PHYSICS TODAY
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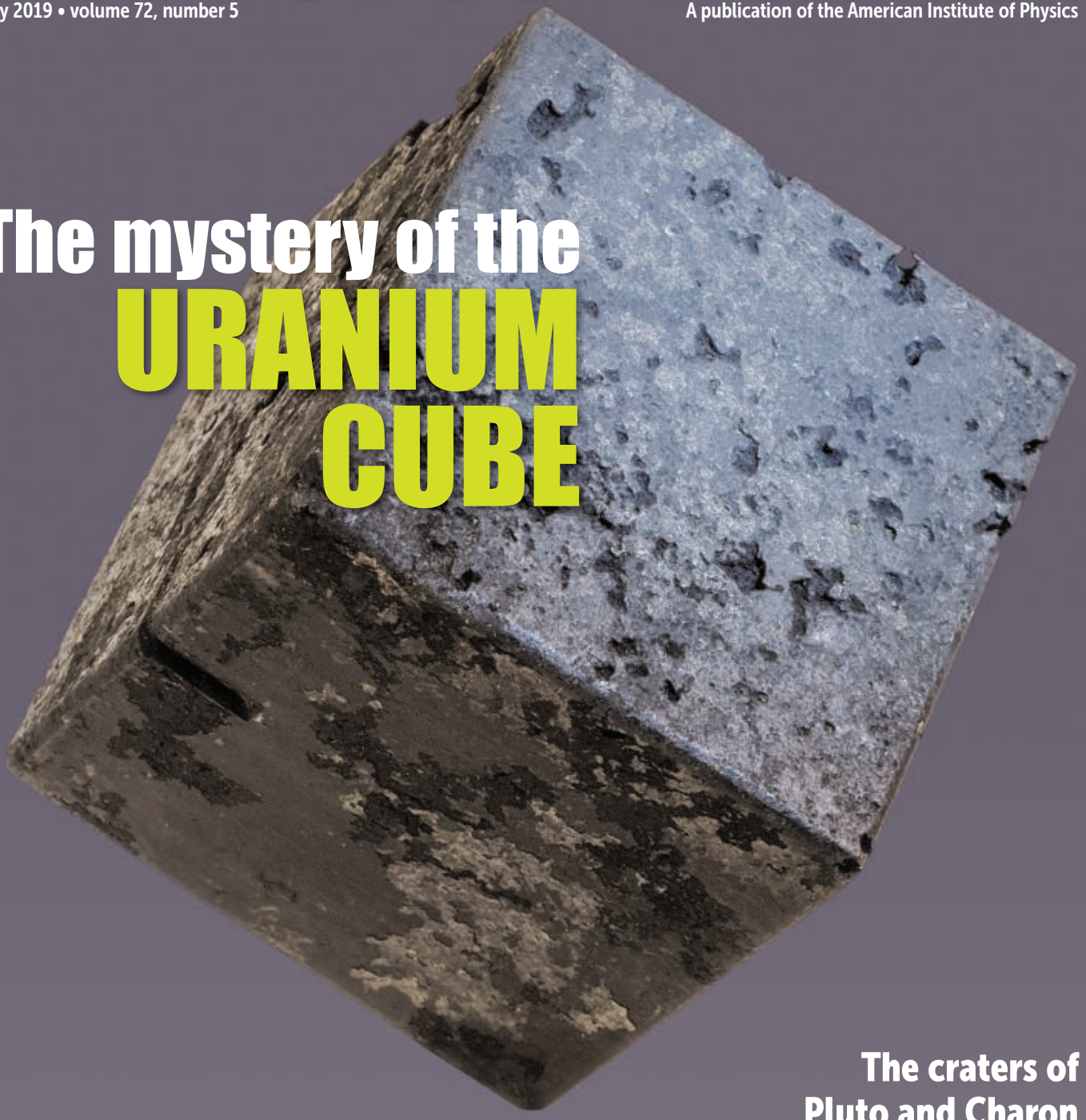

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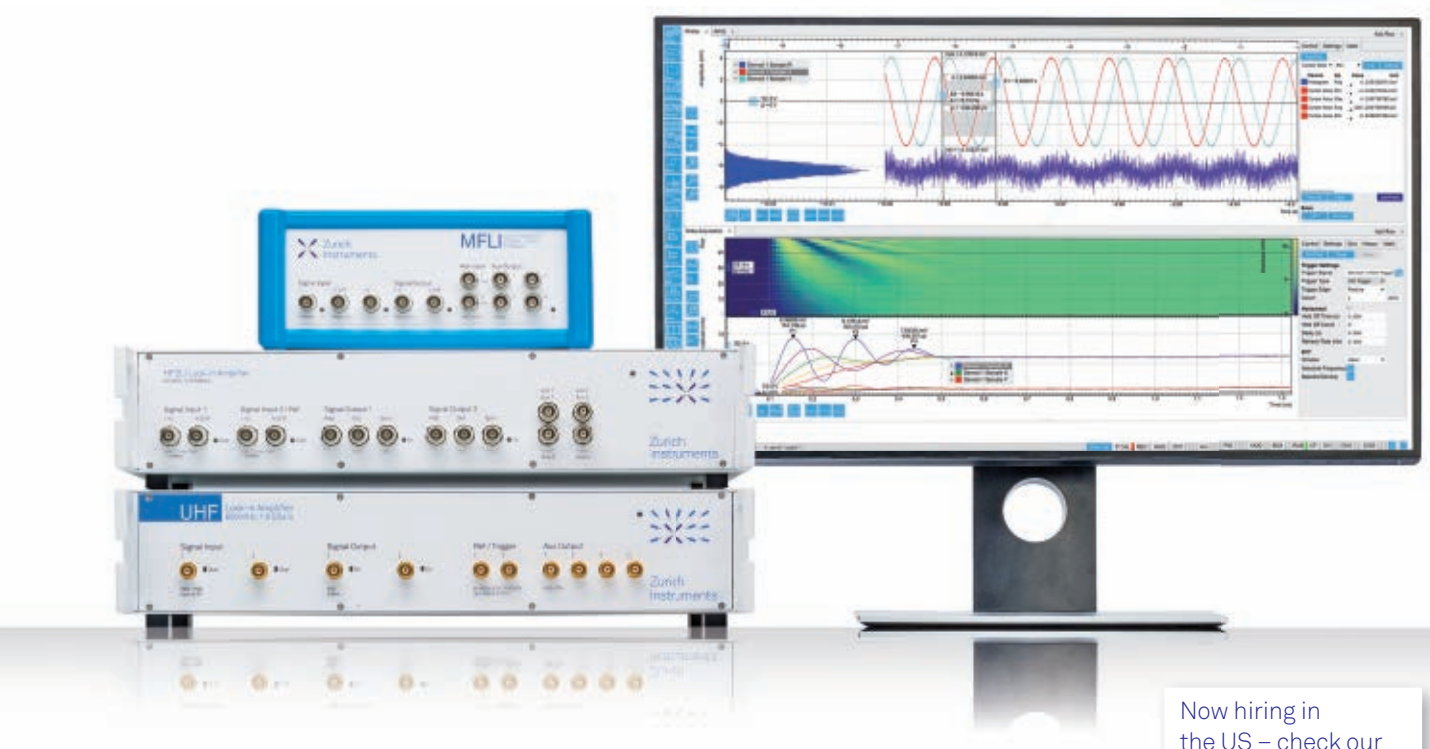

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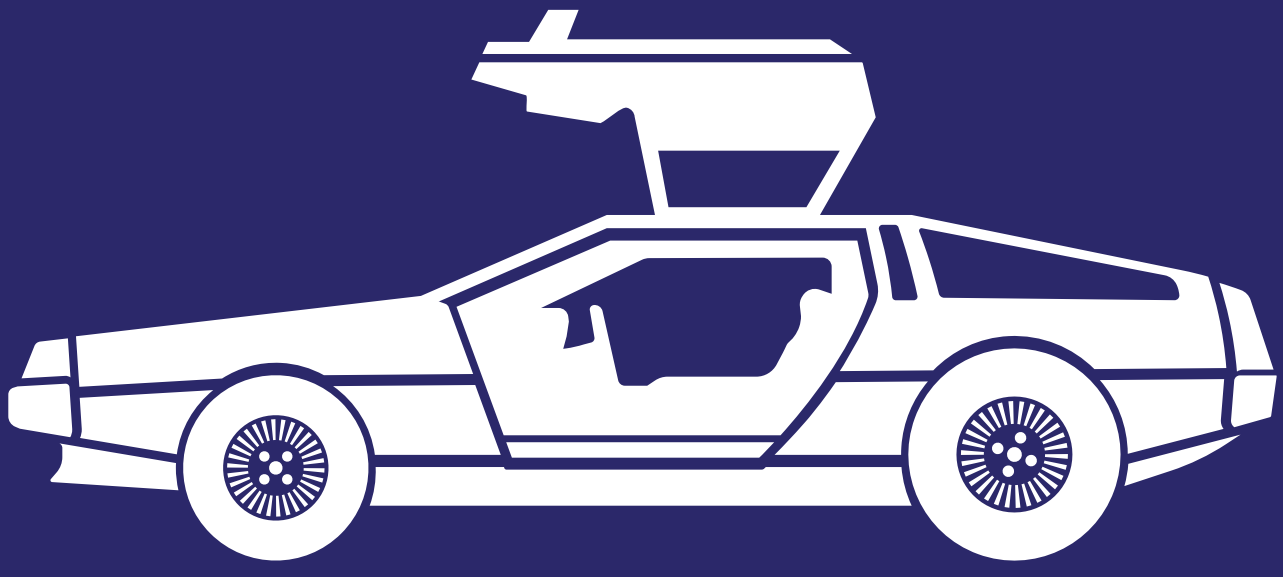

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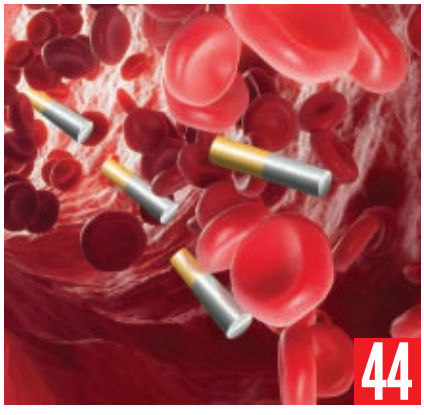

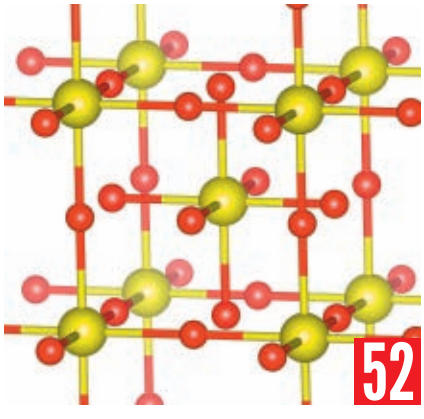

PHYSICS TODAY

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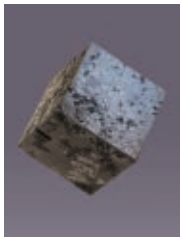
FEATURES



ON THE COVER: During World War II, a team of German scientists led by Werner Heisenberg attempted and failed to build a working nuclear reactor using the small, pockmarked uranium cube shown here and hundreds more like it. On **page 36**, Timothy Koeth and Miriam Hiebert recount their detective work over the past six years to uncover how the cube traveled from an underground laboratory in Berlin to College Park, Maryland. (Photo by Cynthia B. Cummings.)

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Black hole revealed

On 10 April the world marveled at the silhouette marking the position of the first directly imaged black hole, M87*. The raw data behind that image were obtained during an April 2017 survey by eight telescopes scattered across the globe. PHYSICS TODAY breaks down the time stamps, calibration, computational imaging, and general relativistic modeling that enabled the Event Horizon Telescope team to transform petabytes of disparate radio astronomy data into one captivating image.

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Last year PHYSICS TODAY reported on scientific conferences run by a company that the Federal Trade Commission alleged was deceiving customers. Now OMICS International, which also publishes hundreds of journals, has been fined $50 million by a federal judge. PHYSICS TODAY examines the ruling and its implications.

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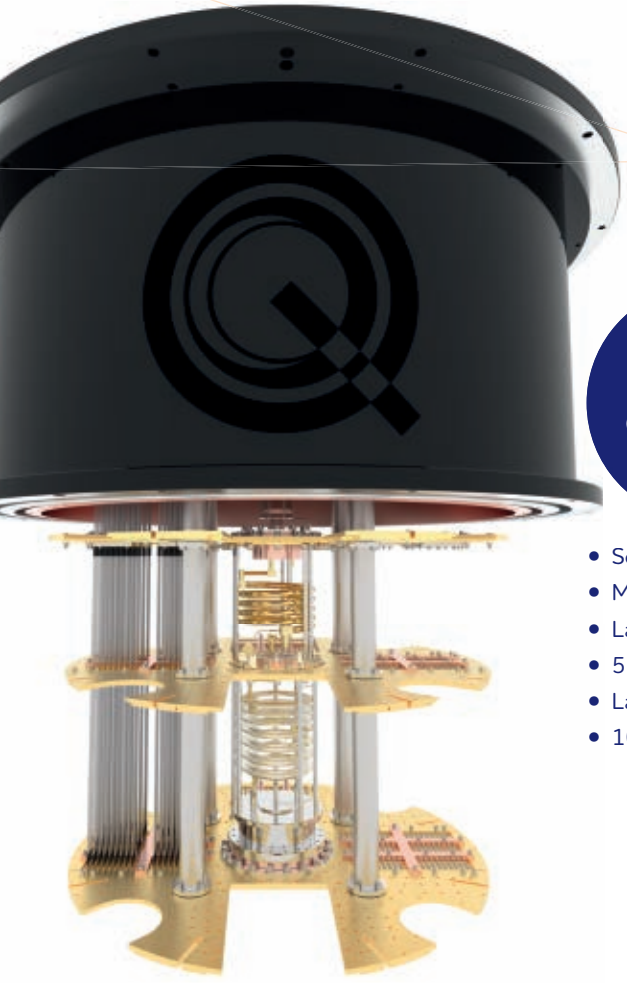

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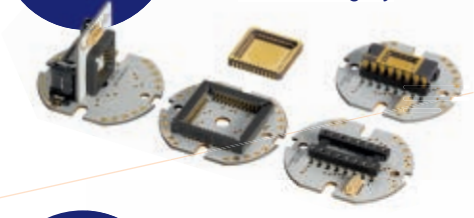

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The power of illustration

Charles Day

My first scientific paper appeared in 1988 when I was a graduate student at Cambridge University's Institute of Astronomy.[1] Among the paper's figures was a cartoon-like illustration of a close binary star system, Hercules X-1. One of the two stars, HZ Herculis, is puffed up to fill its Roche lobe—that is, the teardrop-shaped surface in the system's rotating frame that marks the limit of the star's gravity to retain material. The other is a neutron star, which sits at the center of an accretion disk. The disk is fed by plasma from the photosphere of HZ Herculis. By the time the plasma reaches the neutron star, it's so hot that it glows in the x-ray band.

I did not draw the illustration myself, nor did I use drafting software. Rather, it was created by Richard, the artist retained by the institute.

