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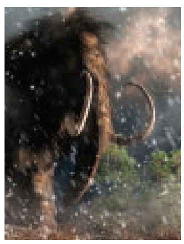
FEATURES



ON THE COVER: Wobbles in Earth's orbit have repeatedly caused the planet's temperature to drop and continental ice sheets to spread. Woolly mammoths, like the one depicted here, developed thick fur to insulate their bodies from the cold. The ice ages may have also affected human evolution and migration. To read more about Earth's temperature swings over time, see Mark Maslin's article on **page 48**. (Image by iStock.com/Daniel Eskridge.)

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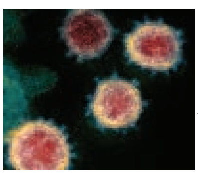

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HANNAH PELL

▶ Three Mile Island

The 1979 nuclear accident at Three Mile Island was notable not only for its seriousness but also for the poor communication to the public during the crisis. Hannah Pell examines the missteps of four decades ago and offers some relevant lessons for today.

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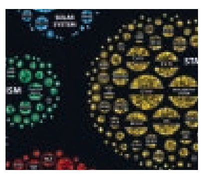

NADIEH BREMER

▶ *Hubble* at 30

The *Hubble Space Telescope* has now spent more than 30 years in orbit. PHYSICS TODAY has produced a package of stories, along with infographics by award-winning designer Nadieh Bremer, that examine *Hubble*'s notable discoveries and famous images.

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FROM THE EDITOR

Friend raising for physics

Charles Day

My title comes from a column by particle physicist Sijbrand de Jong in the most recent issue of *Europhysics News*. His topic was a report that the European Physical Society (EPS) released last year on the contributions of physics to the European economy.[1] Even though the study was undertaken by an independent consultant and was therefore independent of the EPS, and even though the EPS held a press conference to tout the report, it failed to attract much media coverage.

Disappointed by the lack of interest, De Jong urged his fellow EPS members to cultivate influential friends in the hope that subsequent EPS reports and statements would be better received.

Friend raising—to use De Jong's term—is a sound tactic. Physics needs friends in the corridors of power, and not just in Europe. But getting newspapers, radio stations, and other media outlets to pay attention requires more than friends. Understanding how the media operate is just as important.

Media outlets are businesses whose well-being depends on satisfying audiences and, in some cases, advertisers. Even the BBC, Al Jazeera, NPR, Raidió Teilifís Éireann, and other state-supported outlets are more or less businesslike in their strategies and operations. Producing what audiences expect and want is paramount. How might that priority come into play in the case of an EPS report on physics and the European economy?

When contemplating a possible news item, feature article, or opinion piece, an editorial decision maker asks, Will my audience be interested? The fact that physics-based industries contribute significantly to Europe's economic health might seem of general interest. But newspaper editors, TV producers, and other gatekeepers could regard the EPS report as being not so much about physics in particular but about one sector's economic impact. They have likely seen other reports about other sectors. Indeed, without much trouble I found ones on the economic impact of biology, chemistry, and materials science.

"Why, sir," replied Faraday, "there is every probability that you will soon be able to tax it!"

Then there's the matter of news media's skepticism. In essence, every press release is a self-serving bid for attention, regardless of the worthiness of the cause it promotes. Even if the EPS press conference succeeded in inducing journalists to read the report, they could still have declined to cover it if their skepticism was aroused and validated. In the case of the EPS report, that outcome was likely. Physics-based industries identified in the report include the extraction of crude petroleum, the building of ships and floating structures, and the manufacture of central heating radiators and boilers. Those and others in the report seem a stretch to me.

Besides friend raising, what else might the EPS or any other scientific society do to raise awareness of its activities? In the case of the EPS economic impact report, I would have recommended submitting op-ed columns to major European business newspapers. The largest by circulation are the UK's *Financial Times*, Italy's *Il Sole 24 Ore*, Germany's *Handelsblatt*, and France's *Les Echos*. They publish op-eds by outsiders. And because they do so daily, they need a constant stream of prime content.

What would get past an opinion page editor? A grabby opening is essential. If I were touting the EPS report, I'd begin in the 1850s with the purported exchange between Michael Faraday and William Ewart Gladstone, who was in charge of Britain's treasury at the time. After the physicist had explained electromagnetism, the politician questioned its use. "'Why, sir,' replied Faraday, 'there is every probability that you will soon be able to tax it!'"[2]

My op-ed would go on to mention James Clerk Maxwell's prediction of electromagnetic waves, Heinrich Hertz's detection of them, and Guglielmo Marconi's use of them to transmit messages wirelessly. By the time radio was a mass medium in the 1930s, physicists were already doing the basic research that would lead to the transistor. And when the first PCs were in offices, physicists already were working on the nanomagnetic phenomena that would revolutionize data storage.

What might the physicists of Europe discover now that will beget new products? We can't be sure, I'd say. But we do know, thanks to the EPS report and similar ones by the UK's Institute of Physics[3] and the American Physical Society,[4] that physics increases prosperity. We need to keep funding it.

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Commentary

Transparency for nuclear weapons test sites

David Kramer reported in the February 2020 of PHYSICS TODAY (page 23) on the planned billion-dollar-plus upgrade to the diagnostics of US subcritical plutonium implosion experiments beneath the Nevada National Security Site. His excellent piece came eight months after the Defense Intelligence Agency (DIA) declared that "the U.S. government, including the Intelligence Community, has assessed that Russia has conducted nuclear weapons tests that have created nuclear yield."[1] The Trump administration has not said when the alleged tests took place, only that they occurred after Russia signed the Comprehensive Nuclear-Test-Ban Treaty (CTBT)[2] in 1996.

RN15 IN RESOLUTE, NUNAVUT, CANADA, is one of 80 radionuclide stations worldwide that watch for violations of the Comprehensive Nuclear-Test-Ban Treaty. (Photo from the CTBTO.)

The DIA declaration may have been a first step toward President Trump unsigning the CTBT as a group of Senate hawks urges, so that the US can resume nuclear explosive testing.[3] For the president to unsign a treaty, however, would require that the Senate return it to him. The CTBT has been with the Senate since President Bill Clinton submitted it for ratification in 1997. Even though the US has not ratified the CTBT, the United Nations Vienna Convention on the Law of Treaties provides that a signatory to a treaty "is obliged to refrain from acts which would defeat the object and purpose of a treaty." The departure of John Bolton and Tim Morrison from the National Security Council a few months after the DIA statement may, however, have taken the pressure off the CTBT for the moment.

The Trump administration's public accusation that Russia is violating the CTBT probably relates to the suspicion that Russian weapons scientists have conducted hydronuclear experiments. In those experiments, plutonium is imploded into a barely supercritical mass that is then irradiated with a burst of neutrons at its point of maximum compression. The supercriticality results in a slow-growing fission chain reaction until the plutonium expands enough to become subcritical again. The fission-energy yield is typically less than the equivalent of a kilogram of chemical explosives.

The planned US subcritical experiments would have a fission-energy yield too, but a much smaller one. The proposed experiments would reach a maximum multiplication factor of about 0.95 from one generation of fissions to the next, with irradiation by a burst of neutrons to ignite a chain reaction. The neutrons could come from an external source or be produced in the plutonium by a beam of high-energy x rays causing photofissions. For target values of 10^{10} total fissions per experiment the fission energy yield would be about 0.3 joules, about the equivalent of that from the detonation of 0.07 milligrams of chemical explosive.[4] The fissions would, however, release enough prompt gamma rays so that the die-away of the fission chain reactions over a hundred nanoseconds or so could be used to measure the level of criticality achieved and thereby the compressibility of the plutonium.

Article I of the CTBT defines banned activity only as "any nuclear weapon test explosion or any other nuclear explosion." It is therefore necessary to review the statements of the negotiators to shed light on where to draw the line. In 2011 the US State Department put out a collection of statements made by the officials of the five nuclear-armed states that are parties to the Nuclear Non-Proliferation Treaty; France, Russia, and the UK, unlike the US and China, have ratified the CTBT.[5] Here are three of the most relevant statements.

- The CTBT "permits experiments . . . including those of the explosive nature, but under the condition that they are purely chemical (the so-called 'hydrodynamic experiments')." —Grigory Berdennikov, chief Russian negotiator, 7 December 2005.
- "My government's position [is] that the CTBT should not permit any nuclear weapon test explosion involving any release of nuclear energy, no matter how small." —John Weston, UK ambassador to the United Nations, 14 September 1995.
- "It maintains the possibility of testing called 'cold' tests and 'subcritical', no nuclear chain reaction." —Serge Vinçon, former vice president of the French Senate, 25 March 1998.

When the CTBT was submitted to Congress in 1997, the State Department included an article-by-article analysis with the following statement:

> The U.S. decided at the outset of negotiations that it was unnecessary, and probably would be problematic, to seek to include a definition in the Treaty text of a "nuclear weapon test explosion or any other nuclear explosion." . . . It is clearly understood by all negotiating parties, as a result of President Clinton's announcement on August 11, 1995, that the U.S. will continue to conduct a range of nuclear weapon-related activities to ensure the safety and reliability of its nuclear weapons stockpile, some of which . . . may result in the release of nuclear energy. Such activities . . . could include: . . . inertial confinement fusion . . . and hydrodynamic experiments, including subcritical experiments involving fissile material. None of these activities will constitute a nuclear explosion.

I don't believe that neutron-irradiated subcritical experiments were discussed in the negotiations. Since they involve nuclear chain reactions and are not purely chemical, they fall between cold, allowed subcritical tests and the forbidden, barely supercritical hydronuclear tests. They allow the US to accomplish, with its billion-dollar-plus setup, what Russia or China could accomplish much more cheaply with hydronuclear tests.

Recently, after the DIA accused Russia of cheating, the State Department offered the following explanation:

> Dating back to 1993, the United States has defined its own nuclear testing moratorium as a commitment not to conduct "nuclear explosive tests", and after August 1995 made clear that this means any test that produces a self-sustaining, supercritical chain reaction of any kind. This is what the United States refers to as the "zero-yield" standard. Beginning with President Clinton's announcement in August 1995, the United States led efforts to ensure the Comprehensive Test Ban Treaty (CTBT) was a "zero-yield" treaty, but these efforts did not produce a documented agreement among the nuclear weapons states on a definition of "nuclear explosion."[6]

Although the CTBT established the now-operational global nuclear-test-monitoring network, the treaty-mandated option for short-notice, on-site inspections of test sites is not yet available because the treaty has not formally entered into force.

To help clarify whether their ongoing experimental activities are fully compliant with the zero-yield ban on testing, nuclear-weapons-state signatories to the CTBT could pursue test-site transparency procedures. One approach would allow measurements of induced radioactivity or neutron transmutation products in the containment vessels to determine the fission yield after subcritical tests.

Unfortunately, Russia refuses access to its Novaya Zemlya test site until the US ratifies the CTBT, as Russia has. In the case of China, Los Alamos physicists visited the Chinese Lop Nor test site 10 times[7] between 1990 and 2001. The visits were to be reciprocated, but when the Chinese delegation arrived in the US, their permission to visit the US test site was vetoed in the Department of Energy, and they were given briefings at Livermore instead. Since then, the Chinese have not been interested in transparency unless the US goes first. As Kramer's report illustrates, the US weapons labs have been open in publishing photos and decriptions of their subcritical-experiment setups. However, the Trump administration is not encouraging them to discuss test-site transparency.

All 184 signatories to the CTBT would do well to support additional test-site transparency measures to reinforce the quarter-century moratorium on nuclear testing by the nuclear-weapons-state signatories.

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LETTERS

A nod to Philip Bevington

I read with appreciation Charles Day's important, lucid, and interesting editorial on reproducibility (PHYSICS TODAY, December 2019, page 8). When he mentioned the need for better education in data analysis and named Philip Bevington's *Data Reduction and Error Analysis for the Physical Sciences* and its importance to him, I gasped audibly. For the first time, I appreciated how much that one small, clear tome had influenced not only my career but my whole approach to life and decision making in nontechnical areas.

For me, Bevington, as the book was affectionately known in my undergrad physics department, encapsulates the essence of the scientific method. I know such an ideal is infeasible on so many levels, but I believe that the world would be a much better place if everyone, not just every physicist, were to read the book as part of an undergraduate education.

We might want to revisit Bevington as an exemplar not just of scientific-method education but of meta-instruction in effective pedagogy in general. Phil Bevington seems to have struck the perfect balance of detail, rigor, practicality, and clarity.

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Neckties or not, and a quick fix

I appreciate Brian Kraus's review of my book *Real Scientists Don't Wear Ties: When Science Meets Culture* (PHYSICS TODAY, March 2020, page 52). The photo spread of diverse physicists mostly not wearing ties underlines a point I made in the book: More than ever, we physicists look different from each other and dress the way we want to. However, I must correct an error Kraus made when he wrote that I retired from academia in 1990. As I stated in my book's introduction (page xi), I continued academic research and teaching until 2011, when I retired as Charles Howard Candler Emeritus Professor of Physics after 42 years at Emory University.

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A physicist out of academia

The commentary from Elizabeth Frank (PHYSICS TODAY, October 2019, page 10) about her career move from academia to industry resonated with me in many ways . I largely agree with Frank's statement that "you don't have to justify your motivations to anyone but yourself," but I also point out that career changes can deeply affect one's family.

As Frank mentions, physics professors often have limited awareness of opportunities outside academia; therefore, input from someone with a career like mine is important. My path is significantly different from Frank's, and I speak from later in life. Furthermore, the variety of careers available to physicists is much greater outside academia than within.

My experiences in academic physics began when I was a precocious elementary school student and grew through wonderful experiences at Harvard, Princeton, and Stanford Universities to a tenure-track assistant professor position at the University of Massachusetts Amherst. At Harvard, I had strong physics courses and valuable interaction with renowned physicists, including my adviser Norman Ramsey. At Princeton, I completed a PhD in experimental high-energy physics in less than four years.

During my postdoc at Stanford in the early 1970s, I had the good fortune to work at SLAC on two experiments that led to Nobel Prizes—one for Burton Richter and one for Martin Perl. I then took a tenure-track assistant professorship at UMass, where I continued the work at SLAC while helping a local UMass team start an experiment at Brookhaven National Laboratory. All was going well.

Nonetheless, at age 30 I had a midlife crisis and decided to move from academia to industry. To Frank's point, the switch was deeply personal. At least three factors contributed to my malaise. First, I felt locked into my high-energy-physics specialty and was concerned about its future. The significant projects were getting much bigger, taking much longer, based in more distant laboratories, and producing increasingly arcane results. It seemed harder all the time for me to continue to derive personal satisfaction from the field.

A second factor was that as an experimenter, I felt that I should understand the theories pertaining to my experiments, but they had reached a level of abstraction beyond my comprehension. Third, I was concerned about the 1970s energy crisis associated with the Arab oil embargo, and I wanted to help address it. I landed a job at the GE Research and Development Center in Schenectady, New York. My wife was shocked but supportive: Our two children were young and portable, and her career actually benefited from the move.

My experiences in industry during 37 years with GE were also wonderful, but in different ways from my time in academic high-energy physics. My work at GE was mostly in lighting technology. After a decade I moved to the headquarters campus of GE Lighting in Cleveland, Ohio. I have done research that has been published in refereed journals. It has always been on problems with near-term, real-world significance. I have also worked on developing and producing new energy-saving lighting products.

Every few years my role morphed as the business changed and new needs arose. Those changes were invigorating as I gained new insights. I often started new assignments with little of the requisite technical know-how, but I was a quick learner with a background in basic physics and wonderful, talented, and technically diverse coworkers. The business funded the work, with no external grant proposals needed. I have had plenty of opportunity to teach, and I have enjoyed it. Toward the end of my career at GE, I was involved in the LED technology revolution. Since retiring, I have developed a successful consulting business that draws heavily on technical knowledge of light sources.

I look back to my decision at age 30 as the most important one of my career. On the one hand, academia *might* have provided better opportunity for long-term career focus and development of deep expertise. On the other hand, industry *did* provide stimulating work with near-term, beneficial, real-world significance. It also offered invigorating career and assignment changes. I have never regretted my decision, but I will never know where the path not taken might have led.

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Radar points the way to detecting cosmic neutrinos

A laboratory experiment at SLAC offers the first observations of radio-wave reflections from ionization trails of particle showers in a transparent solid.

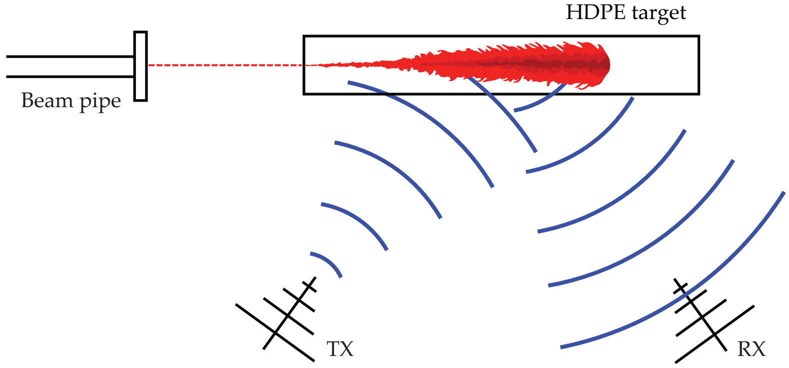

FIGURE 1. RADAR ECHOES IN ARTIFICIAL ICE. Electron bunches shot into high-density polyethylene (HDPE) create a cascade of relativistic particles that mimic those produced in ice by cosmic neutrinos. At the same time, radio waves from a nearby transmitter (TX) reflect from an ionized trail in the cascade's wake and are detected by an antenna (RX). (Adapted from ref. 1.)

Cosmic rays—the electrons, protons, antiparticles, and nuclei that penetrate Earth's atmosphere—can exceed 10^{20} eV. Accelerating particles to such high energies requires a violent, impulsive process, such as the merger of neutron stars, the collapse of a massive star, or the rapid conversion of a supermassive black hole's rotational energy. Ultrahigh-energy neutrinos are thought to emerge from such exotic sources (see the article by Peter Mészáros, PHYSICS TODAY, October 2018, page 36). But unlike cosmic rays, which interact with photons from the cosmic microwave background and are deflected by magnetic fields, cosmic neutrinos point directly back to their sources—the most powerful accelerators in the sky.

The neutrinos' feeble interaction with matter makes them powerful messengers of new physics, but it also complicates their detection. For example, the IceCube neutrino observatory in Antarctica relies on catching the flashes of Cherenkov light from muons produced by neutrinos inside a billion tons of ice. The 1 km^3 observatory requires an array of more than 5000 photomultiplier tubes because the flux of ultrahigh-energy neutrinos is so small and plummets with neutrino energy. The highest-energy neutrinos IceCube ever measured are a few peta-electron volts (1 PeV = 10^{15} eV).

How energetic is such a neutrino? One joule is about 10^{19} eV, roughly equivalent to the energy of a slow-pitched baseball. At one-thousandth of a joule, 10 PeV is the kinetic energy equivalent of a honeybee in flight. But whereas the honeybee's energy is distributed over some 10^{23} atoms, extreme astrophysical events concentrate the energy in a single cosmic neutrino. To have much chance of catching one, you need to increase the search volume or change methods.

An international collaboration led by Steven Prohira (a postdoctoral fellow at the Ohio State University) now reports[1] a proof-of-concept measurement of an old proposal: using radar to detect the interaction of a neutrino in ice. The approach requires no new technology and could scan potentially enormous volumes inexpensively. More importantly, it could detect neutrinos in an energy window that is a blind spot to existing methods.

Radio waves

In 1962 Gurgen Askaryan realized that air showers, or cascades, of relativistic electrons, muons, and other particles that beget Cherenkov light contain a negative-charge excess of about 10–20%.[2] The charge asymmetry generates coherent radio waves, whose power scales with the square of the primary particle's energy. With that scaling, the RF signal should be most intense at ultrahigh energies. The ANITA collaboration's experiment—made of an array of radio antennas hanging from a helium balloon (see PHYSICS TODAY, December 2010, page 22)—repeatedly monitors a million square kilometers of Antarctic ice during month-long flights in search of Askaryan's predicted radio waves from neutrino-triggered cascades. Other radio projects look for signals from Greenland's ice pack and from the lunar regolith. (See the article by Francis Halzen and Spencer Klein, PHYSICS TODAY, May 2008, page 29.)

Twenty years before Askaryan's work, Patrick Blackett and Bernard Lovell considered another signature of cascades—although at the time the two researchers had cosmic-ray-induced cascades in mind, not neutrino-induced ones. As a cascade travels through the atmosphere, it ionizes oxygen and nitrogen atoms and leaves a plasma trail of quasi-stationary electrons. Blackett and Lovell calculated that the ionization trail should be observable when radio waves are bounced off it.[3] But despite decades of attempts, no one has ever been able to capture either a cosmic-ray- or neutrino-triggered event that way.

As Krijn de Vries (Vrije University Brussels) and coworkers realized just a few years ago,[4] the ionization trail in air is too dilute to robustly reflect a signal. But they calculated that a cascade through ice, whose density exceeds that of air by a factor of 1000, produces a far denser plasma trail of electrons in its

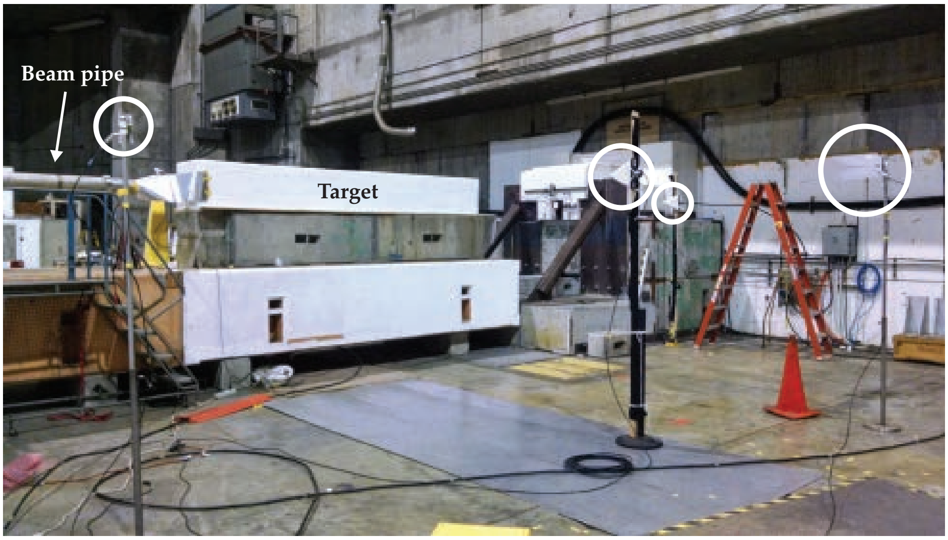

FIGURE 2. THE EXPERIMENT AT SLAC. Electrons exit the beam pipe (far left) and enter the 4-m-long polyethylene target, surrounded by transmitter and receiver antennas (circled). Second from left is the transmitter; the others are receivers. (Adapted from ref. 5.)

wake, about 10 m long and 10 cm wide. Prohira, de Vries, and their colleagues now report[1] the first convincing measurements of radar reflections from the ionization trail of high-energy particles in a transparent solid.

Electrons stand in for neutrinos

Prohira and his coworkers were not looking for neutrino interactions. Their experiment at SLAC was designed to mimic a neutrino-triggered cascade by using electrons as a proxy for neutrinos and high-density polyethylene (HDPE) as a proxy for ice. Figure 1 depicts the basic concept: Intense bursts of a billion electrons are repeatedly shot into the HDPE, each time producing a cascade (red) equivalent to what's expected from a 10^{19} eV neutrino interaction in ice. Radio waves are transmitted into the polymer at the same time, and antennas around it detect any echoes reflected from free electrons in the cascade's wake.

Ice is nearly transparent to radio waves. Whereas Cherenkov light travels only about just 200 m in ice, radio waves travel an order of magnitude farther. Transmitting and receiving antennas may thus be spaced much farther apart than IceCube's photomultiplier tubes.

Unlike IceCube, ANITA, and other passive-monitoring experiments, radar is an active system. Says de Vries, "Radar provides tremendous control over all our experimental parameters. The signals we receive largely depend on what we send." The transmission power is one adjustable knob: The higher the power, the brighter the reflection. And above a critical primary-particle energy of about 10 PeV, the cloud of free electrons produced in its wake is dense enough to reflect a 0.1–1 GHz radar signal coherently. All the free reflecting electrons radiate in phase.

Transmission frequency also matters for another reason. The ionization trail in ice lives just a few nanoseconds before the free electrons reattach to nearby water molecules. To capture an electron's oscillation before it dies, the transmission frequency must be on the gigahertz scale.

Perhaps radar echo's most advantageous feature is its peak energy sensitivity, which is in the 10- to 100-PeV window, a blind spot for other neutrino-detection methods. Those energies are above what IceCube can efficiently resolve given its low volume, and they are below the limits of balloon-borne, satellite-borne, and some in-ice experiments.

Improving signal to noise

In the new experiment, radio noise turned out to be two orders of magnitude higher in amplitude than the expected signal. The noise was largely from "transition radiation," produced when a charged particle crosses the interface between materials having different indices of refraction—in this case, from the vacuum of the beam chamber into the air of the lab or into the polyethylene slab. Transition radiation won't be a problem when researchers eventually look for ionization trails from neutrino-induced cascades. In nature, those cascades take place inside the ice. But in the proof-of-concept experiment, the researchers had to address the transition radiation. Fortunately, that RF noise was similar from pulse to pulse.

To extract persuasive evidence of a cascade reflection, the researchers filtered out of their data the transition radiation and other noise—Askaryan RF fields, telecommunication signals, and reflections from concrete and metal features in the SLAC station, shown in figure 2. They performed three types of experiments: ones with both the electron beam and radar on; ones with the radar on but not the electron beam; and ones with the electron beam on but not the radar. Armed with those data, they subtracted the background to resolve a real radar signal. To constrain the analysis, they confirmed that the signal had the expected timing, frequency, and power dependence.

Prohira and his colleagues next want to repeat the experiment on a high-altitude ice sheet in Antarctica. It's radio quiet there—though even the passage of wind generates residual RF hum—and the altitude increases the likelihood that a cosmic-ray-induced cascade will make it into the ice; the ionization trail will come from that cascade. Antennas just below the surface would transmit radar and pick up reflected signals.

After that in-nature test the researchers will turn their attention to neutrino-induced cascades.

