ice face as a solid boundary that exerts frictional drag, which shapes the velocity field.

The velocity boundary layer can be decomposed into distinct regions, as seen in figure 3. Closest to the ice is a millimeter- to centimeter-thick viscous sublayer, where the flow motion is extremely weak and momentum transport is dominated by viscosity. It encompasses the temperature and salinity boundary layers, in which heat and salt travel only by diffusion, and is critical to the exchange process between ocean and ice.

Beneath the viscous sublayer lies a meter-scale shear layer, which exists only when the current is strong enough to generate significant shear in the velocity boundary layer. In the shear layer, the velocity increases rapidly with distance from the ice, a consequence of the drag that the ice exerts on the flow.

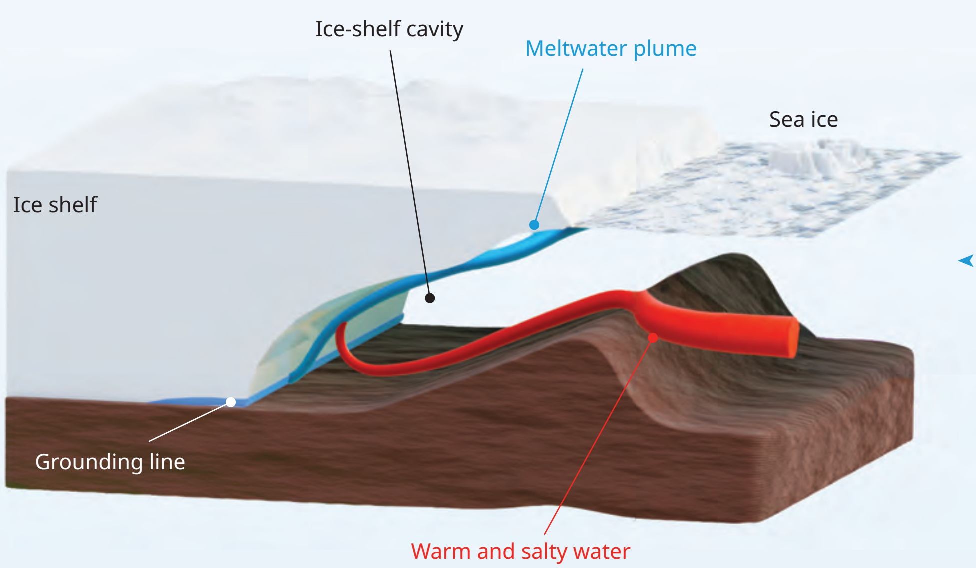


Figure 2. A schematic view of an Antarctic ice-shelf cavity. At bottom left is the grounding line, the boundary between ice resting on bedrock and the floating ice shelf. Melting at the bottom of the shelf can produce meltwater plumes (blue), which draw in warmer and saltier water (red) circulating in the Southern Ocean.

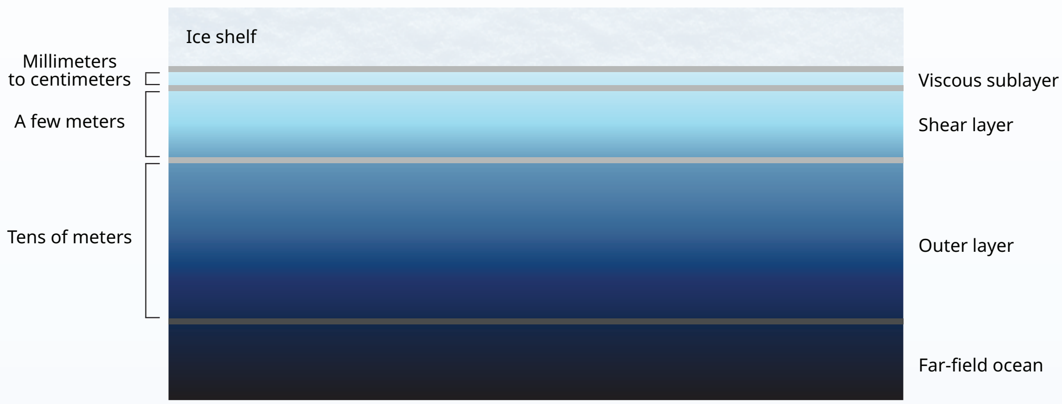


Figure 3. The ocean layers underneath an Antarctic ice shelf. The velocity boundary layer, in which momentum exchange takes place, encompasses three layers: the viscous sublayer, the shear layer, and the outer layer. Immediately below the ice is the viscous sublayer, a few millimeters to centimeters thick, where flow is extremely weak. It encompasses the temperature and salinity boundary layers, in which heat and salt exchange takes place. Below that is the shear layer, approximately a few meters thick, which forms when the current is sufficiently strong. That is followed by the outer layer, on the order of tens of meters thick, where the flow is still partially governed by the presence of the ice. Below that is the far-field ocean, which is unaffected by the overlying ice shelf. (Ice texture adapted from iStock.com/rusm.)

The fate of Antarctic ice is determined not just by large-scale climate forcing but by what happens in a much narrower area within boundary layers typically just several millimeters to a few centimeters thick beneath the ice shelves.

Extending tens of meters deeper is the outer layer, in which Earth's rotation bends the direction of the current, but the flow is still partially governed by the presence of the ice. Beyond that layer lies the far-field ocean, in which the flow is largely unaffected by the overlying ice.

Regimes of ice-shelf melting

A melting ice shelf not only responds to the surrounding ocean flow in the velocity boundary layer but also organizes that flow. As ice melts, it releases cold, fresh meltwater, which makes the water immediately beneath the ice more buoyant than the ocean layers below. Depending on the slope of the ice shelf and the strength of the ocean currents, that buoyancy difference can either destabilize or stabilize the flow. Our present understanding of the ocean dynamics under ice shelves reveals four distinct flow regimes, presented in figure 4, that develop when shelves melt: plume, stratification, shear current, and diffusive convection.