Most of the illustrations you see in PHYSICS TODAY are created by the magazine's art department, which consists of Donna Padian, the art director, and Freddie Pagani, the art and production associate. Donna and Freddie also redraw artwork. Sometimes that's because an author draws a crude sketch and seeks professional help, as I did. But other times, they redraw an illustration because the original is, well, too crummy for a self-respecting magazine to publish.

Good illustrations aid understanding. Among my favorites are the ones in the classic textbook *Molecular Biology of the Cell* by Bruce Alberts and six coauthors. Biomolecules are transparent. If human vision could somehow circumvent light's diffraction limit and allow us to see biomolecules interacting, they would resemble mating jellyfish. But in the book, they are rendered as blobs of different shapes and colors. A biophysicist, whose name I forget, once told me that each illustration was, in effect, a PhD thesis problem—that is, a challenge to understand and quantify the interactions embodied in the artwork.

Out of curiosity, I checked arXiv.org to evaluate the prevalence and quality of explanatory illustrations in my old field, astronomy. The first thing I noticed was that the preprints were all formatted to match the article templates of their intended destinations: *Astronomy & Astrophysics*, *Astrophysical Journal*, *Monthly Notices of the Royal Astronomical Society*, and—new to me—white papers that will inform the upcoming decadal survey from the National Academies of Sciences, Engineering, and Medicine. The papers and the data plots they contained looked impressively publication-ready.

For my investigation, I had looked at the most recent 20 papers in the catch-all category, astro-ph. Only two in the sample had explanatory illustrations. One of them appeared as figure 1 of a preprint by Anusha Kalyaan and Steven Desch of Arizona State University.[2] It consists of three panels that nicely depict the subject of their investigation: the transport and distribution of water in protoplanetary disks. As if to emphasize its power to inform, the figure is accompanied by a caption of 266 words.

This past February, I encountered another helpful illustration. It came from a 2008 paper, "High- and low-velocity magnetized outflows in the star formation process in a gravitationally collapsing cloud," by Masahiro Machida and Shu-ichiro Inutsuka of Kyoto University and Tomoaki Matsumoto of Hosei University in Tokyo.[3] I consulted the paper because it provides a theoretical explanation of a recent observation from the Atacama Large Millimeter/Submillimeter Array,[4] which was the subject of an online news story I was writing.

The illustration was the last figure in the paper. The 14 that preceded it were technical graphs, mostly from the numerical simulations that form the paper's basis. By contrast, the schematic was a cartoon-like representation of the paper's principal finding: that the two types of outflow from protostars—slow and wide, and narrow and fast—originate at different stages in the protostar's evolution. Depicting both outflows together in the same illustration, even though they're separated in time by hundreds of thousands of years, might not seem to make sense physically. But because the two outflows are often observed together, the illustration served as a visual embodiment of the paper's aim: to explain what astronomers see.

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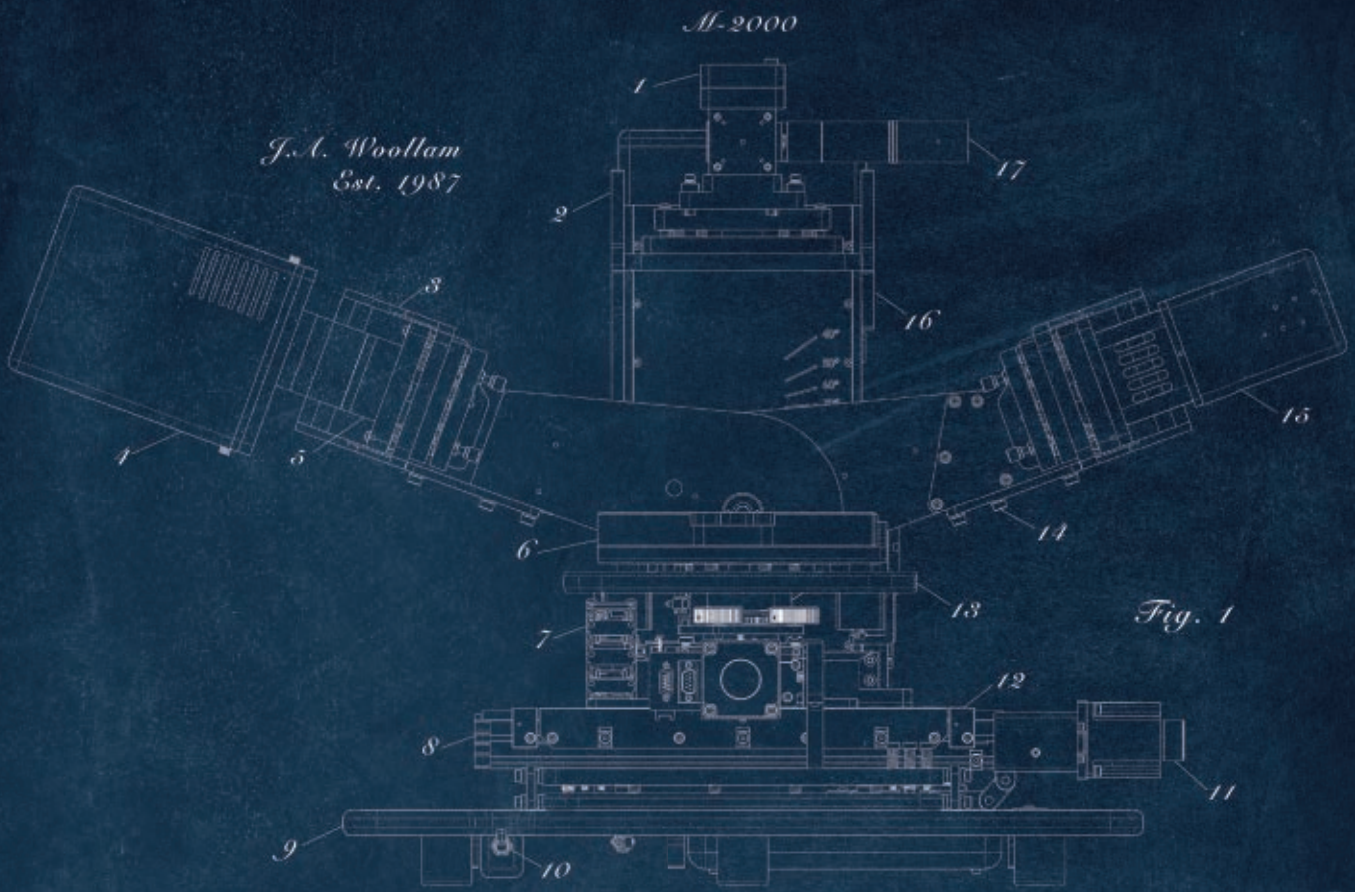

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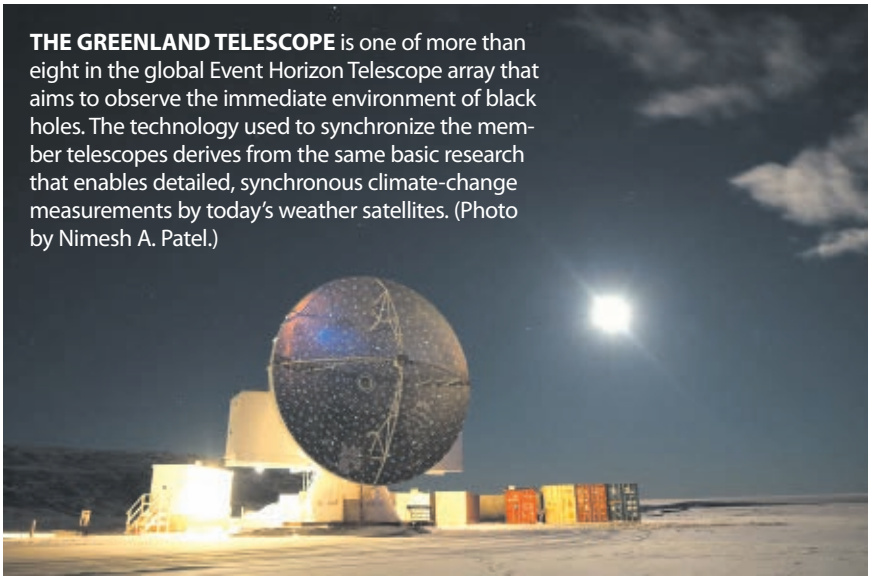
Commentary

Basic research in a time of crisis



THE GREENLAND TELESCOPE is one of more than eight in the global Event Horizon Telescope array that aims to observe the immediate environment of black holes. The technology used to synchronize the member telescopes derives from the same basic research that enables detailed, synchronous climate-change measurements by today's weather satellites. (Photo by Nimesh A. Patel.)

Pierre Teilhard de Chardin, a paleontologist, geologist, philosopher, and Jesuit priest, wrote, "The history of the living world is an elaboration of ever more perfect eyes in a cosmos in which there is always something new to be seen." Teilhard's epigram provides a stunning description of mankind's longing to understand the natural world, which is to say mankind's instinct for science.

Today it is essential that science continue to flourish because society desperately needs science to deal with the growing problems due to our changing climate—ocean-level rise, destructive storms, forest fires, drought, and above all, the need for new sources of energy. But society also desperately needs science that although not focused on those problems could be crucial for solving them. A glance at some modern developments shows why.

Teilhard's phrase "ever more perfect eyes" accurately portrays the evolution of telescopes from crude optical devices at the dawn of the 17th century to today's space telescopes. That fabulous development was driven by curiosity about the nature of the universe: It was the product of basic research, which is motivated by the joy in understanding the natural world, in contrast to applied research, which is motivated by the need to solve a particular problem. Teilhard's phrase is a pretty good description of basic research.

Albert Einstein's search for a theory of gravity—his general theory of relativity—is an iconic example of basic research. The problem he struggled to solve, to create a theory that avoided some inconsistencies in Newton's theory of gravity, worried hardly anyone else and had no conceivable use, at least not at that time.

A startling consequence of Einstein's theory is that gravity affects time. A clock on top of a mountain runs faster than an identical clock at sea level, although not by much: At the peak of Mount Everest, a clock runs fast by only a few millionths of a second each month.

Einstein's prediction for the effect of gravity on time stimulated an experimental search. It originated on 21 January 1945 when a *New York Times* article carried the headline "'Cosmic pendulum' for clock planned." It was the report of a speech at an American Physical Society meeting in New York City; the speaker was I. I. Rabi, a physicist at Columbia University. Rabi proposed creating a clock whose "ticks" were governed not by the swing of a pendulum but by pulsations in an atom on one of its natural frequencies that could be measured by a technique he had invented.

The accuracy of such an atomic clock could be fabulously high. The newspaper article reported, "Professor Rabi said that he would like to see someone build an atomic clock that would be capable of providing, for the first time, a terrestrial check on the Einstein postulate that the gravitational field produces a change in the frequency of radiation." Thus the creation of atomic clocks sprang directly from curiosity about whether gravity affects the rate of a clock—that is, whether gravity affects time. Lacking any other conceivable application for such an accurate clock, the quest is a perfect example of basic research.

Nobody rushed to build an atomic clock after Rabi's 1945 talk. The research establishment was in disarray from World War II, and there were some technical barriers. Serious work on atomic clocks started around 1950, and in 1954 the first such clock was demonstrated in the UK. It came to be known as the cesium-beam atomic clock.

In 1956 Norman Ramsey, a former student of Rabi's, proposed a different type of atomic clock that would be capable of investigating Einstein's prediction about gravity and time. The device, known as the hydrogen maser, was demonstrated in 1960. Today hydrogen masers are found in most primary timekeeping laboratories along with other atomic clocks that set the international time.

Although the hydrogen maser was created to verify Einstein's conjecture about time and gravity, its unanticipated applications are noteworthy. For instance, it made the radio astronomy technique known as very long baseline interferometry (VLBI) possible. In each radio observatory, a nearby maser provides a time-stamp signal that permits distant laboratories to synchronize their observations. With VLBI, astronomers can create radio telescope antennas that are effectively the size of Earth; they enable astronomers to create maps of hydrogen throughout the universe with astonishing detail and to look back in time toward the infancy of the cosmos.

Recent progress has been reported on a new frontier of gravity. At the center of our

galaxy, a massive black hole is swallowing nearby masses. Matter falling into the black hole vanishes forever, but as the matter crosses a surface called the event horizon, it radiates brilliantly. The Event Horizon Telescope, an advanced VLBI array, is letting us see that process by combining signals from radio telescopes around the world. Last month the EHT team released its first remarkable image, of the central black hole in galaxy M87. The EHT is making it possible to study the predictions of general relativity for phenomena never before witnessed: matter moving in fantastically strong gravitational fields.

The greatest effect of atomic clocks on society is from the creation of the global positioning system. It is fundamentally a timing system, and atomic clocks are at its heart. To my knowledge, nobody had thought about such a system before atomic clocks became a reality, and nobody could have imagined its powers. Today GPS enables the air control systems that guide planes in flight and the ground navigational systems in smartphones and automobiles. It keeps our communications networks and power grids synchronized and is crucial for medical emergency systems. Above all, GPS is critical for understanding the existential threat that climate change is to civilization.

Understanding the global climate requires data on a vast number of variables: radiant energy flow to and from Earth, vertical and horizontal temperature profiles, cloud covering and temperature, sea- and land-surface profiles, ocean-surface temperature and wind speed, global precipitation, water content of the atmosphere, the list goes on. And the quantity of data gathered is enormous.

The primary source of data on Earth's climate is a fleet of weather satellites in polar orbits, some from the US and some from Europe. The fleet scans Earth's entire surface four times a day. Often, the satellites work together in pairs, exchanging radar and lidar signals to measure the water content of the highest region of the atmosphere. That particular measurement is vital because most of the atmospheric water is stored there. In addition to the polar fleet of weather observatories, clusters of synchronous satellites from different nations continuously view Earth. The US has two clusters viewing the entire country, one looking east, the other west.

Because few of those global climate measurements could have been made without GPS, it is valuable to keep in mind the system's origin: mere curiosity about general relativity. GPS is a transformational technology that grew out of basic research. One can cite many other examples of how basic research drives transformational advances. In physics, for instance, investigations of molecules in space by Charles Townes led to the invention of the laser, and studies of atomic nuclei by Edward Purcell and Felix Bloch led to the invention of MRI.

I stress the unexpected rewards from basic research because society urgently

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needs new ways to deal with the rapidly growing crises of climate change. The latest report of the Intergovernmental Panel on Climate Change (IPCC) concludes that previous reports erred in being too cautious: The time to stem the flow of greenhouse gases is shorter than had been estimated. We face the possibility of a runaway situation in which an increase in global temperature feeds back to accelerate global heating. Such a process would lead to a massive change in climate and a catastrophic elevation of sea level. We face a threat to civilization.

In the US today, support for basic research is dwindling. Opportunities for a career in basic research are decreasing, and our ability to attract excellent students from home and abroad is declining. When considered in the context of the most recent report of the IPCC, the neglect of basic research may be disastrous.

If our civilization succeeds in learning to live in harmony with the natural world, science will have played a crucial role in the transition. The immediate problem in the US is to convince Congress that the situation is urgent. Happily, the years of developing STEM education in the US are starting to pay off. The numbers of scientifically literate citizens and members of Congress are growing. Our representatives will listen if citizens—both scientists and nonscientists—speak up for science and particularly for the value of basic research.