Mark Wilson

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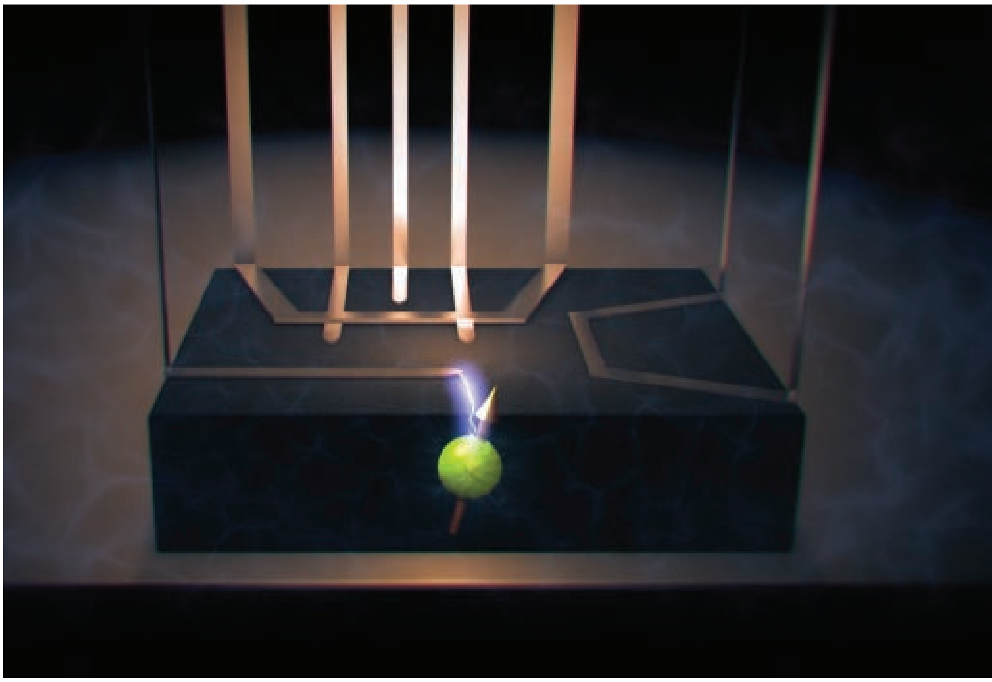
Localized electric field manipulates a nuclear spin

The atom-level control could provide the precision required for some quantum computing applications.



One promising approach for quantum information processing involves embedding tightly spaced arrays of identical atomic nuclei in a silicon substrate. In that design, each nucleus's spin serves as a quantum bit, or qubit. The qubit's spin, which can be set to different states, is used to store and process information. However, before spin-based devices can be scaled up for practical use, quantum engineers need to be able to control a single nuclear spin in silicon without affecting adjacent spins.

In principle, NMR could do the job. Radio-frequency (RF) magnetic field pulses can excite and control nuclear spins that are polarized in a static magnetic field. Because of the pulses' wide spatial extent, however, they tend to influence adjacent spins, which renders NMR impractical for manipulating individual spins in a collection of identical atoms. Ideally, a method for controlling individual nuclear spins would match the ease of exciting individual electron spins in a row of semiconductor quantum dots, in which each dot is equipped with a separate electrode. Adapting that approach for nuclear spins offers a potential advantage because nuclear spins have longer coherence times than electron spins and can be measured with minimal readout error.

Electric fields, rather than magnetic ones, provide an intriguing possibility for nuclear spin control. The fields can be efficiently routed and tightly confined in complex nanoscale devices. Indeed, highly focused electric fields make possible the sophisticated interconnections found in modern silicon computer chips.

Now researchers in Andrea Morello's lab at the University of New South Wales in Australia have demonstrated electrical control over nuclear spin.[1] The re-

FIGURE 1. IN THIS ARTIST'S IMPRESSION of a nuclear electric resonance device, a sharp metallic antenna applies a strong oscillating electric field directly to an antimony atom (green) embedded in a silicon chip. Other metallic components include electrostatic gate connections and readout electrodes. (Image by Tony Melov/UNSW.)

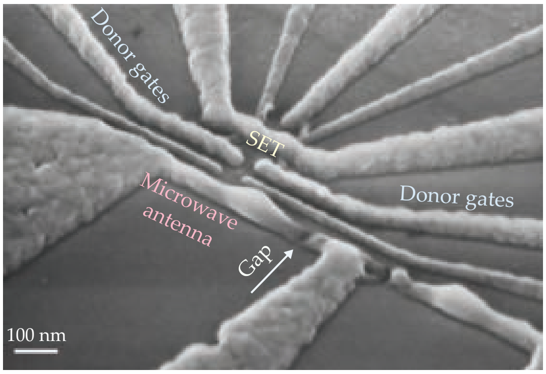


FIGURE 2. A SCANNING ELECTRON MICROGRAPH shows the metal-oxide-semiconductor device used in the experiment. An antimony donor atom is implanted in the silicon substrate. Electrostatic gates control the potential of the Sb atom embedded in the chip between the gates. The device contains a single-electron transistor (SET) for spin readout and a microwave antenna carrying an electric current that normally generates an oscillating magnetic field for performing NMR. (Adapted from ref. 1.)

searchers developed a technique for controlling the spin of a single atom embedded in a silicon chip, illustrated in figure 1, by using an electric field produced at the tip of a nanometer-sized electrode.

Bulk efforts

The suggestion that electric fields could control nuclear spins dates to the 1960s.[2] Nico Bloembergen predicted that an external electric field can induce spins larger than ½ to transition from one energy level to another in crystals with low symmetry. Such nuclei can have nonspherical charge density distributions, or quadrupole moments, which couple to local electric field gradients. When placed in a crystalline environment without inversion symmetry, a time-varying external electric field should modulate that coupling and change the spin state.

Bloembergen's efforts to demonstrate electrical control over spin saw partial success. His studies proved that static electric fields could shift spins between energy levels in a bulk crystal.[3] But those early experiments could not achieve dynamic coupling between an oscillating electric field and nuclear spins. Although they were "heroic experiments," says Morello, the investigations were unable to create the requisite huge RF electric fields in bulk crystals.

Only recently did experiments cleanly demonstrate nuclear electric resonance (NER) in a bulk crystal. In 2013 Masaaki Ono and colleagues at Tohoku University, Japan, excited spins in gallium arsenide at their resonant frequency using an oscillating electric field.[4] Ono's team proved the viability of using NER to manipulate spins in a bulk crystal.

Electrical accident

Coherent control over a single nuclear spin in a silicon device remained an unsolved problem. To investigate possible solutions for single spin control, Morello's PhD student Serwan Asaad and postdoc Vincent Mourik used an antenna to magnetically probe an antimony-123 nucleus embedded in silicon. The researchers had originally set out to perform NMR on a single ^{123}Sb nucleus, which has spin 7⁄2. They fabricated the device, shown in figure 2, with an Sb atom and a special antenna optimized to create a high-frequency magnetic field to control the nucleus. But when they applied power to the antenna, they observed a resonance spectrum that was missing several expected NMR peaks.

Asaad realized that the high power had damaged the antenna and transformed it into an open circuit. As a result, the antenna was creating a strong electric field focused directly on the Sb atom. Conveniently, the device also included several tiny electrodes with which to control the potential of the atom. The researchers redesigned their experiments to apply an oscillating voltage to one of the electrodes and observed the same resonance spectrum as when applying power to the damaged antenna. Then, they calculated the rate at which transitions between different energy-dependent spin states should occur in response to either a magnetic or an electric field (see figure 3). Comparing those calculations to experimental data persuaded them that the electric field was causing the Sb resonances.

Still, the result puzzled the researchers. The electric quadrupole moment—the nonspherical charge distribution of the nucleus—does not couple directly to an electric field, but to the field's gradient. To understand the effect, Morello enlisted Andrew Baczewski of Sandia National Laboratories to perform *ab initio* calculations of the phenomenon. The simulations revealed that the applied electric field distorted the charge distributions in the bonds between the Sb atom and the Si atoms around it. Then

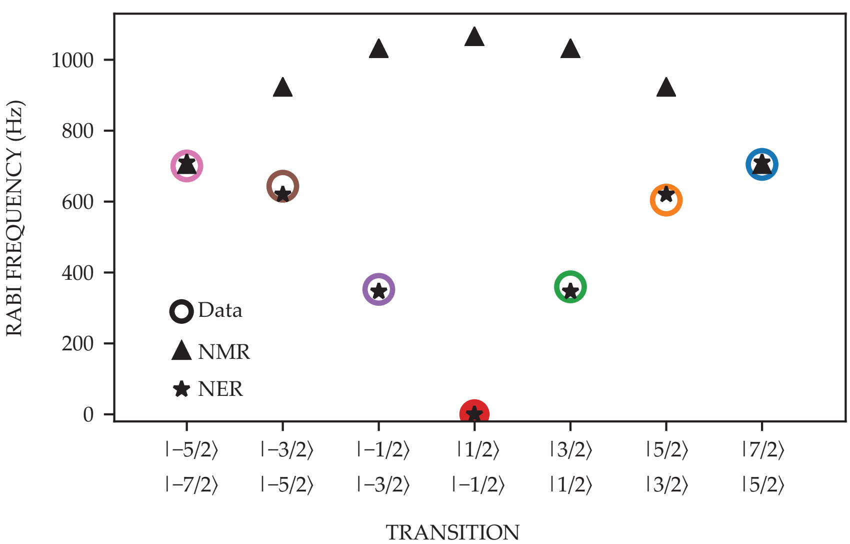


FIGURE 3. AN RF FIELD drives antimony-123 atom transitions between different nuclear spin states at different rates, the so-called Rabi frequency. The measured rates (colored circles) match theoretical predictions for transitions due to an electric field (NER, stars) but not those due to a magnetic field (NMR, triangles). (Adapted from ref. 1.)

the distortion of the charges produced a strongly nonuniform electric field around the Sb nucleus. That field provided the gradient that caused the nuclear spin transitions. The calculated effects match the experimental results.

Because electric fields decay rapidly with distance from the electrode and can easily be screened with other metallic structures, NER allows control that is localized enough to manipulate individual nuclei. The technique could help scale up a key component in quantum computing applications, according to Anthony Sigillito from Princeton University. The level of localized control demonstrated by Morello and coworkers could provide the precision needed to drive one qubit without affecting the other in a two-qubit gate, which is the fundamental building block of a scalable quantum computer. The new result opens the possibility of all-electrical driving of a donor qubit embedded in a silicon device.

Rachel Berkowitz

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Spongy hydrogels clean textured paintings

Washing away the dirt from an artistic masterpiece is especially tricky when the surface is not flat. New materials can help.

There will never be another Vincent van Gogh, Pablo Picasso, Georgia O'Keeffe, or Frida Kahlo. Each of the great works of visual art that together make up humankind's cultural heritage is unique and irreplaceable. Conservators at museums thus face a pair of often contradictory tasks: Keep the artwork in their care safe for future generations and allow as many people as possible to enjoy it now.

Even under the best of conditions, a painting on display for decades accumulates dirt and dust that mar its appearance and dull its colors. Although cleaning everyday grime from ordinary objects isn't technically challenging—scrubbing with soap and water usually does the trick—priceless works of art require a gentler, more sophisticated touch to avoid any risk of damage. Worse, many artists, especially in recent decades, apply paint to canvas in thick brush strokes to create three-dimensional textured paintings, like the one in figure 1a, with lots of nooks and crannies where dirt can hide.

Now Piero Baglioni and colleagues at the University of Florence in Italy have developed a polymer hydrogel—a network of polymer chains bound together into a porous, water-bearing solid—that safely removes dirt from the roughest of painted surfaces.[1] "These gels are unique in the conservation field," says Bronwyn Ormsby, the principal conservation scientist at Tate, a network of art museums in the UK. "They can offer solutions to some of our more intractable problems."

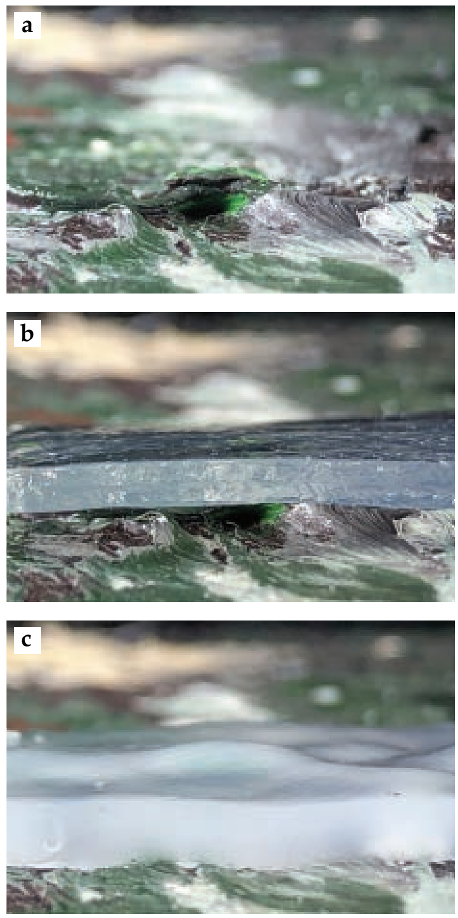

FIGURE 1. TEXTURAL FEATURES of contemporary paintings can be bumpy, **(a)** as shown by the uncovered mock-up. **(b)** Most cleaning gels, including this one developed for restoring paper artwork,[2] are unable to cover the rough surfaces uniformly. **(c)** A gel of polyvinyl alcohol, however, is soft enough to do the job. (Images adapted from ref. 1.)

Freeze–thaw gels

Pastes, poultices, thickeners, and absorbent materials have been used for thousands of years to apply fluids to surfaces. You'd probably clean up a mess using a wet rag or sponge rather that dousing it with soapy water. Confining a liquid in a solid or semisolid matrix prevents it from immediately inundating the surface and flowing away.

The use of gels for cleaning art and artifacts, which dates back to the 1980s, is based on a similar principle. A sheet of gel, imbued with water, surfactant solution, or other solvent, is gently placed onto the surface to be cleaned and left there for a minute or two. During that time, tiny amounts of fluid seep out of the gel and loosen the dirt particles. The gel is then peeled away, and with it, one hopes, comes the dirt.

Conventional gels—many of which

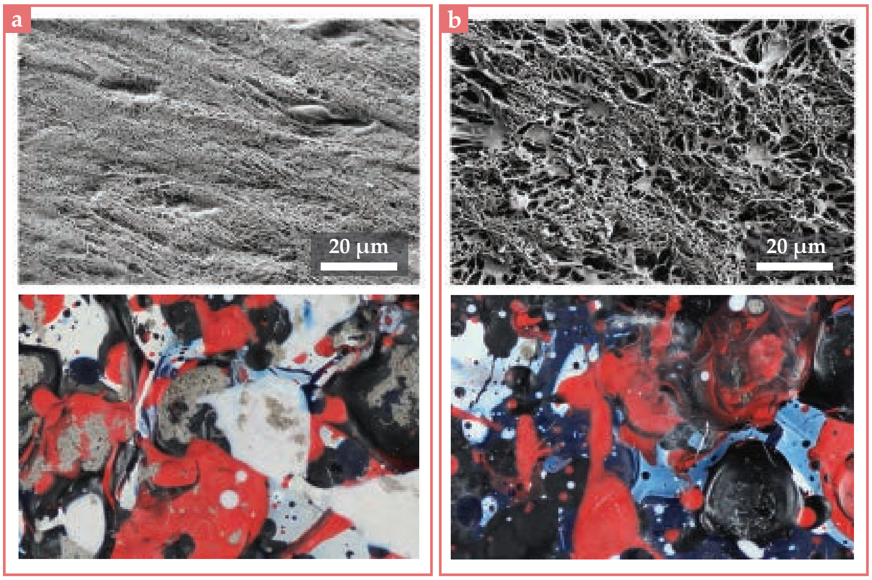

FIGURE 2. TWO POLYVINYL ALCOHOL GELS were tested at cleaning an artificially soiled mock painting. **(a)** The first, made from uniform-length polymers, formed a gel with narrow, parallel pores, as seen in the scanning electron microscopy image in the top panel. That gel left much of the dull gray dirt behind. **(b)** But the second, a twin-chain gel made from a mix of long and short polymers that gave it larger and more irregular pores, removed almost all of the dirt. Both gels were soaked in the same cleaning fluid, a solution of 99% water and 1% surfactant. (Adapted from ref. 1.)

were adapted from food additives such as agar and gellan gum—don't solve all cleaning problems, and they sometimes introduce their own. A gel can lose its structural integrity and leave bits of itself behind. It may deposit a chemical residue that alters the finish and appearance of the paint. Or it might just be ineffective at removing dirt.

But gels aren't all created equal; their diverse chemical, mechanical, and structural properties affect their cleaning performance. Baglioni and colleagues' idea is to use the tools of soft-condensed-matter physics to design new materials tailored to the needs of art conservation. They've already concocted a polymer hydrogel that can remove the residue of adhesive tape from centuries-old sheets of paper.[2] (See PHYSICS TODAY, July 2018, page 21.) That gel works well on flat surfaces, but as figure 1b shows, it's far too stiff to conform to the irregularities of a contemporary textured painting.

In search of a more mechanically compliant gel, the Florence researchers turned to polyvinyl alcohol (PVA), a material long known in the biomedical field for being soft yet sturdy, resilient, and chemically benign. Some of its advantageous properties stem from its gelation mechanism. Typically, polymers are transformed from viscous goop into elastic solid through chemical cross-linking, the addition of a curing agent that binds nearby polymer chains together. Any excess curing agent, however, can leach out of the gel and cause problems later.

A PVA hydrogel, in contrast, can be solidified simply by freezing and thawing a solution of PVA in water.[3] As ice crystals in the mixture grow and expand, they press the PVA molecules closer together. And by some mechanism that's not totally clear—maybe through a combination of hydrogen bonding and the formation of tiny PVA crystallites—that compression is enough to lock adjacent PVA chains together permanently.

Into the pores

As figure 1c shows, a PVA hydrogel is soft enough to drape over the peaks and into the troughs of a rough painted surface. It is not, however, effective at cleaning. The problem, Baglioni and colleagues hypothesized, is the gel's pore structure. Ice crystals in PVA grow long, thin, and straight, so the hydrogel is thus honeycombed with narrow, parallel pores, as shown in figure 2a—hardly ideal for fluid mobility and dirt pickup.

But how does one modify that structure without compromising the gel's softness? It's known that a PVA gel's properties can be tuned by repeating the freeze–thaw cycle more than once. Subsequent cycles widen the pores while retaining their shape. But repeated cycling also makes the PVA walls a bit thicker and thus more rigid—exactly the opposite of what the researchers wanted.

Baglioni's pivotal idea was to try making a hydrogel out of a mixture of PVA molecules of two different lengths. PVA's temperature-dependent solubility in water also depends on the length of the polymer chain: As a watery mixture of long- and short-chain PVA is cooled, the short polymers become insoluble before the long ones do. The difference in miscibility would push the short- and long-chain molecules to phase separate, but their sluggish motion would keep them at least partially intertwined. The resulting tangle, Baglioni reasoned, must have some effect on the size and shape of the ice crystals and thus on the gel's pore structure.

That effect turned out to be surprisingly dramatic. Instead of having long, thin pores like a homogeneous PVA hydrogel, the twin-chain PVA gel, as it's come to be known, looks more like a sponge. As figure 2b shows, its pores are larger, rounder, more irregular, and more interconnected. When tested on a mock painting, the twin-chain gel proved excellent for cleaning.

To see how that pore structure formed, the Florence researchers tagged their PVA molecules with contrasting fluorescent dyes: green for long-chain molecules and red for short-chain ones. Sure enough, as the solution cooled, the short-chain molecules clumped together into blobs several microns in diameter. The blobs disrupted the growth of the ice crystals and formed the basis for the gel's pores.

What is it about the sponge-like structure that makes it so good for cleaning? Baglioni and colleagues aren't sure, but they suspect it has to do with the ease with which the gel both releases fluid and reabsorbs it. As the gel rests on the soiled painting, water gradually evaporates from its upper surface. To compensate, water from the lower surface gets pulled through the interconnected pores into the gel bulk—and the dirt from the painting get pulled with it. Dirt particles are more reliably removed when they're lodged in the gel's pores rather than clinging to its surface. "But this is all still a hypothesis," says Baglioni. "We were working on testing it when the coronavirus hit."

Masterpieces renewed

Beyond demonstrations on mock-ups, the twin-chain PVA gels have already been used to clean real works of art. In collaboration with conservators at the Peggy Guggenheim Collection, a modern-art museum on Venice's Grand Canal, the Florence researchers used their gels to restore two Jackson Pollock paintings, *Two* and *Eyes in the Heat*, to their original 1940s glory. Guggenheim used her inherited fortune to boost the careers of young artists of her day, Pollock among them, and her collection includes several of his works that predate his most famous poured paintings.[4] Whereas *Two* was painted with traditional brushstrokes, *Eyes in the Heat* was created by squeezing thick paints onto the canvas and smearing them with blunt instruments. Both paintings have rough surfaces that have been, until now, hard to clean.

Baglioni's group has also collaborated[5] with Ormsby and others at Tate to clean *Whaam!*, a large two-panel painting by Roy Lichtenstein that the gallery bought in 1966. As with the rest of Lichtenstein's comic-book-inspired pop art, the surface of *Whaam!* isn't especially rough, although its cotton canvas has a texture to it. The main cleaning challenge it poses is Lichtenstein's use of three kinds of paint, each with its own chemical properties and distinct finish to maintain. A version of Baglioni's new PVA gel—frozen and thawed a few more times to give it different mechanical properties—proved the best tool for the task. "Each work of art degrades in a different way and needs different conservation," says Baglioni. "With different tiny modifications, our versatile family of gels can address many needs."

Johanna Miller

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MILLIE DRESSELHAUS

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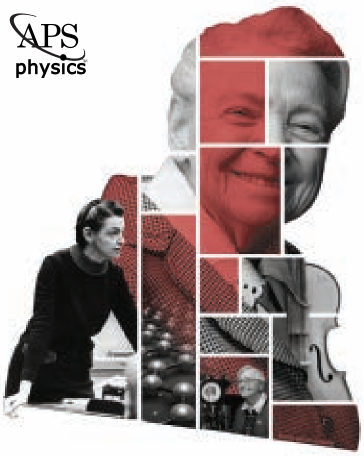

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World's physics instruments turn their focus to COVID-19

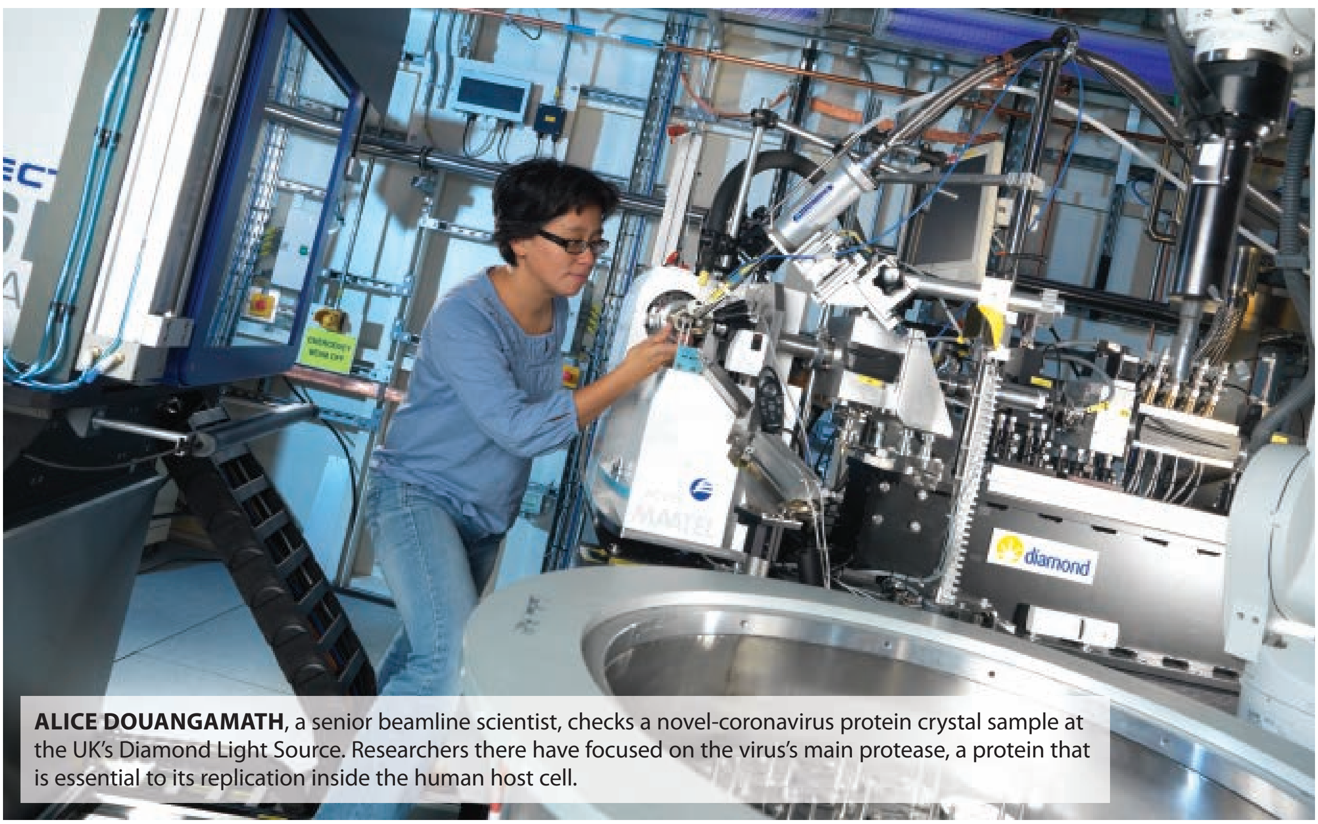
Scientists are employing x rays, electrons, and neutrons to decipher and disable the molecular machinery of the novel coronavirus.

Although most basic research has been suspended by the coronavirus pandemic, some labs remain open to engage in a furious effort to find treatments for the disease. Physicists and chemists are vital to a key part of that quest: decoding the three-dimensional structures of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) proteins and finding locations where drugs could latch on and disable the viral machinery. The virus itself is not used for those experiments, only the cloned proteins that are its principal working parts.

As of early April, the life sciences beamlines were open for SARS-CoV-2 research at the UK's Diamond Light Source. In the US, at least 23 groups were working at the Advanced Photon Source at Argonne National Laboratory as of press time, according to Bob Fischetti, life sciences adviser at the APS. The National Synchrotron Light Source II at Brookhaven National Laboratory, SLAC's Stanford Synchrotron Radiation Lightsource (SSRL), and the Advanced Light Source at Lawrence Berkeley National Laboratory are operating with minimal staff, each keeping open several x-ray protein crystallography beamlines strictly for coronavirus research.

The BESSY II light source in Berlin closed briefly but resumed operations on 2 April for coronavirus research, which is also ongoing at the Shanghai synchrotron in China, where the first 3D structure of the main protease protein was resolved. Officials there did not respond to requests for comment. The European Synchrotron Radiation Facility in France has been closed for an upgrade, but it announced in early April that it would consider reopening beamlines on a case-by-case basis for coronavirus research.

Structures of many of the virus's 28 or 29 proteins (estimates vary on the exact number) have been resolved, both alone and in complexes with various molecules, known as ligands, that bind to them. Among those resolved structures are the main protease (M^{pro}), an enzyme that processes long viral polyproteins into shorter functional units; an endoribonuclease called Nsp15; and the spike protein that protrudes from the coronavirus



ALICE DOUANGAMATH, a senior beamline scientist, checks a novel-coronavirus protein crystal sample at the UK's Diamond Light Source. Researchers there have focused on the virus's main protease, a protein that is essential to its replication inside the human host cell.