When the base of an ice shelf is sloped—near, for example, the grounding line, where the ice, ocean, and seafloor meet—the buoyant meltwater rises along the slope, forming a plume, as seen in the top-left panel of figure 4. The melt-induced buoyancy initially drives small, irregular motions that then organize into convective plumes, which draw in warmer, saltier water from farther away and move it toward the ice. In the plume regime, convection continuously draws heat to the ice interface and sustains and amplifies melting. Because meltwater plumes are large and slow moving, they are difficult to observe. But possible plume signatures have been detected under the Ross Ice Shelf, among other locations.[8]

When the base of an ice shelf is roughly horizontal, the buoyant meltwater tends to pool beneath the ice, which creates a stably stratified layer that suppresses vertical flow motion, as seen in the top-right panel of figure 4. In the stratification regime, the amount of heat reaching the ice is largely determined by external flows, such as tides, that generate shear and turbulence. Those external flows can move warm water toward the ice, which increases melting. But as has been observed beneath the Thwaites Eastern Ice Shelf,[9] strong stratification can also dampen turbulence in the shear layer, which effectively insulates the ice and slows its loss. The result is a dynamic balance, in which buoyancy, current shear, and turbulence interact to dictate the local rate of melting.

When the current flow is sufficiently strong, as seen in the bottom-left panel of figure 4, turbulence is fully driven by shear and buoyancy is only passive. In that scenario, termed the shear-current regime, the velocity boundary layer becomes well mixed, and temperature and salinity gradients are largely erased by vigorous turbulent motions. Heat and momentum are transported efficiently across the layer, which maintains nearly uniform temperature and salinity profiles up to the base of an ice shelf. The shear-current regime can typically be found in energetic, cold cavities, such as the cavity beneath the Larsen Ice Shelf, in which strong inflows and tides overwhelm buoyancy effects close to the ice base.[10]

In quiescent regions with shallow ice slopes and minimal ocean flow, the diffusive-convection regime—shown in the bottom-right panel of figure 4—governs ice-shelf melting. Because heat diffuses about 100 times as fast as salt, two separate layers form next to the ice: a thicker thermal boundary layer and a thinner salinity boundary layer. That imbalance creates small but persistent diffusive convection, in which cooler, denser water near the ice forms gentle downward plumes that mix with the slightly warmer, saltier water below. As observed beneath the George VI Ice Shelf,[11] the result is a series of double-diffusive layers, each typically a few meters to tens of meters thick, in which heat and salt slowly diffuse at different rates toward the ice. Although those layers are weaker than the convective plumes in the plume regime, they can still enhance melting above what would occur through diffusion alone.

Both the plume and diffusive-convection regimes result in an enhanced melting rate because the buoyancy differences in those regimes generate flow, increase turbulence, and boost the rate at which heat and salt are supplied to the ice. In contrast, the shear-current regime has weak buoyancy effects, which generally do not affect the flow turbulence. And in the stratification regime, buoyancy acts to increase stable stratification, which suppresses turbulence and moderates the melt rate.

Some regions are not easily categorized into one regime. A region can oscillate between the stratification

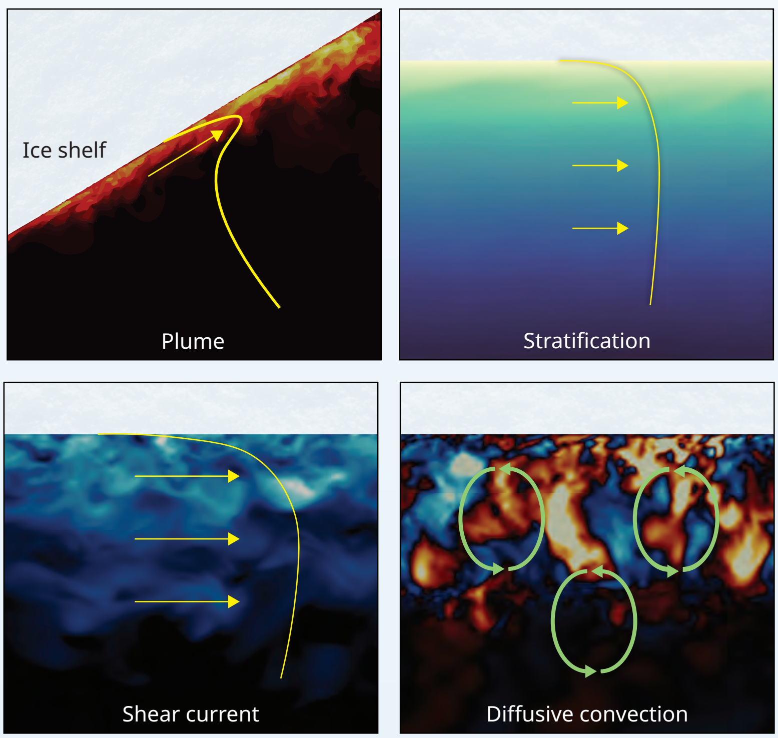


Figure 4. The four regimes of ice-shelf melting. Yellow lines indicate the profile of ocean flow; yellow arrows, relative flow velocity; and green arrows, diffusive convection. In the plume regime, buoyant meltwater forms a plume and rises along a sloped segment of the ice shelf. In the stratification regime, buoyancy acts to increase stable stratification, suppress turbulence, and moderate the melt rate. In the shear-current regime, temperature and salinity gradients are largely erased by vigorous turbulent motions. In the diffusive-convection regime, a series of double-diffusive layers slowly transport heat and salt toward the ice at different rates and increase the melt rate. (Ice texture adapted from iStock.com/rusm.)

and shear-current regimes, for example, when tides cause the flow speed to change. Other ocean dynamics, including the formation of marine ice—seawater frozen into small crystals or directly onto the ice base—also influence the flow dynamics and melt rate. Researchers are currently attempting to improve our understanding of the effects of ocean dynamics in those more complex cases.