Daniel Kleppner
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LETTERS

Rediscovering the roots of our work

Acknowledging the priority of ideas in the scientific literature can be difficult. One can hardly be faulted for not being aware of all papers on a topic. The problem is hard enough with the many foundational papers that get cited but rarely read; it is much worse with the masses of others that have faded into obscurity along with their precocious insights.

Charles Day's editorial "Crediting our predecessors" (PHYSICS TODAY, September 2018, page 8) and Ray Goldstein's article "Coffee stains, cell receptors, and time crystals: Lessons from the old literature" in the same issue (page 32) remind us of the pleasurable thrill (and for those who thought their ideas were original, the disappointment) of rediscovering those old gems.

My favorite example of the form is a not-so-obscure paper, "Gravitational machines," by Freeman Dyson.[1] That brilliant article, ostensibly about the limits of power generation by a spacefaring civilization, is occasionally cited for its insights into the gravitational-wave radiation of binary systems.

But Dyson's article made a series of other remarkable scientific leaps that are rarely cited. He offered what is apparently the first published speculation on the existence of tight binaries comprising two neutron stars; his comment predated the discovery of pulsars by five years. He also calculated the gravitational-wave signal strength of those binaries and identified them as an observable source of gravitational waves, even at intergalactic distances. He did not imagine that such binaries could form naturally, but he speculated that they could be the by-product of deliberate energy extraction and argued that the detection of a merger event would constitute evidence for alien technology.

Despite having presaged the discovery of gravity waves from the inspiral of binary neutron star GW170817 by more than 50 years, Dyson's work is not cited in that paper[2] or any other paper I can find on that topic, presumably because most people are unaware of that particular aspect of Dyson's publication. Many who cite his paper thus apparently do so without reading it, which is a shame because it is a model of clarity, simplicity, and brevity and is a joy to read.

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Craters on Pluto and Charon show that Kuiper belt collisions are rare

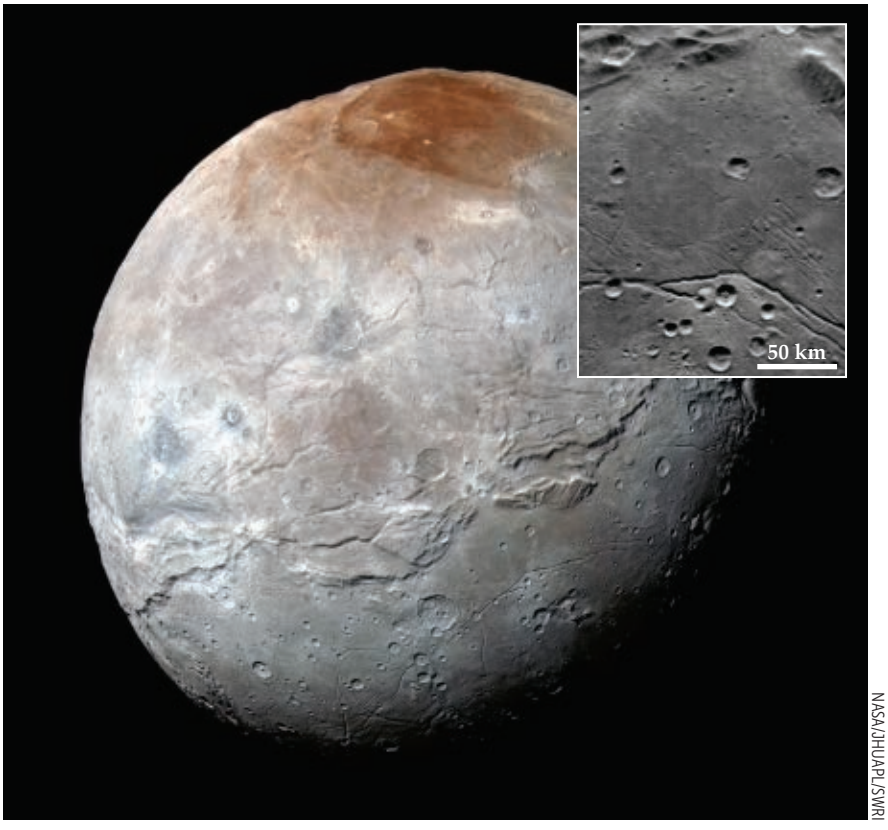
There are far fewer small bodies in the solar system's outer reaches than there would be if collisions were common.

The number of known objects in the solar system's asteroid belt, between the orbits of Mars and Jupiter, has exploded in recent years. In 2000 just a few thousand asteroids had been numbered, meaning that they'd been observed precisely enough to determine their orbits. Since then, the catalog has grown to more than half a million, with tens of thousands of additions each year.

The increase is easily explained. Newer telescopes can detect smaller asteroids—with diameters as small as hundreds of meters—and there are vastly more small asteroids than large ones. The size distribution reflects the asteroid belt's collisional equilibrium. For billions of years, asteroids have crashed into each other, sometimes sticking together and sometimes breaking into pieces, and the balance of those processes has reached a rough steady state.

Something fundamentally different seems to be going on in the Kuiper belt, the torus-shaped zone of dwarf planets and smaller objects beyond the orbit of Neptune. In 2015 NASA's *New Horizons* probe transmitted the first close-up images of Pluto—the best known resident of the Kuiper belt—and its largest moon Charon (shown in figure 1). The images showed hundreds of craters on both bodies, formed by the impacts of Kuiper belt objects (KBOs) of various sizes.

Now Kelsi Singer (Southwest Research Institute in Boulder, Colorado) and her colleagues on the *New Horizons* team have analyzed the crater size distributions.[1] The smallest craters they observed still outnumber the larger ones, but by more than an order of magnitude less than collisional equilibrium would predict. The result, which implies that KBO collisions are not frequent enough for the Kuiper belt to have reached collisional equilibrium, provides an important new constraint on models of how the solar system formed 4.5 billion years ago.



NASA/JHUAPL/SWRI

FIGURE 1. IMAGES OF CHARON, captured in July 2015 by NASA's *New Horizons* probe, show parts of the moon's surface to be peppered with craters, a record of 4 billion years of impacts by Kuiper belt objects.

Far out

In the wake of the 1930 discovery of Pluto, several astronomers, including Gerard Kuiper, speculated that more small bodies might occupy the same general region at the outer edge of the known solar system. But it wasn't until 1992 that David Jewitt and Jane Luu made the first observation of a KBO other than Pluto or Charon (the latter discovered in 1978).

More KBO discoveries followed, and their number grew to hundreds and then thousands. (See the article by Mike Brown, PHYSICS TODAY, April 2004, page 49.) The 2005 discovery of Eris, a KBO more massive than Pluto and almost as large, made clear that not only was Pluto not alone in the Kuiper belt, it wasn't uniquely outstanding among KBOs. The realization prompted the International Astronomical Union to issue a new formal definition of "planet," and Pluto famously—or infamously—no longer qualified.

Pluto and Eris are both more than 2000 km in diameter, and Charon is about half that. All three can be seen by Earth-based telescopes, even at their great distance. But it's much harder to observe smaller KBOs, especially those with diameters less than tens of kilometers, so the overall KBO size distribution has been shrouded in mystery.

There have been a few clues. Occasionally KBOs get kicked out of their orbits and launched toward the inner solar system. Some leave craters on the icy moons of the gas-giant planets that were imaged by probes such as *Galileo* and *Cassini*, and

some enter eccentric orbits around the Sun and are visible from Earth as comets (see the article by Don Brownlee, PHYSICS TODAY, June 2008, page 30). Neither the icy-moon craters nor the comets show any sign of the vast numbers of small KBOs one would expect if the Kuiper belt were like the asteroid belt. But neither population is a smoking gun, because some unknown mechanism might destroy or disrupt small KBOs on their journey inward.

Old and cold

Launched in 2006, *New Horizons* had among its goals the determination of the KBO size distribution. The distribution would have to be inferred from craters: *New Horizons* was designed to study the surfaces and atmospheres of Pluto and its moons, not to survey large portions of the sky to look for KBOs themselves.

But nobody knew if there would be any craters. Pluto and Charon's geology was as yet unknown, and maybe some process was at work to renew the surfaces and erase the craters. Indeed, some regions—such as the Tombaugh Regio, the bright heart-shaped feature on Pluto—had been renewed recently and were crater-free. But others appeared much older and had many craters.

Before the probe's arrival at Pluto, Sarah Greenstreet, Brett Gladman, and William McKinnon (all of them also authors on reference 1) worked out a model of the cratering physics on Pluto and Charon to help interpret the observations.[2] Based on what was known from Earth-based observations of the KBO size distribution, they predicted the number of craters formed per size bin per unit time. Prediction in hand, they could immediately estimate the surface ages when the images came in.

Figure 2 shows a log–log plot of the results, scaled by the inverse cube of the crater diameter D. "The D^{-3} power law is about what you'd expect in collisional equilibrium," explains Singer, "so we normalize by that slope to see differences from it more easily."

The blue curve is what Greenstreet and colleagues' model predicts for a surface age of 4 billion years; the gray, purple, yellow, and red data points are crater counts from regions of Charon. The agreement for craters between 20 km and 100 km in diameter (formed by KBOs roughly 2–15 km in diameter) shows that the surfaces are probably almost as old as the solar system itself.

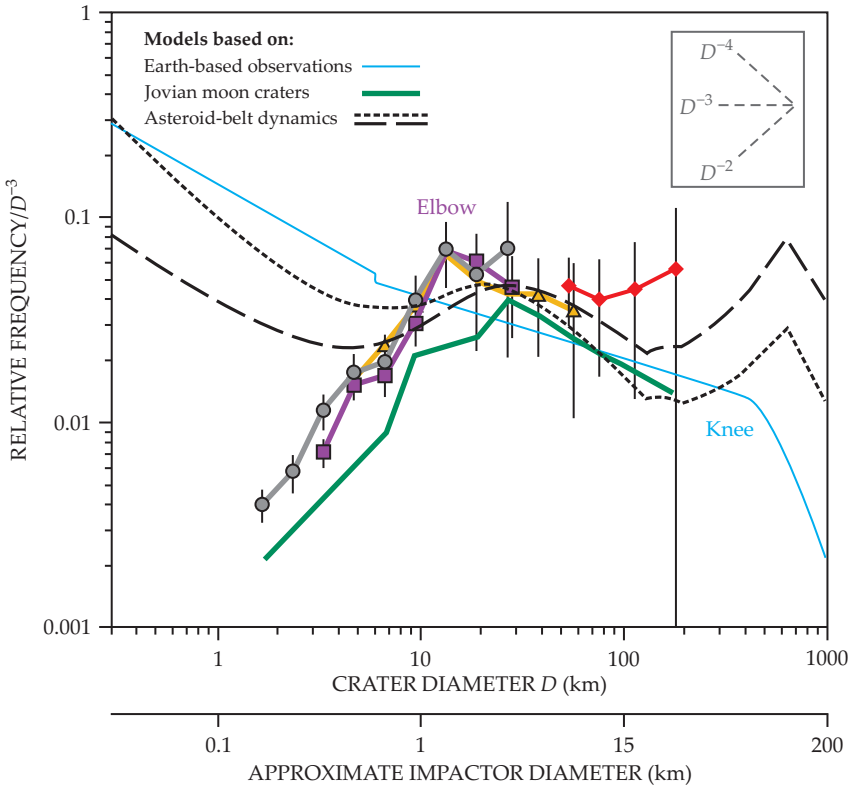


FIGURE 2. CRATER FREQUENCY as a function of crater diameter D and scaled by D^{-3}. Collisional equilibrium predicts a power-law dependence of between D^{-3} and D^{-4}, but below D = 15 km, Charon crater distribution (shown by the gray, purple, yellow, and red data) abruptly switches to $D^{-1.7}$. Craters on Pluto, not shown here, exhibit a similar shift. The slope change, or elbow, is not reproduced by any model of collisional dynamics, but a similar frequency distribution (shown in green) is predicted by the craters observed on Jupiter's moons Europa and Ganymede. (Adapted from ref. 1.)

Disjointed

The smaller craters revealed a more striking result: Around D = 15 km, the power-law slope abruptly shifts from −3 to −1.7. All cratered regions on both Pluto and Charon show the same shift, and at approximately the same size scale. Singer was surprised. "I was expecting a more subtle result," she says. "But the strong change is more interesting." She's dubbed the bend in the curve the "elbow," because the KBO size distribution already has a "knee" at an object diameter of 100 km.

Singer and colleagues considered the possibility that the craters they saw weren't reflective of all the KBOs that have struck Pluto and Charon. Perhaps geological processes were erasing some craters but not others. But they could identify no process that would erase more than 90% of the small craters, leave all the large ones untouched, and work in exactly the same way on Pluto and Charon despite their geological differences. Pluto's thin atmosphere, for example, could produce a snow of frozen nitrogen that might obscure some craters. But Charon lacks an atmosphere.

Models inspired by the asteroid belt's dynamics can reproduce something like the elbow, as shown by the black dotted and dashed curves in figure 2. But they always show an upswing in slope at still smaller diameters, and there's no sign of that in the data. On the other hand, a model based on the craters on the Jovian moons Europa and Ganymede, shown in green, matches the data well. The agreement suggests that the KBOs that reach the inner solar system are a reasonable representation of the Kuiper belt as a whole.

The researchers had another chance to test their interpretation a few months ago when *New Horizons* flew by 2014 MU69, a KBO nicknamed Ultima Thule. At just 32 km long, it doesn't have room for many

craters, but it does have some. Before the flyby, Greenstreet and colleagues worked out how many there should be based on their analysis of Pluto and Charon.[3] When they compared their model to the images, says Gladman, "It appears to be bang on. It was incredible."

No chip off the old block

The dearth of small KBOs suggests not only that the Kuiper belt is not in collisional equilibrium, but that it's barely collisionally evolved at all. Even a small number of destructive collisions between large KBOs would produce many more small KBOs than the researchers see, so the logical conclusion is that those collisions haven't happened. "These objects condensed out of the solar nebula," explains Gladman, "and they've been sitting there, just like that, ever since." In the much denser asteroid belt, in contrast, virtually every small object seen today is either a fragment broken off a larger one or a collection of such fragments.

If KBOs are representative of the original planetesimals that populated the infant solar system, then their size distribution is an important benchmark for researchers seeking to understand how the solar system formed in the first place. The mechanism by which dust grains combined to form pebbles, boulders, and eventually planets is a major unsolved problem in planetary science, because pebbles and boulders are too small to stick together under their own gravity.

Modelers have some ideas of mechanisms that might work, but testing them is another story. Lab experiments can't mimic the formation of the solar system in detail, so researchers are left to test their computer simulations against rough measures, such as whether they produce the right number of planets. (See PHYSICS TODAY, November 2015, page 16.) The Kuiper belt, as a surviving remnant of the early solar system, could provide another test: Somewhere along the way, a successful model will now have to reproduce the KBO size distribution.

Johanna Miller

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Wireless sensors for the tiniest patients

Paper-thin electronics measure heart rate, blood flow, and more—and could save children's lives.