DIAMOND LIGHT SOURCE

surface and initiates infiltration to human cells.

As of 25 March, 108 structural determinations of SARS-CoV-2 proteins, both alone and with attached compounds, had been deposited in the open-access Worldwide Protein Data Bank (PDB). At that time, 77 structures of M^{pro}, with various ligands, had been submitted by teams working at the Diamond Light Source. More structures were expected to be released in mid-April.

Several scientists caution that some of the deposited structures are not very well defined. "Fast and automated does not always mean good quality," says Andrzej Joachimiak, who heads a crystallography group at the APS. Crystallographers traditionally deposit structures in the PDB before their research has been refereed, notes John Helliwell, a retired University of Manchester biophysicist, chemist, and crystallographer.

For structural biologists, x-ray crystallography is by far the most commonly used tool for unraveling protein structures. It also produces the highest-resolution images of structures. The process typically is performed at cryogenic temperatures to limit ionizing-radiation damage to proteins. (See the article by Bob Glaeser, PHYSICS TODAY, January 2008, page 48.)

Small-angle x-ray scattering has dedicated beamlines at each of the synchrotron light sources. The technique lacks the angular resolution of crystallography, but it can be used to examine macromolecules in solution, nearer a protein's native state at room temperature. The scattering can explore how structures change over time as the virus matures. That evolutionary process could occur over hours or days, says Britt Hedman, SSRL science director.

Main protease

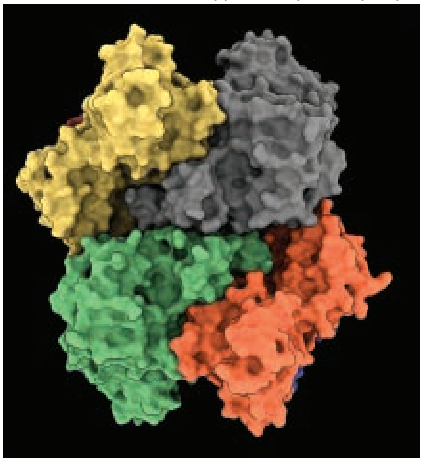
When crystal-growth conditions are known, as they are for ligand-binding analyses, x-ray crystallography is the fastest method to determine 3D structures and can produce diffraction data in fractions of a second. One of the most important SARS-CoV-2 structures solved by crystallography is M^{pro}.

When the viral RNA enters the human cell, it hijacks the host's protein factories—the ribosomes—to make two long polyproteins that contain the components needed for viral replication. Among them are two proteases, which cut the polyproteins into individual proteins. M^{pro} makes most of the cuts. It's 96% identical to that of the SARS coronavirus of 2003, says Andrey Kovalevsky, a senior scientist at Oak Ridge National Laboratory, and it's "absolutely essential for the virus to reproduce."

The APS has 16 beamlines devoted to protein crystallography, though not all are currently in use. With other light sources trained on M^{pro}, teams at the APS turned their focus to some of the virus's other nonstructural proteins (NSPs). A group led by Joachimiak at the APS announced the decoding of the Nsp15 structure on 2 March. The functions of many NSPs are not as clearly understood as those of proteases, but Nsp15, which is 89% identical to its counterpart in the SARS 2003 virus, may increase SARS-CoV-2 virulence by interfering with the body's immune response, says Joachimiak, whose group also has determined structures of four other NSPs. Research on the SARS 2003 Nsp15 protein showed that its inhibition could slow viral replication, although no drugs have sprung from those findings.

Groups from Northwestern and Purdue Universities, Scripps Research Institute, and Walter Reed Army Institute of

ARGONNE NATIONAL LABORATORY



RESEARCHERS AT ARGONNE NATIONAL LABORATORY'S Advanced Photon Source solved the structure of a severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) protein known as Nsp15, an endoribonuclease. It consists of six identical protein chains, four of which are visible here. Nsp15 cleaves specific regions of RNA and is believed to interfere with human antiviral defenses. From preliminary results, other research groups have identified compounds that may deactivate the protein by disrupting its assembly.

DIAMOND LIGHT SOURCE

AN AERIAL VIEW OF THE DIAMOND LIGHT SOURCE near Oxford, UK. Researchers have used the synchrotron to determine dozens of three-dimensional structures of the main coronavirus protease in combination with various ligands that may inhibit the protein's function. That information could be used in the design of new antiviral drugs.

Research are using the APS to determine structures of three other NSP proteins and the spike protein. As of 1 April, scientists using the APS had found structures of six proteins. They also found seven more structures of those proteins in combination with potential antiviral compounds or antibodies. The lab issued a notice of availability on 25 March for SARS-CoV-2 research proposals to its 15 000-member user community. Since then, 25 groups have either collected data or requested beamtime to do so, says Fischetti.

The Shanghai synchrotron's determination of the M^{pro} structure was published in the PDB on 4 February. A second determination, made at BESSY II by a University of Lübeck team led by Rolf Hilgenfeld, was posted to the bioRxiv preprint server on 20 February. A third structure followed a week later from Diamond crystallographers. Each replicated and refined earlier work. Several teams are examining the raw diffraction data that Diamond crystallographers have made available via Zenodo, a CERN-operated data repository. "Every group in the world that has the means to look at this protein will be trying to do that," says David Owen, a structural biology postdoc at Diamond.

From 0 to 1000 in 10 days

Diamond was the first to take the next step, the rapid screening of compounds for binding with M^{pro}. In a process known as fragment screening, crystals are paired in solution with hundreds or thousands of small organic compounds with a molecular weight of 200–300 daltons. The combined structures are then examined in a high-throughput process that screens for insightful interactions. "In 10 days we went from having nothing at all to over 1000 crystal structures, and over 60 molecules were found to bind to the protein so far," says Owen.

As do most light sources, Diamond offers an automated crystallography system that allows experimenters to work and obtain their data from home. An operator need only load the crystals once a day. Diamond can produce hundreds of crystal–compound combinations in a day and expose them at a rate of 30 per hour.

Through screening, "you can build a picture of what portions of a drug are going to work because you look at fragments of the compound and see whether individually the fragments bind to the protein binding site," says Helliwell. "It's proved effective to build from fragments upward to find new drugs. The synthetic chemist can take the information and string [fragments] together by chemical organic synthesis."

Each major light source hosts industrial users. Pharmaceutical and biotech companies perform proprietary research, but also benefit from openly available results from academic users. "We have provided drug companies with a lot of structural information," says Owen. "We've been able to put out the structure of [M^{pro}] to a very high resolution, better than 1.3 Å. That provides really precise information about the location of each atom in the structure and is very useful to people designing drugs." Among other things, chemists will be looking at the strength and tightness of the binding attraction between the protease and the molecules they themselves have built.

On 31 March, Diamond announced an initiative with Exscientia, a UK artificial-intelligence-driven drug discovery company, and Calibr, the drug-development arm of Scripps Research, to screen existing, clinically approved drugs against several SARS-CoV-2 protein targets. If inhibiting action against the pathogen is discovered, approved drugs could accelerate the path to a treatment, although human trials will still be needed.

Exscientia will have access to Scripps's collection of 15 000 approved and human-tested drugs, Martin Redhead, head of quantitative pharmacology at Exscientia, said in a statement. The protein targets to be screened include M^{pro} and the spike protein.

Other pharmaceutical companies are working with Diamond, but a spokesperson declined to name them.

On 2 April, BESSY II began fragment screening against M^{pro}, and scientists were analyzing the data at press time. "We start with 1.5 million commercially available compounds that you can buy in quantities of at least 1 milligram," says Manfred Weiss, director of the macromolecular research group at BESSY II. "We filter the compounds according to the size, solubility, and some rules that medicinal chemists have." Some 1200 compounds met those criteria. A typical fragment screening produces 10 to 12 compounds that bind and can serve as starting points for drug development, Weiss says. He adds that the terminology is misleading because the molecules aren't actually fragments of anything.

Industry has begun fragment screening, says Lisa Keefe, executive director of IMCA-CAT, an industry-funded nonprofit association that, unlike academic users, pays to operate beamlines at the APS. Formed in 1992, IMCA-CAT restricts membership to industrial users, including Merck, Pfizer, Bristol-Myers Squibb, Novartis, and Abbvie. Nonmember companies can arrange to use the IMCA-CAT beamlines. Firms can screen their large proprietary collections of fragments and don't have to make the results public. Keefe won't say which companies are screening or what proteins they are targeting. But she notes that in the current crisis "there has been some reaching out between members" to compare findings.

Weiss laments the inability of most academic researchers to gain access to industry's compound libraries. But Aled Edwards, director of the Structural Genomics Consortium (SGC), a public–private international nonprofit organization, says the differences between public and proprietary collections of compounds are not that great. "There's no evidence to suggest that one is massively better than the other," he says.

Electrons and neutrons

Apart from crystallography, several other techniques are used for protein structure determination. For molecules that resist crystallization, such as large protein complexes, researchers can turn to cryoelectron microscopy (cryo-EM). (See PHYSICS TODAY, December 2017, page 22.) A team led by Jason McLellan of the University of Texas at Austin used the technique to determine the structure of the spike protein; the results were published in *Science* on 13 March. The spike protein is considered a prime candidate for a vaccine target. However, because the base of the protein is anchored to the hydrophobic viral membrane while the rest of the protein is hydrophilic, the full-length spike protein is hard to crystallize.

Stanford University has kept one of its six cryo-EM instruments at SLAC open for SARS-CoV-2 research. Diamond has five cryo-EM instruments available, one of which is reserved for industrial use.

With the cryo-EM technique, as in x-ray crystallography, myriad individual molecules contribute to a structural determination. Whereas a crystal's molecules are identically arrayed, the molecules embedded in vitreous ice in cryo-EM are randomly oriented, and their fuzzy, individual 2D projection images are assembled computationally into a single, clear 3D image.

In favorable conditions, where molecules are well-preserved on an electron microscope support grid, it takes about 10 hours to collect enough data to generate a structure with atomic detail, says Wah Chiu, who heads SSRL's cryo-EM and bioimaging division. More difficult projects could require 48 hours or longer. Cryo-EM can be used to image a thin region of vitrified cells and generate a 3D tomogram from which maturing virus particles can be identified.

In addition to studying noncrystallizing molecules, cryo-EM, in combination with advanced image processing, can obtain from a single sample multiple conformations of proteins. That approach offers insight into the dynamical properties of protein molecules under different biochemical and functional conditions. An emerging use of cryo-EM is to uncover the overall architecture of cellular structures *in situ* under normal and pathological conditions, Chiu says.

Neutron crystallography allows investigators to elucidate the positions of hydrogen atoms, which are invisible to crystallography, in 3D protein structures. That advantage is important because the strongest binding sites on a protein involve hydrogen bonds. In x-ray crystallography, the photons scatter off the electron charge clouds of the protein molecule's constituent atoms. As the lightest element, hydrogen scatters x rays extremely weakly. So x-ray crystallographers often must infer the location of hydrogen atoms in the structure, especially in the ionizable amino acids that are often involved in enzyme reactions. In contrast, neutrons interact with atomic nuclei to provide a hydrogen signature comparable to those of the protein's nitrogen, oxygen, and carbon atoms.

Matthew Blakeley, a chemist and crystallographer at France's Institut Laue-Langevin (ILL) neutron source, notes that x rays produce structurally damaging free radicals when they pass through crystals. To limit the radicals' diffusion, x-ray data collections are typically performed at 100 K. Neutrons don't damage protein samples, so crystallography with neutrons can be performed at room temperature. Neutron beam intensity, however, is several orders of magnitude less than is achievable with x rays, and structural data gathering can take 7 to 10 days, says Kovalevsky. That makes neutron techniques less suited for fragment screening. It also requires much larger crystals, which are difficult to grow.

Oak Ridge National Laboratory reopened its Spallation Neutron Source on 7 April and gave priority to SARS-CoV-2 research. The lab's other neutron source, the High Flux Isotope Reactor, was scheduled to resume operations on 27 April, and coronavirus research is to be prioritized on two beamlines there. At the outset of the pandemic, both facilities had been shut down for routine scheduled maintenance. The ILL is closed, and no reopening date has been set.

Although x-ray free-electron lasers (XFELs) could be highly useful for SARS-CoV-2 research, both the Linac Coherent Light Source at SLAC and the European XFEL in Germany were offline as of early April. The LCLS has been shut down for an upgrade, but a SLAC spokesperson says a restart could occur soon after California's shelter-in-place order is lifted. European XFEL group leader Bernd Ebeling said in an email that beam time will be devoted to coronavirus research once operation becomes possible. It was unclear at press time whether Japan's SACLA, the planet's other XFEL, was conducting coronavirus research.

XFELs offer two advantages over synchrotrons, says Helliwell: They can determine structures at room temperature, and their femtosecond pulse length and high intensity allow the collection of diffraction data before radiation damages the protein. Radiation damage can change the protein structure and thus affect its interpretation.

Because of those advantages, XFELs can obtain structural information from submicrometer crystals. Using the LCLS, a team led by Lars Redecke of the University of Hamburg in 2012 reported the first new biological structure solved with an XFEL.

Follow-through needed

Despite the frantic pace of research, many scientists are skeptical that drugs or vaccines to fight the virus will come in time to ease the current pandemic. Human trials could be a year or more away, even for approved drugs or antibodies found to provide some action against the coronavirus; the timeline for newly identified medicinal compounds is even longer. "Neither synchrotrons nor cryo-EM will likely make a big impact on this pandemic," says Edwards of the SGC, "but both will be really powerful tools in getting science ready to stop the next one."

Stephen Streiffer, APS director, disagrees; he argues that any existing compound approved for human use that's found to be therapeutically useful would be moved into clinical use immediately. He notes that current public health strategy is aimed at slowing the spread of infection until a vaccine can be deployed.

Joachimiak laments the lack of follow-through on drug development efforts from SARS and MERS (Middle East Respiratory Syndrome, which appeared in 2012). "NIH spent $700 million in the past 20 years to study SARS and MERS. And we have no antiviral, no antibodies, no vaccine for SARS and MERS," he says. Drugs developed in response to the earlier outbreaks might have worked against the current pathogen, he notes.

David Kramer

Teaching science in prisons brings rewards

Highly motivated, incarcerated students surmount obstacles to further their education.

Brian Lenardo pulls into the parking lot at San Quentin State Prison in Marin County, California. Heading inside, all he has with him are course materials, a plastic water bottle, and his car keys. He doesn't wear white, green, or blue; the colors worn in prison are off limits for instructors. After he clears security, he is escorted to an empty classroom. A few minutes later, a couple dozen incarcerated students file in. Class begins.

"I love teaching in prison," says Lenardo, a postdoc in nuclear physics at Stanford University who volunteers through the Prison University Project. "The students are more motivated and engaged than any other undergraduates I've taught. They don't try to boost their grades. They are not shy about asking for help. They show up prepared. They are there to learn."

The US is home to 5% of the world's population but 25% of the incarcerated population, notes Dyjuan Tatro, the government affairs and advancement officer for the Bard Prison Initiative (BPI) in New York State. Although some 95% of people in prison will get out someday, he says, about 40% return within three years. "If we don't start putting better programming in place and moving away from punishment to rehabilitation, the revolving door will keep revolving."

What's more, college in prison saves taxpayers money. The 2014 RAND Corp comprehensive evaluation *How Effective Is Correctional Education, and Where Do We Go From Here?* found that "the direct costs of reincarceration were far greater than the direct costs of providing correctional education" and that education significantly reduces the incidence of reincarceration. Tatro, who himself has served time, notes that less than 4% of BPI students return to prison.

Many US prisons offer programs for obtaining a high school equivalency diploma. But a high school diploma doesn't mean someone is college ready, and prisons often offer courses to prepare people for college classes. Traditionally, most programs have focused on humanities, criminal justice, and related areas. Math and science classes are less common. The offerings span à la carte college-credit classes to associate's and bachelor's degrees. Some classes even include lab experiments. (For a first-hand perspective, see the interview with Sean Bearden about how he went from taking correspondence courses while incarcerated to being a physics doctoral student; http://physicstoday.org/bearden.)

PETE MAUNEY

A BARD PRISON INITIATIVE MATH CLASS in 2013. BPI enrolls more than 300 students across six prisons in New York State. It is part of Bard College and was founded in 1999.

Back to basics

College Behind Bars is a four-part documentary series about BPI in New York State that first aired on PBS in 2019. BPI is a competitive, full-time program in which students can earn associate's and bachelor's degrees. Among the instructors appearing in the series is MIT history professor Craig Steven Wilder, who describes how he goes "back to a more basic teaching structure" when he teaches for BPI. The students show up "extraordinarily well prepared, and so a lot of the sort of gimmickry . . . we don't need here as much, because actually everyone's done the reading."

Everything that is brought into prison requires approval. In some prisons, incarcerated students have to use short golf pencils; in others, standard pencils are fine. Students may have limited computer access. Instructors typically use a whiteboard, a blackboard, or an overhead projector. Mixed media are mostly off-limits.

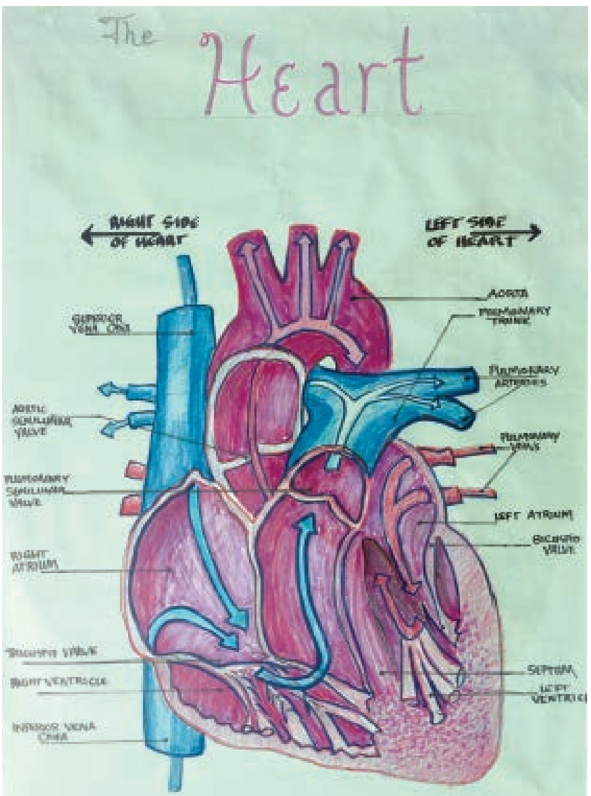
For a biology class at San Quentin, instructor Adam Williamson had his students extract DNA from strawberries. "We got permission to bring in the strawberries, buffers to break up the cells, and chemicals to precipitate DNA," says Williamson, who taught there for several years when he was a graduate student before joining the faculty at Bryn Mawr College in Pennsylvania last fall. Another experiment involved quantifying aspects of photosynthesis. "The labs worked well," he says. "There was no lack of rigor."

Courses in geology and human biology have always been offered through Returning & Incarcerated Student Education (RISE) at Raritan Valley Community College, says director Sheila Meiman. Started in 2009, the RISE program serves seven prisons in New Jersey. For human anatomy, the models are made of plastic. For biology classes, instructors bring in compounds that students mix and microscopes with premade plastic slides. Calculus-based physics, she says, was "sort of our Holy Grail."

Raritan Valley's Peter Stupak guided the modifications to the physics lab equipment to make it acceptable for a prison environment. "Several items didn't feel right to our corrections partners," he says. "We modified the list and finally got it to the point where it was acceptable." A strong relationship with the corrections partners is necessary, he says. The authorized items for physics labs include a plastic car with low-friction wheels instead of a massive block and a track made of foam instead of metal, measuring tape and protractors made of paper, and induction cookers in place of hot plates.

Goni Halevi, who is working on her PhD in astrophysics at Princeton University, leads the four-person team that teaches the RISE physics class, which debuted in January with three students at East Jersey State Prison. She volunteers through the university's Prison Teaching Initiative (PTI), which coordinates with Raritan Valley for course offerings and college credit. Since restrictions were enacted to slow the spread of the coronavirus, Halevi's team and instructors for other courses are completing the semester through written notes, worksheets, videos of the lab experiments, and other distance-learning means. "The students have put in so much effort, we want to do everything we can to make sure they can finish and get the credit they deserve," Halevi says.

As a graduate student in biophysics at Princeton, Matthew King spotted a feature story about PTI on the university's homepage and decided to apply. "It was half personal, half political," he says. He taught environmental science in 2014. "We sat in a semicircle, the students were engaged, they had done the reading—which is unusual for college students. I was hooked." King went on to design experiments and help introduce labs to the PTI program. Now a postdoc at Washington University in St Louis, he is teaching biology through the school's prison education program.



THIS DRAWING was made by students at Fort Dix Federal Correctional Institution in New Jersey. Groups of four students prepared lectures on different organs for the physiology section of a biology course in 2017. Matthew King taught the course through Princeton University's Prison Teaching Initiative. The drawing is by Blaine Dorsey III, Jeramy Eddington, Kyle Inch, and Brandon Quinn.

The motivation to study while in prison varies, says Mark Krumholz, an astrophysicist at Australian National University who has taught at four US prison facilities and cofounded PTI in 2005. The program now has two paid administrators and 100–120 volunteers who teach 20–30 courses per semester. Some people in prison take courses to pass the time, he says. Others want to earn a degree in tandem with their children outside or otherwise prove something to their families. Many want to prepare for a better future. "Most had never really engaged in anything academic," Krumholz says, "so the sense of accomplishment they feel when they discover they are good at something is a huge revelation. I found that very rewarding."

Uncomfortable spaces

College classes are available in a smattering of county jails in addition to state and federal prisons—wherever programs have sprung up. New instructors worry about feeling intimidated in the prisons, says PTI director Jill Stockwell, "but the students bend over backwards to make instructors feel safe and respected. They know it's not a comfortable space to come to."

Between long drives to prison facilities, waits to get in, and security measures, teaching in prison takes more time than teaching on a college campus. Instructors have to work around students missing class and canceled classes due, for example, to prison lockdowns. Communication with incarcerated students outside of class is tricky. And class time and duration may have to be scheduled around prison constraints; for example, at Lockhart Correctional Facility, the Texas Prison Education Initiative—which was started in 2018 and is supported through donations and crowd funding—offers only evening classes because the prison uses the classroom space in the daytime.

For their part, students have to arrange their study time around lockdowns, quarantines, crowded conditions, noise, and prison schedules, including frequent head counts. In *College Behind Bars*, several students say they study best in the wee hours of the night. Many of them work and don't have much spare time, and getting school supplies can be hard. "In New

SUMMER SPROFERA (right) graduated from Raritan Valley Community College in August 2015; the college's president, Michael McDonough, congratulates her. She earned her associate's degree while incarcerated in the Edna Mahan Correctional Facility in Clinton, New Jersey. (Photo provided by Summer Sprofera.)

York State prisons, everyone has a job—and you have 100 guys sweeping the same hallway. It's a joke," says Tatro. BPI students are off the hook for such make-work chores.

"Prison is not conducive to getting a college education," says Tatro, who got out of the New York State prison system in 2017. "You can't get research materials in a timely manner, you don't have access to huge libraries, there is no internet access. Classes are interrupted. Professors may assign 42 books, but the prison only allows 25 in a cell. The list of hurdles is absurd."

Tatro learned about BPI by chance from an episode of *60 Minutes* that aired in 2007. "Seeing that segment allowed me to see myself as a college student," he says. It took him six years and repeated prison transfers to finally land in one of the six facilities where the BPI program was offered.

After his release, Tatro completed his bachelor's degree in math at the main Bard campus in Annandale-on-Hudson in 2018. Since then he has worked for a US congressman and managed a data-collection project for a software developer. Now at BPI, he works with legislators to allocate public funding for college education in prison and for reentry services. Unlike many higher-education programs in prisons, BPI does not rely on volunteer instructors. The program is "essentially a department of Bard College responsible for the education of 300 students in prisons," says Tatro. Over the past decade, BPI has partnered with 14 other universities and colleges to launch similar programs.

Dameon Stackhouse started taking classes in 2010 while he was incarcerated in New Jersey. "I took anything and everything—psychology, precalculus, calculus, Arabic—because I knew that once I was released, I would need to do something that used my mind," he says. He wrote essays on his own to prepare himself for college. "I could see the big picture." In the prison classes, he says, "we all had drive, we pushed ourselves, and we didn't let anyone else fail." Today he is at Rutgers University working on his master's degree in social work, with a focus on autistic people, and plans to do a PhD.

At the urging of her instructor in an office skills class in prison, Summer Sprofera started taking classes through Raritan Valley. She knew she liked science: She semisecretly grew tomato plants that she started from seeds she collected from the mess hall. "It changed the environment in the prison," she says. "The women were away from their kids, they all became protective of the plants. It brought us all together."

Even with a degree, reintegrating into society can be challenging for formerly incarcerated people. After serving nine years, Sprofera got out in 2016 and continued her studies at Rutgers. She commuted to school because people with felony convictions are not allowed to live on campus. She confided in a professor about her criminal record and learned that getting licensed in her preferred field of landscape architecture would be tough, so she switched to environmental planning and design. She graduated last year and is still seeking a job in her field. "Society is not ready for us," she says. "Even if we have a degree, once it comes to the background check, it's hard to be accepted. I'd be more accepted in a prison-oriented field like social work."

Toni Feder PT

A Vibrant Federation

AIP actively supports its 10 Member Societies in a variety of ways, ranging from conducting media training to arranging meetings with members of Congress to hosting special programming and events. AIP also escorted the 20 members of the US Physics Team — high school students sponsored by AAPT and AIP to represent the United States at the International Physics Olympiad Competition — around Capitol Hill.

On the education front, AIP provided funding for the first ComSciCon specifically for graduate students in the physical sciences. ComSciCon is a series of workshops focused on the communication of complex and technical concepts. For two days, students gathered at AIP headquarters to discuss diversity, equity, and inclusion; media engagement; science communication; and science policymaking.

Building on the importance of communications, AIP sponsors two scientists annually to spend a year providing scientific and analytical expertise to members of Congress through its Congressional Science Fellows program. Brian Gray was placed with the office of Rep. Jan Schakowsky (D-IL), and Nicholas Montoni was placed with the office of Rep. David Price (D-NC).

Through a generous contribution from AAS, AIP also sponsors a State Department Fellowship program. 2019 fellow Allison Davis was placed at the Bureau of Oceans and International Environmental and Scientific Affairs, Office of Conservation and Water.

A Pledge to History

AIP's dedication to preserving our history continues through the Niels Bohr Library & Archives (NBL&A) and the Center for History of Physics (CHP). In 2019, the NBL&A completed its inventory on the Wenner Collection of more than 3,800 rare and valuable books and launched a new blog, *Ex Libris Universum*, where NBL&A staff discussed, among other topics, their archival and book collections.