Revealing hidden boundary layers

Obtaining direct observations of ocean cavities beneath Antarctic ice shelves is one of the great difficulties of polar research. The cavities are vast and remote, and they lie under hundreds to thousands of meters of ice, which makes accessing them both technically demanding and hazardous. Despite those obstacles, researchers have made remarkable progress over the past decade in directly observing the ice–ocean boundary layer.

Historically, most data on ocean cavities came from ships near the edges of ice shelves. The ships provided valuable information on ocean waters entering and exiting the cavities. Starting in the 1960s, satellite measurements began helping researchers infer ice-shelf extent and thickness. But the real breakthrough came in the late 1970s, with the development of borehole drilling. Using hot-water drills, scientists can now melt narrow access holes—typically just tens of centimeters wide—all the way through the ice and insert instruments beneath the shelf. Offering the first *in situ* view of processes at the ice base, borehole studies measure local melt rates, turbulence properties, temperature, salinity, and small-scale ice topography.

In recent years, autonomous vehicles, such as the remote-controlled underwater robot Icefin, have enabled measurements to be taken across wide swaths of the ocean cavities (for more on Icefin, see the April 2023 *PT* article "Melting underneath Thwaites Glacier is more complicated than expected"). They are able to reach dynamically important regions near the grounding line.[12] Those missions have revealed how the ice base's rich topography, four examples of which are shown in figure 5, can change dramatically over just a few meters. Those differences hint at the flow dynamics present in the boundary layers.[12,13]

Given that observations of ice–ocean interactions remain difficult to obtain, researchers have developed a hierarchy of modeling approaches to complement them. Large-scale and regional ocean models simulate the circulation in ice-shelf cavities and capture the interactions of meltwater and currents. But those models cannot resolve the thin, turbulent boundary layers that control melting. Instead, they parameterize small-scale processes by using simplified 1D formulations. The widely used three-equation model, for example, links the melt rate to local differences in temperature and salinity between the ocean and the ice by solving coupled equations for heat balance, salt balance, and the interface temperature.[14,15]

Because our knowledge of the underlying physics remains incomplete, formulations like the three-equation model contain large uncertainties. To improve our un-

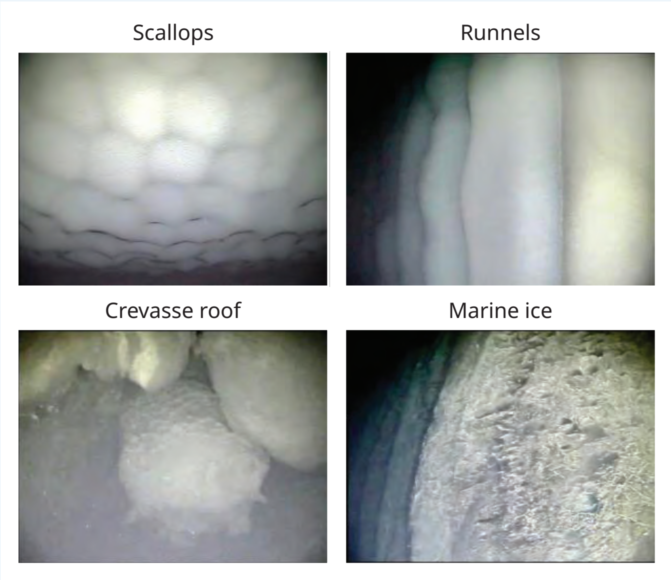


Figure 5. Images of topographical ice features in the base of the Ross Ice Shelf taken by the remotely operated underwater vehicle Icefin. The top two images show scallops and runnels on the top of the ice-shelf cavity. At bottom left is an image of the roof of a crevasse in an ice-shelf cavity, and at bottom right is an image of marine ice: seawater that has frozen directly onto the top of the ice-shelf cavity. (Images adapted from ref. 12.)

Obtaining direct observations of ocean cavities beneath Antarctic ice shelves is one of the great difficulties of polar research. The cavities are vast and remote, and they lie under hundreds to thousands of meters of ice, which makes accessing them both technically demanding and hazardous. Despite those obstacles, researchers have made remarkable progress over the past decade in directly observing the ice–ocean boundary layer.

derstanding, scientists have begun using state-of-the-art laboratory experiments and boundary-resolving simulations that explicitly capture the flow and turbulence near the ice base. Laboratory studies of ice melting in seawater date back more than four decades and remain invaluable for exploring meltwater plumes, double-diffusive layering, and the interplay of buoyancy, turbulence, and rotation.[16] Today's experiments, often conducted in cold rooms or on rotating tables, allow researchers to track ice-face evolution, measure turbulence, and visualize flow structures at millimeter resolution.[6] They are complemented by numerical simulations that can resolve the thin boundary layers and turbulent plumes responsible for heat and salt transfer.

Those approaches often use principles of dynamical similarity to infer the ocean-cavity dynamics. Both experiments and numerical simulations are crucial for revealing the fundamental balances in the boundary layer and for identifying the distinct melting regimes observed around Antarctic ice shelves. They provide insights that can help improve the simplified parameterizations used in larger-scale ocean models.

When combined, observations, laboratory experiments, and boundary-resolving numerical simulations provide a pathway toward obtaining an accurate picture of melt rate, which is crucial to improving projections of sea-level rise. As each new generation of instruments and models brings us closer to resolving the turbulent boundary layer in detail, the once-inaccessible world beneath Antarctica's ice shelves is gradually coming within reach.

New frontiers

Recent advances in observations, laboratory studies, and modeling are finally illuminating the turbulent boundary layer where Antarctic ice shelves meet the ocean. Those efforts reveal how buoyancy, shear, and stratification interact to shape the many regimes of melting that govern the stability of the ice shelves. Improving our understanding of those regimes, each of which responds differently to currents, stratification, and buoyancy, offers a pathway to improve how large-scale models represent ice-shelf melting so that simulations more closely align with real-world observations.