NORTHWESTERN UNIVERSITY

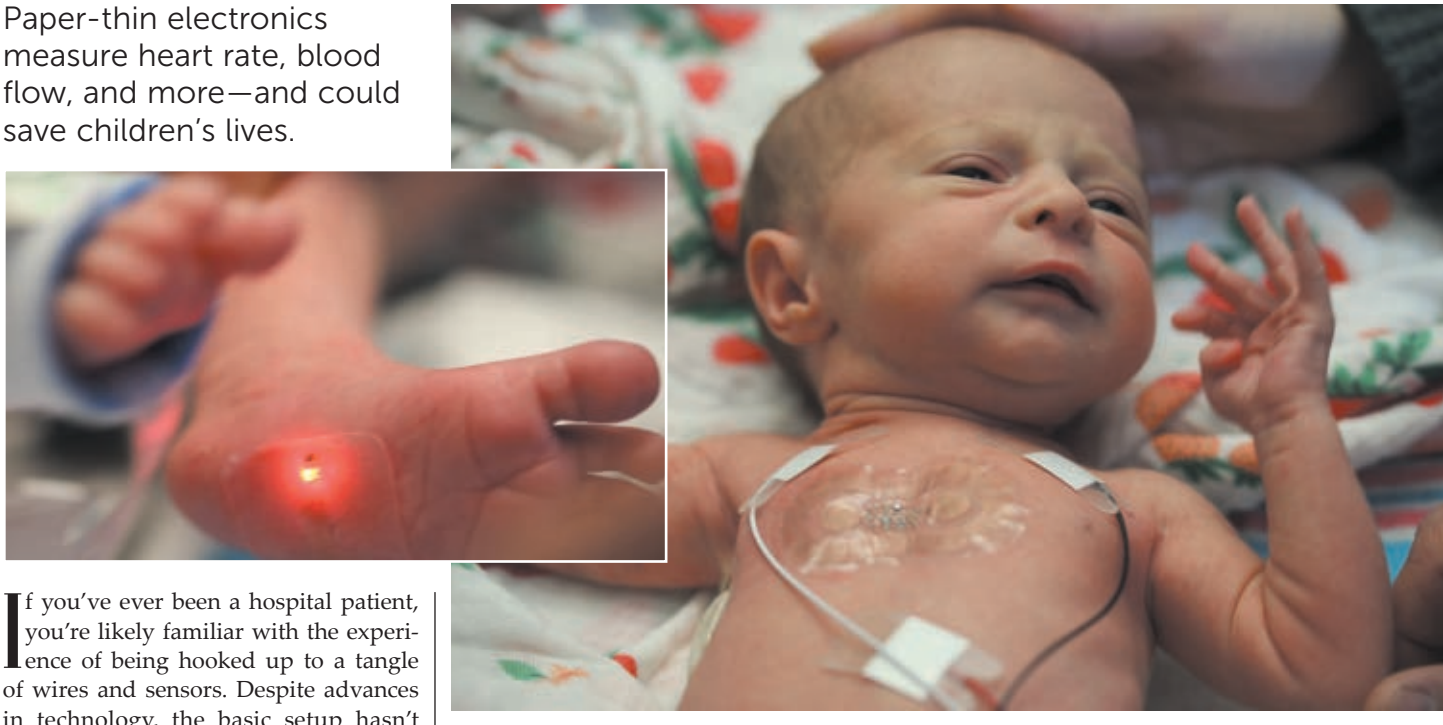

FIGURE 1. JUST TWO WIRELESS SENSORS, one on the foot and one on the chest, suffice to monitor all of an infant's vital signs. But until the wireless devices are approved for use on their own, test patients need to wear the standard wired sensors too.

If you've ever been a hospital patient, you're likely familiar with the experience of being hooked up to a tangle of wires and sensors. Despite advances in technology, the basic setup hasn't changed much in 50 years: Rigid sensors are held against the body with mechanical clamps or strong adhesives, and they're connected by wires to an external box of electronics that processes the signals. The sensors are necessary to monitor your vital signs. But they restrict movement—you can't get up from your bed without assistance—and they're uncomfortable.

The problems are compounded for hospitalized newborns, especially those born prematurely. The skin of infants born at less than 32 weeks' gestation can easily be traumatized by the harsh adhesives. More than 90% of children born prematurely bear scars later in life from their early hospitalization. Not all of those are from the sensors, but many are.

Wired sensors also get in the way of bedside care such as feeding, bathing, and diaper changing. And they inhibit

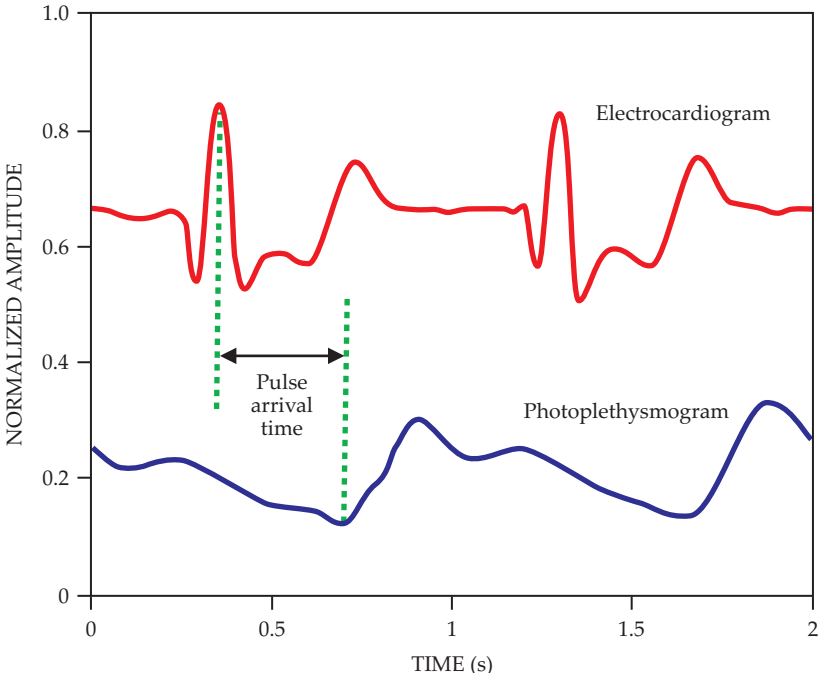

FIGURE 2. FROM THE SYNCHRONOUS STREAMING of two measures of the heartbeat—an electrocardiogram recorded by a chest-mounted sensor and a photoplethysmogram measured by a foot sensor—clinicians can extract the pulse arrival time from the heart to the foot, a measure of systolic blood pressure. (Adapted from ref. 2.)

crucial interactions between babies and their parents. Cuddling a new baby is an emotional experience, of course, but skin-to-skin contact also carries real medical benefits: It stabilizes the baby's heartbeat and body temperature, promotes feeding and weight gain, and ultimately paves the way for a shorter hospital stay.[1]

Researchers at Northwestern University are working toward obviating the drawbacks of wired sensors. The project is led by materials and electronics engineer John Rogers, pediatric dermatologist Amy Paller, and physician-engineer Shuai Xu, formerly a postdoc under the joint mentorship of Paller and Rogers but now in charge of coordination between the medical and clinical halves of the team.

The researchers have created a system of two flexible, wireless sensors, shown in figure 1, that capture all the same data as the wired systems and more.[2] Because they're so light, the sensors can stick to the skin by van der Waals forces alone, without any adhesives. They can be sterilized and reused, or they can be mass-produced economically enough to be thrown away.

Cutting the cords

Rogers and his engineering colleagues have been developing flexible, stretchable, skinlike electronics for more than a decade. (See PHYSICS TODAY, May 2008, page 84.) With slender, ribbonlike electronic elements prescrunched like accordions to better tolerate strain, some of their devices are thin enough to be applied to the skin like temporary tattoos.[3] Applications pursued include keeping track of UV exposure, analyzing sweat composition, and monitoring athletes' condition while on the field.

Three years ago, Paller attended a talk at which Rogers spoke about his flexible electronics work, and she realized they had the potential to meet a pressing need in neonatal intensive care units (NICUs). She'd worked with him before on sensors to monitor wound healing, and a new branch of their collaboration was born.

The conventional system for monitoring a newborn's vital signs uses five wired sensors. One is a simple adhesive-backed temperature probe. Three are electrodes that together record an electrocardiogram (ECG), which monitors the speed and regularity of the heartbeat. Because the heart signals look different when the lungs are full, the ECG also provides a measure of respiratory rate.

The final sensor records a photoplethysmogram (PPG), an optical measurement of blood flow. If you shine a

flashlight through a thin part of your flesh, you'll see the transmitted light tinged with red from your blood. If you could gauge its intensity precisely enough—and especially if you could see in the IR—you'd see it pulsate with each beat of your heart. From the oscillation amplitudes at different wavelengths, you could determine your blood oxygenation level, a measure of how effectively you're breathing. In adults, a PPG sensor is often clamped onto a finger. In infants, it's taped around the foot.

The building blocks more or less existed to reproduce all those functions wirelessly. For example, sensors could transmit data via near-field communication (NFC), an offshoot technology of RFID that's used in contactless payment schemes. Electronics can also be powered wirelessly, thereby obviating the need for bulky batteries.

The hard part was in putting all the pieces together into a device that would meet the stringent requirements of the NICU. Says Paller, "We spent two years just doing and redoing," testing different materials, layouts, electronic designs, and algorithms for the sensors, in search of the ones that could operate continuously and reliably. "We couldn't have any risk that they would fall off or stop working."

Design challenge

The system that Rogers and colleagues came up with combines an hourglass-shaped sensor placed on the chest, holding two electrodes for recording an ECG, and a rectangular sensor wrapped around the foot, holding red and IR LEDs and a photodiode for recording a PPG. Either of the silicone-encased devices could easily be equipped with a temperature probe, so the researchers added one to each. As a result, they could measure not only an infant's core body temperature, but also the temperature difference between the core and the periphery of the body. That quantity isn't monitored with the current system of wired sensors, but it could help to diagnose circulation problems.

Because the ECG and PPG both track the heartbeat, an integrated system that records them synchronously can also measure the time it takes for a pulse to travel from the heart to the foot, as shown in figure 2. That pulse arrival time, it turns out, is a measure of systolic blood pressure. NICU clinicians don't currently monitor blood pressure at all, because even a scaled-down blood-pressure cuff would be too harsh for their patients.

To reduce the amount of data that needs to be transmitted through the NFC link, the researchers designed circuitry to do much of the signal processing—for example, identifying the peaks in the ECG waveform—on the sensors themselves. The resulting signals don't need expensive, specialized electronics; they can be streamed to any laptop, tablet, or smartphone.

The sensors are stretchy enough to function under strains of up to 16%, about the same as can be tolerated by skin. But stretching applies a shear force to the skin that can cause bruising. To mechanically decouple the electronics from the skin, the researchers added a thin fluid-filled layer to each sensor; the shear forces that remain are so slight they can't even be felt. Even with the extra layer, the sensors are less than 300 μm thick.

The NFC link operates at a frequency,

13.56 MHz, that's negligibly absorbed by biological tissues. The sensors are visually transparent, so doctors and nurses can tell at a glance if the skin underneath is becoming irritated. They're waterproof and compatible with MRI and x-ray machines, so they can be left on while the babies are bathed or taken for routine imaging.

Clinical need

The wireless sensors have performed well in clinical trials so far, with no adverse effects on any of the patients. But before they can be approved by the Food and Drug Administration for general use in the US, more rounds of testing are needed to prove that they're just as dependable as the current wired sensors. Until then, test patients must continue to wear wired sensors too.

While they're waiting on FDA approval, the researchers have been working with hospitals in countries where mortality rates are high, even among full-term infants, due in part to a lack of diagnostic equipment. They have active pilot programs in several countries in Africa, and with grant funding from the Save the Children Fund and the Bill & Melinda Gates Foundation, they'll be deploying their sensors to more sites in the developing world later this year.

Although the cost to hospitals in the US and elsewhere has yet to be determined, the researchers estimate that the wireless sensors could be mass-produced for less than $20 each. That's less than hospitals currently pay for a set of adhesive-backed leads and connectors that are thrown away after a single use.

Older children and adults can also use the sensors—indeed, the first round of tests was on healthy adult volunteers. "We focused on the NICU because that's where the clinical need was the greatest," says Xu, "but I also see opportunities for the elderly or for burn victims with compromised skin."

Johanna Miller

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Atoms on a surface quickly slip through crowds

High-speed scanning tunneling microscopy reveals recently identified atomic movements that hasten diffusion.

Most industrial chemicals are the products of catalysis. A catalyst's efficacy depends not only on its ability to facilitate and accelerate reactions but also on its ability to mix with reactants and spread, which, on a surface, is determined by lateral diffusion. Despite the importance of surface diffusion, researchers have yet to observe and understand all its basic atomic-scale dynamics.

Early diffusion studies focused on clean or sparsely populated surfaces with quick diffusion rates. But when the density of atoms increases or there are two or more different species on the surface, as is often the case in industrial processes, diffusion becomes more complicated. Intuitively, one expects higher density and the presence of other particles to slow down diffusion as the adsorbed species get in each other's way. But that doesn't have to be the case.

Joost Wintterlin of the Ludwig-Maximilians University Munich and his colleagues have taken a step toward tackling more complicated diffusion dynamics. Using high-speed, variable-temperature scanning tunneling microscopy (STM), they observed a previously unidentified mechanism that allows for surprisingly rapid diffusion of atoms on a surface crowded with molecules.[1]

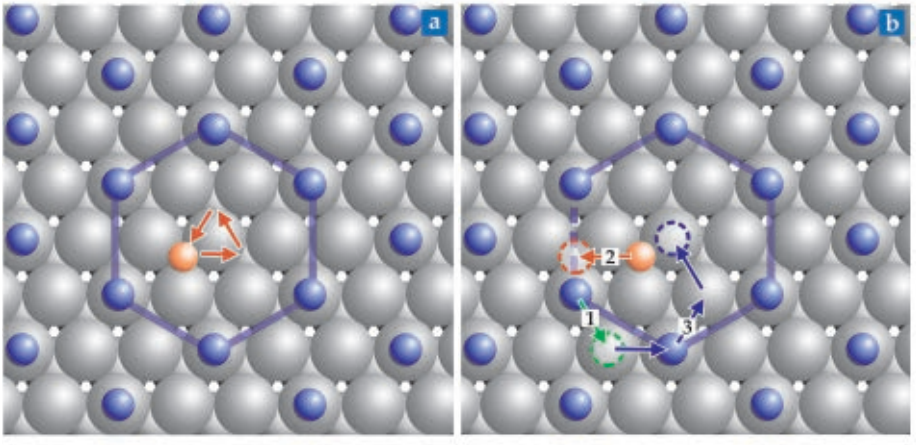

FIGURE 1. TWO TYPES OF ATOMIC MOTION. (a) On a ruthenium surface (gray), an oxygen atom (orange) trapped by a hexagonal ring of carbon monoxide molecules (blue) can move only among the three sites at the center of the hexagonal cage. **(b)** By moving out of position (green arrow), a CO molecule opens the door for the O atom to escape (orange arrow). The CO molecules then rearrange into a new hexagonal pattern, as indicated by blue arrows. (Adapted from ref. 1.)

Diffusion mechanisms

When an atom is alone on a surface, it settles into a low-energy binding site. To move around, it receives a temporary boost to its energy through thermal fluctuations and hops from binding site to binding site. For a higher density of atoms or two species on a surface, diffusion suffers two complications: First, particles must compete for binding sites in an effect called site blocking. Second, particles attract or repel one another. Those factors alter and limit the types of motion available to an atom.