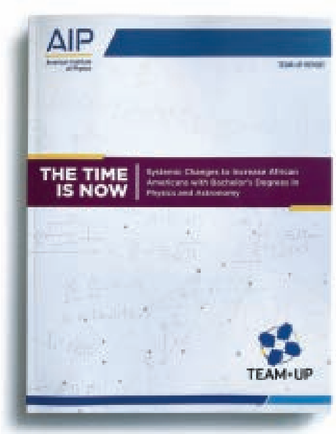
AIP continued to engage educators and students of all ages with initiatives that introduced the physical sciences to young students, provided supportive spaces for educational and networking events for undergraduate and graduate students, and disseminated a host of educational tools and resources.

In 2019, AIP made a $1 million pledge to the University of Maryland College of Arts and Humanities to establish an endowed professorship in the history of natural sciences and support of humanistic and scientific research and scholarship. *Physics Today* senior editor Melinda Baldwin was appointed as the first endowed professor.

The AIP-chartered National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP) has spent two years examining the persistent underrepresentation of African Americans in physics and astronomy. The resulting report lays out a plan to double the number of African Americans graduating with bachelor's degrees in physics and astronomy by 2030.

The 2019 US Physics Team does some problem solving with Congressman Bill Foster (D-IL), currently the only PhD physicist in Congress.

University of Maryland president Wallace D. Loh, left, and Michael H. Moloney, chief executive officer at AIP. The $1 million gift from AIP will establish an endowed professorship in the history of natural sciences and support the appointee's scientific research and scholarship. Credit: Thai Nguyen of University of Maryland

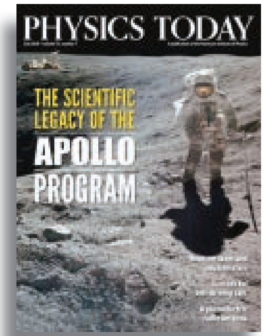


A Trusted Source of Information

The demand for trustworthy news and information about science continues to rise, and AIP publications continue to deliver. One such example was "Venus is not Earth's Closest Neighbor," an article that reevaluates the way we think about the distances between planets. Of the article's 125,000 page views on the *Physics Today* website, 100,000 came within the first four days, making it the quickest *Physics Today* article ever to reach that figure. Dozens of other media outlets covered the story, including *Gizmodo, Popular Mechanics,* and the UK's *Daily Mirror.*

Meanwhile, the audience for AIP's Inside Science continued to grow. The number of original stories topped 200, and the number of stories that were reprinted increased by more than 70 percent from 2018 to 2019. Page views also increased by more than 227,000 year-over-year.

In 2019, AIP introduced 60-second social media videos — "Science in 60" — based on Inside Science articles. Views of Inside Science's news videos topped 850,000 on YouTube, with syndication extending the video audience to the website of ABC News as well.



Physics Today – July 2019

AIP BENEFITS EVERY MEMBER SOCIETY

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AAPM
AVS
ACA
πάντα ῥεῖ
OSA The Optical Society
AMS American Meteorological Society
AAPT PHYSICS EDUCATION
AAS AMERICAN ASTRONOMICAL SOCIETY
APS physics

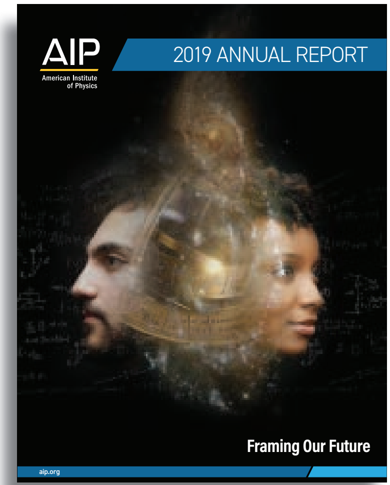
A Commitment to Excellence

One of the most significant and transformative accomplishments was the development of a Strategic Framework by the AIP Board of Directors, along with input from staff and Member Societies. The framework serves as a roadmap for the future. Core to that effort is a new Statement on Diversity that makes diversity, equity, inclusion, and belonging a top priority.

AIP Publishing, the Institute's wholly owned subsidiary, continues to serve the community through scholarly publishing activities in the physical and related sciences fields, with around 31 million full-text downloads, 15,000 peer-reviewed articles, and 147 volumes of conference proceedings in 2019.

A few of the year's highlights include the following:

- Partnering with AVS to launch *AVS Quantum Science.*
- Welcoming new editors-in-chief to six journals: *Applied Physics Letters, AIP Advances, Journal of Renewable and Sustainable Energy, Journal of Mathematical Physics, Biomicrofluidics,* and *AVS Quantum Science.* Editors come from diverse backgrounds and geographies, reflecting the global nature of AIP Publishing's authors and reviewers.
- Reaching an agreement with China Academy of Engineering to publish the open-access journal *Matter and Radiation at Extremes.*
- Establishing two new awards for early-career researchers.



To read the full report visit aip.org/aip/annual-report

The platinum–iridium cylinders are replicas of the one in Paris that defined the kilogram until 2019. (Courtesy of J. L. Lee/NIST.)

Wolfgang Ketterle is the John D. MacArthur Professor of Physics at the Massachusetts Institute of Technology in Cambridge, director of the MIT–Harvard Center for Ultracold Atoms, and associate director of the Research Laboratory of Electronics. **Alan Jamison** is an assistant professor of physics and a member of the Institute for Quantum Computing at the University of Waterloo in Ontario, Canada.

An atomic physics perspective on the kilogram's new definition

Wolfgang Ketterle and Alan O. Jamison

A fixed value for Planck's constant connects the kilogram to frequency measurements.

Although often the bane of freshman physics students, units of measure are important for applications from commerce to fundamental physics. The current Système International (SI) units emerged early in the French Revolution to unify and promote *égalité* ("equality") in commerce. Over the past two centuries, major changes and updates to SI units have occurred, but the redefinitions introduced on 20 May 2019 were the biggest conceptual transformation in metrology since the French Revolution.

All prototype-based definitions have now been replaced with ones based on the cesium atom and fundamental constants. (See the article by David Newell, PHYSICS TODAY, July 2014, page 35.) The most profound change in units is the kilogram, which is no longer defined by the artifact in Paris but by the fixed value of Planck's constant $h = 6.626\,070\,15 \times 10^{-34}$ kg m^2/s. The new definition became possible when the best two measurements of h, the Kibble balance and the silicon spheres, reached an accuracy similar to the mass drift of the urkilogram over 130 years. At that point, the General Conference on Weights and Measures (CGPM), the SI's governing body, decided to define h as its precisely measured numerical value, which then defines the kilogram[1,2] in combination with the speed of light c and the Cs hyperfine frequency ν_{Cs}. Realizations of the kilogram standard, whether conceptual or practical, connect the mechanical or relativistic energy of a particle or object to a frequency, which is compared to an atomic frequency standard. In that way, atomic physics is central to the new definition of the kilogram.

From artifacts to fundamental constants

Over time, physicists have defined and redefined units based on natural objects, then objects of human creation and scale, and finally microscopic objects paired with fundamental constants. For example, the meter was first defined as one ten-millionth of the distance from the equator to the North Pole. In 1799 that standard was replaced by a manufactured prototype meter bar, which was more precise. But the accuracy was still limited to 10^{-7}, and calibration measurements required a precise temperature and pressure; also required was that the meter bar be supported at the so-called Airy points, for which bending is minimized.

In 1960 the CGPM introduced a microscopic reference by defining the meter as a specific number of wavelengths of the emission from a transition in krypton-86. Now every laboratory in the world could create their own standard. But the length standard was still tied to a specific atomic transition, and with the development of lasers, krypton was no longer the best choice available. Instead of picking another atomic or molecular line, in 1983 CGPM defined the speed of light as 299 792 458 m/s and the meter as the distance travelled by light in vacuum in 1⁄299 792 458 of a second. In practice, because researchers can measure time and frequency much more accurately than length, they measure any laser's frequency and then convert it to a wavelength using the speed of light. With a defined c, any laser wavelength can serve as a ruler for the meter.

The kilogram's definition has a history similar to that of the meter. Originally, in 1795 the kilogram was defined as the mass of one liter of pure water at the melting point of ice. But unavoidable impurities in the water limited the precision. Manufactured prototypes were thus developed. In 1799 a cylinder made of platinum was introduced, and in 1879 one made of platinum–iridium, shown in the opening image on page 32, came into use; it provided the definition of the kilogram for 140 years. The problem was that when the original platinum–iridium cylinder, or the urkilogram, and its copies were compared after a year, their masses differed by up to 50 micrograms, likely because atoms fell off or hydrogen was absorbed from air contaminants or cleaning products.

The urkilogram was difficult to replace because microscopic and macroscopic masses differ by a factor of 10^{25}, which is hard to measure accurately; in contrast, the meter is on the order of 10^6 optical wavelengths. To define the kilogram in a microscopic way, metrologists could have used the mass of a specific number of a specific atom, or of electrons or protons, similar to the meter's definition in terms of krypton radiation. Instead, the new definition relied on a set value for a fundamental constant, similar to the meter's definition through the speed of light. For the kilogram, the fundamental constant was Planck's quantum h. Researchers can use many systems and measurement methods to realize the kilogram, as long as the result can be expressed by h and a frequency.

With the new definition of the kilogram, all unit definitions in physics rely on microscopic quantities or fundamental constants and no longer involve manufactured artifacts. Any laboratory in the world can create primary standards; Paris, the home of the meter bar and the urkilogram, has lost its special role.

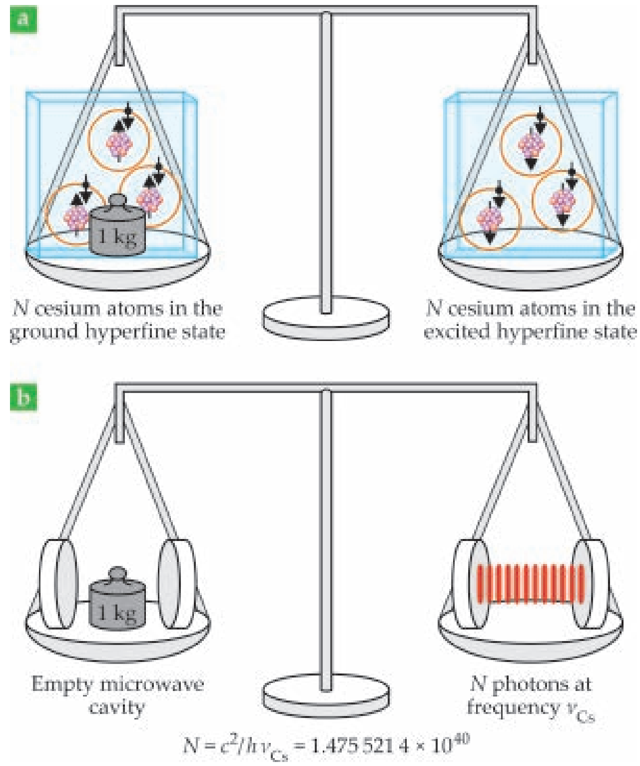


FIGURE 1. THE NEW KILOGRAM DEFINITION can be understood as **(a)** the mass difference between $1.475\,521\,4 \times 10^{40}$ cesium atoms in the ground state and the same number in the excited hyperfine state or as **(b)** the mass of $1.475\,521\,4 \times 10^{40}$ photons at the Cs hyperfine frequency trapped in a microwave cavity. The definitions of Planck's constant h, the speed of light c, and the Cs hyperfine frequency ν_{Cs} fix the number of photons or atoms at $N = 1.475\,521\,4 \times 10^{40}$/kg $= c^2/h\nu_{Cs}$. (Courtesy of Wolfgang Ketterle and Alan Jamison.)

Kilogram in terms of frequency

Time is central to the SI because it can be measured in terms of frequencies much more precisely than any other quantity. The International Committee of Weights and Measures defines the second as "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom"; that is, the Cs hyperfine frequency is defined as 9.192 631 770 GHz. Cesium is a practical choice: Its frequency is convenient, and its heavy mass leads to low atomic velocities and thus to small transit-time spectral broadening. A single photon at the

Cs hyperfine frequency ν_{Cs} has an energy $E = h\nu_{Cs}$, which, through the Einstein relation $E = mc^2$, converts into a mass equivalent $m_{ph} = h\nu_{Cs}/c^2$. The new kilogram definition fixes the relativistic mass of a photon at the Cs hyperfine frequency as $m_{ph} = 6.777\,265 \times 10^{-41}$ kg.

Because total energy is conserved, if a Cs atom absorbs a photon of frequency ν_{Cs} and transitions to its higher-energy hyperfine state, its mass must increase by m_{ph}. That effect was observable in the mass difference of two isotopes of silicon or sulfur.[3] One isotope transformed into the other by capturing a neutron, but because of the nuclear binding energies, the measured change in mass was smaller than that of the captured neutron. The gamma-ray photons emitted during the process accounted for the apparent loss of mass with a precision of 10^{-7}. But the Cs microwave photon produces a far smaller change in mass than do the gamma rays emitted in a nuclear reaction.

In the new definition, one kilogram is the mass difference between $c^2/h\nu_{Cs} = 1.475\,521\,4 \times 10^{40}$ Cs atoms in the upper and lower hyperfine states. In theory, a researcher could measure 1 kg of a substance using a mechanical balance with the substance and ground-state Cs atoms on one side and excited-state Cs atoms on the other side, as shown in figure 1a; the mass of the ground-state atoms alone, though, would be 3.26×10^{15} kg and fill a cube with 12 km sides. That expression for the kilogram is similar to the original 1999 proposal to use a fixed value of h to replace the kilogram artifact: "The kilogram is the mass of a body at rest whose equivalent energy equals the energy of a collection of photons whose frequencies sum to 135,639,274 × 10^{42} hertz."[4]

A Cs atom isn't even necessary to turn a photon's relativistic mass into rest, or invariant, mass. If photons are in a cavity, their total momentum is zero, and they are at rest in the lab reference frame. The composite rest mass is the mass of the empty cavity plus the photons' relativistic masses. The kilogram can then be defined as the mass of $1.475\,521\,4 \times 10^{40}$ photons at ν_{Cs} stored in a microwave cavity, as shown in figure 1b. But creating one kilogram of pure electromagnetic energy is demanding. Even in a lossless microwave cavity, one kilogram of photons would require pumping the cavity for a full year with about 3 GW of microwave power, the output of a medium-sized nuclear power plant.

The definition above is impractical or even impossible for calibrating masses. But through highly accurate (10^{-20}) frequency ratios and frequency combs, researchers can use any radiating system to define the kilogram. As a simple but still impractical example, they could annihilate an electron and a positron to create radiation at a frequency linked directly to the electron mass m_e. The process emits two gamma-ray photons of energy $m_ec^2 = 511.0$ keV, or frequency $\nu_{ep} = 1.2356 \times 10^{20}$ Hz. The mass of the electron is $m_e = h\nu_{ep}/c^2 = 6.777\,265 \times 10^{-41}$ kg (ν_{ah}/ν_{Cs}), in terms of fundamental constants h and c and the frequency ratio relative to a Cs clock.

Kilogram through atomic spectroscopy

A kilogram based on gamma rays is not practical, given how difficult it is to measure their frequencies with high precision. So instead of converting the rest energy m_ec^2 into radiation and measuring its frequency, physicists convert kinetic energy $\frac{1}{2}m_ev^2$ into more manageable ultraviolet radiation. But they need to know the velocity v very well.

In hydrogen spectroscopy, the electron has a well-known velocity. Besides some small well-understood corrections, the ionization energy of hydrogen is the Rydberg energy Ry, which equals the kinetic energy of the 1s electron with velocity c times the fine-structure constant α. Through hydrogen spectroscopy and the Cs frequency standard, Ry is known with a precision of nearly 10^{-12}. The fine-structure constant α can also be measured with high accuracy through several independent methods, including the quantum Hall effect, determination of the magnetic moment of the electron, and atom interferometry. Finally, the mass of the electron derives from the equation $\frac{1}{2}m(c\alpha)^2 = Ry$.

Hydrogen spectroscopy is thus a feasible way to measure the mass of the electron. The experimental realization has a precision of 2×10^{-12} for the Rydberg constant, limited by the uncertainty in the finite size of the proton.[5] But how does the mass of the electron define a macroscopic mass? The first step is to relate the mass of the electron to the masses of atoms. An electron and an atomic ion placed sequentially in a Penning trap have cyclotron frequencies $qB/2\pi m$, which depend on their masses, the magnetic field B, and their electric charges q. The ratio of those frequencies yields the mass ratio[6] with a precision of 4×10^{-10}.

The International Avogadro Coordination (IAC) project, led by Physikalisch-Technische Bundesanstalt (PTB) in Germany, took the remaining step to convert microscopic to macroscopic mass. The project members used hydrogen spectroscopy and Penning trap mass comparisons to connect ν_{Cs} to m_{Si} as described above. (Atom interferometry, described in box 1, provides a more direct connection from ν_{Cs} to m_{Si}.) To go from m_{Si} to bulk silicon, they counted the number of silicon atoms in a macroscopic sphere of about 1 kg, as shown in figure 2. One kilogram of silicon has about 2×10^{25} silicon atoms, so counting them, even at 50 million atoms per second, would take about the age

FIGURE 2. A SILICON SPHERE like the ones used by the International Avogadro Coordination. The IAC measured the diameters and lattice constants of the nearly perfect spheres to count the atoms and convert from the mass of a silicon atom to the mass of the silicon sphere. (Courtesy of NIST.)

of the universe. The solution was to determine the volume per atom and the total volume of the object.

The IAC researchers started by creating the world's most perfect sphere out of single-crystal isotopically enriched silicon. They determined the sphere's diameter d of 9.4 cm with an uncertainty of 0.2 nm through optical interferometry and characterized the surface layer, which contributed about 80 ± 10 μg to the mass. To find the volume per atom, they performed x-ray diffraction on the sphere to determine the lattice constant a with a precision of 2×10^{-9}, which was limited by strain from point defects. Each unit cell has a volume of a^3 and contains eight silicon atoms. The total number of atoms in the sphere, then, is $(4\pi/3)d^3/a^3$. The silicon sphere provides a macroscopic mass standard[7] with a total uncertainty of about 10 μg or relative precision of 10^{-8}.

The conceptual definition of the kilogram involved $1.475\,521\,4 \times 10^{40}$ photons at the Cs hyperfine frequency. Instead of counting 10^{40} photons, the Avogadro project counted approximately 10^{25} silicon atoms. The mass of a silicon atom is 15 orders of magnitude larger than the relativistic mass of a Cs photon. Those additional 15 orders of magnitude come in roughly equal factors from comparing frequencies ($(Ry/h)/\nu_{Cs}$), comparing masses (m_{Si}/m_e), and using α^{-2} for the ratio of the electron's rest energy (mc^2) and kinetic energy in the hydrogen ground state.

Kibble balance

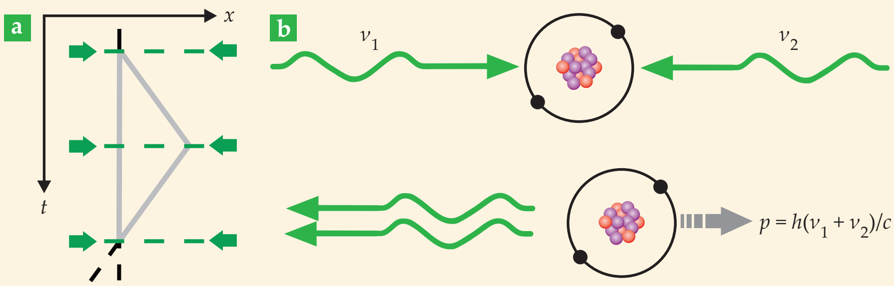
A final method to realize a mass standard is the Kibble balance, formerly called the Watt balance. Until 2019 the Kibble balance was used to measure the value of Planck's constant h. After the new SI unit definitions with the fixed numerical value of h, it became a method to calibrate the kilogram with a precision on the same order as the silicon spheres. Box 2 gives the standard explanation of the Kibble balance, but a conceptual explanation compares it with the other methods.

The basic idea is to measure a change in mechanical energy, which is proportional to the mass of an object, using electrical power. When a motor lifts an object with velocity v in a gravitational field, the mechanical power $P = mgv$ must equal the electrical power $P = IU$, in terms of current I and voltage U. In a process similar to that of atomic spectroscopy or atom interferometry, researchers determine the mass of a now-macroscopic object with well-known velocity and acceleration from the mechanical energy. They measure v and g precisely by forming a Michelson interferometer with the object serving as one mirror.

In the Kibble balance, the motor is replaced by a levitating coil with current I in a magnetic field. The current is adjusted until the magnetic force on the coil compensates for the gravitational force on the object—that is, until the object is levitated. With no extra mechanical force, the object's gravitational potential energy can be increased at a rate mgv. To conserve energy, the power $P = mgv$ must come from electrical power.

Researchers use the Josephson effect to measure the product of voltage and electron charge, eU. When a DC voltage is applied to a tunnel junction between two superconductors, it creates a current oscillating at the Josephson frequency $\nu_J = 2eU/h$, which can be measured precisely. The factor of two appears in the equation because superconducting currents are carried by electron pairs with a charge of $2e$. In Josephson voltage stan-

BOX 1. ATOM INTERFEROMETRY



Hydrogen spectroscopy connects the mass of the electron to the hyperfine frequency of cesium by measuring the electron's kinetic energy in the ground state. For those measurements, small corrections from quantum electrodynamics effects and the finite proton size must be determined by other measurements. Atom interferometry, on the other hand, directly determines the kinetic energy of an atom by a frequency measurement.

In an atomic recoil measurement, a photon transfers to an atom a precise momentum, $p = h\nu/c$, controlled by the photon's frequency ν. A spectroscopic measurement of the kinetic energy $p^2/2m$ determines the atomic mass. An atom interferometer implements that concept using two photons and kinetic energy measured as the phase shift between two arms of the interferometer, with one path getting a precise momentum kick and the other staying at rest.

A pulse of counterpropagating laser beams (green arrows traveling along the dashed green lines in panel a) at different frequencies places an atom, initially at rest (solid black line) into a superposition of moving and resting states (solid gray lines). A second laser pulse with both beams at the same frequency reverses the direction of the moving arm without disturbing the resting arm. A final pulse, identical to the initial pulse, reads out the arms' phase difference, which results from the kinetic energy of the moving arm, through the relative populations in the two output ports of the interferometer (dashed black lines).

When an atom scatters a photon from one beam into the other after each pulse, as shown in panel b, it receives a momentum transfer p equal to the sum of the two photon momenta, $p = \hbar(k_1 + k_2) = h(\nu_1 + \nu_2)/c$, where k_1 and k_2 are the wavenumbers and ν_1 and ν_2 are the frequencies of the two laser beams. A measurement of that momentum transfer, at least in principle, has the precision of laser-frequency measurements, which are currently limited only by the Cs frequency standard.

After the momentum transfer, an atom initially at rest has a kinetic energy $E_k = p^2/2m$. The stimulated light-scattering process becomes resonant, as it is in panel a, when the kinetic energy equals the difference of the two photon energies, $h(\nu_1 - \nu_2)$. If the atom is not initially at rest, the resonance frequency is Doppler shifted, but in most interferometer schemes, the Doppler shift cancels out to leading order. In that way, frequency measurements now directly determine an atomic mass.[11] The most recent atom-interferometry measurement was more accurate than the previous best value of the atomic fine-structure constant α, and in combination with hydrogen spectroscopy it provided a new value for α.[12] (Image courtesy of Wolfgang Ketterle and Alan Jamison.)

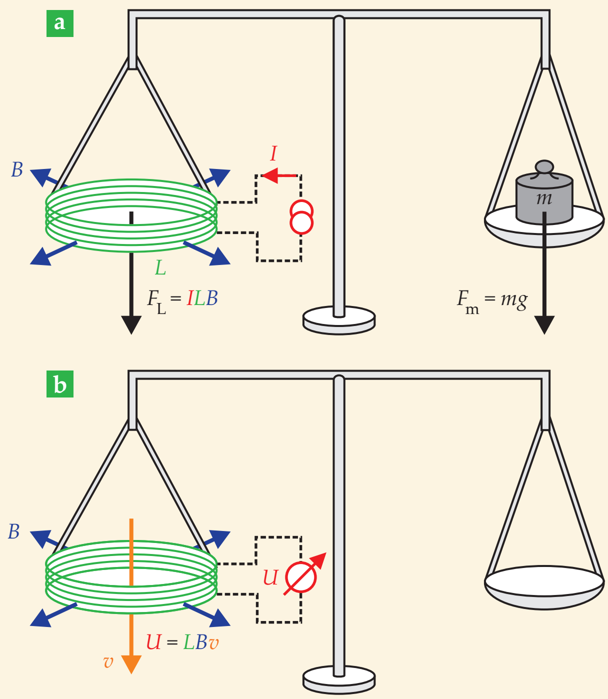
BOX 2. KILOGRAM WITH THE KIBBLE BALANCE

In the main text, the concept of the Kibble balance is explained through energy conservation: The electrical power required to levitate an object of mass m at velocity v is equal to the rate of change of mechanical energy, mvg. But the Kibble balance measures virtual rather than real power to eliminate contributions from friction and ohmic dissipation. To do so, it operates in two modes.

In force mode (panel a in the figure), the Kibble balance magnetically levitates the test object. The Lorentz force $F_L = ILB$ equals the weight $F_m = mg$, where I is the current through the solenoid, L is the length of the solenoid conductor, and B is the external radial magnetic field.

In velocity mode (panel b), the Kibble balance moves the solenoid at a constant velocity v. When the coil is lowered by an amount Δz, a magnetic flux of $BL\Delta z$ leaves the solenoid. By Faraday's law, the change in magnetic field induces a voltage U in the solenoid's open loop equal to LBv, the time derivative of the magnetic flux.

With the current measured in force mode and the voltage measured in velocity mode, their product $IU = mvg$ is independent of the quantities B and L, which are difficult to measure. The result is the same as discussed in the main text, that electrical and mechanical power are equal, but now in terms of virtual powers. (Image courtesy of Bureau International des Poids et Mesures.)



dards, microwaves are applied to the junction, and the current–voltage plot shows quantized jumps in voltage steps given by the equation above.

Single-electron pumps operate with currents up to 100 pA at frequencies[8] near 1 GHz and count the macroscopic number of electrons per time, $\dot{n}$, where $I = \dot{n}e$. Combined with the Josephson frequency relation, the electrical power becomes $P = IU = h\nu_J\dot{n}/2$ and depends on a frequency measurement and the counting of electrons.

With electrical power measured that way, the Kibble balance realizes masses by obtaining the energy, or voltage times e, of an electron through a frequency measurement, as in the atomic spectroscopy technique, and by counting electrons, similar to counting silicon atoms in the Avogadro project. Although the Kibble balance method is an electrical measurement, it doesn't need e (which has a fixed value in the new SI units) or any electrical units.

The accuracy of current standards based on single-electron-pumps[8] is around 10^{-7}, so researchers chose a different way to measure the current. It passed through a quantum Hall device kept at a resistance plateau equal to the von Klitzing constant $R_K = h/e^2$, a newly defined quantity of 25 812.807 Ω. The voltage $U = IR_K$ is measured by the Josephson effect, and the electrical power becomes the product of two Josephson frequencies and h. With the quantum Hall effect, researchers no longer need to count a macroscopic number of particles. Microscopic and macroscopic physics are not connected by counting but by a macroscopic quantum effect.