The next frontier in Antarctic ice-shelf research lies in uniting those diverse approaches into an integrated Earth-system framework. New coupled atmosphere-ocean-ice models, informed by laboratory and field measurements, are beginning to illustrate how surface winds, sea-ice loss, and turbulent boundary layers interact to control basal melting. And scientists are working toward the development of models that link boundary-resolving simulations, which explicitly capture the fine-scale turbulence and melt processes, with large-scale ocean models that simulate cavity-wide circulation. Running those models side by side would help us better understand how small-scale physics informs global climate behavior.

Understanding ice-shelf melting is critical to modeling the future behavior of the Antarctic Ice Sheet: When ice shelves thin, they weaken and become unable to fully buttress the grounded ice sheets they are holding back. As a result, inland ice flows into the ocean and increases sea levels.[17] Global climate models currently struggle to simulate how ice-shelf melting affects the stability of inland ice sheets. Coupling models of ice-sheet dynamics with models of the ocean and atmosphere is a key, albeit difficult, step toward improving projections of climate change and sea-level rise.[18]

Meanwhile, advances in robotics and machine learning are enabling autonomous vehicles to collect and interpret sub-ice data in near real time. Interdisciplinary teams will be needed to stitch all the approaches together to better understand the underlying physics and the climate impact (see the June 2021 *PT* article "Accelerating progress in climate science," by Tapio Schneider, Nadir Jeevanjee, and Robert Socolow).

Together, those innovations are moving us closer to the point at which we will be able to accurately predict the stability of Antarctic ice shelves, which is crucial to projecting the pace of global sea-level rise in a warming world.

Catherine A. Vreugdenhil is supported by an Australian Research Council Discovery Early Career Researcher Award, grant number DE220101027. Both authors appreciate the support of the Australian Research Council Discovery Project (grant number DP240102823) and the Australian Centre for Excellence in Antarctic Science (project number SR200100008). Numerical simulations were performed on the National Computational Infrastructure at the Australian National University in Canberra. For valuable discussions and assistance in creating the figures, the authors thank Bajrang Chidhambaranathan, Kaushik Mishra, Madelaine G. Rosevear, Benjamin K. Galton-Fenzi, Taimoor Sohail, Peter Washam, and John R. Taylor. **PT**

References

1. M. Morlighem et al., "Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic Ice Sheet," *Nat. Geosci.* **13**, 132 (2020).
2. N. J. Abram et al., "Emerging evidence of abrupt changes in the Antarctic environment," *Nature* **644**, 621 (2025).
3. H. A. Fricker et al., "Antarctica in 2025: Drivers of deep uncertainty in projected ice loss," *Science* **387**, 601 (2025).
4. C. A. Greene et al., "Antarctic calving loss rivals ice-shelf thinning," *Nature* **609**, 948 (2022).
5. K. A. Naughten, P. R. Holland, J. De Rydt, "Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century," *Nat. Clim. Change* **13**, 1222 (2023).
6. Y. Du, E. Calzavarini, C. Sun, "The physics of freezing and melting in the presence of flows," *Nat. Rev. Phys.* **6**, 676 (2024).
7. M. G. Rosevear et al., "How does the ocean melt Antarctic ice shelves?," *Annu. Rev. Mar. Sci.* **17**, 325 (2025).
8. C. Stevens et al., "Ocean mixing and heat transport processes observed under the Ross Ice Shelf control its basal melting," *Proc. Natl. Acad. Sci. USA* **117**, 16799 (2020).
9. P. E. D. Davis et al., "Suppressed basal melting in the eastern Thwaites Glacier grounding zone," *Nature* **614**, 479 (2023).
10. P. E. D. Davis, K. W. Nicholls, "Turbulence observations beneath Larsen C Ice Shelf, Antarctica," *J. Geophys. Res. Oceans* **124**, 5529 (2019).
11. S. Kimura, K. W. Nicholls, E. Venables, "Estimation of ice shelf melt rate in the presence of a thermohaline staircase," *J. Phys. Oceanogr.* **45**, 133 (2015).
12. P. Washam et al., "Direct observations of melting, freezing, and ocean circulation in an ice shelf basal crevasse," *Sci. Adv.* **9**, eadi7638 (2023).
13. A. Wåhlin et al., "Swirls and scoops: Ice base melt revealed by multibeam imagery of an Antarctic ice shelf," *Sci. Adv.* **10**, eadn9188 (2024).
14. D. M. Holland, A. Jenkins, "Modeling thermodynamic ice–ocean interactions at the base of an ice shelf," *J. Phys. Oceanogr.* **29**, 1787 (1999).
15. M. S. Dinniman et al., "Modeling ice shelf/ocean interaction in Antarctica: A review," *Oceanography* **29**, 144 (2016).
16. H. E. Huppert, J. S. Turner, "Ice blocks melting into a salinity gradient," *J. Fluid Mech.* **100**, 367 (1980).
17. T. L. Noble et al., "The sensitivity of the Antarctic Ice Sheet to a changing climate: Past, present, and future," *Rev. Geophys.* **58**, e2019RG000663 (2020).
18. R. S. Smith et al., "Coupling the U.K. Earth System Model to dynamic models of the Greenland and Antarctic Ice Sheets," *J. Adv. Model. Earth Syst.* **13**, e2021MS002520 (2021); D. T. Bett et al., "Coupled ice–ocean interactions during future retreat of West Antarctic ice streams in the Amundsen Sea sector," *Cryosphere* **18**, 2653 (2024).

Catherine A. Vreugdenhil is a senior lecturer in the department of mechanical engineering at the University of Melbourne in Australia and a chief investigator with the Australian Centre for Excellence in Antarctic Science. Her research focuses on the modeling of Antarctic ice shelf–ocean interactions and ocean circulation. **Bishakhdatta Gayen** is an associate professor in the department of mechanical engineering at the University of Melbourne in Australia and a chief investigator with the Australian Centre for Excellence in Antarctic Science. He is also an assistant professor at the Centre for Atmospheric and Oceanic Sciences at the Indian Institute of Science in Bengaluru. His research focuses on the modeling of Antarctic ice shelf–ocean interactions and ocean circulation.