A few different types of lateral diffusion occur on covered surfaces. One common mechanism in two dimensions, and the most prominent in 3D diffusion, is the vacancy mechanism. As atoms jostle on a surface, vacancies between them change position. A given atom can move only

when a vacancy gets close to it. Because the atom must sit and wait for a vacancy, the process is often slow. A second mechanism, known as direct exchange, was observed for the first time 10 years ago on a chlorine-terminated silicon surface with some Cl replaced with hydrogen.[2] In direct exchange, two adjacent atoms swap positions. By repeating that process, the Cl atom randomly walks its way across the surface. In a related ring-exchange mechanism, a sulfur atom on a chlorine-covered copper surface exchanges sites with Cl atoms in a ring through a rotation by a site.[3]

However, it was not clear whether any of those three mechanisms apply to diffusion on a catalyst surface. The allowed motions necessarily change in systems with different types of bonding to the surface and different particle interactions.

Another door opens

In the course of their research on the fundamental steps of catalytic reactions, Wintterlin and his colleagues developed and combined two STM operational capabilities—high speed and variable tem-

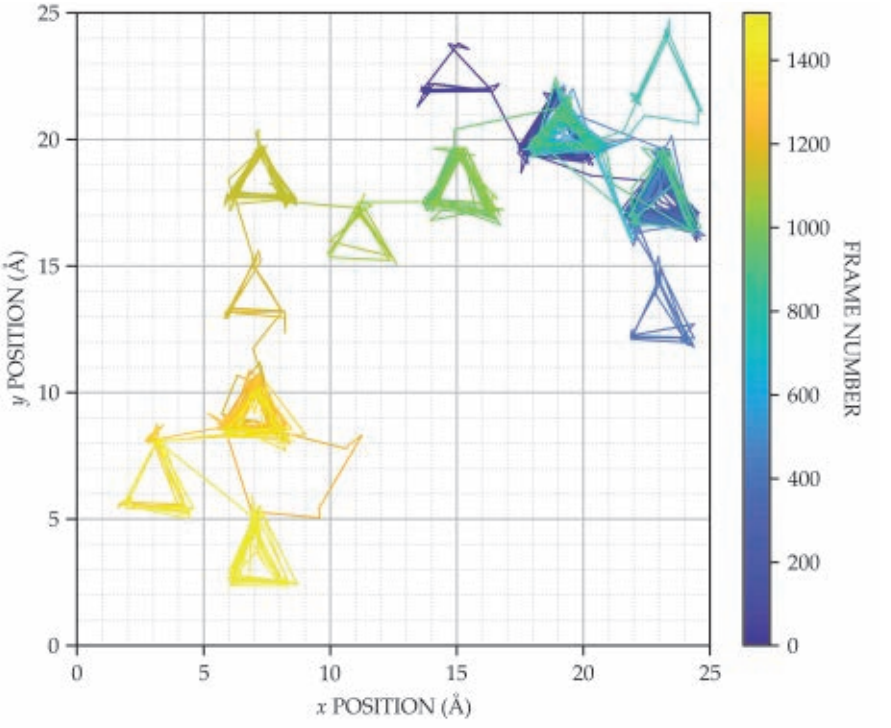

FIGURE 2. TRAJECTORY OF AN OXYGEN ATOM on a highly covered ruthenium surface, as measured by high-speed scanning tunneling microscopy, is plotted as a function of frame number. The triangular patterns arise from the trapping of the O atom by hexagonal cages of carbon monoxide molecules. Despite the high density of CO molecules on the surface, the O atom moves tens of angstroms in two minutes. The measurements were taken at 12 frames per second at 273 K. (Adapted from ref. 1.)

perature—to observe short-time-scale dynamic processes over a wide range of relevant activation energies. Whereas standard STM takes on the order of a minute to complete one image, high-speed STM completes 50 frames in a second. To achieve the increase in speed, the researchers scan the tip at a constant height rather than the usual method of maintaining a constant current, which requires a delay for the feedback loop.

Variable-temperature STM is difficult to perform because the positioning piezoelectric crystal is sensitive to thermal drift. Wintterlin and his colleagues measure between 50 K and 500 K with a beetle-type STM, in which three piezo legs hold the STM tip and scanning piezo. The instrument reduces horizonal thermal drift with its near-cylindrical symmetry and reduces vertical drift because the expansion or contraction of the legs compensates for that of the scanning piezo. Although those capabilities are not unique to Wintterlin's group, the marriage of the two is uncommon.

Ann-Kathrin Henss, the first author on the study, recorded 10 STM images per second of an oxygen atom on a ruthenium surface covered with a saturation layer of carbon monoxide molecules, shown schematically in figure 1. The STM images, taken at various temperatures from 234 K to 303 K, were crisp enough that the team identified the O atom by eye, but there were too many images to analyze them manually. The researchers developed a wavelet-transform-based algorithm, adapted from a biophysics tracking routine for fluorophore-labeled molecules, to identify and track the position of the O atom in each STM image as a function of time. They expected to observe the well-known vacancy mechanism at work with the atom moving only occasionally. Instead, they found that the atom raced around the surface.

Figure 2 shows a representative trajectory for an O atom. The observed movement falls into two categories: circulation among three positions in a triangular pattern and the short-lived migration between the triangular patterns. The researchers found that an O atom (orange in figure 1) prefers to sit in hollow sites at the center of three Ru atoms (gray), whereas CO molecules (blue) occupy lattice sites directly on top of Ru atoms. When an O atom finds itself trapped inside a hexagonal ring of CO molecules, it jumps among the three available sites at the center of the hexagon, as shown in figure 1a. In the second process, an O atom and a CO molecule appear to exchange positions (figure 1b). The O atom, now free from its initial CO cage, steps into the center of a newly arranged ring of CO molecules. By repeatedly swapping places with CO molecules, the O atom makes its way across the surface.

Making the first move

The experimental time resolution wasn't fast enough to show whether the O and CO move simultaneously, the O moves first, or the CO moves first. Axel Gross of the University of Ulm in Germany and his colleagues joined the project to answer that question through density functional theory calculations. They found that the total activation energy was high for concerted motion and the oxygen-initiated scenario, whereas thermal fluctuations of the CO density easily sufficed to free the O atom.

A CO molecule moves from its post on the hexagonal ring to a site next to an adjacent CO molecule, as shown by the green arrow in figure 1b. The O atom races through the open door (orange arrow) before the CO molecules rearrange to restore the space between them (blue arrows). The final arrangement places the O atom in a new hexagonal ring of molecules. That process flies in the face of the common image of co-adsorbates as stationary obstacles impeding motion. Instead, the CO layer forms a dynamic obstacle course for the O atom to dart through.

Surprisingly, the door-opening diffusion mechanism is almost as fast as the diffusion of O on a bare surface. But atomic processes do not always translate directly into macroscopic diffusion constants. Disorder, defects, and particle–particle interactions influence macroscopic diffusion and perhaps explain why previous diffusion measurements in similar systems showed slower rates.

The situation is further complicated in catalytic reactions, crystal growth, and other chemical processes when reactions and phase transitions must be taken into consideration. It is also not yet clear how common the door-opening diffusion mechanism is. "However, the system investigated—oxygen atoms embedded in a CO layer on ruthenium—should not be special," explains Wintterlin. "It can be generalized to strongly bound particles embedded in a layer of weakly bound other particles, adsorbed on a metal. This situation is quite general in heterogeneous catalysis."

High spatial- and temporal-resolution *in situ* experiments are important for theoretical studies of diffusion as well. "One can readily provide an *ab initio* description of system thermodynamics," says Jim Evans of Iowa State University, an expert in modeling nonequilibrium processes at surfaces. "But it is extremely difficult to anticipate the dominant dynamics or kinetics controlling transport processes."

Heather M. Hill

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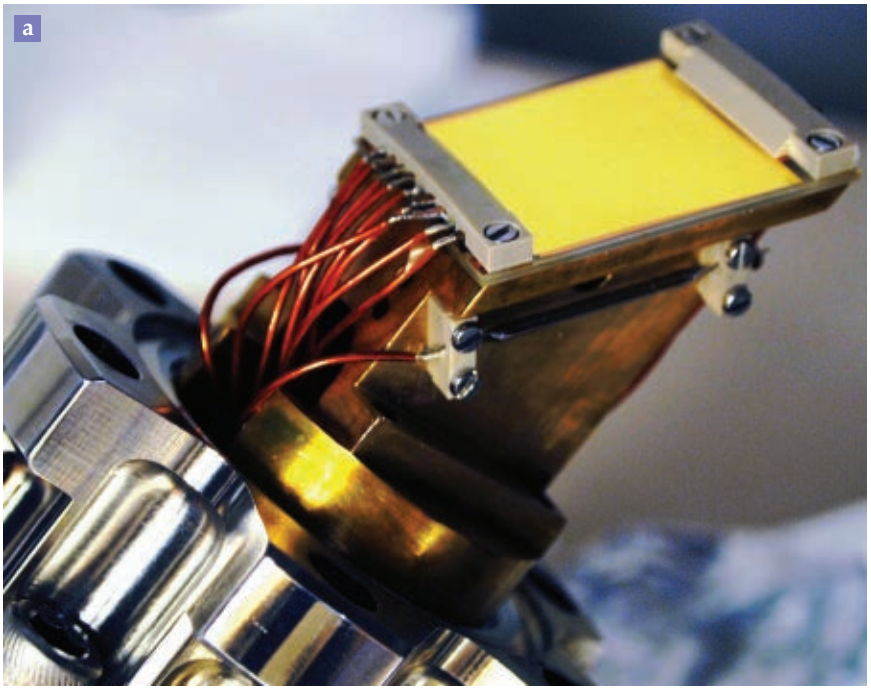
The hydrodynamics of a quantum fluid

The behavior of a one-dimensional gas of ultracold atoms confirms a generalized theory.

Hydrodynamics deals primarily with the flow of water and other fluids. A branch of fluid dynamics, it describes the behavior of many-body systems, from molecules in a cup of tea to cars on a highway. The framework, which assumes that each point in a fluid-like collection of particles is locally at equilibrium, characterizes the local quantities that are conserved for an entire system. For a classical fluid like water, those local quantities are mass density, momentum density, and energy density. Models encode the evolution of local quantities in the form of continuity equations based on mass, momentum, and energy conservation.

In the quantum world, many-body systems are notoriously difficult to model because the computational memory needed to retain their characteristics grows exponentially with the number of particles. Instead of trying to describe the complex movement of each individual particle, quantum theorists seek ways to explain many-body systems in terms



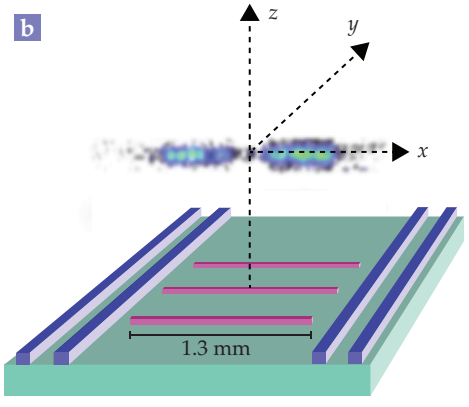


FIGURE 1. A MAGNETIC TRAP ON A CHIP confines a Bose gas of several thousand rubidium atoms. **(a)** Tiny current-carrying wires distributed on the chip create the trap. (Image courtesy of Max Schemmer and Isabelle Bouchoule.) **(b)** The current through the three parallel pink wires creates strong confinement in the *y*- and *z*-directions, trapping atoms 15 μm above the central wire. Current through the four purple wires creates weak confinement; when that current is shut off, the atoms are free to spread along the *x*-axis. (Adapted from ref. 1.)

of a reduced number of local characteristics. Hydrodynamics offers an appealing tool.

However, hydrodynamical models work only for systems that quickly forget the details of their initial configuration—that is, those that reach thermal equilibrium without any external influence. For example, each small parcel of water in a bucket reaches a local equilibrium because the motion of the molecules is chaotic. Through collisions, the water molecules' mechanical, chemical, and thermal parameters quickly reach constant values.

The same models fail to explain the dynamics of systems that retain a memory of their initial state and don't reach thermal equilibrium. One-dimensional collections of ultracold atoms offer an opportunity to study that very selected class of systems. Because of the oddities of quantum physics, the atoms in such systems not only collide with each other, they also pass through one another. Collisions among particles cannot change the velocity distribution of the fluid and bring about thermal equilibrium.

Since the early 2000s, experiments with 1D collections of weakly interacting bosons, or Bose gases, have inspired theorists to develop models of nonequilibrium quantum particle transport. Only in the past two years have quantum theorists proposed a form of hydrodynamics that extends to nonequilibrium systems.

Now Max Schemmer, Isabelle Bouchoule (both at the University of Paris-Saclay), and their colleagues have provided the first direct evidence in support of new hydrodynamic models that are sufficiently general to describe the nonequilibrium behavior of ultracold atoms albeit in one dimension.[1]

Motus aeternus

An experiment known as the quantum Newton's cradle, published in 2006 by David Weiss and colleagues at the Pennsylvania State University,[2] motivated a series of efforts to model the observed behavior of nonequilibrium quantum particles. The classical Newton's cradle is a familiar desktop toy that involves several steel balls, suspended in a row by wires. When one ball is set swinging, it hits the other balls and its momentum is transferred until the ball at the opposite end swings away while the intermediate balls remain stationary. In the quantum version, tens to hundreds of ultracold rubidium atoms replace the steel balls, and lasers confine the atoms in an elongated trap to create a 1D system. Additional lasers set the atoms into motion and cause them to oscillate like the desktop toy.

The quantum Newton's cradle was a first surprising experimental finding of many interacting particles that showed undamped motion. The motion continued undamped over thousands of collisions and the atoms did not reach thermal equilibrium.

The underlying equations of motion that describe the quantum Newton's cradle are based on Elliott Lieb and Werner Liniger's 1963 paradigm for describing the interaction strengths in a cloud of ultracold atoms constrained to a straight line.[3] Solving those deterministic equations could in principle predict all the motion-related properties of the particles at any time in the past and the future.

But for clouds of atoms larger than 20 particles, describing the time evolution of the system becomes too complex to solve on a classical computer. "Starting from Newton's cradle, thousands of theoretical papers have tried to simulate what happens for larger numbers of atoms," says Bouchoule.

Generalized hydrodynamics

In 2016 both Olalla Castro Alvaredo (City, University of London) and collaborators[4] and Bruno Bertini (International School for Advanced Studies in Italy) and collaborators[5] proposed an efficient way to describe the dynamics of nonequilibrium 1D quantum systems. Instead of explicitly detailing the dynamics of each particle, the research teams adopted a hydrodynamics approach, conceptually zooming out so that the particles appeared as one continuous fluid. The new framework helped to model experiments and theoretical situations that were previously beyond description.