The new definition of the kilogram has the advantage not only that it can be realized everywhere in the world, independent of artifacts, but also that it can be directly applied to objects at any mass. For a 1 kg object, the precision of the Kibble balance and silicon spheres is about the same as the urkilogram. But for smaller masses, the old definition required dividing masses using pairwise comparisons of equal masses, and each order of magnitude typically involved five weights.[2] Reaching milligrams, for example, required many steps with huge losses in precision, whereas the new definition works the same for a kilogram or a milligram.

The various routes to the new kilogram can be reduced to connecting a frequency to the mechanical or relativistic energy of a particle. Conceptually, that means using the relativistic energy of a particle (through annihilation radiation). Practically, it means using the kinetic energy of a microscopic object with either a well-known velocity (electron in the hydrogen atom) or momentum (atom interferometry) or of a macroscopic object with well-known velocity and acceleration (Kibble balance).

Planck units

The new SI units almost reach Max Planck's 1899 vision to define all units using only fundamental constants without reference to specific particles.[9] Planck suggested defining the gravitational constant G, which would then define the mass in Planck units, or Planck mass, $m_P = \sqrt{\hbar c/G}$. Although used widely in particle-physics theory, the Planck mass is not a practical way to define units, given that G is currently the fundamental constant with the largest relative uncertainty by far (2×10^{-5}). But how, in principle, could Planck's suggestion be implemented?

First, what is the Planck mass? If the mass of a point-like object increases, its reduced Compton wavelength $\hbar/mc$ becomes shorter, whereas the Schwarzschild radius $2Gm/c^2$—the event horizon of the black hole created by the point particle—becomes larger. Those two lengths are the same when the object has the mass $m_P/\sqrt{2}$.

To measure masses in units of the Planck mass, a gravitational effect must be measured at some distance r. That distance can be in units of the reduced Compton wavelength $\lambda\!\!\!^{-}_0 = \hbar/(m_0c)$ of a suitable reference particle of mass m_0. The simplest gravitational effect is Newtonian acceleration $g = Gm/r^2$, which can be written as $\tilde{g} = (m/m_P)^2\,(m_0/m)/\tilde{r}^2$ in units of the speed of light per Compton time, or $c^2/\lambda\!\!\!^{-}_0$, and the length $\tilde{r}$ in units of $\lambda\!\!\!^{-}_0$. The mass m is then in units of the Planck mass through measurements of a mass ratio m_0/m, a length ratio $\tilde{r}$, and the acceleration

DO YOU UNDERSTAND THE NEW DEFINITION OF MASS? TAKE THE QUIZ:

1. In the new SI units, is the mass of one mole of carbon exactly 12 g or does it now have an experimental uncertainty?
2. In the new SI units, does the weight of a 1 kg object have an accuracy better than 10 µg, the limit for comparing the urkilogram to its copies?
3. Do the new SI units reduce the uncertainty of microscopic masses, such as the mass of the electron?
4. Do the new SI units increase the uncertainty of the mass of certain objects?
5. Would it be possible to define the units of time, length, and mass without referring to any natural or artificial particle—for example, an electron, hydrogen atom, photon at the cesium hyperfine frequency, or urkilogram—by fixing the numerical values of fundamental constants, or is at least one such particle always needed?

(For answers see this article online.)

$\tilde{g}$ using λ_0 as a ruler. Currently, no precise methods exist to measure the mass ratio between a large object, for which gravity can be observed, and a microscopic reference particle.

A more elegant but equally unrealistic method is the gravitational redshift $\delta\nu/\nu$. In the weak-gravity limit, the redshift is proportional to the gravitational potential and given by $Gm/(rc^2)$. The redshift becomes $\delta\nu/\nu = (m/m_P)^2(m_0/m)/\tilde{r}$, and masses in units of the Planck mass are determined by ratios of mass, frequency, and length.

Unlike Planck's vision, the new SI units still use one specific particle, the cesium atom, although that unique role will soon likely pass to another atom with an optical frequency, such as strontium, ytterbium, ytterbium ions, or aluminum ions.[10] Planck argued that the selection of an atom and a spectral line to define frequency is arbitrary, whereas definitions based on fundamental constants would be valid for all times and all cultures, including extraterrestrial and extrahuman cultures ("*ausserirdische und aussermenschliche Culturen*").[9]

Planck's units and the new SI units could, in principle, be fundamentally different. For example, if the expectation value of the Higgs field slowly changes as a function of position, the masses of elementary particles would subtly alter, but fundamental interactions would remain unchanged. SI units based on a selected particle would then drift in value from place to place, whereas the Planck units would remain fixed. That example illustrates one of the many connections between metrology and fundamental science.

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NSF and POSTWAR US SCIENCE

Emily Gibson

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In the early days of NSF, its leaders dreamed of large-scale federal investment in basic science but had to carve out a place for the new foundation in the complicated landscape of US science funding.

A crowd began to form at the train station in Pocatello, Idaho, around 5:15am on Wednesday, 10 May 1950. Some 700 bleary-eyed townspeople had come to see the president and neither the day's cold weather nor the hour would deter them. When the train chugged into town, President Harry Truman was standing on the rear platform, ready to greet the crowd. The trip to Pocatello was part of a whistle-stop tour of the northern US that took the president to numerous small towns dotting the railway.

Although Truman spent most of his time in Idaho addressing local agricultural and economic issues, in Pocatello, he talked to the crowd about science. Earlier that morning, as his train sped along the tracks, Truman had signed the National Science Foundation Act of 1950. It created the first federal agency devoted to supporting fundamental research and education across all scientific disciplines. Standing before a group of chilly Idahoans, Truman made a case for the importance of large-scale federal support for scientific research.

The story of NSF's creation and early years of operation serves as an important window into the growth of postwar federal science policy. Science's role in World War II had convinced many in the government that public support was needed for scientific research. Once open, NSF became an important site where debates over science policy, federal support for civilian research facilities, and federal support for education in STEM (science, technology, engineering, and mathematics) played out in postwar America.

NSF's World War II roots

In June 1940, anticipating that the US might decide to enter World War II, the US government created the National Defense Research Committee (NDRC). Its role was to supplement the military's ongoing R&D activities by enlisting civilian scientists and industrial research laboratories. Vannevar Bush (see figure 1), president of the Carnegie Institution of Washington and a member of the National Academy of Sciences, became the head of the NDRC and worked to bring US scientific research to bear on the war effort. By June 1941 the NDRC was expanded into the Office of Scientific Research and Development (OSRD). The NDRC had been created through an executive order and funded through the president's emergency funds; the OSRD, in contrast, was established under the Office of Emergency Management and had its own budget and a more secure organizational home in the White House. The OSRD also expanded the NDRC's work to include medical research and new capabilities for weapons development and testing.

Bush funneled unprecedented levels of funding through the OSRD into the hands of civilian scientists working in universities and industrial laboratories and helped expand and deepen federal connections to those institutions. Primarily through the mechanism of the research contract, Bush ensured that scientists played a greater role than they'd had during previous military engagements, when they served largely as consultants who directed federal dollars to scientific and technological projects they deemed most likely to yield strategic advantages.

By the end of the war, the OSRD had spent nearly half a billion dollars and made 2300 R&D contracts with 321 different industrial companies and 142 academic and nonprofit organizations. The contracts greatly favored the industrialized Northeast and well-established centers of academic excellence. The top four contractors by funding—MIT, Caltech, and Harvard and Columbia Universities—revealed the patterns of patronage the OSRD followed and helped entrench in the postwar period.[1]

The OSRD coordinated research that led to the tactical use of radar, the production of penicillin, and the development of the atomic bomb. In short, it revolutionized the relationship between US science and the state. By demonstrating the importance of federal support for scientific research, the OSRD cemented important financial relationships between academia, industry, and the government. Pleased with the OSRD's success, scientists and administrators began to advocate for continued federal support after the war.

Competing visions for postwar science policy

Bush and the other leading scientists at the OSRD were not the only ones with a vision for federally supported scientific research. In 1942 and 1943, Harley Kilgore, a Democratic senator from West Virginia who served on the Military Affairs Committee, introduced two bills calling for the creation of an office of science and technological mobilization. Although Kilgore himself was not a scientist, he had become persuaded that the nation should strengthen its scientific resources in the name of national defense. His bills outlined plans for a new federal office that would fund and conduct science and technological research, coordinate all federal and private scientific research, engage in international activities, and promote the training and education of future scientists.

FIGURE 1. VANNEVAR BUSH, head of the Office of Scientific Research and Development during World War II and one of the architects of NSF. The photograph is inscribed to Hugh Dryden, director of the National Advisory Committee for Aeronautics. (National Archives and Records Administration, courtesy of the AIP Emilio Segrè Visual Archives.)

Neither of Kilgore's initial bills made it out of committee, but his vision for postwar science policy was enough to arouse Bush's ire. In a 12-page letter to the senator, Bush outlined his objections to the 1943 bill. His chief criticism was that Kilgore's legislation conceived of science and technology's benefits to society too narrowly. He charged that Kilgore's bill advanced science in the name of military preparedness at the expense of science's primary aim of "increase[ing] the knowledge and the understanding of man … [and] extending his grasp of the environment in which he lives and his appreciation of the vast and intricate system of nature by which he is surrounded."[2]

His critique of Kilgore's proposal helped Bush frame his own vision for postwar science policy. He laid out his ideas in a July 1945 report titled *Science—The Endless Frontier*, which he prepared in response to President Franklin Roosevelt's request for a plan that would continue the successes of the OSRD into peacetime. His most crucial suggestion was for the creation of a national research foundation.

In the report, Bush made a strong case for why the federal government needed to support basic scientific research in the postwar period. The war had devastated the European centers of learning that had been crucial to the education of Bush's generation of scientists. "We can no longer count on ravaged Europe as a source of fundamental knowledge," he wrote. "In the past we have devoted much of our best efforts to the application of such knowledge which has been discovered abroad. In the future we must pay increased attention to discovering this knowledge for ourselves particularly since the scientific applications of the future will be more than ever dependent upon such basic knowledge."[3] To fulfill that goal, Bush argued that US universities and researchers would need more resources—and those resources could come only from the federal government. "New impetus must be given to research in our country. Such new impetus can come promptly only from the Government. Expenditures for research in the colleges, universities, and research institutes will otherwise not be able to meet the additional demands of increased public need for research."[4]

Without consulting Kilgore, Bush arranged for Democratic senator Warren Magnuson of Washington State to introduce a bill based on the ideas put forward in *Science—The Endless Frontier*. On Thursday, 19 July 1945, Magnuson introduced S. 1285, which had been drafted by OSRD staff with Bush's guidance. Kilgore reportedly considered himself "double-crossed" by Bush's move to undercut his efforts and decided to submit a new bill, S. 1297, the following Monday.[5] The stage was set for a protracted legislative debate that would last nearly five years.

FIGURE 2. THE US CAPITOL BUILDING in Washington, DC, where Congress votes on legislation and budgets. (Photo by Martin Falbisoner, CC BY-SA 3.0.)

The main disagreements surrounded patent rights for government-funded research, support for the social sciences, geographic diversity of funding distribution, and political control of foundation operations.[6]

The NSF Act Truman signed into law in 1950 represented a compromise between the two camps. It called for the creation of a new organization that would develop a national policy for promoting basic research and education in the natural sciences. The agency would have three main categories of functions: support for basic scientific research, support for science education, and the evaluation and exchange of scientific research and information. NSF would be led by a presidentially appointed director who would share planning and decision making with the National Science Board, a new advisory body comprising 24 representatives from the scientific community.

Should there be a national policy for science?

NSF was born into a complex federal R&D landscape that skewed heavily toward research focused on national security. At the time of NSF's creation, the newly organized Department of Defense and the Atomic Energy Commission accounted for 90% of the $1 billion federal R&D budget[7] in 1949–50. Although Bush had hoped NSF would become the centralized place in the federal government for medical and military research, other agencies remained involved. The military services continued their individual basic research programs; the AEC and the Office of Naval Research maintained their support of fundamental science related to nuclear research and the operational needs of the US Navy; the National Institutes of Health became the primary patron of medical research. Such competition, along with the outbreak of the Korean War, led to meager initial budgets for the fledgling NSF. Congress voted to appropriate just $225 000 (around $2.4 million in current dollars) for NSF[8] in fiscal year 1951 (see figure 2).

The man charged with staffing NSF and building operational capacity with that shoestring budget was Alan Waterman (see figure 3), a seasoned science administrator who had worked for Bush's NDRC and served as the Office of Naval Research's first chief scientist after the end of World War II. A short, silver-haired man with square features and a stocky, athletic build, Waterman was 58 years old when Truman appointed him as NSF's first director. During his 12-year term—the longest tenure of any NSF director to date—Waterman carefully paced the agency's growth, making decisions that would shape both its development and the landscape of federal civilian research funding.

The NSF Act laid out science policy and evaluation duties for the new foundation. Waterman was careful not to take on too much, too quickly. In the first few years of NSF's existence, Waterman worked closely with the Bureau of the Budget to work out the agency's scope and organization. The bureau, a predecessor to the Office of Management and Budget, had been tasked with implementing the president's strategies by issuing organizational directives to government agencies and setting budget priorities. Influential members of the bureau had become concerned about the proliferation of basic research programs across various agencies and in DOD. They viewed NSF as an opportunity to rein in federal R&D programs and eliminate any potential duplication of efforts by centralizing control and evaluation in one agency.

Waterman and the National Science Board, however, recognized that the fledgling agency would face great operational difficulty if the bureau successfully saddled it with the herculean task of coordinating and evaluating all federal R&D programs. That would have required NSF to request detailed information about funding priorities and research performance from all existing federal science programs. They argued that the agency didn't have the necessary legal authority to evaluate and give direction to sister agencies and that such duties fell under the direct purview of the bureau. Waterman also disagreed with the bureau about how much control NSF should attempt to exercise over the direction of US science policy. "Those who insist that policy must be handed down 'ready-made' in the form of a proclamation or edict do not understand the nature of policy in the realm of science," he later wrote in a retrospective for *Science*. "To be workable, policy must evolve on the basis of experience; further, it must take fully into account the fundamental principles essential to the effective performance of research in science."[9]

Under Waterman's leadership, the foundation organized its operational activities and policymaking around the central belief that scientists, not government agencies or administrators, knew best how to organize and conduct scientific research. Therefore, the agency's process of evaluating proposals and awarding grants relied on the expertise and advice of scientists, which they solicited through in-person panels and mail-in proposal reviews. NSF's approach to policymaking also relied on information from the scientific community and careful policy studies and statistical surveys to produce general recommendations. A significant early example of that approach was the foundation's decision to support the development and operation of national research facilities.

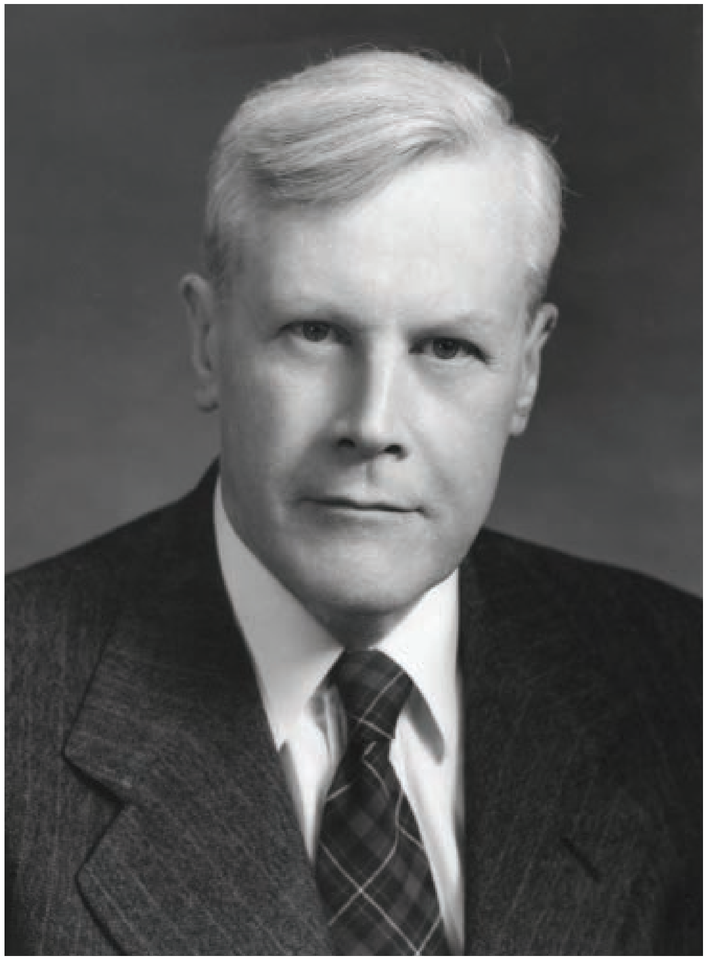

FIGURE 3. ALAN WATERMAN, first director of NSF. (Photograph by Harris and Ewing, courtesy of the AIP Emilio Segrè Visual Archives, Physics Today Collection.)

New centers for research

Although NSF's budgets remained modest during its early years, the agency's policy decisions played a crucial role in establishing civilian-led, basic research in the military-dominated federal R&D landscape. The rising cost of conducting cutting-edge scientific research limited many researchers' access to essential equipment. After World War II, defense agencies and industry made large capital investments in research facilities, but those laboratories were largely occupied by military and industry-sponsored researchers working toward mission-oriented goals. When proposals requesting funds for research facilities in nuclear physics, astronomy, and computing began arriving at NSF offices, the leadership saw an opportunity not only to support individual research projects but also to encourage the construction and operation of entire facilities for civilian-led, basic scientific research.

Although the agency's original mandate did not mention research facilities specifically, the National Science Board at its May 1955 meeting adopted an official policy regarding facilities investment. It directed NSF to support large, basic scientific facilities "when the need is clear and it is in the national interest, when the merit is endorsed by panels of experts, and when funds are not readily available from other sources."[10] The facilities policy created a new budget category, "special budgets," to ensure that the funds for large projects were kept separate from research funds for individual investigators and small-scale projects. In presenting the new policy to the White House, Waterman justified the expansion of NSF support for civilian-led basic research facilities by pointing out that various defense agencies had also funded facility construction to support mission-related research.

NSF hoped that the facilities it funded would both improve the quality of basic research in fields that depended on specialized and costly equipment and redress geographical imbalances in equipment location. The US's leading research facilities and best equipment tended to cluster around elite universities on the East and West Coasts, and NSF recognized that researchers in other areas of the country encountered more difficulty gaining access to equipment such as large telescopes and particle accelerators.

NSF submitted its first request for construction funds to Congress for FY 1956. During that year the agency awarded \$125 000 for grants to support research facilities in biological and medical sciences and \$397 500 for facilities to support mathematical, physical, and engineering sciences.[11] The facilities grants represented only 3% of the agency's total financial obligations for FY 1956, but they supported a wide range of projects: the beginning phases of construction of a national optical observatory on Kitt Peak in Arizona and the National Radio Astronomy Observatory in Greenbank, West Virginia; a nuclear reactor at MIT; several biological research field stations; and computing centers at Caltech, MIT, Oregon State College, the University of Washington, and the University of Wisconsin.[12]

NSF's early investment in astronomy, in particular, demonstrated the importance of the agency's support for fundamental, scientific research as a balance to military and private funding sources. In contrast to mission-related research, which guided the direction of scientific inquiry toward specific aims, NSF support offered astronomers access to observatories regardless of institutional affiliation and the chance to pursue curiosity-driven research. (See Patrick McCray, "The contentious role of a national observatory," PHYSICS TODAY, October 2003, page 55.) NSF's early support of astronomy facilities also illustrates how the needs of the scientific community shaped agency priorities, and it served as an early example of the type of "bottom-up" science policy formation that Waterman championed.

Influencing federal STEM education policy

Support for US STEM education also became a fast-growing area of investment for NSF during its first decade. Before 1958 the federal government primarily left education funding and support to individual states. Wide variation in public schools' funding led to large discrepancies in education quality and access between towns, cities, and states.

Although the US government had passed various measures to provide funding for agricultural and vocational schools during the early 19th and 20th centuries, federal investment in education remained a politically contentious issue. The political landscape began to change, however, when concerns about scientific manpower started to chip away at long-held resistance to the idea of federal education funding. After World War II, scientists began to directly connect the state of US education with national security concerns. In *Science—The Endless Frontier*, Bush had warned that the US would emerge from the war with a grave shortage of scientists. He had also expressed great concern over the state of US math and science education, saying that schools were failing to produce enough high-quality scientists and that the US needed them to secure the national defense. The growing specter of Soviet competition during the 1950s added increasing urgency to his warnings.

The NSF Act gave the foundation a broad mandate to support science education. Immediately after its creation, the agency initiated a program of support for a range of science education activities, beginning with the Graduate Research Fellowship Program in 1952. Although the majority of NSF's initial education programs focused on the university level, it became increasingly clear that major improvements needed to be made at the secondary level. NSF officials were initially hesitant to venture into the comparatively more politically contentious realm of precollege education, but they recognized the need to assist science, math, and engineering teachers whose training had become outdated after the rapid scientific developments during World War II. One NSF-supported study from the period found that the average public high school math teacher had some college coursework in math but had not majored in the subject.[13]

Strengthening high school STEM courses through improved teacher training became a focus for the agency. In 1954, scientists, mathematicians, and NSF staff members began organizing training programs for high school and college teachers at university campuses across the country. The Institutes Programs sought to update teachers' subject knowledge to include the latest scientific advancements, upgrade teachers' basic training in their subject areas, and increase teacher familiarity with the latest STEM curricula—some of which had been developed with NSF support.[14]

FIGURE 4. A REPLICA OF *SPUTNIK 1* (RIGHT), AND A 1957 SOVIET STAMP (LEFT) commemorating the successful launch of the satellite. (*Sputnik 1* image courtesy of the Smithsonian National Air and Space Museum; stamp is PD-RU-exempt, via Wikimedia Commons.)

The postwar fears about Soviet competition that had largely fueled congressional support for NSF's secondary education programs reached a fever pitch on 4 October 1957. The Soviet launch of *Sputnik 1*, the first artificial, Earth-orbiting satellite, sent shock waves throughout the US (see figure 4). The subsequent launch on 3 November of *Sputnik 2*, which carried a dog named Laika, prompted an alarmed Congress to summon scientists, including Bush, to testify in public hearings later that month. Legislators wanted to know why Soviet developments had seemingly eclipsed US capabilities and what could be done to regain the US's position as the global leader. In response to those questions, Bush reiterated one of his key points from *Science—The Endless Frontier*: that US scientific and technological competitiveness depended on a strong system of scientific education and training.

The Sputnik program became a potent symbol of the damage that US underinvestment in science education and research might cause to national security and prestige. Congress responded with across-the-board increases for federal science support. For FY 1959, NSF received a total budget of $132 940 000, nearly triple the FY 1958 budget. NSF's education programming received the largest boost from the post-Sputnik influx of funds, taking in a total of $62 070 000 for FY 1959—over $12 million more than NSF's entire budget from the previous year.[15]

Although the Sputnik program spurred Congress to provide much-needed financial support for the agency's ongoing education programs, it also increased political pressure on President Dwight Eisenhower's administration to formulate a strong, far-reaching education policy. To help craft it, the White House turned to NSF, which, as a federal innovator in the field, could boast a well-established record in science education programming. On 27 January 1958, the White House released its plan for strengthening US education. Eisenhower's accompanying statement explained that his administration had developed the proposed program in consultation with the directors of NSF and the Office of Education. He included high praise for NSF's science education improvement efforts, calling them "among the most significant contributions currently being made to the improvement of science education in the United States."[16]

NSF STEM education activities served as a model for the STEM-focused parts of the 1958 National Defense Education Act (NDEA), which Eisenhower signed into law on 2 September 1958. It transferred $1 billion to the Department of Health, Education, and Welfare for the administration of a need-based loan and college fellowship program, the expansion of school science labs and foreign language instruction, and the creation of state programs to improve science and mathematics education. The first example of comprehensive federal education legislation, the NDEA formed a cornerstone of a postwar federal strategy focused on strengthening the US scientific and technological workforce that continues today.

Foundations for future science and education policy

Even though the agency did not immediately become the counterbalance to military and applied research that many had hoped it would be, the strategic investments made during NSF's early years in fields such as science education and research infrastructure support made it possible for the foundation's limited budget to have an outsized impact. The early budget restrictions also revealed to agency leadership that the link between basic research and national security was not a firm one. NSF's place in the federal funding landscape would need to be perennially justified and reasserted through the lens of an ever-changing geopolitical and fiscal landscape.

During the first 12 years of the agency's existence, Waterman charted a course of steady, considered growth. In the face of attempts to saddle NSF with burdensome duties, Waterman kept the foundation true to its core mission: the support of fundamental science research and education. Although he often drew criticism from government officials and fellow scientists for his cautious approach, many observers attributed NSF's survival during lean budgetary years to his prudence and planning. His work positioned NSF for the rapid expansion it experienced at the end of the decade.

Waterman's guidance of the agency won the respect of Eisenhower as well. In a letter dated 6 January 1961, just two weeks before his departure from the Oval Office, Eisenhower wrote to Waterman to praise the foundation's work during his administration. Professing his wish to "pay tribute" to Waterman and NSF's staff for their work promoting the progress of science, Eisenhower reflected with pride on the fact that NSF appropriations had risen drastically during his administration, from $4.7 million in 1953 to $154.7 million in 1960. He noted that NSF served as an "excellent barometer" of the nation's response to the urgent need for "increasing the scientific effort."[17]

In the 60 years since Eisenhower stepped down, NSF has also served as a barometer of the nation's attitudes toward and concerns about government support of basic science. Many of the debates that existed at the time of NSF's creation—the extent to which the agency should fund applied research, the appropriate level of support for social-science research, the geographic distribution of research funding, and more—have continued to shape agency policy throughout its 70 years. Changing political, economic, and social forces, however, have given rise to new concerns. In recent years, attention to access and equity has driven a range of different agency initiatives focused on increasing the participation of women and minorities in STEM research and careers. New geopolitical tensions have given renewed urgency to the challenges of balancing national security with scientific openness and collaboration. Like science itself, NSF's programs and ambitions have never been static; they have evolved and changed in response to policy debates, public opinion, and the needs of civilian researchers in the US.

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Uganda's Margherita glacier, in the Rwenzori Mountains, provides the Nile River with some of its water. (Morgan Trimble/Alamy Stock Photo.)

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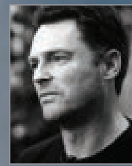


Tying celestial mechanics to Earth's ice ages

Gradual falls and sharp rises in temperature for millions of years have profoundly affected living conditions on the planet and, consequently, our own evolution.