WHAT CAN PHYSICISTS DO?

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

David Gagnon

analyzes baseball to give his team a competitive edge

By Toni Feder

Team lead, baseball sciences, Washington Nationals Baseball Club

BS, mechanical engineering, Brown University, 2010
PhD, mechanical engineering and applied mechanics, University of Pennsylvania, 2017

What was your research focus?

I started off in physics but switched to mechanical engineering to work in a particular fluid dynamics lab. As a graduate student, I studied how biological organisms swim through non-Newtonian fluids. For practical applications, like fertility studies, you want to know how organisms move through biologically relevant fluids like mucus.

(Photo by Amanda Bowen/Washington Nationals.)

How did you end up with the Washington Nationals?

As a postdoc in physics at Georgetown University, I was ready to go on the faculty market. I wanted to keep doing experimental fluid dynamics, but I saw a posting for a full-time analyst role at the Washington Nationals and thought it would be a fun and interesting application of my skill set. The quote "Pitching is not mysterious, it's just physics" [said by Brian Bannister in the 2019 book *The MVP Machine: How Baseball's New Nonconformists Are Using Data to Build Better Players*] was a nudge to look into it. I started with the Nationals in January 2020.

How did you make the transition?

My postdoc and PhD advisers encouraged me to explore, and they made it clear that it didn't have to be a permanent career change.

How do you spend your time?

I work with vast troves of information about how players, the ball, and the bat move and interact. I build models to evaluate our players' pitching, hitting, and defensive skills. I provide tools to help the rest of our organization make decisions about players and their development and how to interpret the game to get competitive advantages.

How do you use physics in your job?

Thinking about throwing a ball that spins and translates through the air, or swinging a bat that has inertia and mass, or the collision dynamics between a ball and a bat, or the kinematics of a fielder moving toward a ball involves physics. Fluid dynamics is helpful. I often apply physics concepts for models and data analysis.

What new skills did you need to pick up?

I had to learn how to write deployable code. I have also developed stronger skills in machine-learning modeling.

What do you like about your job?

I am immersed in a dynamic, collaborative, and competitive environment.

Is there anything you'd like to add?

Every major sports team, not just in baseball, has analysts and scientists. There are plenty of opportunities to get involved. PT

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

Megaflashes: The world's longest lightning discharges

Lightning is sometimes described as just a big spark. But just how big can the spark get? Satellite sensors say … very!

By Randall S. Cerveny, Michael J. Peterson, and Walter A. Lyons

Given that lightning's electric discharge moves at a significant fraction of the speed of light, how far can it travel during its lifetime? The length of lightning strikes, whether intracloud or cloud to ground, is typically less than 10 km. But in October 2017, one 7.4-second flash blazed an 829 km path from east Texas to near Kansas City, as shown in figure 1. Official US storm data show that the storm complex created significant hail, severe winds, and a few short-lived tornadoes over the central and southern Great Plains. Fortunately, no deaths resulting from the thunderstorm were reported.

In 2025, after analyzing reprocessed satellite data, the United Nations World Meteorological Organization certified the 2017 flash as the new world record for the longest megaflash. In decades past, the idea that lightning could propagate more than 100 km horizontally was considered unlikely. Are megaflashes a different form of lightning? How are they monitored? And why do they matter?

The big spark

Most lightning flashes are born in the updrafts of convective cumulonimbus clouds. Within turbulent updrafts, which reach speeds of up to 50 m/s, conglomerates of soft hail called graupel collide with supercooled liquid water and ice particles; the ice particles transfer negative charge to the graupel. Given differences in terminal velocities, gravitational sorting typically redistributes lighter positively charged ice into the upper reaches of the updraft, and heavier negatively charged graupel descends. As the electric field strength increases, the air's impedance is exceeded, and lightning occurs.

The hot, bright channels that you see during lightning strikes, such as the ones shown in figure 2, are called leaders. A spectacular cloud-to-ground stroke starts as a stepped leader discharge that descends incrementally to within tens of meters of the ground, where it connects with an upward leader that completes the circuit. The currents of the pencil-thin ionized plasma channel heat the air to 30 000 °C, causing a brilliant flash and the rumble of thunder. Cloud-to-ground strokes typically transport negative charge to Earth with peak currents in the 10–30 kA range, though about 10% are of positive polarity and can have peak currents up to an order of magnitude larger.

Intracloud discharges, which make up about 80% of all flashes, are bidirectional, quasi-horizontal leaders. Many flashes contain both intracloud and cloud-to-ground components. A megaflash is an intracloud flash with cloud-to-ground components—it's just a much, much bigger spark than usual.

The electrically charged regions in convective cumu-

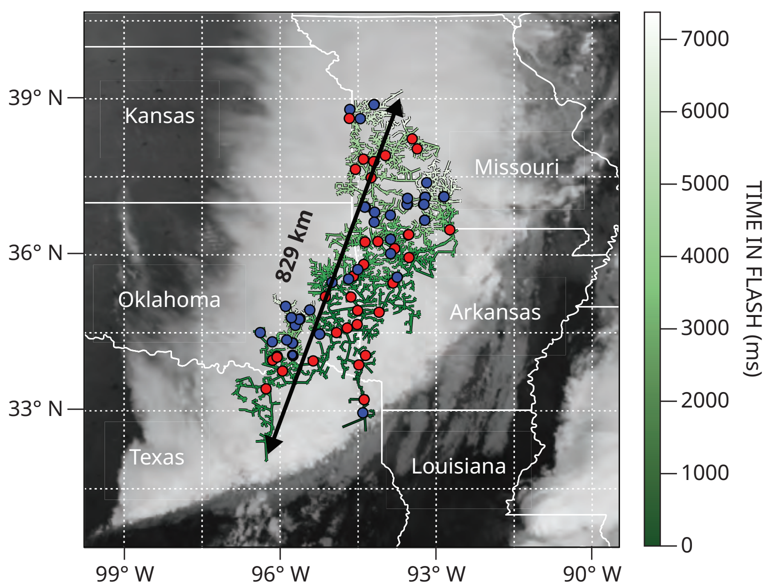


Figure 1. The world record for the largest megaflash lightning (green), certified by the World Meteorological Organization, struck the central US on 22 October 2017. The megaflash data shown here come from composite *GOES-16* satellite imagery. Also shown are 116 associated cloud-to-ground discharges: 83 negative strokes (blue) and 33 positive strokes (red). (Figure adapted from M. J. Peterson et al., *Bull. Am. Meteorol. Soc.* **106**, 627, 2025.)