Hydrodynamical descriptions of particle number, momentum, and energy density suffice to model the time evolution of a quantum system that reaches thermal equilibrium. But a system that in theory never reaches thermal equilibrium—like the undamped oscillations of the classical and the quantum Newton's cradle—has a distribution of quasiparticle

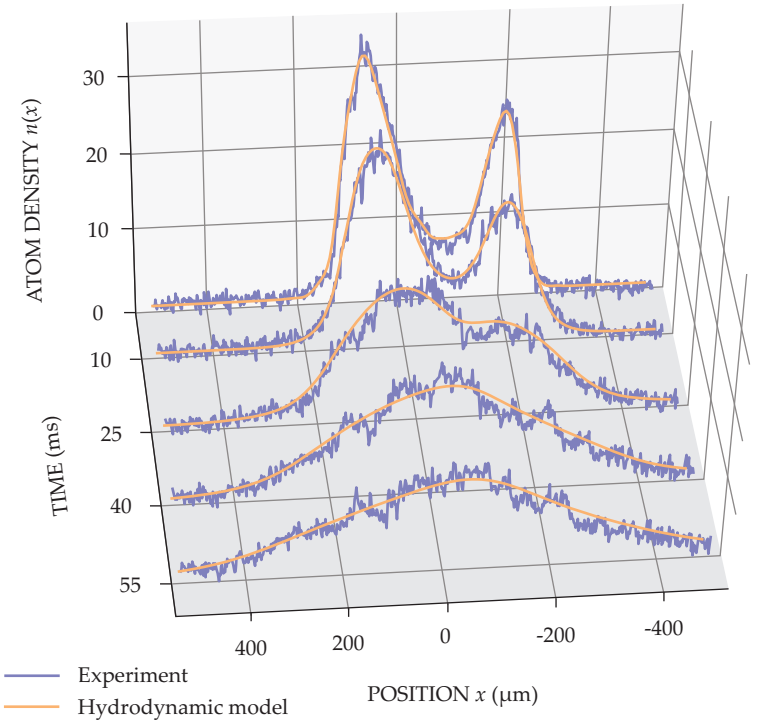


FIGURE 2. COLD ATOMS WERE INITIALLY TRAPPED in a distribution with two peak densities. When the confinement was relaxed, the atom density $n(x)$ evolved into the distribution predicted by generalized hydrodynamics. Solid orange lines represent the atom density distribution predicted by models, and purple lines represent experimental data. (Adapted from ref. 1.)

velocities. An infinite number of densities must be globally conserved, each of which is characterized in the form of a continuity equation. Careful mathematical representation of the particles' momenta made it possible to identify a set of equations that represent the continuity of all the conserved quantities. Hydrodynamics adapted for an infinite number of conserved quantities is known as generalized hydrodynamics, and it offers a way to predict the behavior of systems that remember their initial state.

Not just a conjecture

The quantum Newton's cradle and other 1D quantum systems are real-world scenarios in which generalized hydrodynamics should apply, but until now the framework remained a hypothesis. Schemmer's new work, says Weiss, "provides the first explicit experimental application of generalized hydrodynamics."

To test the theory, Schemmer and colleagues confined several thousand cold ^{87}Rb atoms in a magnetic trap built on a chip, shown in figure 1. The trap comprised three parallel conducting wires several millimeters long. The atoms were guided 15 μm above the wires, and the large magnetic field gradient provided strong confinement along the y- and z-axes. Four longer wires, parallel to the y-axis, provided weak confinement along the x-axis. By suddenly turning off the current in the longer wires, the researchers could relax the longitudinal confinement and free the atoms to flow along the x-axis.

The researchers tested several initial configurations, such as the two separate peak-density locations shown in figure 2. When the confinement was relaxed, the atom density $n(x)$ evolved into a smooth distribution, as predicted by generalized hydrodynamics, rather than maintaining the two peaks. In contrast, conventional hydrodynamics models applied to the same situation wrongly predicted that the atoms would develop two large density waves.

However, when the atoms started from a single initial density peak and the system was at thermal equilibrium, both conventional and generalized hydrodynamics made the same successful prediction: that the atoms would evolve into a broad distribution when allowed to expand freely in one dimension. The experiment confirmed that the generalized model's infinite coupled equations reduced to the finite equations of the conventional model.

The study also addressed the quantum Newton's cradle. In a configuration that mimicked the Weiss group's original 2006 experiment, Schemmer and Bouchoule released atoms from a double-peak distribution then immediately set them into harmonic oscillation. In that situation, conventional hydrodynamics models mistakenly predicted that shock waves should develop in the experiment. Generalized hydrodynamics predicted what was observed: The atom density oscillated between one and two peaks.

Theory and experiment did not conform perfectly, though. At later times (hundreds of milliseconds), atomic density distributions began to deviate slightly from the generalized hydrodynamics prediction. Schemmer and Bouchoule attributed the deviation to the gradual leakage of atoms from the trap over the course of the experiment.

Paradoxically, it takes a specialized experimental system to realize the infinite conservation laws of generalized hydrodynamics. Bertini, one of the founders of generalized hydrodynamics, says that "the compromises adopted to experimentally realize a system describable by the theory have left both experimental and theoretical open questions." Those questions include what the behavior is of multicomponent ultracold gases and of clouds of atoms that are more strongly repulsive than rubidium. Still, Hendricus Stoof at Utrecht University in the Netherlands says the new experiments verify that generalized hydrodynamics "really works in the lab and is not just a weird conjecture from theorists."

Rachel Berkowitz

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Let's Talk about Science

AIP
American Institute of Physics

AIP advances, promotes, and serves the physical sciences for the benefit of humanity.

2018 Highlights:

(excerpts from AIP's 2018 Annual Report)

Let's Talk about Diversity

AIP's Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP) is examining the persistent underrepresentation of African Americans in physics and astronomy. For the latest updates, follow the task force on Twitter @AIP_TEAMUP, and join in on the Twitter Chat series, #TEAMUPTalks.

On July 5, AIP partnered with organizations around the world to celebrate LGBTSTEM Day to raise awareness and support for LGBTQ+ people in science, technology, engineering, and math. Follow the LGBTSTEMDay hashtag to contribute to the conversation and share personal stories.

Let's Talk about Awards

The AIP Science Communication Awards—recognizing the best science writing aimed at the public—turned 50. Winners included:

- **BOOKS:** American Eclipse: *A Nation's Epic Race to Catch the Shadow of the Moon and Win the Glory of the World* by David Baron
- **ARTICLES:** *The Economist:* "Here, there and everywhere" by Jason Palmer
- **WRITING FOR CHILDREN:** *What a Waste! Where Does Garbage Go?* by Claire Eamer
- **BROADCAST/NEW MEDIA:** Science Channel: "How the Universe Works—Secret History of Pluto" by Wyatt Channell

Physics Today received the following awards from Association Media & Publishing, an organization that promotes excellence in nonprofit publishing:

- **Gold:** "Olive Spoons and Terrapin Forks," February 2017 editorial
- **Bronze:** Journals, General Excellence, 2017
- **Bronze:** Journals, Cover Design, February 2017
- **Bronze:** Magazines (circulation of 100,001+), Feature Article Design: "The secret search for uranium in Cold War Morocco", June 2017

Read more about AIP awards at aip.org/aip/awards.

Let's Talk about Public Policy

AIP continues to be at the forefront of national science policy. FYI was the first public news outlet to report on the House Science Committee's plans to introduce the *National Quantum Initiative Act.* Meanwhile, AIP, AIP Publishing, and Member Societies delivered a coordinated message to the White House Office of Science and Technology Policy about policy options related to open access in scientific scholarship publishing.

AIP BENEFITS EVERY

APS
ASA ACOUSTICAL SOCIETY OF AMERICA
AGA
πανεα ρει
OSA The Optical Society

Let's Talk about History

AIP received nearly $1 million in grants for the Niels Bohr Library & Archives, one of the nation's most concentrated collections dedicated to the history of physical sciences. Over the summer, the Wenner Collection—comprising more than 3,800 rare books and journals—was transported from Florida to AIP headquarters. A grant from the US National Endowment for the Humanities will help to create a secure vault to house these and other rare books and archival material.

Let's Talk about Jobs

The job market for the physical sciences and allied fields was robust, with institutions and organizations posting 25 percent more openings on the Career Network in 2018 over the previous year.

Two popular resources, **Who's Hiring Physics Bachelors** and **Physics is for YOU,** were updated with new employment data, and a new resource, **Physics Faculty Salary Calculator,** allows faculty to see how their compensation compares to their colleagues.

Let's Talk about Students

A few of the coordinated industry efforts to nurture future scientists included the following:

- Funding 90 travel awards for students to attend professional conferences
- Awarding more than $100,000 in grants, scholarships, and awards
- Supporting/helping to conduct more than 20 regional meetings for students
- Placing 15 interns with science and policy organizations in Washington, DC, through a summer internship program
- Launching an Alumni Engagement Program to connect undergraduates with professionals
- Relaunching JURP as the ***Journal of Undergraduate Reports in Physics*** to feature original undergraduate student research and articles
- Cementing an agreement with the National History Day to sponsor the first-ever History of the Physical Sciences & Technology Prize aimed at middle and high school students

Let's Talk about the News Media

AIP offers news and media services at meetings organized by Member Societies and promotes the activities of AIP programs and the journals of AIP Publishing and its publishing partners. The result has been coverage in top-tier media outlets, including the *New York Times, The Washington Post, People* magazine, *USA Today,* BBC, Associated Press, the *Los Angeles Times,* and *Wired.*

Inside Science News Services cemented syndication agreements with Chinese internet giant Tencent, ABC's Good Morning America, and Kalmbach Media, publisher of *Astronomy* and *Discover* magazines.

Let's Talk about AIP Publishing

More than 91,000 authors worldwide submitted their work. Across the portfolio, more than 15,000 peer-reviewed articles and 135 volumes of conference proceedings were published.

A Chinese language version of the AIP Author Services website was launched and a new partnership with Overleaf was formed to provide authors with AIP Publishing's LaTex article templates, collaborative authoring tools, and a simplified submission process.

New international partnerships were forged with The Physical Society of Japan and the China Academy of Engineering Physics to provide publishing services beginning in 2019.

To read AIP's full Annual Report, please visit bit.ly/AIP18Report.

MEMBER SOCIETY

Australia sees big opportunity in hydrogen energy

As one company brings a hydrogen-carrying fuel to market, researchers focus on ammonia as an optimal storage compound for export.

Over the next 10–20 years, motor vehicles and trains powered by carbon-free hydrogen fuel cells could become commonplace. With limits on greenhouse gas emissions looming and with their streets choked with exhaust, Japan and other energy-importing East Asian nations are already searching abroad for sources of readily usable hydrogen.

If renewable energy is to supplant fossil fuels on a global scale, wind and solar power from nations with abundant resources will need to be moved across oceans to energy-poor countries. Hydrogen, which can be cleanly burned or used to generate electricity in fuel cells, is a convenient energy carrier—a clean alternative to liquefied natural gas.

Despite its huge, largely unpopulated land mass and abundant sunshine, Australia has been slow to capitalize on its vast solar and wind energy potential. But policymakers are beginning to recognize the economic development potential of exporting cleanly generated hydrogen gas. Federal and state governments are backing demonstration projects. Hydrogen is an issue in the parliamentary election due to take place this month: The Labor opposition party has pledged to invest Aus$1 billion ($711 million) to develop and deploy a hydrogen export industry.

The ruling coalition government has not proposed a similar plan. Instead, it promised that by the end of the year it would develop a national hydrogen strategy that will consider both export and domestic uses. The plan is to be developed by a task force headed by Alan Finkel, the country's chief scientist. A 68-page white paper he prepared for the government stated that hydrogen exports could generate Aus$1.7 billion annually and a total of 2800 new jobs by 2030.

CSIRO ENERGY

CSIRO ENERGY BUILT AND DEMONSTRATED this vanadium-based membrane system for extracting pure hydrogen from ammonia. It's currently being scaled up to produce 200 kg/day.

Hydrogen itself, however, may not be the ideal shipping or storage medium. California has most of the 6100 fuel-cell vehicles (FCVs) on US roads today. The majority of the cost of hydrogen, currently about $14 per kilogram at the pump in California, comes from compressing, transporting, and storing it at pressure. Liquefying hydrogen requires temperatures below −253 °C and heavily insulated storage containers. The US Department of Energy says that to compete with gasoline, hydrogen should be priced down at $6/kg.

A MOTORIZED BICYCLE demonstrated the potassium borohydride system that Electriq Global is developing as a hydrogen source for fuel-cell electric vehicles.

Various inorganic and organic compounds could carry hydrogen in a more concentrated or convenient fashion. None are quite ready to challenge compressed hydrogen, but two—borohydride compounds and ammonia—are prominent candidates. Australia is playing an outsized role in both.

An Australian–Israeli company, Electriq Global, says it is on the cusp of commercializing a mixture of potassium borohydride and water to power fuel-cell buses and trucks. The company claims its KBH_4 fuel will deliver twice the range of the same volume of gasoline for half the price: $4/kg at the pump, says CEO Guy Michrowski. A kilogram of hydrogen will propel a car about 60 km.

In February, Electriq announced an agreement with the Dutch company Eleqtec to commercialize the fuel technology in trucks, buses, barges, and mobile generators. The first applications are expected to debut next year in the Netherlands, where tightened tailpipe standards are due to take effect in 2025. Michrowski says a separate partnership with a UK firm to demonstrate the technology on a double-decker bus will be announced within weeks.

Borohydrides are energy dense, nonflammable, and stable at ambient temperature. In Electriq's case, releasing hydrogen at the point of use is done on demand by way of an onboard proprietary catalyst. As with conventionally fueled FCVs, the hydrogen reacts with oxygen in a proton-exchange-membrane fuel cell to produce electricity that drives the wheels. In Electriq's process, depleted fuel will be pumped out of the vehicle at a refueling station and trucked back to a recycling plant.

Electriq's low cost is largely because half the hydrogen extracted onboard the FCV is from the water that constitutes 60% of the fuel's volume, Michrowski says. It's also because of low capital and operating costs, since hydrogen does not need to be stored and transported at high pressures, nor does energy need to be expended to keep the hydrogen compressed at 700 times normal atmospheric pressure, which is how it currently is dispensed into FCV tanks.

An uphill process

Regeneration is where borohydride encounters its major drawback: Hydrogenating borate to borohydride requires so much energy that the fuel is likely to be uneconomic, says Zhenguo Huang, leader of the research group on boron for energy storage and transfer at the University of Technology Sydney. Staff scientist Thomas Autrey, in the catalysis group at Pacific Northwest National Laboratory, is also skeptical. "My first

question would be, How are they going to do the regeneration? It's thermodynamically uphill." Replenishing the spent fuel isn't as simple as applying hydrogen to the borate under pressure. Multiple chemical reactions driven by temperatures of 300 °C or more are required, says Huang.

Michrowski, however, says Electriq's multiple catalysts provide a high conversion efficiency with a reduced energy input. The cost of replenishing the fuel is included in his $4/kg estimate, he notes. If Electriq's claim holds up, it could be a "game changer," says Huang.

So far, Electriq has demonstrated its processes only at lab scale and with a fuel-cell-powered bike. A pilot regeneration plant in Israel aims to demonstrate the technology at an industrial scale this summer, Michrowski says. Similar pilot plants are planned in China, where Electriq has an agreement with that country's largest FCV manufacturer to demonstrate the fuel on a long-haul truck. A plant is also planned somewhere in Europe; Michrowski wouldn't say where, nor would he provide capacities for any of the pilot plants. The company has received grants from Israel and other governments, the amount of which he declined to specify.