Mark Maslin

Milutin Milanković, a brilliant Serbian mathematician and climatologist, postulated in 1941 that variations in Earth's orbit could push the planet's climate in or out of an ice age.[1] Vital to that idea is the amount of insolation—incoming solar radiation—at 65° N, a bit south of the Arctic Circle. At that latitude, insolation can vary seasonally by 25%. Milanković argued that reductions in summer insolation allow some winter ice to survive. Each year for thousands of years, ice accumulates around 65° N and eventually forms sheets large enough to trigger an ice age.

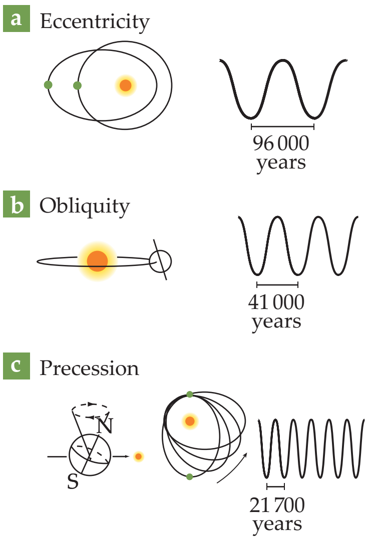


FIGURE 1. MILANKOVITCH CYCLES comprise three types of variation in Earth's motion. Eccentricity **(a)** describes the shape of Earth's orbit around the Sun, which varies from nearly circular to more elliptical with a period of about 96 000 years. Obliquity **(b)** is the tilt of Earth's axis of rotation with respect to the plane of its orbit and oscillates with a period of some 41 000 years. Precession **(c)** consists of the spin of Earth's rotational axis and its orbital path over time; the combined effects of those two components produce an approximately 21 000-year cycle. (Adapted from ref. 3.)

Three scientists joined forces 30 years later to verify Milanković's theory using deep-sea sediment cores collected by the international Ocean Drilling Program. James Hays examined marine microfossils in the cores to estimate past sea-surface temperatures. Nicholas Shackleton measured the oxygen isotope composition in the sediment's layers, which showed changes in past global ice volume. And the last member of the team, John Imbrie, brought an expertise in time-series analysis to the project. In 1976 they published a seminal paper showing that their climate record contained the same temporal cycles as three parameters, summarized in figure 1, that describe Earth's orbit: eccentricity, obliquity, and precession.[2]

Eccentricity describes the shape of Earth's orbit around the Sun. As Earth experiences a gravitational force from Jupiter, its orbit adjusts during a 96 000-year period from nearly a perfect circle to an ellipse, which causes minor variations in total insolation. Obliquity—the tilt of Earth's axis of rotation with respect to the plane of its orbit—fluctuates during a period of 41 000 years between 21.8° and 24.4° and is currently at 23.4°. A larger obliquity generates a greater difference in the insolation Earth receives during summer and winter.

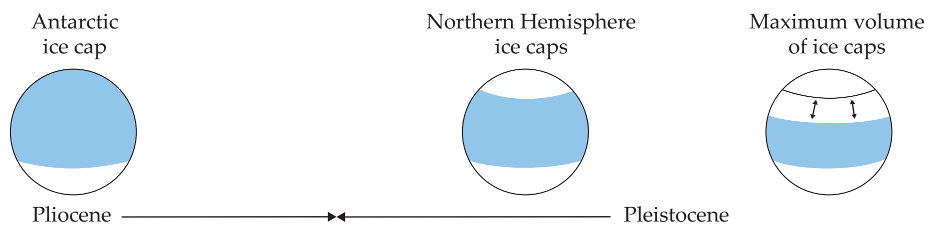
The third orbital parameter, precession, occurs every 21 700 years and influences Earth's closest approach to the Sun. During each hemisphere's summer, precession has the greatest effect in the tropics. Tidal forces of the Sun and Moon, amplified by Earth's oblate spheroid shape, cause one component of precession. Those forces exert gyroscopic motion on the planet that changes the orientation of its rotational axis. The second component of precession moves Earth's entire orbit around the Sun in space and resembles the petals of a flower, as shown in figure 1c.

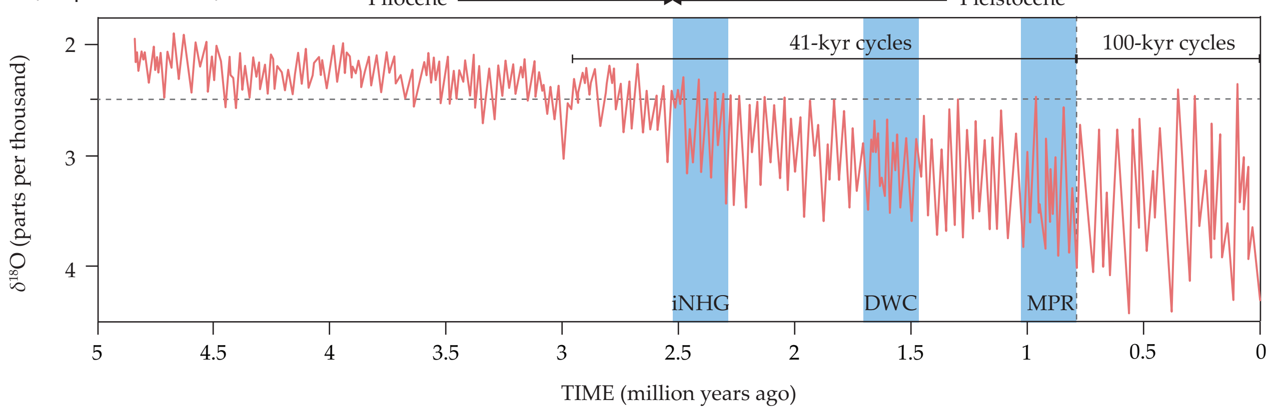
The great ice ages

Over the past 2.5 million years, Earth has undergone some 50 major ice ages and each has substantially changed the planet's climate.[3] During the last one 21 000 years ago, a nearly continuous ice sheet spanned North America. At its thickest, across what is now Hudson Bay, it was more than two miles deep and reached as far south as New York City and Cincinnati, Ohio. The British–Irish ice sheet spread as far south as Norfolk, and the Scandinavian ice sheet extended from Norway to the Ural Mountains in Russia. In the Southern Hemisphere, large ice sheets covered Patagonia, South Africa, southern Australia, and New Zealand. So much water was locked in all those ice sheets that global sea level dropped 120 m, yet if all the Antarctic and Greenland ice melted today, sea level would rise only by 70 m.

How did small wobbles in Earth's orbit cause those ice ages? Summer temperatures must first decrease a little bit. The con-

FIGURE 2. MANY GLACIAL–INTERGLACIAL CYCLES (red solid line) during the last 5 million years can be seen from measurements of the oxygen isotope composition of lake records. Large ice sheets started to grow in North America 2.5 million years ago during the intensification of Northern Hemisphere glaciation (iNHG). The development of the atmospheric Walker Circulation (DWC) started 1.7 million years ago in the Pacific Ocean and is sustained by a large east-to-west sea-surface-temperature gradient. About 1 million years ago, during the Mid-Pleistocene Revolution (MPR), the polar ice caps expanded toward the equator, and the glacial–interglacial cycle period increased from an average of 41 000 years to 100 000 years. (Adapted from ref. 3.)





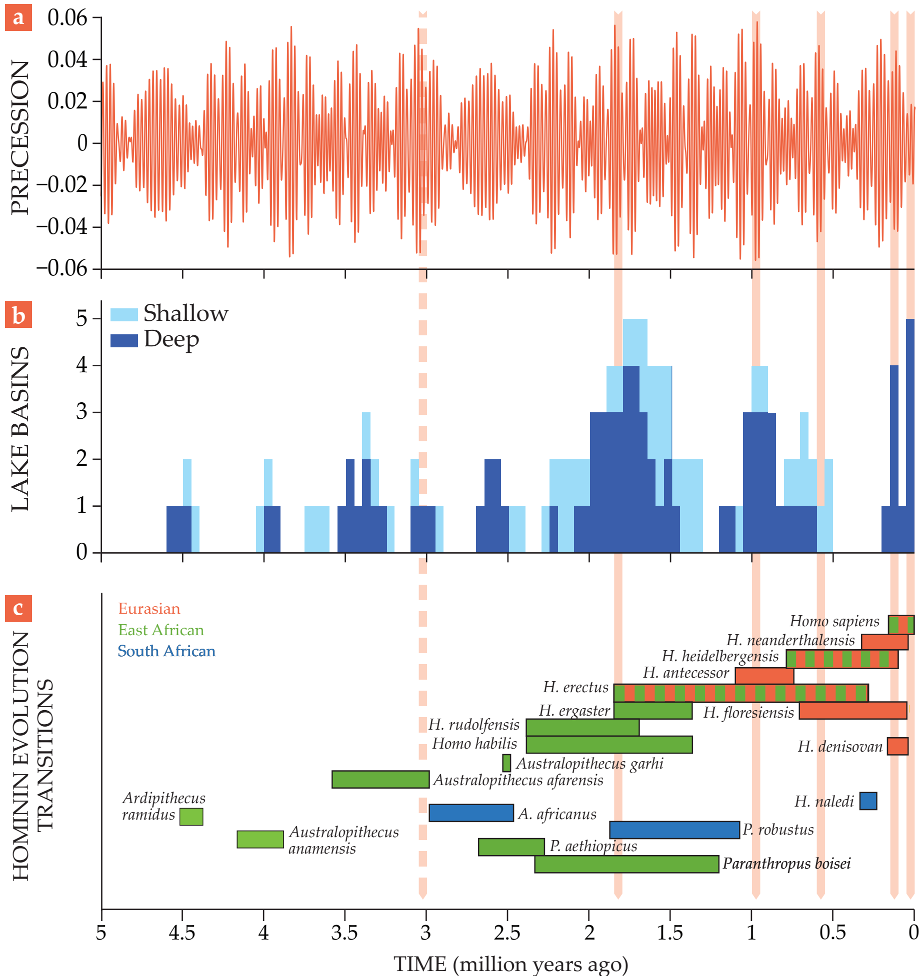


FIGURE 3. HUMAN EVOLUTION is connected to African climate change. Large variations in the precession of Earth's orbit **(a)** help determine the size and number of deep freshwater lakes in the East African Rift Valley **(b)**. Those lakes, in turn, can be linked to major evolutionary changes in early humans **(c)**. The red dotted line marks the first dispersal of hominins throughout Africa; solid red lines identify the times when hominins dispersed from Africa to Europe and Asia. (Adapted from ref. 8.)

sequent accumulation of snow and ice increases Earth's albedo—the reflection of sunlight to space. Reflecting more sunlight suppresses local temperatures and promotes more snow and ice accumulation, which increases the albedo further. The process, called an ice–albedo feedback, is responsible for building increasingly bigger ice sheets.

Another positive feedback cycle triggers when ice sheets, such as the Laurentide sheet that once covered much of North America, become big enough to deflect atmospheric planetary waves. The change redirects storm paths across the North Atlantic Ocean and prevents the Gulf Stream and its northeastward arm, the North Atlantic Drift, from penetrating as far north as they do today. The surface ocean effects, combined with melt-water increase in the Nordic Seas and the Atlantic, cause a decrease in the sinking of cold, salty water (see PHYSICS TODAY, April 2019, page 19). As less water in the North Atlantic is driven to the deep ocean, the Gulf Stream pulls less warm water northward, and increased cooling in the Northern Hemisphere expands the ice sheets.

Greenhouse gases (GHGs) in the atmosphere reinforce ice-sheet feedbacks. Analyses of air bubbles trapped in polar ice indicate that during glacial periods carbon dioxide concentrations dropped by a third and methane by half. Changes in GHGs always precede variations in global temperatures and are therefore a clear driving force of climate change, not a response to it.[4]

Runaway positive feedbacks froze most of Earth's water billions of years ago during snowball Earth events, but moisture limitation has prevented a more recent episode. Forming an ice sheet requires a cold, wet climate. But as an ice sheet forces warm surface water farther south, the supply of moisture decreases. By changing the atmosphere and ocean circulation, ice sheets starve themselves of moisture, and that negative feedback loop limits the effects of positive ones.

For the past million years, ice sheets have taken at least 80 000 years to reach their maximum extent, which occurred most recently about 21 000 years ago. However, ice melts much quicker than that: 80% of expanded ice sheets can be lost in 4000 years. Summer sunshine at 65° N triggers deglaciation and starts the melting of Northern Hemisphere ice sheets. Rising concentrations of carbon dioxide and methane in the atmosphere promote climate change and further melt large continental ice sheets. Such processes work against the ice–albedo effect, which acts to keep the ice sheets intact by producing a cooler microclimate.

Ultimately, rising sea levels diminish large ice sheets because the coldest that seawater can be is −1.8 °C, whereas the temperature of the ice sheet's base is −30 °C. As seawater melts the ice sheets by undercutting them, ice calves into the ocean. The calving raises sea level further and causes more undercutting (see PHYSICS TODAY, October 2019, page 14). The sea-level feedback mechanism can be extremely rapid. Once the ice sheets are retreating, the other feedback mechanisms—albedo, atmospheric and ocean circulation, and GHGs—are reversed. That's why glaciologists and climatologists worry about future climate change: It will activate those feedbacks and cause irreversible instability to the Greenland and West Antarctic ice sheets (see PHYSICS TODAY, July 2014, page 10).

The eccentricity myth

The last million years of glacial–interglacial cycles, each lasting about 100 000 years, have a saw-toothed pattern with a long period of cooling followed by a short, warm one of rapid melting. More than a million years ago, the cycles were smoother, and each lasted only 41 000 years, as shown in figure 2. That period corresponds to the length of the orbital change associated with obliquity, which controls the heat transfer between low and high latitudes and thus regulates ice growth.

For many years, scientists struggled to explain the 100 000-

year glacial–interglacial cycles because the 96 000-year eccentricity mechanism has a similar length. But eccentricity is by far the weakest of the orbital variations, and many thought it predominantly modulated precession, so scientists suggested several nonlinear feedbacks to explain the discrepancy. But they found an answer when they realized that the 100 000-year cycle is a statistical artifact.

The average length of the last eight cycles is indeed 100 000 years, but each one varies from 80 000 to 120 000 years. Every fourth or fifth precessional cycle is weak enough that ice sheets can grow bigger and thus more vulnerable to sea-level rise during deglaciation. The next precessional cycle is always much stronger than the previous one and initiates rapid, extreme deglaciation through the sea-level feedback.[5] Although the timing of deglaciation seems to better match precession, some researchers have argued that the long glacial–interglacial cycles may correspond to every second or third obliquity cycle.[6]

Celestial mechanics and human evolution

In addition to high-latitude climate, orbital forcing also greatly influences the climates of tropical Africa, Amazonia, and Asia, particularly through precession. Climate models show that precession forcing increases annual precipitation in the tropics by at least 200 mm per year and significantly shifts the timing of seasons.[7] Such a change in moisture availability is equivalent to switching from a glacial period to an interglacial one. The influence of precession further increases every 96 000 years when eccentricity peaks, and it is greatest once every 413 000 years when Earth's orbit reaches its most elliptical.

Precession affects tropical climate by changing what time of year coincides with the closest Sun–Earth distance and thus the amount of insolation received during each season. (Eccentricity controls what that Sun–Earth distance is.) For example, during Northern Hemisphere summer, the tropics and subtropics heat up as the Sun steadily moves from directly overhead at the equator to the Tropic of Cancer at 23° N. At the maximum positive precession, the Sun–Earth distance will be shortest when the Sun is overhead at the Tropic of Cancer, and so the amount of solar energy and convection reaching the subtropics significantly increases.

The strengthened trade winds empower the Intertropical Convergence Zone and greatly increase the amount of rainfall in the Northern Hemisphere tropics (see the article by Thomas Birner, Sean Davis, and Dian Seidel, PHYSICS TODAY, December 2014, page 38). Meanwhile, Southern Hemisphere summer will coincide with the longest Sun–Earth distance, and rainfall will be greatly reduced in the tropics south of the equator. The situation reverses 21 000 years later, and the Southern Hemisphere tropics then become the place with the most intense insolation and rainfall.

Many paleorecords show the inverse relationship of each hemisphere's hydrological cycle. During the past 10 000 years, North African lakes have steadily been drying, while Amazon River discharge has increased.[8] Starting 5 million years ago, marine-dust evidence from the eastern Mediterranean Sea shows periodic increases in aridity in the eastern Algerian, Libyan, and western Egyptian lowlands.[8] Corroborating those records are sediment observations from the Arabian Sea, the North Atlantic Ocean, and the ocean adjacent to the West Africa coast. Records from sapropel formations—the dark organic-rich layer found in Mediterranean marine sediments that are made by a reduction in the oxygen content of the water—show increased rainfall and higher river discharge to the sea, and the variation in those records has a dominant periodicity of 21 000 years, which indicates precessional orbital forcing.

FIGURE 4. THE DEEP, EAST AFRICAN LAKE TURKANA experienced extreme wet and dry episodes during periods of high orbital forcing. Big swings in the precession of Earth's orbit create significant variations of the area's local insolation and rainfall intensity. Those variations lead to ephemeral deep freshwater lakes, like the one pictured here, in the East African Rift Valley. Scientists think that major developments in human evolution are linked to the short periods of highly variable environmental conditions. As the lakes dried out at the end of a precessional cycle, humans' brain size may have increased in response to the environmental pressure. (Belikova Oksana/Shutterstock.com.)

Climate reconstructions of the times when prehistoric hominin populations were evolving show a strong link between orbital forcing and the African environment. Eccentricity maxima generated periods of extreme climate variability every 400 000 years, which caused lakes to repeatedly grow and fill much of the African Rift Valley and then disappear on approximately a 20 000-year precessional time scale.[9] Shown in figure 3, those periods indicate statistically significant correlations with the majority of the first and final appearances of hominin species during the last 5 million years.[10,11]

The speed at which deep freshwater lakes, such as Lake Turkana in northern Kenya (shown in figure 4), appeared and disappeared from the landscape may have stressed the hominin species living in the region. Although orbitally forced climate oscillations operate on time scales longer than the rapid changes observed in lakes, all orbital parameters are sinusoidal, which means that periods of little or no variation are followed by ones with large changes. For example, the sinusoidal precessional forcing at the equator consists of periods of less than 2500 years during which 60% of the total variation in daily insolation and seasonality occurs. Those stretches of time are followed by ones that last 8000 years with relatively little change in daily insolation. The mismatched time scales produce brief stretches of strong forcing and long ones of relatively weak forcing. Combined with the idea that many East African lakes are amplifier lakes that respond quickly to small changes in the precipitation–evaporation balance, the landscape and climate may have responded swiftly to precessional forcing.

Anthropologists and climatologists have suggested that the presence or absence of lakes is associated with hominin dispersal events, which took place 3 million years ago in Africa and in other areas 1.8, 0.9, 0.6, and less than 0.1 million years ago.[8] Hominin migration would have most likely occurred when the basins were completely filled with water and both food and water were abundant. Hominins could have followed the Nile River's tributaries northward through a green Levant region, the area due east of the Mediterranean.[10]

Some evidence shows that early humans took multiple routes from Africa to the Middle East.[11] Wet conditions in East Africa correlate with a similar climate in the Levant and the Middle East. With each successive precessional cycle, deep freshwater lakes would have enabled hominin populations to migrate northward to the Ethiopian highlands, the Sinai peninsula, and, for a smaller population, southern Africa.

Creating a super-interglacial

To predict the next ice age, scientists are studying not only orbital forcing but also GHG emissions. Air bubbles trapped in the Greenland and Antarctic ice sheets show low GHG concentrations during cold glacial periods and high concentrations during warm interglacial times. Carbon dioxide usually varies between 180 ppm and 280 ppm and methane from 350 ppb to 700 ppb. Atmospheric carbon dioxide peaks as the Earth system rebounds from an ice age, and then it steadily declines until reaching a critical value of 240 ppm. (That level is 40 ppm lower than preindustrial times and more than 170 ppm lower than today.) At the critical value, orbital forcing pushes Earth's climate to another ice age, and glaciers grow slowly until eventually full glaciation is reached. Without human interference, ice sheets should have been growing now, and the next glaciation would have happened sometime during the next 1000 years.[12]

Paleoclimatologist William Ruddiman recognized odd GHG trends during the current interglacial period, the Holocene.[13] Ice-core records for each of the last eight warm interglacial periods show that GHGs begin at high levels and then slowly decline. But carbon dioxide started to rise some 7000 years ago and methane, about 5000 years ago, and those gases haven't declined as expected. Ruddiman suggested that human deforestation of land for agriculture, including the massive expansion of wet rice farming and domestication of cattle, caused the rise in atmospheric carbon dioxide and methane.

The extended interglacial period caused by persistently high GHG emissions produced an unusually stable climate and may have helped human empires emerge. Those emissions, however, are small compared to what humans have emitted since the start of the industrial revolution. Atmospheric carbon dioxide has increased by 47% to more than 410 ppm and methane by some 250% to more than 1860 ppb. Depending on future carbon emissions, global temperatures could rise 1.5–5.6 °C during the next century.[14] The GHGs already emitted have delayed the next ice age for 60 000 years, as shown in figure 5, according to climate models.[15] If the emissions reach the highest predicted level, glaciation would be delayed for 0.5 million years. Human fossil-fuel use has created a super-interglacial period that has overridden the effect of orbital forcing on Earth's climate.

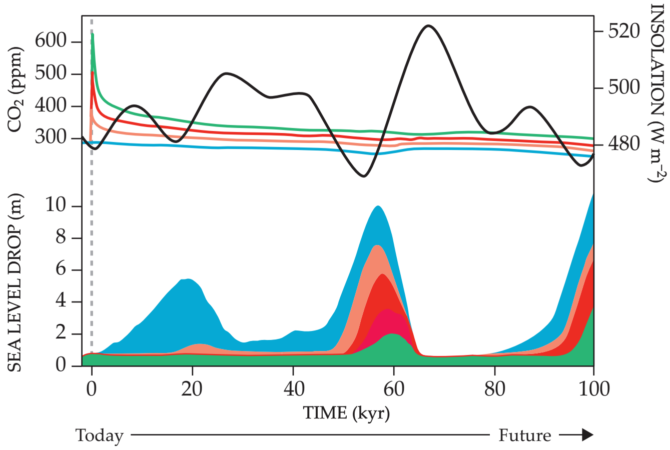


FIGURE 5. FUTURE ICE AGES depend on orbital forcing and on the quantity of greenhouse gases humans will emit (colored lines) during the next 100 years. The four corresponding emission scenarios graphed here from climate model simulations—green illustrates the highest emissions, followed by red, orange, and blue—show that anthropogenic climate change dwarfs the effect of orbital forcing and could delay the next ice age for 60 000 years. (Adapted from ref. 15.)

The Quaternary may still be an appropriate term for the current geologic epoch if humans have delayed the next ice age. But if humans have permanently altered glaciation processes in the Earth system, some scientists propose naming the current period the Anthropocene.[16] The knowledge of orbital forcing has provided scientists with a framework to understand past environmental changes, and the knowledge gained may improve researchers' ability to predict the future environment.

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PT

ISTOCK.COM/ELEN11

Exploring two centuries of the science of water

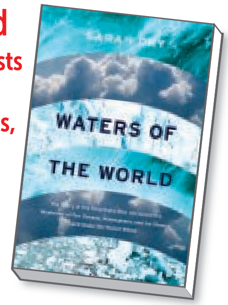
Scientists experience firsthand how the vagaries of politics, funding, interpersonal relationships, and personal motivations influence the march of science. Historian Sarah Dry's new book, *Waters of the World: The Story of the Scientists Who Unraveled the Mysteries of Our Oceans, Atmosphere, and Ice Sheets and Made the Planet Whole*, highlights that human side of science by focusing on the lives and accomplishments of six scientists, all of whom studied water in its different forms. The stories cover nearly 200 years of history, and along the way, Dry builds a clear and cogent picture of Earth's climate system from the different disciplinary foundations of her chosen characters. It is unusual for a history book to contribute to the readers' appreciation and knowledge of both science and history, but Dry has accomplished that.

Although the author's name is Dry, the text is anything but. *Waters of the World* has an engaging narrative, and I enjoyed reading the stories behind geophysical theories and processes I learned about in graduate school. Dry explains scientific concepts clearly enough to enable lay readers to gain a basic understanding of the physical climate system; her explanations also help readers appreciate the accomplishments of the historical figures. I especially admired the way Dry's narrative referenced other great scientists of the day, which supplemented the rich and vivid picture of the six main characters' lives with a reminder of which other scientific giants were working in parallel with them.

Waters of the World is relatively short for a history book. Pithy chapters exploring the science of ice bookend the text; the middle four chapters explore atmospheric phenomena and ocean water. The volume begins with physicist John Tyndall, known for his study of glacial movement. His work helped scientists begin to see that Earth's climate had shifted enough to create vast ice sheets over Europe and North America. Tyndall also studied the absorption of heat by water vapor in the atmosphere; Dry uses that work as a link to the next chapter, which is about the atmospheric phenomena studied by scientist Charles Piazzi Smyth.

Moving from the midlatitude atmosphere to the tropics, Dry covers the life and work of Gilbert Walker, a mathematician by training who made strides toward understanding the Indian monsoon and tropical atmospheric circulation by taming the growing pile of data amassed by the global administrative power of the British Empire. Her next subject is physicist Joanne Gerould, more commonly remembered by her married names of Joanne Malkus and Joanne Simpson and known for her contributions to our understanding of tropical atmospheric convection. The ocean provides heat for all of that tropical convection, and Dry examines global ocean circulation and heat transport in a chapter about physical oceanographer Henry Stommel. The whirlwind tour through the history of water science ends with Willi Dansgaard's investigations into water isotopes and the record of past Earth temperatures archived in the isotopes of ice.

Waters of the World
The Story of the Scientists Who Unraveled the Mysteries of Our Oceans, Atmosphere, and Ice Sheets and Made the Planet Whole
Sarah Dry
U. Chicago Press, 2019. $30.00



Dry explores not just the scientific accomplishments of her subjects but also their motivations and foibles. Her nuanced stories teach readers about how we arrived at our present state of knowledge, how science works in the real world, and how we learned about Earth's climate system from the investigations of different forms of water spread over time and space. Dry shows us that science is done both despite and because of the human flaws we all have, and she illustrates how politics and governments influenced the arc of scientific history. She highlights how the pursuit of knowledge by scientists is often also a personal pursuit of wonder, adventure, beauty, and peace.

As a paleoclimatologist, I am a student of both history and climate; *Waters of the World* merges both, and I highly recommend it. I think experts and nonscientists will enjoy the read, and both will gain perspective they didn't have before. I am certainly thinking about getting more copies to give to my family for Christmas this year, and I am even considering asking my graduate students to read it as part of my course on climate change.

K. Halimeda Kilbourne
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Solomons, Maryland

The Kremlin in Moscow.