Figure 2. Intracloud and cloud-to-ground components of an expansive lightning flash in Bella Vista, Arkansas, during the 22 October 2017 storm. (Photo courtesy of Douglas Keck.)

lonimbus clouds typically measure a few kilometers across, though some supercells span tens of kilometers. The advent of meteorological satellites revealed that thunderstorms can organize into much larger entities comprising multiple clusters arranged in a variety of recognizable configurations, collectively known as mesoscale convective systems (MCSs).

One type of MCS propagates as a long front of towering electrically active cores, known as a squall line, followed by extensive areas of shallower, layered clouds that produce gentle rain. During the warmer months, such systems traverse the central US, often persisting for more than 12 hours. Though far removed from active updrafts, those shallower clouds contain layers of weak electric charge.

Along with some locally generated charge, positively charged ice crystals lofted atop the distant convective towers recirculate rearward and downward into the shallow trailing clouds. Those pockets of slowly accumulating charge can become interconnected to form a cloudy capacitor large enough to cover a multistate area and provide an ideal environment for a megaflash.

Finding the megaflash

An early hint at the possibility of megaflashes came in the 1980s when videos taken from space shuttles documented unexpectedly large lightning flashes tens of kilometers long. In the mid 1990s, triangulated observations from ground cameras revealed eight red sprites—transient luminous phenomena that can occur during intense strikes—that appeared sequentially over a distance of 200 km above an MCS in Texas. The sprites emerged at intervals consistent with intracloud-leader propagation velocities, which signaled that they could possibly be connected by a single flash.

The ability to confirm a discharge more than 100 km long—the megaflash definition—was achieved in the late 1990s through the use of ground-based 3D lightning mapping arrays comprising radio receivers distributed around a city-sized region. One of about a dozen such research systems deployed worldwide is the North Georgia Lightning Mapping Array, which has eight receivers throughout the Atlanta metro area.

Like weather radar, such arrays are constrained by line-of-sight coverage, so it was fortuitous in 2007 when an array in Oklahoma captured a megaflash's lightning channels traversing 321 km. That became the first record discharge length certified by the World Meteorological Organization.

Observing lightning from geostationary orbit solved the spatial coverage limitations. Launched in 2016, the first such detector was NOAA's Geostationary Lightning Mapper on the Geostationary Operational Environmental Satellite *GOES-16*. High-speed optical detectors continuously report lightning flash rates and 2D lightning maps across the Americas and portions of the Atlantic and Pacific Oceans. The mapper domain covers two known hot spots for megaflashes: the Great Plains in North America and La Plata Basin in South America. More recently, EUMETSAT, the European Organisation for the Exploitation of Meteorological Satellites, launched its Meteosat Third Generation satellite system, with a lightning imager sensor that continuously monitors megaflash hot spots around the Mediterranean Sea and parts of Africa.

Because data-processing algorithms were not originally designed to recognize long-lasting, spatially extensive flashes, detailed postprocessing techniques were developed to identify megaflashes. Consequently, in 2025, the World Meteorological Organization was able to certify the 2017 megaflash as a world record. With ongoing global monitoring, that record may someday be surpassed, and our understanding of megaflashes' parent convective systems will be enhanced.

Safety concerns

Studying the maximum extent of lightning also has important public safety implications. A single megaflash can unexpectedly produce a hundred or more cloud-to-ground discharges that strike tens to hundreds of kilometers away from active lightning centers. Megaflash cloud-to-ground strikes prompt concerns similar to "bolts from the blue"—rare cloud-to-ground strikes that escape their thunderclouds into the clear air for distances approaching roughly 15 km. Bolts from the blue can strike unexpectedly with deadly consequences. Megaflash cloud-to-ground strikes can, similarly, strike unexpectedly from cloudy skies (making them more like bolts from the gray) long after the apparent thunderstorm threat has ended. Moreover, some megaflash cloud-to-ground strikes pose additional hazards, such as exceptionally high peak electric currents and lengthy continuing currents, both of which can start fires and cause infrastructure damage.