Electriq is developing an improved fuel that will double the hydrogen-carrying capacity, says Michrowski. The company's current formulation holds 40 grams of hydrogen per liter, about the same as compressed hydrogen at 700 bars. Liquid hydrogen, used in a few places in Germany, has a density of 70 g/L.

Others who have worked with borohydrides are skeptical of their usefulness in mass-market applications. In the US, Ballard Unmanned Systems in Massachusetts has built demonstrations of sodium borohydride–powered fuel-cell soldier power packs and underwater and aerial unmanned vehicles. Unlike KBH_4, $NaBH_4$ is a reducing agent used by chemical companies and manufactured in quantity. Phil Robinson, Ballard's vice president, says that although the compounds could be useful for niche applications, "I'm not sure that any borohydride makes sense for automotive use." The growing infrastructure for compressed hydrogen in California, parts of the East Coast, and East Asia, he argues, "negates the need for more complex, more expensive hydrogen storage means for vehicles."

Borohydrides are perhaps better suited to provide energy storage in stationary applications that don't require frequent regeneration and are too big for batteries, says Autrey. Examples include backup power for data centers and for seasonal storage of excess hydroelectricity.

Ammonia is favored in Oz

In Australia, interest in hydrogen carriers has focused on ammonia. Because it has a long-established global production and transportation infrastructure, primarily for fertilizer production, ammonia has a head start over other carrier candidates. The second-most-synthesized chemical on the planet, ammonia has a hydrogen content of 130 g/L, nearly twice that of liquid hydrogen. It becomes liquid at −23 °C, well above hydrogen's boiling point. And there is no need for regeneration.

Japan presents the most immediate export opportunity. Importing 94% of its energy, Japan aspires to a hydrogen-fueled economy. The Japanese government has set a goal of having 800 000 FCVs on the road by 2030, from 25 000 currently. More than 250 000 homes in Japan today are powered with residential fuel cells, and 5.3 million are projected by 2030.

The 30 million tons of hydrogen Japan looks to import annually by the late 2020s is nearly equivalent to the energy content of all Australian thermal coal exports, says David Harris, director of research for low-emissions technologies at CSIRO Energy, a branch of the federal Commonwealth Scientific and Industrial Research Organisation. (Australia is the world's largest coal exporter by value.) South Korea, which plans to deploy 20 000 fuel-cell buses by the mid 2020s, is another upcoming hydrogen market.

Ammonia has drawbacks. Exposure to high concentrations will cause burning of the eyes and the respiratory tract. Temperatures of around 500 °C are required to break the chemical bonds and separate the hydrogen from nitrogen. But by burning ammonia in an engine or turbine, a portion of the released energy could be used to provide the heat.

The ammonia synthesis process, known as Haber–Bosch, currently accounts for between 1% and 2% of global energy consumption, according to DOE, and produces a similar proportion of the world's carbon emissions. First, hydrogen is stripped by steam from natural gas

A. HERZOG/EPFL

CHEMIST GÁBOR LAURENCZY of the École Polytechnique Fédérale de Lausanne is shown in his laboratory with models of ants, which produce formic acid. Last year Laurenczy's research group built what they claim is the world's first integrated fuel supply employing a formic-acid fuel cell.

or coal. It is then combined with atmospheric nitrogen at high temperature and pressure. Fossil-fuel combustion is typically the source of the required energy.

Electrolysis powered with renewable energy can decarbonize the hydrogen production step. Norwegian ammonia producer Yara is designing a solar-powered electrolysis facility that will eliminate half of the carbon dioxide emitted by its Western Australia ammonia plant. The government of South Australia has funded another solar-powered electrolysis demonstration plant that will begin operations in 2020. Part of that plant's hydrogen output will be used to make ammonia; the rest will be used to generate power, both via combustion and by fuel cell.

Researchers at Monash University in Melbourne are working to decarbonize the other half of the ammonia synthesis process. With a grant of Aus$2.6 million from the Australian Renewable Energy Agency, they are using ionic liquids to synthesize ammonia directly from air and hydrogen. Douglas MacFarlane, who leads the Monash group, says tuning catalysts and electrode structures will get their devices close to 100% faradaic efficiency (a measure of the efficiency with which charge is transferred in an electrochemical reaction). That compares with the 50% efficiency of the Haber–Bosch process. "Efficiency is a vital aspect of the process as it has a massive impact on overall energy cost of the nitrogen to ammonia process," he says. Although output of devices currently being designed is small—100 g/day—scaling to larger amounts should be straightforward, he adds.

CSIRO is addressing another challenge for ammonia: Palladium membranes commonly used to separate hydrogen from ammonia are too expensive for high volumes. Last fall, the organization demonstrated a vanadium-based membrane in a portable hydrogen fueling station that separated 20 kg of pure hydrogen. After filling the tanks of their cars, says Harris, FCV manufacturers Hyundai and Toyota both were satisfied that the hydrogen contained no ammonia, which would damage or destroy proton-exchange-membrane fuel cells. CSIRO has partnered with Fortescue Metals Group, an iron-ore producer, to build a 200 kg/day demonstration of its membrane system that's expected to be finished next year, says Harris.

Decomposing ammonia would best occur at a central location in major population centers, says Harris, followed by delivery of compressed gas to individual service stations.

Alternative carriers

The first hydrogen supply chain to be demonstrated internationally will use neither ammonia nor borohydride. Japan's Chiyoda Corp is leading a partnership that will begin in Brunei, where the hydrocarbon solvent toluene ($C_6H_5CH_3$) will be hydrogenated with natural gas to become methylcyclohexane (MCH; $C_6H_{11}CH_3$). The compound will be shipped by tanker to Kawasaki, Japan, where the hydrogen will be extracted and mixed into the natural-gas supply system. The spent toluene will be shipped back to Brunei for a reload. For MCH, hydrogen loading is thermodynamically downhill, says Autrey. The reverse process requires a lot of heat, and Chiyoda says a proprietary catalyst is key to the economics.

A research group headed by chemist Gábor Laurenczy at Switzerland's École Polytechnique Fédérale de Lausanne last year demonstrated the use of formic acid (CH_2O_2) as a hydrogen carrier. Researchers there said they had built the world's first integrated power supply employing a formic-acid fuel cell. The simplest combination of hydrogen and CO_2, formic acid is liquid at room temperature, making it easy to store, transport, and handle. It is widely used in agriculture and several other industries.

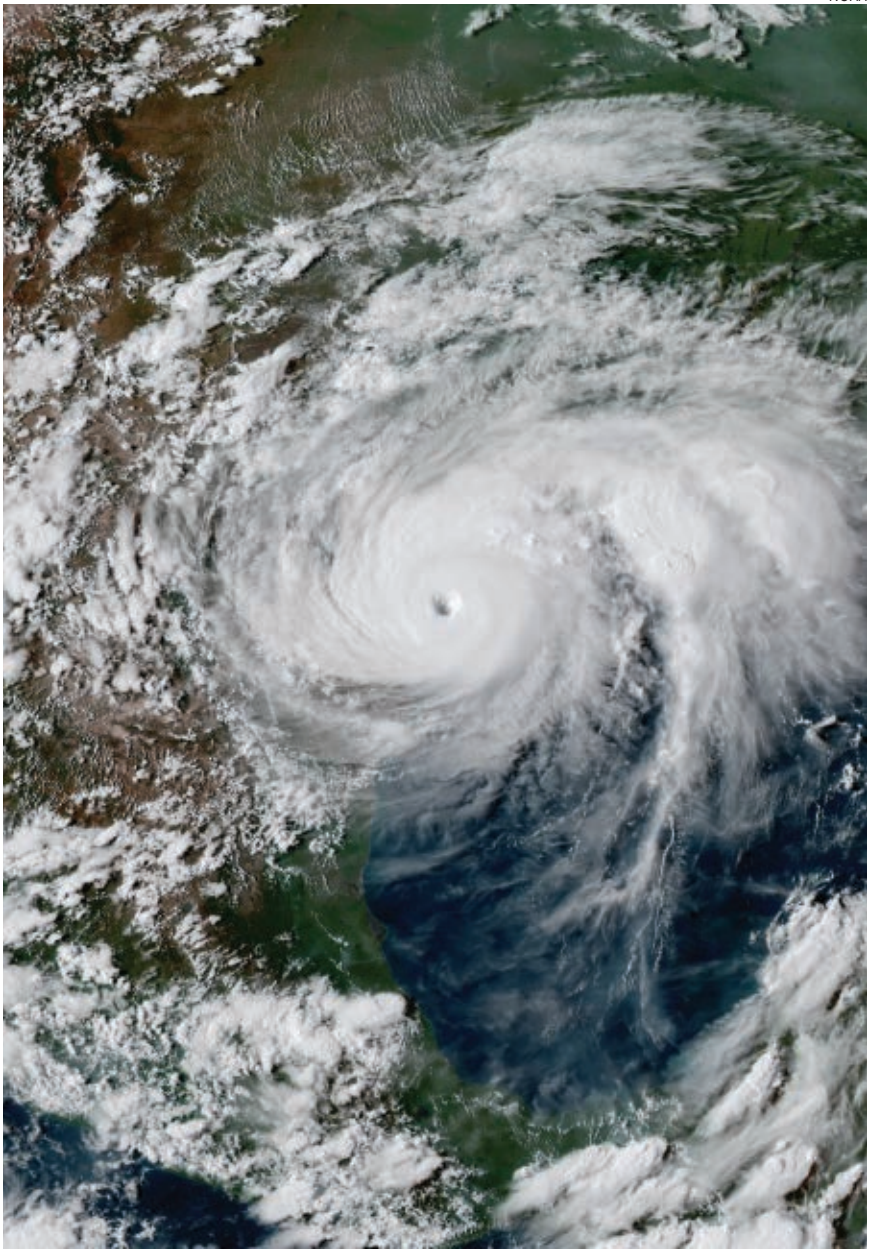
Formic acid, however, is a by-product of petrochemical manufacturing, and its manufacture "has nothing to do with CO_2 and hydrogen," says Huang. Combining CO_2 and hydrogen directly is at best 2% efficient, he says. Autrey, however, says that "on paper," at least, producing formic acid should require less energy than producing borohydrides.

David Kramer

Meteorologists predict better weather forecasting with AI

More advanced estimates of atmospheric conditions depend on merging the knowledge gained from humans and computers.

NOAA



HURRICANE HARVEY killed 107 people and caused $125 billion in damage when it hit the southeastern US in August 2017. Forecasters hope that people in the path of such severe weather events can benefit from local, more detailed weather predictions made possible with the help of artificial intelligence.

"The value of having data now is higher than it's ever been," says Greg Herman, a research scientist at the Climate Corporation in San Francisco, which uses weather information to help farmers manage risk. Weather forecasting is joining a growing number of fields, including financial management, internet advertising, oil and gas exploration, and scientific research, that are adopting artificial intelligence (AI) methods to analyze huge data quantities. (For other examples, see PHYSICS TODAY, February 2019, page 17, and the article by Sankar Das Sarma, Dong-Ling Deng, and Lu-Ming Duan, March 2019, page 48.) By processing more data in a shorter time, weather forecasters could use AI methods to improve the prediction accuracy of tornadoes and other weather patterns over traditional methods. Meteorologists hope those advancements may help save lives and money.

Despite the promise of AI's predictive capabilities, scientists face challenges in developing AI for operational forecasting. Preparing data for an AI algorithm, though faster than traditional methods, takes up to 90% of AI researchers' time, according to Herman. Climate change alters the multidecadal background state of the atmosphere, which makes it difficult for meteorologists to produce accurate predictions even with AI methods. And decision makers at the National Weather Service (NWS), for example, need to choose whether to allocate the limited financial and computational resources to AI-guided forecasts or other existing capabilities.

Artificially intelligent forecasts

Meteorologists currently forecast weather by collecting and processing observations such as temperature and pressure, assimilating those variables into numerical computer models, extrapolating the models into the future, and using the projections as the starting conditions for the next iteration. More data on finer scales improve forecasting, but traditional dynamical modeling and existing computing capabilities can't keep up. AI methods promise improvement by more efficiently mining data for useful features as both inputs and corrections to the outputs of weather forecasting models.

One class of AI method, machine learning, builds on traditional modeling techniques by learning to recognize weather features using training data—satellite imagery and ground observations, for example—that characterize multidimensional and nonlinear processes. NOAA's weather-satellite observing system now produces kilometer-resolution imagery every few minutes. With AI

NOAA NATIONAL SEVERE STORMS LABORATORY

FORECASTERS AND RESEARCHERS test artificial intelligence and other emerging methods to help improve the prediction of severe weather events as part of the NOAA Hazardous Weather Testbed experiment held each spring in Norman, Oklahoma.

methods, programmers can write algorithms to scale as more and better data become available. Thus they can avoid some of the shortcomings of more-established statistical methods, says David John Gagne of the National Center for Atmospheric Research in Boulder, Colorado.

Preliminary research suggests that machine learning results may outperform traditional approximations of some meteorological variables in a forecast. Those variables include soil moisture and temperature, which can fuel thunderstorms under the right atmospheric conditions, says Jebb Stewart, a scientist at NOAA's Earth System Research Laboratory in Boulder. With machine learning, more data are incorporated into the model without increasing the time required to complete the approximation. The traditional approach for estimating soil moisture saves scientists time and money by using only a fraction of the available data: the previously modeled value and the present estimate of surface temperature. By starting with a more accurate initial state of soil moisture, machine learning helps weather models run faster and make more accurate predictions.

Although computational power and memory continue to increase, weather models still must approximate solutions to the Navier–Stokes equations, which describe the fluid dynamics governing the atmosphere's behavior. Machine learning can identify biases and model errors, such as persistently lower surface temperatures compared with observations, and can apply corrections to the output more quickly and systematically than traditional statistical methods. People only acquire intuition for error identification over time.

Another AI technique, deep learning, works similarly to machine learning but extracts features such as low-pressure zones and tropical cyclones from an image by breaking them down to smaller components. Deep learning is often referred to as a black box because the smaller, hidden components of image features are unrecognizable to a human. The algorithm compares those deconstructed components of features with information it's been trained to recognize from an independent dataset. Forecasters can assimilate the satellite imagery analyzed by the deep-learning method into the weather model to make better predictions. Last year, the amount of weather data increased by several orders of magnitude after NOAA began releasing data from its latest *Geostationary Operational Environmental Satellite, GOES-17*.

A healthy skepticism

Some computer scientists have tried generalizing an AI algorithm designed for forecasting a specific weather feature, such as hail, to another, such as severe wind. But each feature has its own dynamical properties that interact with each other in different ways. "You can't just take the same black box and apply it to different problems. If the model doesn't make sense physically, meteorologists

aren't going to use it," says Amy McGovern, a computer science professor at the University of Oklahoma.

An AI method is only as good as the training data it uses. Some of the best sources of data, including the European Centre for Medium-Range Weather Forecasts, charge for access. And, says McGovern, "companies jumping in aren't willing to share data. They live in a world where their competitors can get an edge."

How data are collected may change to bolster the use of AI in forecasting. The training data must first be labeled and classified by a person or pass through a digital quality-control check. Quick and effective labeling by meteorologists or by the data-collection system itself would speed up the AI development cycle.