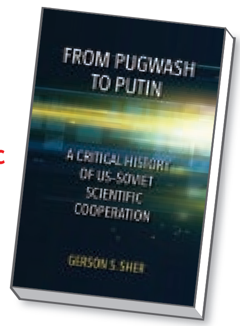
Capturing the human side of Cold War science

Although competition in science and technology is considered one of the defining characteristics of the Cold War, the hostility between the US and the Soviet Union during the mid and late 20th century also prompted the governments to establish scientific exchanges and other collaborative efforts with one another. An even more interesting—and lesser-known—fact is that at the end of the Cold War, after the fall of the Soviet Union in 1991 and the subsequent economic disaster, the US provided massive financial aid and assistance for "the salvation of basic science in Russia." That key episode in the history of international scientific collaboration is the subject of Gerson Sher's new book, *From Pugwash to Putin: A Critical History of US–Soviet Scientific Cooperation*.

Sher, who has a PhD in political science, spent much of his career as a program coordinator for the Soviet Union and Eastern Europe at NSF. *From Pugwash to Putin* draws on his extensive experience with international scientific collaborations and benefits from his personal stories. For example, when chronicling the establishment of the interacademy programs that facilitated scientific exchanges between the US and the Soviet Union, Sher occasionally interjects a personal anecdote. Rather than being distracting, those contributions add value by providing expert insight into a complex and multifaceted story.

The book is organized into three parts. The first, "The Timeline," gives a short yet detailed history of US–Soviet scientific relations throughout the latter half of the 20th century. Sher focuses largely on citizen diplomacy—actions pursued by private citizens that support the goals of public diplomacy—and explores the aspirations behind programs and agreements that facilitated scientific collaboration during the Cold War. He also illustrates the various approaches taken by different political administrations to promote those collaborations and examines how their motivations changed over the decades—from idealistic aims to deterring war to gathering intelligence on Soviet technology.

From Pugwash to Putin
A Critical History of US–Soviet Scientific Cooperation
Gerson S. Sher
Indiana U. Press, 2019. $85.00



The section's last chapter, which focuses on the years after the fall of the Soviet Union, is the most valuable. Little scholarly attention has been given to the enormous US investment in Russian science after the collapse of the Soviet Union. Sher blends his personal experience with rigorous policy analysis, resulting in a much-needed account.

The second part of the book, "In Their Own Words," shares the stories and voices of individuals who were involved in US–Soviet scientific cooperation. The narratives are largely based on interviews conducted by Sher himself. The series of historical snapshots and individual stories build a larger and more human picture from within the institutional and political contexts of the Cold War. The final part, "So What?," unpacks that myriad of human experiences and questions whether collaborative programs accomplished what they aimed to.

Some historians might take issue with the book's style, which is heavy on narration and lighter on analysis. Sher raises many interesting ideas and questions, but he does not present a clear argument. Instead, he starts the book with a series of rhetorical questions and says it will be "up to the reader" to draw their own conclusions from the testimony and facts offered. A skeptical reader might argue that the book has an inherently positive bias, since it highlights mainly the voices of people who dedicated their lives to collaboration or foreign service. Although Sher attempts to give a relatively balanced account and frequently addresses the many challenges and questionable motives involved in international scientific cooperation, there is certainly room for a less rosy interpretation of the events he covers.

But as Sher himself says, "Must we always be cold, hard-nosed realists, or may we also be driven by our vision of a better world?" In that sense, *From Pugwash to Putin* is a history not just of institutions and programs but of an ideal. Judged against that metric, the book is highly successful. Sher captures the human side of scientific exchanges while still giving appropriate attention to institutional and structural components. He is informed, experienced, and a natural storyteller whose style effortlessly infuses heart into what might have been dry policy analysis. The result is a stunning portrait of Cold War scientific cooperation, shining with the voices of those who sought to bring their ideals to life.

On the whole, historians of science have not addressed the impact of US support on science in former Soviet states after the union's collapse or how scientific exchange programs and agreements influenced the story. For that reason, *From Pugwash to Putin* is a book that needed to be written. It has enough substance to be useful to historians and political scientists, but it also has approachable language and vivid storytelling that will appeal to an educated lay audience. International scientific collaboration has become the norm as the world has grown more globalized, and *From Pugwash to Putin* will be of interest to anyone who wants to understand how the structures that facilitate international scientific collaboration came to be and how the Cold War's legacy affects science to this day.

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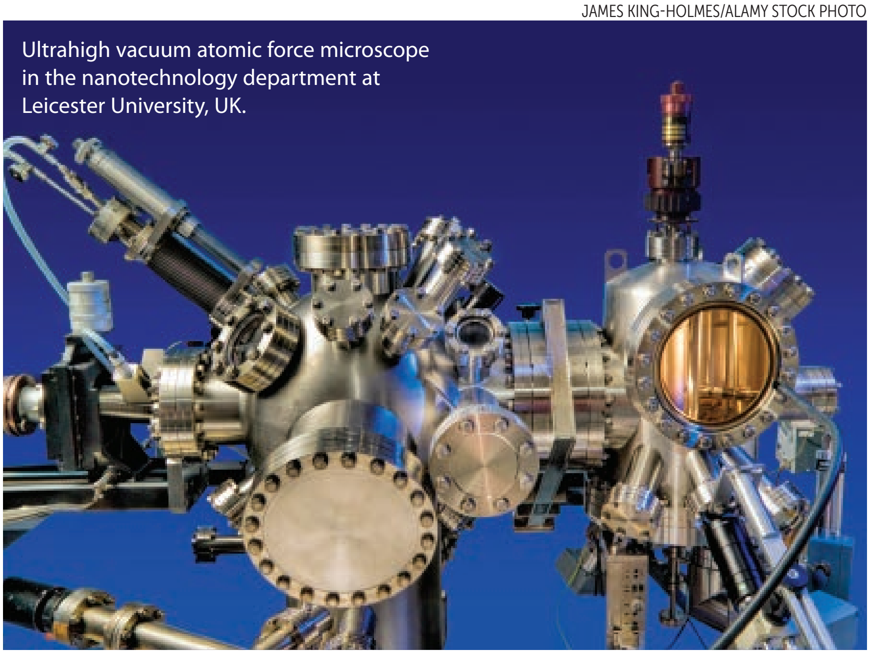
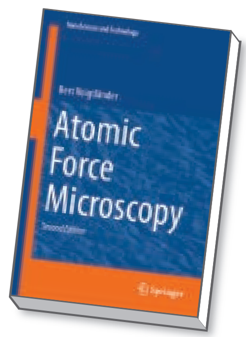
JAMES KING-HOLMES/ALAMY STOCK PHOTO



Ultrahigh vacuum atomic force microscope in the nanotechnology department at Leicester University, UK.

The inner workings of atomic force microscopy

Atomic Force Microscopy
Bert Voigtländer
Springer, 2019
(2nd ed.). $149.99



More than 30 years after its invention, atomic force microscopy (AFM) has grown into a mainstream technique. It is employed in fields ranging from biology to material sciences and is a central tool of nanoscience. It applies to a huge range of samples and environments, from cryogenic to high temperatures and ultrahigh vacuum to liquids. The latest applications include not only the ability to produce topographic images from the several-micrometer range down to the atomic scale, but also the ability to map the physical—mechanical, electrical, chemical, and biological—properties of surfaces with unprecedented spatial resolution. Nowadays, commercial instruments enable researchers to quickly get images of their samples with a minimal knowledge of the operation principles. However, reaching the optimal image resolution or, more importantly, interpreting those images and property maps soundly requires a good understanding of how those instruments work. *Atomic Force Microscopy* by Bert Voigtländer covers those fundamentals.

Atomic Force Microscopy aims to be a comprehensive text that covers most technical aspects of its subject, and it is written with graduate students and newcomers to the field in mind. In just over 300 pages and 18 chapters, it manages to cover the most important aspects of AFM to help readers understand the practical and theoretical concepts behind it. Because of the complexity of the apparatus, the book tackles many practical engineering problems shared between instrumentation and nanoscience, including piezoelectricity, lock-in amplifier detection, motorized positioners and scanners, and vibration isolation.

The quest for exhaustivity and completeness also led Voigtländer to include some basic concepts in the first third of the book, which covers harmonic oscillators, Fourier transforms, and analog and digital electronics. More advanced readers may want to skip those early chapters. They may also want the chapter on linearized dynamic modes to get to the point more quickly and assume more mathematical background knowledge. However, advanced undergraduate students and scientists not familiar with physics will certainly appreciate the slower progression.

The other two-thirds of the book presents necessary background information about force-scanning microscopy and meticulously discusses the most commonly used operation modes of AFM, from static contact to dynamic frequency modulation AFM. *Atomic Force Microscopy* covers most of today's technology fairly and realistically, which is valuable when marketing from manufacturers often oversells the features and capabilities of their instruments. The theoretical content is rigorous and pedagogically effective, giving readers a broad and deep understanding of the subject. Each chapter contains a solid bibliography to guide further learning.

Readers hoping to study a single application of AFM can certainly focus their attention on selected chapters. However, they will probably miss out on pertinent information provided by the frequent comparisons of different modes, with pros and cons of each mode depending on operating conditions. I suggest that, instead, readers complete an initial reading (perhaps skipping the basic first chapters and the more technical final chapters) and then keep the book at hand as a reference work. That advice may seem daunting for newcomers given the book's length, but a more comprehensive reading is certainly worth the time for anyone planning to use the technique regularly. It will also be helpful for anyone wanting to dig further into the specialized literature. For a shorter and lighter introduction with less emphasis on equations, readers may turn to *Atomic Force Microscopy* by Peter Eaton and Paul West (2010).

Whether readers are just starting in the field or running an atomic force microscope daily, Voigtländer's *Atomic Force Microscopy* will be an excellent companion. It will usefully complement the user manual or the application notes of any instrument. I wish it had been available when I was beginning my journey in nanoscience instrumentation 15 years ago, and I will certainly use it as a reference book for all the students coming through our laboratory's door from now on.

Ludovic Bellon
Université de Lyon, École Normale Supérieure de Lyon, and CNRS
France

NEW BOOKS & MEDIA

Georgia's Terrific, Colorific Experiment

Zoe Persico
Running Press Kids, 2019. $17.99

In this book aimed at elementary school students, budding scientist Georgia clashes with her family of artists when they urge her to get creative with her experiments. "Science is about proper calculations and not silly imaginative ideas!" she scolds them. But when Georgia hits a roadblock, she looks to a color wheel to inspire her next experiment. The book sends a lovely message about the value of both science and art, and Zoe Persico's stunning illustrations enhance the appeal. —MB

Science Mom

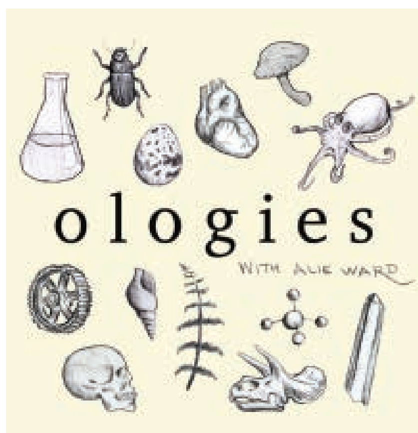
Jenny Ballif, host
YouTube, 2016–present

Which things conduct electricity and why, how to build a strong math foundation, and what extraordinary properties water has are just a few of the topics tackled by molecular biologist Jenny Ballif on her YouTube channel *Science Mom*. According to Ballif, her inspiration sprang from the weekly science demonstrations she started doing for her son's second-grade class. The kids began calling her "Science Mom" and the name stuck, she says. Aimed primarily at the elementary school level, the weekly videos are billed as "engaging science activities for kids of all ages." —CC

Ologies

Alie Ward, 2017–present

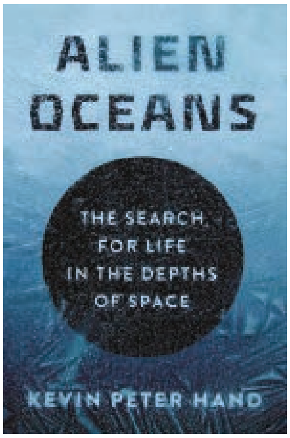
Humorist and science communicator Alie Ward sits down with a wide range of experts to talk about how they became obsessed with their subjects in this engaging interview podcast. Ward is a funny, high-energy host, and her interviews are detailed and accessible. Recent guests have included cryoseismologist Celeste Labedz, psychologist Joseph Ferrari, and neurobiologist Crystal Dilworth. —MB



Science Vs

Wendy Zuckerman, host
Gimlet Media, 2016–present

In every episode of the podcast *Science Vs*, host Wendy Zuckerman talks to experts about the science behind a piece of common wisdom or something in the news. Past episodes include investigations into plastics in our oceans, the health effects of detoxes and cleanses, and whether red wine is really good for us. Recent episodes have focused on the science of detecting and fighting the novel coronavirus. Episodes run about 30 minutes long and are released weekly. —MB



Alien Oceans

The Search for Life in the Depths of Space

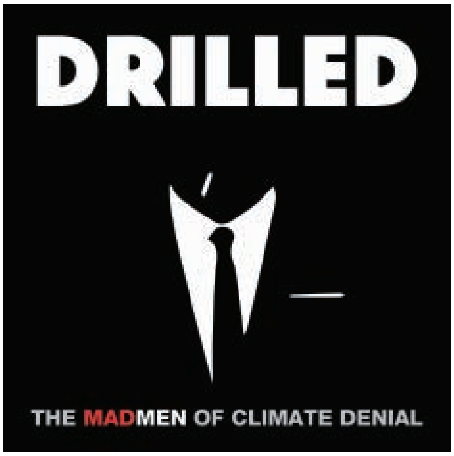
Kevin Peter Hand
Princeton U. Press, 2020. $27.95

"Perhaps we are the only ones…. Or perhaps we live in a universe teeming with life," writes NASA planetary scientist Kevin Peter Hand. In his new book *Alien Oceans*, Hand provides an up-to-date look at the search for extraterrestrial life, based on the data gathered by not only robotic spacecraft and Earth-based telescopes but also the exploration of Earth's oceans. He discusses how the ingredients previously thought necessary to sustain life have been revised and what the new Goldilocks requirements are. Instead of looking at inner-solar-system bodies like Mars, he says, the best candidates may lie farther from the Sun, such as the outer-solar-system moons Europa, Enceladus, and Titan. —CC

Drilled

A True Crime Podcast about Climate Change

Amy Westervelt, host
Drilled News, 2020 (3rd season)



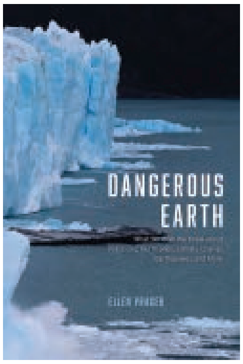
This fascinating and sobering podcast applies investigative journalism to fossil fuels and climate change. The third season, "The Mad Men of Climate Denial," focuses on the ways fossil fuel companies have sought to influence media coverage of climate science. A particularly engaging two-part episode told the story of Mobil Oil PR man Herb Schmertz, who fought for First Amendment rights to be extended to corporations. Episodes are a fast-paced 20 minutes long; the third season concluded in March. —MB

Dangerous Earth

What We Wish We Knew about Volcanoes, Hurricanes, Climate Change, Earthquakes, and More

Ellen Prager
U. Chicago Press, 2020. $25.00

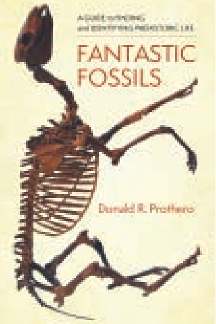
Gale-force winds, torrential rainfalls, catastrophic ground shaking, and searing flows of molten rock are just a few examples of natural phenomena that can be devastating for nearby human populations. In *Dangerous Earth*, marine scientist and author Ellen Prager discusses some of the most destructive natural disasters of recent history, the geologic forces at work, what scientists have learned by studying them, and how much we have yet to understand. —CC



Fantastic Fossils

A Guide to Finding and Identifying Prehistoric Life

Donald R. Prothero
Columbia U. Press, 2020. $35.00



"Fossils are cool. Fossils are amazing," writes Donald Prothero, geologist, paleontologist, and author of more than 40 books. In his preface to *Fantastic Fossils*, Prothero says his goal in writing the book is to provide more practical information than a simple field guide to aid "fossil enthusiasts of every age." He discusses not only how fossils are formed and where to find them, but also best practices for fossil collecting, a brief history of taxonomy, some of the principal phyla, and what fossils can tell us about past climates and geologic time. A handful of color images and more than 350 black-and-white photos, diagrams, and drawings illustrate the text. —CC PT

NEW PRODUCTS

Focus on materials, semiconductors, vacuum, and cryogenics

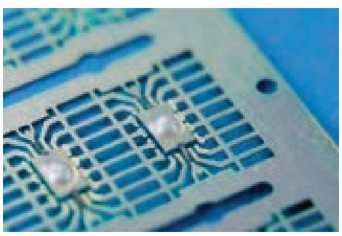
The descriptions of the new products listed in this section are based on information supplied to us by the manufacturers. PHYSICS TODAY can assume no responsibility for their accuracy. For more information about a particular product, visit the website at the end of its description. Please send all new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

Andreas Mandelis

0.8 K benchtop cryostat

ICE has augmented its line of cryogen-free cryostats that take large experimental heat loads. The latest addition to the range is the Dry Ice 0.8K Benchtop Cryostat. An upgrade from the Dry Ice 1.0K Benchtop model, it combines continuous operation in the 0.8–425 K temperature range with a compact benchtop design. The Dry Ice 0.8K is a bottom-loading benchtop cryostat with a large sample space. Because it is designed to take a large experimental heat load, it is suitable for day-to-day research and quantum computing at low temperatures. Available options include sample in vacuum or exchange gas, optical access, custom wiring, and magnet choices. Integrated piezo-driven XYZ positioners, stacks, and rotators can be included. ***ICE Oxford***, *Ave Four, Station Lane, Witney, Oxford OX28 4BN, UK, www.iceoxford.com*

Electrically conductive die attach epoxy

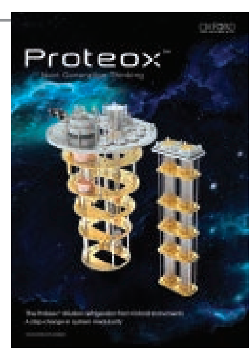


Master Bond EP17HTS-DA is a one-component, no-mix, die attach epoxy that is electrically conductive and withstands high temperatures despite the addition of a silver filler. Typically, glass transition temperature (T_g) declines in a silver-filled system. However, with this specialty formulation, a high T_g of 140–150 °C is maintained, and it passes MIL-STD-883J thermal stability requirements at 200 °C. The strength profile of EP17HTS-DA is robust, with a die shear strength of 35–40 kg-f at room temperature. The epoxy meets NASA low-outgassing specifications, and its service temperature extends from −62 °C to 288 °C. It has a low volume resistivity of less than 0.005 Ω-cm and conducts heat well. The product bonds well to many substrates, including metals, ceramics, and plastics. ***Master Bond Inc***, *154 Hobart St, Hackensack, NJ 07601-3922, www.masterbond.com*

Semiconductor package failure analysis

The Zeiss Crossbeam Laser is a line of site-specific focused-ion-beam scanning electron microscope (FIB-SEM) systems conceived to accelerate failure analysis and process optimization for advanced semiconductor packages. It integrates a femtosecond laser for speed, a gallium ion beam for accuracy, and a field-emission SEM for nanoscale-resolution imaging. In just minutes, the Zeiss Crossbeam Laser family cross-sections deeply buried package interconnects such as copper-pillar solder bumps, through silicon vias, and device back-end-of-line and front-end-of-line structures. In the process, artifacts are minimized, and sample quality under vacuum is maintained. The Zeiss Crossbeam Laser family also enables structural analysis, construction analysis, reverse engineering, FIB tomography, and sample preparation for transmission electron microscopy. ***Zeiss Semiconductor Manufacturing Technology***, *4385 Hopyard Rd #100, Pleasanton, CA 94588, www.zeiss.com/semiconductor-manufacturing-technology*

Multipurpose dilution refrigerator



Oxford Instruments NanoScience has redeveloped its Proteox dilution refrigerator, whose interchangeable unit can support multiple users and various experiments. A side-loading "secondary insert" module lets users install and change samples, communications wiring, and signal-conditioning components. According to the company, quantum applications place increasing demands on experimental volume and wiring capacity and are a key driving factor for cryogenic innovation. The Proteox system addresses those needs through increased line-of-sight access, wider plate spacings, and a 50% increase in the mixing-chamber-plate area. By providing remote connectivity and enhanced data-visualization capabilities, a redesigned web-based control system makes the Proteox system easier to use and service. ***Oxford Instruments plc***, *Tubney Woods, Abingdon OX13 5QX, UK, https://nanoscience.oxinst.com*

Vibrating-sample magnetometer

According to Cryogenic, the second generation of its vibrating-sample magnetometer (VSM) system, the CFM-VSM (v2), offers unique features that ensure high performance in the investigation of the electrical, magnetic, and thermal properties of materials. The VSM operates at temperatures from 1.6 K to 400 K and magnetic fields up to 9 tesla—without the need for liquid cryogens. Key enhancements include a mechanically compensated VSM drive that eliminates vibrational coupling between it and the pickup system and achieves high sensitivity for low-signal samples. To provide long-term system reliability and operation reproducibility, improved sample alignment ensures that the probe is stationary and that the sample is precisely at the center of the pickup system. The pickup system mounted rigidly to the variable temperature insert top flange makes sure the coil set is properly fixed and does not tilt away from the system axis. ***Cryogenic Ltd**, Unit 6, Acton Park Industrial Estate, The Vale, London W3 7QE, UK, www.cryogenic.co.uk*

High-resolution x-ray tubes

Excillum's NanoTube N2 60 kV and NanoTube N2 110 kV x-ray tubes deliver more power and higher voltage to achieve 150 nm resolution in geometric-magnification x-ray imaging systems. With the aim of finding and analyzing hidden features, the NanoTube N2 is targeted toward advanced industrial R&D and inspection and nondestructive testing (NDT) of components in fields such as electronics and semiconductor back-end fabrication, automotive, aerospace, and medicine. The devices have an imaging speed of 60 kV, more than three times as fast as the previous NanoTube N1. According to the company, those capabilities are key to ensuring high materials quality and research and industrial NDT efficiency. Since the NanoTube N2 features fully automated spot size control and high spot stability over time, it will be suitable for future automated inspection systems. ***Excillum AB**, Jan Stenbecks Torg 17, 164 40 Kista, Sweden, www.excillum.com*

Low-temperature alloy

The novel Durafuse LT alloy system from Indium Corporation provides high reliability in low-temperature applications that require a reflow temperature below 210 °C. The company claims that whereas traditional low-temperature solders often produce brittle solder joints that are susceptible to drop-shock failures, Durafuse LT offers improved drop-shock resilience and thus outclasses bismuth–tin or bismuth-tin-silver alloys. With an optimum process setup, it also performs better than Indium's SAC305 solder. Durafuse LT is suitable for use with heat-sensitive components and flex polymers and prevents thermal warpage of processor components and multilayer boards. It meets low-temperature requirements for step soldering, particularly in RF shield attachment and rework applications. ***Indium Corporation***, *34 Robinson Rd, Clinton, NY 13323, www.indium.com*

Pulse energy sensor

MKS Instruments has announced the Ophir PE50U-DIFH-C pulse energy sensor. Designed for use with high-power pulsed lasers operating in demanding conditions, the sensor features materials that can measure UV radiation down to 193 nm, high repetition rates up to 10 kHz, and high energy densities up to 1 J/cm^2 at 193 nm and 2 J/cm^2 above 240 nm. Suitable for use in scientific research, medical, and semiconductor applications, the PE50U-DIFH-C energy sensor operates over a wide range of wavelengths, power levels, and repetition rates. To ensure high accuracy, it is calibrated at 193 nm, 248 nm, 355 nm, 532 nm, 1064 nm, 2100 nm, and 2940 nm. It has a 35 mm aperture and can measure energies from 10 μJ to 10 J. A special diffuser delivers the highest energy density damage threshold available, up to 90 J/cm^2 for millisecond pulses. ***MKS Instruments Inc***, *Ophir Business Unit (US), 3050 N 300 W, North Logan, UT 84341, www.ophiropt.com*

Multiwalled carbon nanotubes

Added to composites, carbon nanotubes can improve the mechanical, thermal, or electrical properties of a material. Goodfellow has introduced three forms of multiwalled carbon nanotubes (MWCNTs) produced by means of a catalytic chemical vapor deposition process. One form, regular powder, is available in amounts ranging from research quantities of several grams up to economical mass-production quantities of several kilos. Exclusive to Goodfellow and available in small quantities for research are "chunky" powder, which is safer and easily dispersed via sonication into a polymer matrix, and free-standing, vertically aligned MWCNT arrays, called "carpets" or "forests." Current research involving carpets revolves around potential uses as free-standing membranes and filters, as thermal interface materials in electronic devices and supercapacitors, and as additives embedded in polymer matrices to produce novel composites. ***Goodfellow Corporation***, *125 Hookstown Grade Rd, Coraopolis, PA 15108, www.goodfellow.com*

Double-inverter helium compressor

Quantum Design and Sumitomo (SHI) Cryogenics of America have collaborated to launch a quiet, compact helium compressor for use with cryogen-free instrumentation. The R-98 double-inverter-driven helium compressor, the first in SHI's Revolution series, is compatible with a range of SHI's Gifford–McMahon and pulse tube two-stage cryocoolers. "Energy-smart" helium compressors can operate at variable speeds. Compared with traditional single-speed compressors, they are more energy efficient and require less servicing. Low-speed operation produces lower vibrations at the cold head and reduces noise for sensitive measuring instrumentation; high-speed operation allows for faster cooldown of the cold head. ***Sumitomo (SHI) Cryogenics of America Inc***, *1833 Vultee St, Allentown, PA 18103, www.shicryogenics.com*

Silicon carbide MOSFET devices

ON Semiconductor has expanded its range of wide bandgap devices by introducing two additional families of silicon carbide (SiC) MOSFETs. Compared with silicon MOSFETs, the 1200 V and 900 V N-channel SiC MOSFETs deliver faster switching performance, enhanced reliability, and greater robustness, according to the company. A fast intrinsic diode with low reverse recovery charge significantly reduces power losses, boosts operating frequencies, and increases the power density of the overall system. High-frequency operation is further enhanced by the small chip size, which lowers device capacitance and reduces gate charge to as low as 220 nC. Besides reducing switching losses, those enhancements improve efficiency, reduce electromagnetic interference when compared with silicon MOSFETs, and allow fewer and smaller passive components to be used. ***ON Semiconductor***, *5005 E McDowell Rd, Phoenix, AZ 85008, www.onsemi.com* PT

OBITUARIES

Murray Gell-Mann

Murray Gell-Mann, the preeminent architect of theoretical elementary-particle physics, died on 24 May 2019 in Santa Fe, New Mexico. He received the 1969 Nobel Prize "for his contributions and discoveries concerning the classification of elementary particles and their interactions." His contributions to physics include many foundational ideas, such as the renormalization group, which is fundamental to quantum field theory and statistical mechanics.

Gell-Mann was a child prodigy, born on 15 September 1929 into a Jewish Ukrainian immigrant family in Manhattan. He graduated valedictorian from the Columbia Grammar and Preparatory School at age 14, received a BS from Yale University in 1947, and earned a PhD from MIT in 1951 under adviser Victor Weisskopf.