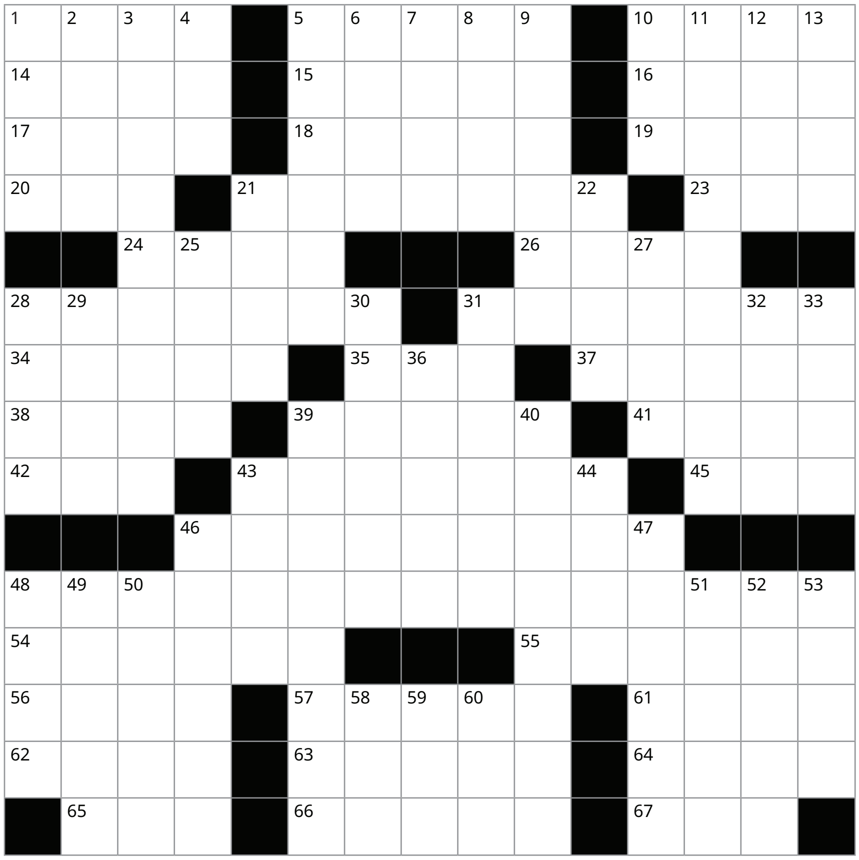
Our growing understanding of megaflashes suggests that there are rare scenarios where existing lightning safety guidelines need finessing. The National Lightning Safety Council and NOAA advise "when thunder roars, go indoors" and wait there until 30 minutes after the final rumble of thunder before resuming outdoor activities. That guidance has been effective, and recent decades have seen historically low lightning fatalities in the US. The guidance, however, is based on the ordinary convective thunderstorms where most lightning occurs. The implications of megaflashes on the initiation of wildfires and the safety of activities that include large outdoor crowd control, the handling of explosive materials, space-vehicle launches, and wind-farm and utility grid operations will need to be increasingly scrutinized. PT

Additional resources

- R. Cerveny, *Judging Extreme Weather: Climate Science in Action*, Routledge (2024).
- W. A. Lyons et al., "Megaflashes: Just how long can a lightning discharge get?" *Bull. Am. Meteorol. Soc.* **101**, E73 (2020).
- M. Peterson, "A survey of thunderstorms that produce megaflashes across the Americas," *Earth Space Sci.* **10**, e2023EA002920 (2023).
- M. J. Peterson et al., "A new WMO-certified single megaflash lightning record distance: 829 km (515 mi) occurring on 22 October 2017," *Bull. Am. Meteorol. Soc.* **106**, 627 (2025).
- World Meteorological Organization, World Weather and Climate Extremes Archive.

Randall S. Cerveny is a President's Professor and directs the meteorology program at Arizona State University in Tempe. He is the World Meteorological Organization's rapporteur of world records on weather and climate extremes. **Michael Peterson** is the director of the Severe Storms Research Center at the Georgia Tech Research Institute in Atlanta. **Walter A. Lyons** is a past president of the American Meteorological Society and spent his career as a lightning researcher.

CROSSWORD



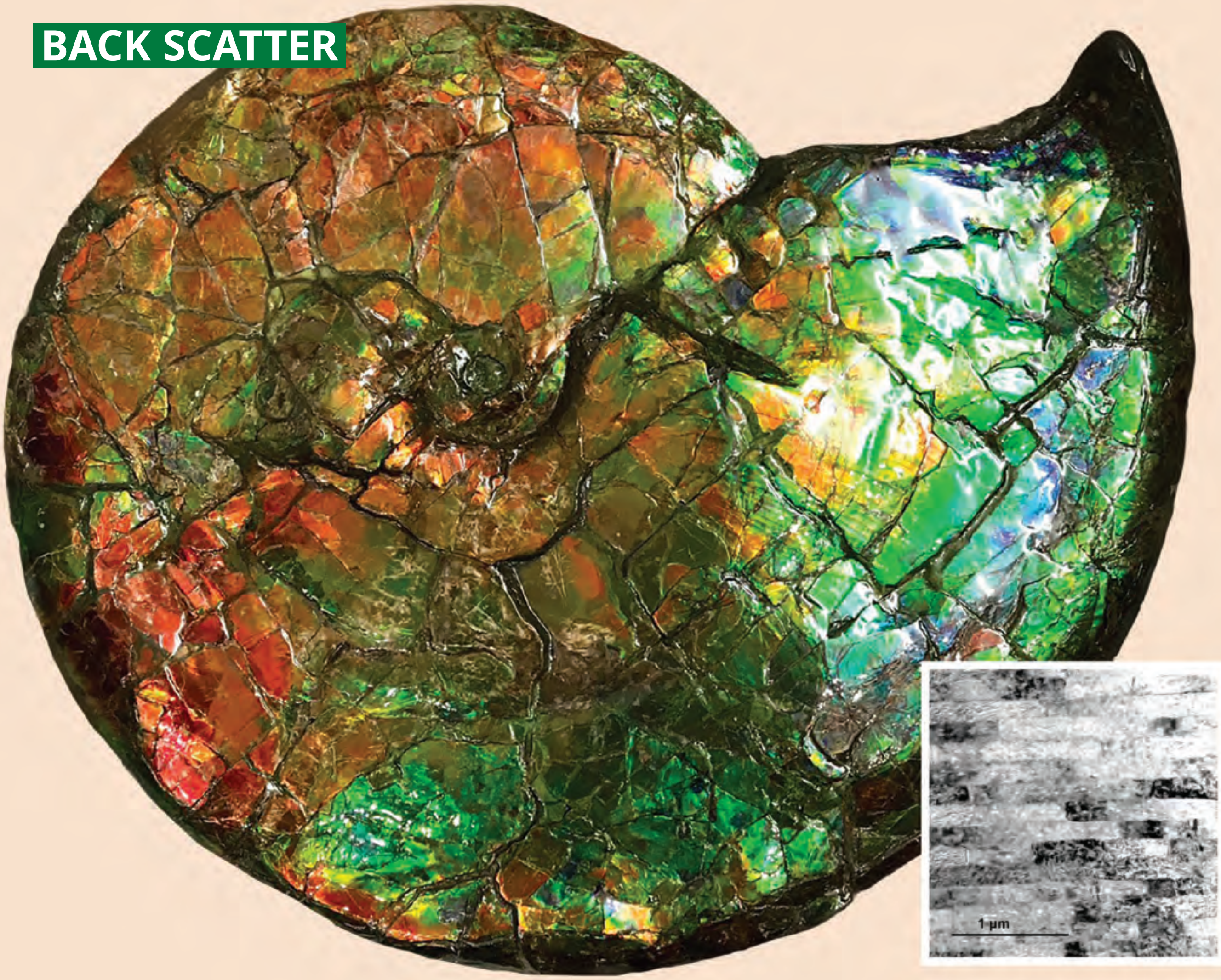
By Doug Mar

ACROSS

1 Physicist Ernst, godfather of Wolfgang Pauli
5 Seats that can accommodate more than one
10 Abominable Snowman
14 Initialism for an ingredient in vinaigrette
15 Substance that is analyzed by Clearblue products
16 Property of bosons and of some balls that are bowled
17 Open-source graphics editor
18 Cinematic awards bestowed in 2024 on *Oppenheimer*
19 Claim on property
20 Serpent whose middle letter is serpentine
21 Respectful Sanskrit greeting associated with bowing
23 Investments with fixed rate and term (abbr.)
24 Dishonest person
26 Wheel shaft
28 With 31-Across, subject celebrated in the year 2025
31 See 28-Across
34 Come together
35 Creature with aerodynamics adapted for silent flight
37 Prefix with -hedral that describes the symmetry of the object that will be introduced in the central column of this puzzle (7-Down, 36-Down, 59-Down)
38 Periodic table fig.
39 Tina, the mascot of the 2026 Winter Olympics, is this animal
41 Cherished
42 Subdivision unit
43 Song lyrics that follow “If I’m not back again this time tomorrow”
45 120 VAC (as a line voltage in the US, where the peak voltage is approximately 170 volts) is an example of this type of stat.
46 Shopping destination for custom tailoring
48 Italian scientist who discovered the flammability of methane and has an SI-derived unit named after him
54 It sometimes appears under an underscore?
55 Movie in which Sean Penn portrays a father who is “not like other daddies”
56 What Pick’s theorem is used to calculate
57 Registered trademark for some rechargeable batteries
61 The natural one isn’t rational
62 Microwave sound
63 Luxury automaker whose logo and slogan both evoke precision
64 Abbr. on an envelope
65 Stat. that describes the variance from a regression model, or the dir. from France’s largest city to its second largest
66 Calyx part
67 Lao-___

DOWN

1 Metric word that loses meaning when applied to toilet paper rolls
2 Rental car company whose stock symbol is CAR
3 What a patient might bring to a physician
4 An eccentrically loaded wheel can do this while rolling
5 Company that manufactures the Crosstrek
6 Electronic musician Daphne
7 Org. that commissioned the Trionda from Adidas
8 Creatures on an Escher Möbius strip
9 City in Washington spelled with two capital letters, or short for the airport it contains
10 French fashion monogram
11 Point above the focus, to a seismologist
12 Deadlocked
13 Hog’s Head and Prancing Pony, for two
21 Silver who founded fivethirtyeight.com
22 Departure
25 “What have I gotten myself ___?”
27 Analytical technique based on the original Davisson–Germer experiment, or a green building certification (abbr.)
28 Familiar name for a first-year graduate exam
29 Golden rule word
30 Ibuprofen brand name
31 Buffy, to vampires
32 Pack densely
33 Galileo was said to have described Saturn as having these
36 “Line” traversed in 4D spacetime
39 Grassy woodland biomes with open canopies
40 Having the shape of a tokamak
43 School of Applied Science where the Michelson–Morley experiment was performed
44 Word that can follow “micro,” “kilo,” and “super”
46 Property of a slalom path or an integral sign
47 Marsupial with distinctive cube-shaped droppings
48 Fictional captain who is quoted in *Star Trek II: The Wrath of Khan*
49 Harp-like instruments
50 Swords wielded by pentathletes
51 Exams for aspiring JDs
52 Sense, or sense of style
53 Last word in Handel's *Messiah*
58 Playing surface for ringette and curling
59 Device named after Faraday that measures ions in vacuum
60 Genus of macaws, or the constellation known as the Altar



A marine shell's brilliant colors

By Alex Lopatka

During the time of the dinosaurs, shelled squid-like organisms called ammonites lived in the oceans. Some fossilized ammonite shells—such as the one shown here that was mined in Alberta, Canada—have blue, green, and red colors that shimmer and vary in hue as the viewing angle changes. The iridescence arises because of interference between waves of visible light that have reflected off the top and the bottom of the shell surface. Even though ammonite fossils are found in abundance worldwide, few of them have the same brilliant colors as ones uncovered in Canada.

Using a transmission electron microscope, Hiroaki Imai of Keio University in Japan and colleagues found that the Canadian ammonite fossils have individual shell layers—a representative sample is shown in the inset—that are separated by air gaps of several nanometers. Incoming light rays are reflected at the gaps, and then interference leads to the distinct colors. The researchers found that the structures of the colorful shells are more consistent than those of other ammonite shells, which tend to have wider air gaps and more variable layer thicknesses.

The researchers then applied their findings to abalone shells from extant sea snails. After removing organic material and applying pressure to shrink the gaps between shell layers, the researchers found that the snail shells exhibited similarly brilliant iridescence. Imai and colleagues hypothesize that the color brilliance of the Canadian fossils results from either environmental factors that affect shell growth or the pressure at which the shells are fossilized. (N. Hizukuri et al., "Brilliant structural colors originating from reflection by nanogaps of nacreous layers in fossilized ammonite shells," *Sci. Rep.* **15**, 37541, 2025; images courtesy of Hiroaki Imai.) PT

To submit candidate images for Back Scatter, visit https://contact.physicstoday.org.