In the early 1950s, Gell-Mann proposed a new quantum number, called strangeness, to explain the unusual properties of novel strongly interacting particles seen in cosmic rays. Strangeness proved to be a successful organizing principle of the vast spectrum of particles that subsequently emerged in accelerator experiments.

In 1961, to unify strangeness with nuclear isospin, Gell-Mann and, independently, Yuval Ne'eman, employed the unitary group *SU*(3). It led to the classification of particles by *SU*(3) multiplets, which Gell-Mann called the Eightfold Way (borrowing from the Noble Eightfold Path of Buddhism). That was pioneering work in the use of group theory to understand particle physics. The Eightfold Way made precise predictions for mesons and baryons, including new states, notably of the Ω^- baryon, discovered at Brookhaven National Laboratory in 1964. A photograph of the bubble-chamber footprint of the Ω^- hung for many years, slightly skewed by a California earthquake, above Gell-Mann's blackboard at Caltech.

With the insight from *SU*(3) symmetry, in 1964 Gell-Mann proposed the concept of quarks as the underlying constituents of strongly interacting particles. (Independently, George Zweig developed it in a more phenomenological approach.) Gell-Mann was reticent about the reality of quarks because of the failure to produce them in the laboratory.

Earlier, in 1958, Gell-Mann, Richard Feynman, and others had realized that the weak β-decay interactions involve exclusively the left-handed "chirality" of particles. Gell-Mann played a major part in understanding the role of chirality and the masses of the spin-0 mesons by incorporating ideas of Yoichiro Nambu into the Gell-Mann–Levy Σ model ("current algebra" is a model-independent abstraction of those ideas). When small underlying quark masses are introduced into the Σ model, one gets precise predictions for the meson masses, known as the Gell-Mann–Okubo mass formula. Conversely, one can extract the light quark masses from the procedure.

Until 1970 no theory existed to explain how quarks were bound together to make baryons and mesons. A major insight came from James Bjorken, who predicted that the binding force would display "scaling behavior," subsequently confirmed experimentally at SLAC. It implies that at very short distances, the quarks are effectively free particles. Gell-Mann, working at CERN in 1971 with William Bardeen, Harald Fritzsch, and Heinrich Leutwyler, considered a gauge theory of quark interactions, in which each quark comes in one of three varieties called "colors." They wrote down the theory now known as quantum chromodynamics (QCD) and established the existence of the three quark colors from the rate of π^0 decay.

In 1973 David Gross, David Politzer, and Frank Wilczek showed that QCD has the property of asymptotic freedom, which explains Bjorken scaling and the confinement of quarks into bound states of the baryons and mesons. The quarks thus became real particles, and together with leptons they form the basic building blocks of the standard model.

In 1954 Gell-Mann and Francis Low introduced into physics a remarkable concept now known as the renormalization group. Developed subsequently by Kenneth Wilson and others, it has proved to be of profound importance across many disciplines. The application of the renormalization group with the standard model has allowed us to contemplate physics at extremely short distances and opened the door to grand unification, modern inflationary cosmology, and superstring theory.

Murray Gell-Mann

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Gell-Mann was an early champion of string theory. He maintained a pioneering effort at Caltech in the 1970s and characterized himself as a kind of "zookeeper of endangered species." John Schwarz, Joel Scherk, Pierre Ramond, Michael Green, and others established the defining principles of superstring theory. Gell-Mann's work with Ramond and Richard Slansky is fundamental to present-day experiments seeking to disentangle the properties of the ubiquitous neutrinos.

Anyone encountering Murray had the feeling of being in the presence of a charming yet superhuman intellect. His far-ranging interests and activities—in physics, linguistics, ornithology, environmental policy, pre-Columbian archaeology, serving on the boards of the Smithsonian Institution and the MacArthur Foundation, establishing the Santa Fe Institute, and more—knew no bounds. Fred Zachariasen, Gell-Mann's colleague, once remarked, "We physicists know and love Murray for quarks, but his work through the MacArthur Foundation to save the planet may ultimately have the greatest impact on everyone."

Christopher T. Hill
Fermi National Accelerator Laboratory
Batavia, Illinois

Evgeny Evgrafovich Meshkov

Experimentalist Evgeny Evgrafovich Meshkov, a legend in fluid dynamics, died of natural causes in Sarov, Russia, on 1 March 2020. His name is attached to a phenomenon about which hundreds of papers are published annually in scientific, mathematical, and engineering journals.

Meshkov was born on 31 January 1937 in the Soviet Union, near the city of Sevastopol, Crimea. During his childhood, he saw the horrors of Nazi occupation. Only after the Great Patriotic War ended in 1945 was Meshkov able to begin his education. He passed school grades in rapid succession and in 1954 entered the Moscow Engineering Physics Institute, also known as the National Research Nuclear University MEPhI. He graduated in 1960 with a master's degree in engineering physics.

Over the next 50 years, Meshkov worked at the All-Russian Scientific Research Institute of Experimental Physics in Sarov, the famous "closed town" of Arzamas-16. He started there as a junior researcher in 1960, earned his PhD in physics and mathematics, and then continued as the head of the hydrodynamic laboratory until his formal retirement in 2009. During 2010–20, he was a professor at the Sarov Institute of Physics and Technology, where he conducted experiments, mentored students, and interacted with colleagues until the very end.

Meshkov's most celebrated work was his experimental discovery in 1969 of the instability of the interface between two fluids with different densities when they are impulsively accelerated by a shock wave. The instability, predicted theoretically by Robert Richtmyer in 1960, is now known as the Richtmyer–Meshkov instability. It has a key role in a broad range of processes in nature and technology, including supernovae, plasma fusion, combustion, and nanofabrication. Meshkov's direct observation, which was made possible by the experimental methodology he developed in the mid 1960s, started a new era in experimental research of unsteady gas-dynamic flows. In conversations, Meshkov would recall those years as the most creative of his life.

In the 1970s and 1980s, Meshkov was involved in research in inertial gas-dynamic fusion. In 1982 he and his colleagues achieved the record value of $5 \times 10^{13}\ s^{-1}$ for the neutron yield and the so-called ρR parameter of 0.8 g cm^{-2} in an inertial fusion facility. Meshkov also participated in research for underground weapons testing. Those studies led to the development of experimental methods for investigating material properties at high energy densities and profoundly influenced modern science and technology.

As an experimentalist, Meshkov had a remarkable gift for finding simple and elegant solutions to complex problems. That talent was best illustrated by a series of experiments on stability of air bubbles in water, which he designed and conducted in the 1980s to observe and diagnose fluid instabilities and interfacial mixing under conditions relevant to, for instance, supernova explosions. The unique data also display the subdiffusive character of fluid mixing in supernovae as predicted by the theory.

Meshkov had a great ability to get to the heart of a phenomenon, abstract and generalize it, and then lucidly obtain the essentials. That indispensable quality was exhibited in the jelly experiments, which he and his colleagues conducted in the 1990s to investigate properties of Rayleigh–Taylor instabilities and the interfacial mixing they cause—the sister phenomena of Richtmyer–Meshkov dynamics. The experiments enabled the study of fluid instabilities and interfacial mixing in a broad range of setups in tightly controlled environments. Through them, he and his team achieved record Reynolds numbers of about 3.2×10^6 and unambiguously observed the essentially interfacial and anisotropic character of Rayleigh–Taylor mixing. Although the results were surprising—canonical turbulence was expected—they were recently explained by group theory, which revealed that Rayleigh–Taylor mixing may exhibit order and laminarize. The effect of the accelerated shear on the laminarization of Rayleigh–Taylor mixing was the focus of Meshkov's research in the past few years.


Evgeny Evgrafovich Meshkov

MESHKOV FAMILY COLLECTION

Meshkov authored more than 300 scientific papers and technical reports, had more than 30 inventions and patents, and shared his unique expertise in his books on fluid dynamics experiments. From about 2000, he educated students and researchers, worked to increase international cooperation, and helped organize international conferences, including the series Turbulent Mixing and Beyond. His achievements were recognized by the international scientific community, and the government of Russia bestowed on him the Order of Friendship in 2011. He cared immensely for science, and he loved life and his family, collaborators, students, and friends. With his passing, science has lost one of its great minds and sensitive hands.

We are grateful to Evgeny Meshkov's family, friends, and colleagues for sharing with us their reminiscences of him.

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Eric Lutz is director of the Institute for Theoretical Physics I at the University of Stuttgart in Germany.

A single-atom heat engine

Eric Lutz

The power of an engine scales with the number of particles that make up its working fluid, a generalization that has proven true down to a single atom.

By converting thermal energy into mechanical work, heat engines are used almost universally to generate motion. The working substance in which the heat-to-work conversion takes place is typically a gas or liquid consisting of some 10^{24} atoms. During his 1959 lecture, "There's Plenty of Room at the Bottom," presented at an American Physical Society meeting at Caltech, Richard Feynman envisioned motors operating at the atomic level. The realization of such devices, however, had to wait for the advent of nanotechnology for the experimental techniques required to control matter at tiny length scales.

Thermodynamics of small systems

The laws of thermodynamics were originally formulated for macroscopic systems. The typical example, found in most textbooks, dates back to the Industrial Revolution: a gas trapped in a cylinder attached to a moving piston. Work is performed on the gas when the piston is pressed in, whereas work is produced by the gas when it pushes the piston back out. In cases in which both processes take place at the same temperature, the two work values are equal in magnitude—but not in sign—and their sum vanishes.

Net positive work can be obtained when expansion is carried out at a higher temperature than compression. Work production thus necessitates distinct heating and cooling phases and the coupling of the system to two heat reservoirs. Heat engines work by cyclically repeating those expansion and compression steps.

Colloidal particles, enzymes, and molecular machines are common in nature. And because of the particles' minuscule size, their thermal fluctuations are comparable to their mean energies and cannot be safely neglected, as is often done in the macroworld. As a result, key thermodynamic quantities, such as heat, work, energy, and entropy, are intrinsically random variables. In the past two decades, the framework of thermodynamics has been successfully extended to describe microscopic objects and to include the effects of fluctuations. (See the article by Carlos Bustamante, Jan Liphardt, and Felix Ritort, PHYSICS TODAY, July 2005, page 43.)

Those random variables can be defined along single stochastic trajectories that are experimentally measured by tracking the position of a microparticle. In stochastic thermodynamics, as the formalism is now called, work refers to the energy change induced by the variation of an external parameter, such as the position of the piston in a gas-filled cylinder. Heat is the energy exchanged with the surrounding medium, whose temperature sets that of the small system.

Tiny motor

Four years ago, my colleagues and I wanted to build a heat engine that uses a single atom as the working fluid. To achieve that vision, we held a calcium ion in an electromagnetic Paul trap having an unusual conical shape; the trap is named after Wolfgang Paul, whose invention of the device earned him a share of the Nobel Prize in Physics in 1989. Reservoir-engineering techniques allowed us to couple the ion to hot and cold baths by moving it back and forth in the trap.

To make a cold reservoir, we used standard laser-cooling techniques on the $^{40}Ca^+$ ion, which loses heat to the photons. To make a hot reservoir, we shook the ion with an electric field, whose noise increases the ion's kinetic energy. We then modulated the ion's temperature by passing it back and forth between the reservoirs. Because of energy fluctuations, the ion exists in a thermal distribution whose width is proportional to its temperature.

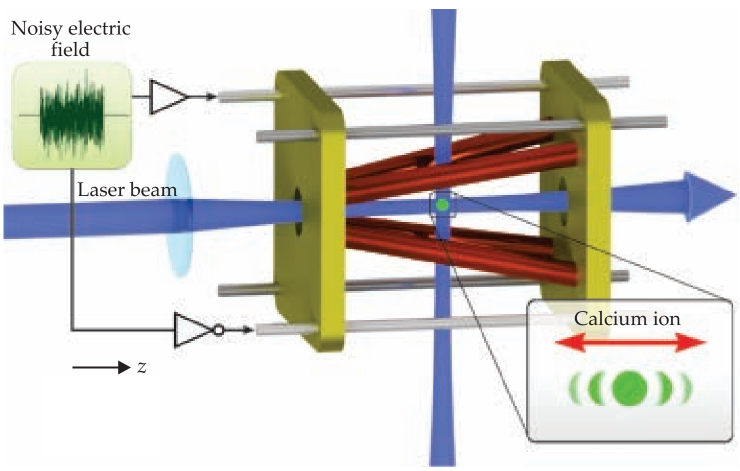

FIGURE 1. A SINGLE TRAPPED ION (green) is confined in a conical ion trap with four RF electrodes (red) having a tapered geometry. The ion is alternately cooled (blue) and heated by noisy electric fields applied to outer electrodes (gray). The engine cycle is implemented in the radial directions, and the work produced after each cycle is stored in the axial (*z*) direction. The position of the ion, whose oscillatory motion acts like a flywheel, is imaged on a CCD camera. (Adapted from J. Roßnagel et al., *Science* **352**, 325, 2016.)

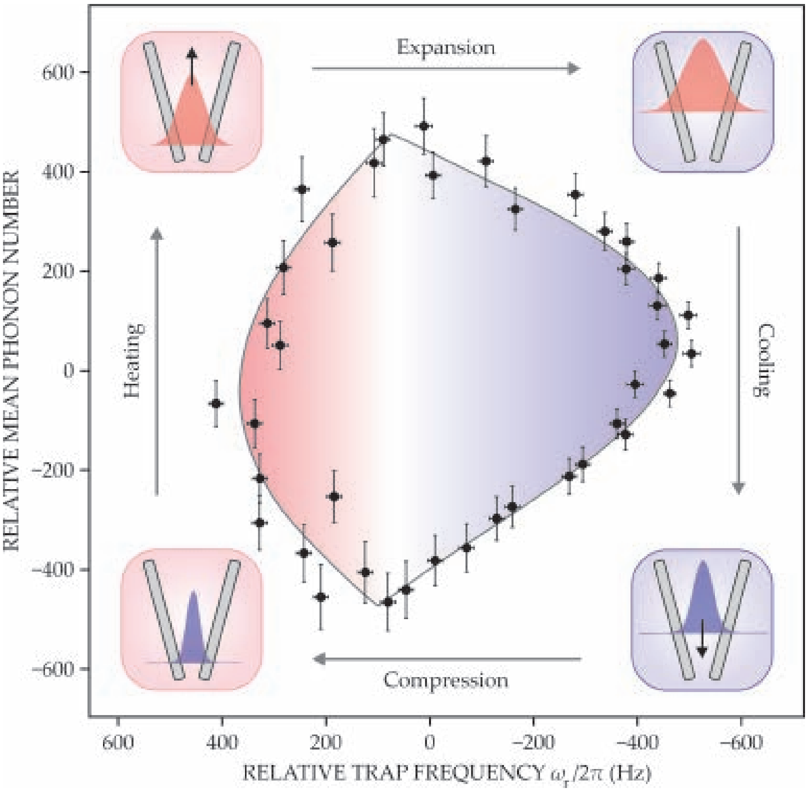

FIGURE 2. THIS THERMODYNAMIC CYCLE of the engine shows the mean occupation, or phonon, number of a $^{40}Ca^+$ ion as a function of the (radial) trap frequency ω_r of the harmonic trapping potential. The area inside the curve is proportional to the work produced during each cycle. The insets illustrate the four steps of the engine: compression, expansion, heating, and cooling. Blue corresponds to cooling and red to heating. (Adapted from J. Roßnagel et al., *Science* **352**, 325, 2016.)

The engine's cycle starts with the atom located in the narrow region of the conical trap, shown in figure 1. During the heating phase—once electrical noise has been switched on—the width of the thermal distribution increases and pushes the atom to the wide region of the trap. At that point cooling begins: The noise is switched off, the thermal distribution shrinks, and the atom moves back to its original position, where the cycle starts anew.

My colleagues and I determined the ion's temperature stroboscopically using a fast thermometry method that works from the observation of thermally induced broadening of levels in the Ca ion's fluorescence spectrum. The level broadening showed that the temperature varied between 6 mK and 51 mK, and a high-resolution camera captured the atom's position and displacement through 11 nm. That displacement corresponds to changes of the force inside the trapping potential of 2×10^{-22} N.

Knowing the trap's geometry, we inferred the ion's oscillation frequency as 450 kHz. The work generated by the ion, which acts much like a flywheel in a mechanical engine, drives the harmonic motion along the axial (z) direction. After each cycle, the ion's oscillation amplitude increases slightly, during which the ion stores the generated energy.

Power and efficiency

Figure 2 captures the engine's performance as it passes through the four steps of the cycle. As in a familiar pressure–volume diagram, the work produced during each cycle is given by the enclosed area. When divided by the cycle time, given by the inverse oscillation frequency, the enclosed area yields the motor's power, 3×10^{-22} W. The corresponding power-to-particle ratio is about 1.5 kW/kg, a value comparable to that of a typical car engine. The comparison reveals that the power scales with the number of particles of the working medium.

We calculated the absorbed heat from the corresponding temperature-entropy diagram. The efficiency, defined by the ratio of produced work to absorbed heat, is roughly 0.3%. That modest value indicates that the trap parameters were not optimal. (The average efficiency of a modern gasoline car engine is about 15–20%.) The performance of the engine could be improved by, for example, increasing the angle of the conical trap, which would lead to a higher radial frequency. For comparison, the first piston engine built by Thomas Newcomen around 1710 had an efficiency of about 0.5%.

To judge by our proof of concept, heat engines can be reduced in size to the ultimate single-particle limit. They also offer insight into different energy-conversion mechanisms at the nanoscale. Developed over 3 billion years, microscopic molecular motors in nature extract mechanical work out of thermal fluctuations from a single heat bath as the motors are driven away from equilibrium by chemical energy. Such motors are often referred to as Brownian ratchets (see the article by Dean Astumian and Peter Hänggi, PHYSICS TODAY, November 2002, page 33). In contrast, macroscopic heat engines, developed by engineers in the past 300 years, produce useful work out of heat while being coupled to two heat baths. The realization of a single-atom engine shows that the same mechanism is at work down to the subnanoscale level.

The high level of control achieved in our experiments opens the possibility of pushing heat engines into novel regimes not accessible to common molecular motors. When the reservoirs are cooled to a few nanokelvin, quantum effects such as coherent superposition of states are expected to appear. Interestingly, researchers predict that quantum coherence is a physical resource—a so-called quantum fuel—that may be exploited to increase the efficiency of a quantum heat engine beyond what is possible in classical physics.

By using ground-state cooling techniques already developed in conventional ion traps, one could operate the single-atom heat engine in the quantum domain to verify that tantalizing prediction.

Additional resources

▶ R. Feynman, "There's plenty of room at the bottom," *Eng. Sci.* **23**, 22 (1960).
▶ U. Seifert, "Stochastic thermodynamics, fluctuation theorems and molecular machines," *Rep. Prog. Phys.* **75**, 126001 (2012).
▶ D. Leibfried et al., "Quantum dynamics of single trapped ions," *Rev. Mod. Phys.* **75**, 281 (2003).
▶ J. Roßnagel et al., "A single-atom heat engine," *Science* **352**, 325 (2016).
▶ M. O. Scully et al., "Extracting work from a single heat bath via vanishing quantum coherence," *Science* **299**, 862 (2003). PT

VR's balancing act

Some 1 million people in the US live with multiple sclerosis (MS). Among other symptoms, the disease makes them far more susceptible to falling than the general population, and because people living with MS have decreased bone density, they're more likely to break bones. Even those who show minimal or no other symptoms still fall, so researchers have been working toward understanding who with MS might be most at risk. Now Jason Franz from the University of North Carolina at Chapel Hill and his colleagues have applied virtual-reality (VR) technology to better investigate the balance issues of people with MS.

In the experiments, 14 participants with MS and a same-sized group without the disease walked on a treadmill while viewing a virtual hallway, shown in the picture. The researchers randomly accelerated the hallway so the participants would feel like they were losing their balance. The two groups walked similarly under normal conditions, but the optical perturbations uncovered differences: Participants with MS significantly varied their stride length and wobbled, whereas those without MS were more steady. The VR tool may help doctors diagnose previously undetected balance problems. (B. P. Selgrade et al., *PloS ONE* **15**, e0230202, 2020; photo by Franz Lab/UNC.) —AL

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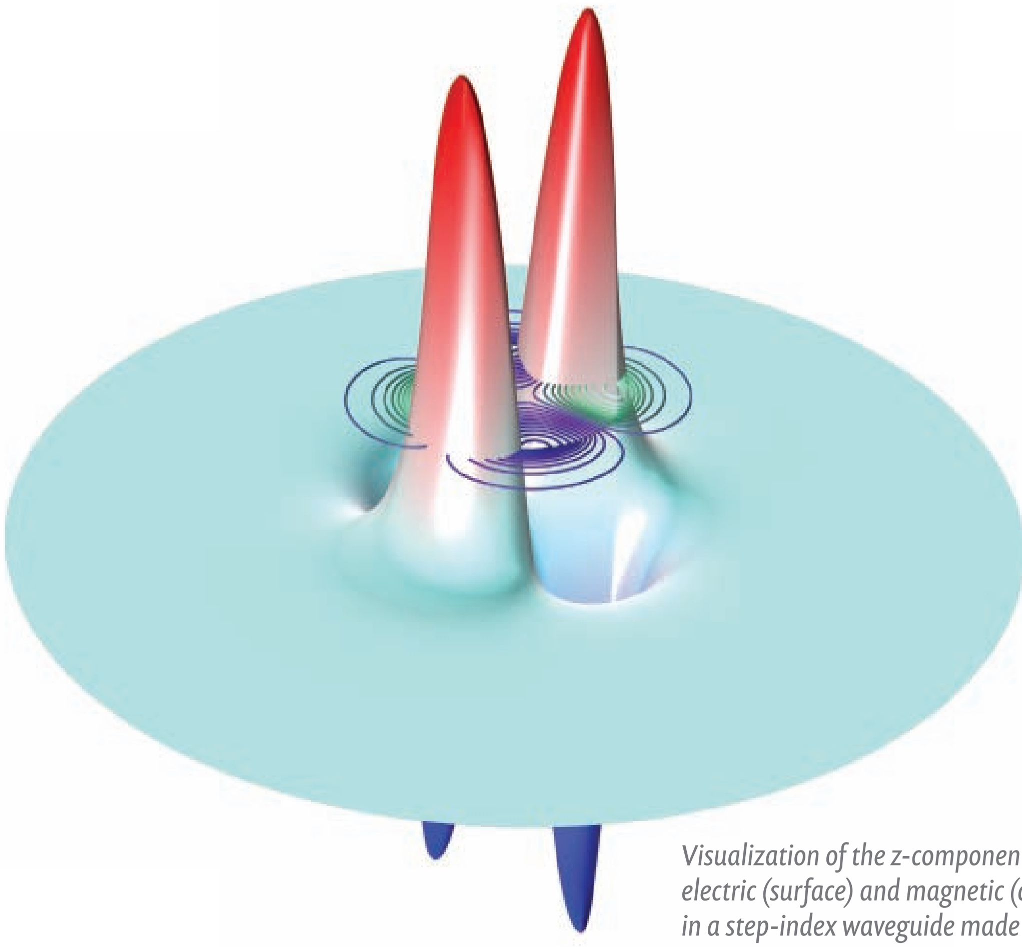

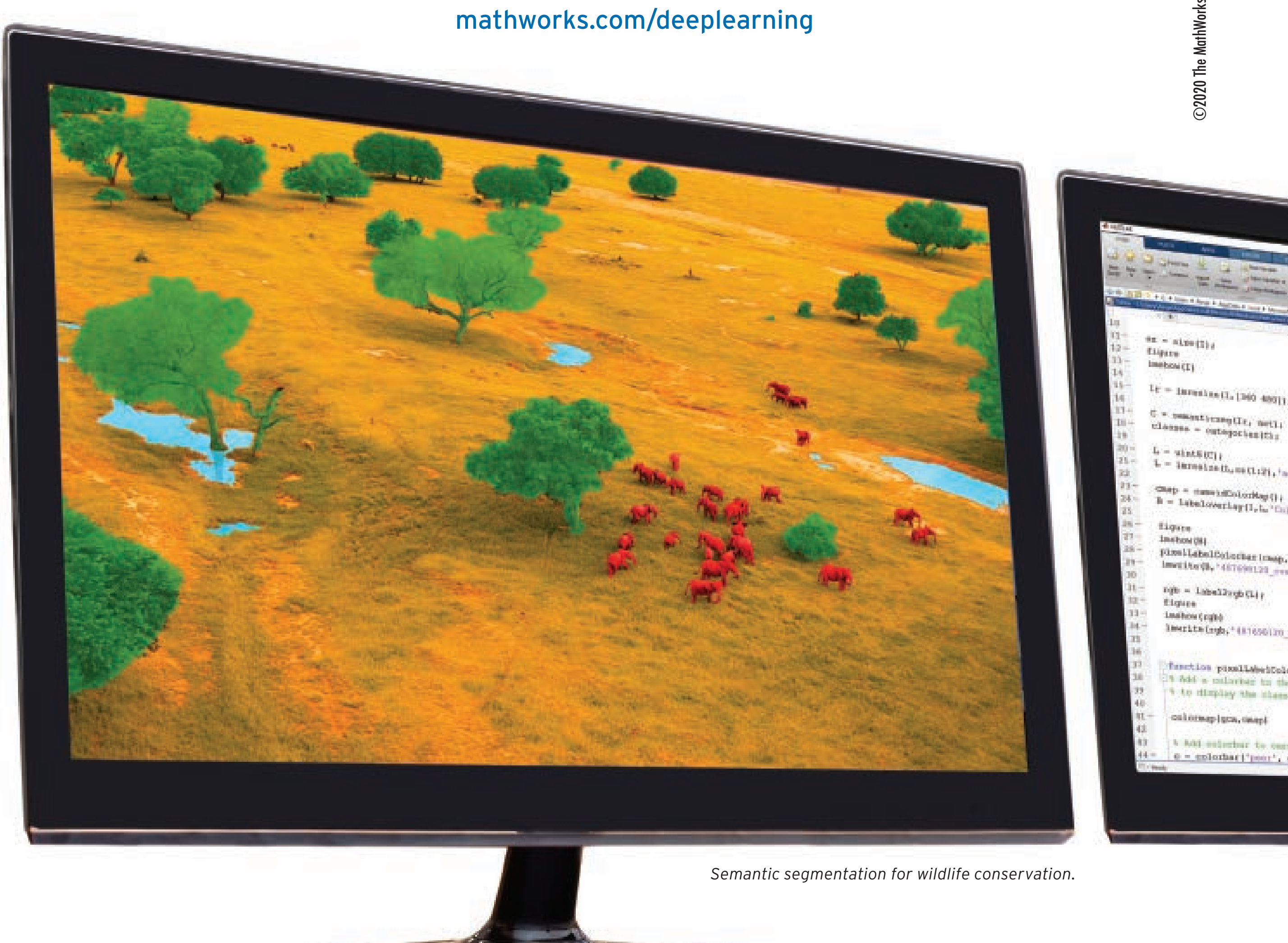

Semantic segmentation for wildlife conservation.