Computer scientists are still figuring out how to generalize an algorithm to work in different scenarios. AI methods, particularly deep learning, don't extrapolate well when the information used in their training changes to an unfamiliar pattern. Climate change makes training data less representative by altering the intensity, frequency, and spatial extent of extreme weather events.

Putting theory into practice

In meteorology and other fields, researchers are still working out how to overcome the limitations of nonrepresentative training data and develop more flexible AI. Despite the challenges, applying AI to weather forecasting is gaining in popularity. Several hundred people attended the AI applications conference at the American Meteorological Society's annual meeting in January, up from 40 or 50 a decade ago, says John Williams, former AI committee chair and a senior manager at the Weather Company, a forecasting and technology business of IBM.

AI adoption has already started, says Rich Sorkin, CEO and cofounder of Jupiter Intelligence, a Silicon Valley–based company that predicts damage, risk, and cost from severe weather and climate change. "A lot of the new graduates have been exposed to this in their academic studies, or they're just reasonably well-read," he says.

Later this year the Weather Company will deploy the IBM Global High-Resolution Atmospheric Forecasting System to provide hourly updates of weather conditions at 3 km resolution on land and forecasts out to 15 hours. The system will use machine learning to automate quality control, fuse data from many different sources—including pressure measurements collected with cellphone barometers—and apply corrections to the weather model output.

Since 2000 the NOAA Hazardous Weather Testbed in Norman, Oklahoma, has brought together meteorologists, computer scientists, software developers, broadcasters, and students for five to six weeks each spring to experiment with and evaluate the many emerging advances in severe weather forecasting. As part of the program, researchers and forecasters use the latest methods, including AI, to make daily severe weather predictions. Forecasters benefit from exposure to the latest scientific advances, and researchers gain valuable feedback about the strengths and weaknesses of their experimental methods. "Here, promising techniques can be shared with on-duty storm forecasters with almost the flip of a switch," says Patrick Marsh, a meteorologist at NOAA's Storm Prediction Center in Norman.

The promise that AI methods show in the experimental test bed doesn't guarantee success in an operational setting, cautions Marsh. The NWS weighs the benefits against the costs of each forecasting approach to uphold its mission of protecting life and property. To focus on producing superior hurricane-track forecasts using AI at the expense of accurate hurricane intensity, for example, may result in an overall worse prediction. "The AI is the easy part," says Marsh. "Prioritizing the results is the really hard part."

As AI weather forecasting enters the economy, some meteorologists worry that computers may take the jobs of people. "This is part of a much larger conversation we're having in our society," says Marsh. "Most people prefer a human there when the machine goes off the rails." And if forecasters aren't practicing their craft, skills and knowledge will atrophy over time, he says. A successful workflow requires humans to be in the loop, he adds. Humans can act both as a check for the AI and as a resource for AI developers to strive for the best possible weather forecast.

Alex Lopatka PT

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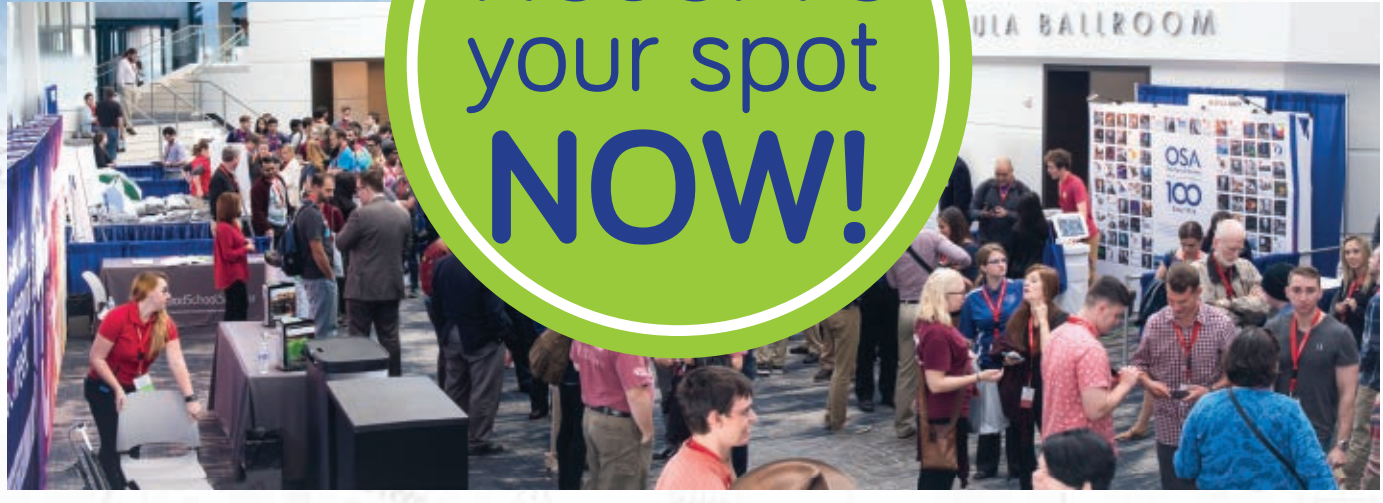

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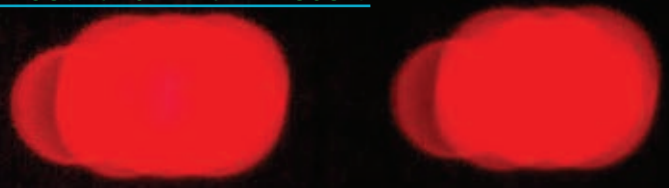
Tracking the journey of a URANIUM CUBE

A mysterious object led two physicists to investigate the German quest and failure to build a working nuclear reactor during World War II.

Timothy Koeth and Miriam Hiebert



In the summer of 2013, a cube of uranium two inches on a side and weighing about five pounds found its way to us at the University of Maryland. If the sudden appearance of the unusual metal cube wasn't intriguing enough, it came with a note that read, "Taken from the reactor that Hitler tried to build. Gift of Ninninger."

The world entered the nuclear age when the Trinity bomb was detonated on 16 July 1945 near Alamogordo, New Mexico. The origin of the age can be traced back through a small uranium metal cube and 663 others like it. The Manhattan Project and the immense power unleashed by the weapons it produced were created in response to fears that scientists in Nazi Germany were working on their own weapon. The cube, a component of the "reactor that Hitler tried to build," represents the Germans' failed endeavor that catalyzed the nuclear age.

Some questions remain. How did a piece of uranium from Germany end up in Maryland 70 years later? How many like it are out there? What happened to the rest? Who is Ninninger? Years of research into the cube and its history has revealed a complex, intriguing, and incomplete story. From our research, we have uncovered some new information about the German nuclear program itself: The Germans could have built a nuclear reactor.

The reactor that Hitler tried to build

Our investigation of the cube's origin began with the obvious. Had Timothy Koeth not recognized the cube immediately from old grainy photos in books on nuclear history, the first sentence of the accompanying note provided a starting point. "Taken from the reactor that Hitler tried to build" undoubtedly referred to the nuclear research program undertaken by German scientists during World War II in pursuit of nuclear

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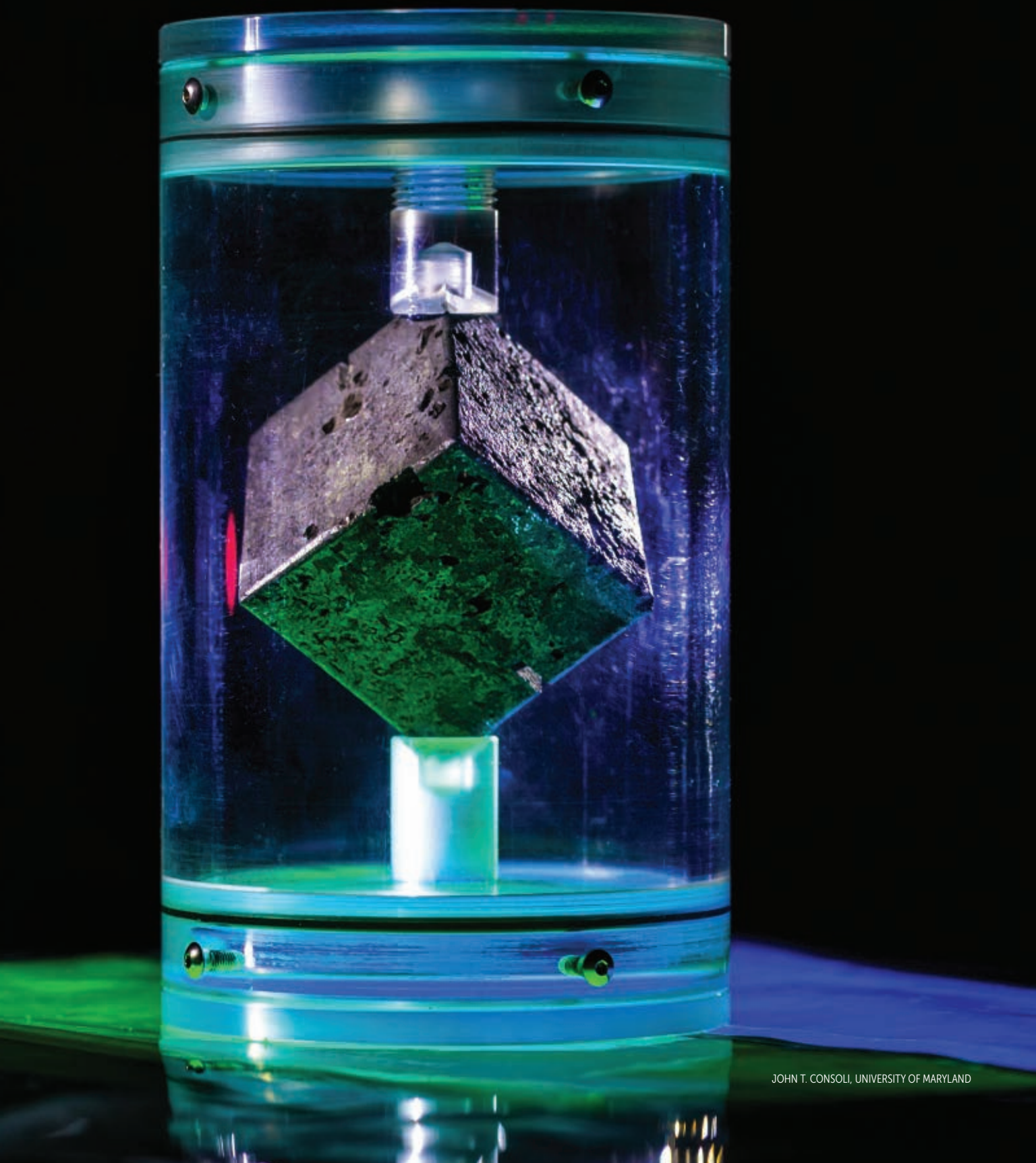


JOHN T. CONSOLI, UNIVERSITY OF MARYLAND

power and, potentially, a nuclear weapon. Several German physicists were involved in that research program; perhaps the most widely recognized was Werner Heisenberg.

Rather than working together under central leadership the way the Manhattan Project scientists eventually would, the German nuclear researchers were divided into three groups that each ran a separate series of experiments. Each was code-named after the city in which the experiments took place: Berlin (B), Gottow (G), and Leipzig (L). Although the Germans began their work nearly two years before serious US efforts began, their progress toward creating a sustained nuclear reactor was extremely slow.[1] The reasons for the delay were varied and complex and included fierce competition over finite resources, bitter interpersonal rivalries, and ineffectual scientific management.

In the winter of 1944, as the Allies began their invasion of Germany, the German nuclear researchers were trying desperately to build a reactor that could achieve criticality (see the box on page 41 for a description of the physics of nuclear reactors). Unaware of the immense progress the Manhattan Project had made, the Germans hoped that though they were almost certainly going to lose the war, they would be able to salvage the reputation of their physics community by being the first to achieve a self-sustaining nuclear reactor.[2]

In holding out that hope, officials moved the Berlin reactor experiments headed by Heisenberg south ahead of the Allied invasion. They eventually landed in a cave underneath a castle, shown in figure 1, in the small town of Haigerloch in southwest Germany.[3]

In that cave laboratory Heisenberg's team built their last experiment: B-VIII, the eighth experiment of the Berlin-based group. Heisenberg described the setup of the reactor in his 1953 book *Nuclear Physics*.[4] The experimental nuclear reactor comprised 664 uranium cubes, each weighing about five pounds. Aircraft cable was used to string the cubes together in long chains hanging from a lid, as shown in figure 2. The ominous uranium chandelier was submerged in a tank of heavy water surrounded by an annular wall of graphite. That configuration was the best design the German program had achieved thus far, but it was not sufficient to achieve a self-sustaining, critical reactor (see the article by Hans Bethe, PHYSICS TODAY, July 2000, page 34).

FIGURE 1. THE ENTRANCE TO THE LABORATORY of the B-VIII reactor experiment was underneath a castle in Haigerloch, Germany. The site is now home to the Atomkeller Museum. (Courtesy of the AIP Emilio Segrè Visual Archives, Goudsmit Collection.)

The cube

Our cube, shown in figure 3, was part of Heisenberg's B-VIII experiment. The faces of the cube contain large voids from bubbles that formed during a rough casting process. Those features are consistent with early uranium-processing methods where the metal components were cast individually.[5]

Two of the cube's edges have notches that were painstakingly hand filed. They would have served as tracks to hold in place the aircraft cable that was used to suspend the cubes in the long chains of the B-VIII setup.

We used nondestructive analytical techniques and nuclear forensics on the B-VIII reactor cube to confirm its identity in greater detail. High-resolution gamma-ray spectroscopy of the cube showed that its composition is that of natural uranium, not depleted or enriched, as shown in figure 4. Spectroscopy also confirmed that the cube of uranium was never part of a reactor that achieved criticality; it contained no telltale fission products, such as cesium-137. Both findings are consistent with what has been documented about the uranium used in the B-VIII reactor operation, which leads us to conclude that the cube is indeed an authentic one from Heisenberg's experiment.

The Manhattan Project and the Alsos mission

The next question to consider was how a component of the German nuclear reactor experiment ended up on the western side of the Atlantic Ocean. The answer lies in a well-studied and extensively documented aspect of World War II history: the Alsos mission.

In 1944, as Allied forces began moving into German-occupied territory, Leslie Groves, commander of the Manhattan Project, ordered a covert mission code-named Alsos (Greek word for "groves") to take a small number of military personnel and scientists to the front lines in Europe to gather information on the state of the German scientific program. The mission broadly aimed to gather information and potentially capture data and instrumentation from all scientific disciplines from microscopy to aeronautics. The most pressing task was to learn how far

German physicists had gotten in their study of nuclear reactions. The initial leg of the Alsos mission began in Italy and moved to Germany as the Allied military forces swept south.[6] Among the men involved in the mission was Samuel Goudsmit. After the war, he went on to be the American Physical Society's first editor-in-chief and the founder of *Physical Review Letters*.

As the Allies closed in on southern Germany, Heisenberg's scientists quickly disassembled B-VIII. The uranium cubes were buried in a nearby field, the heavy water was hidden in barrels, and some of the more significant documentation was hidden in a latrine. (Goudsmit had the dubious honor of retrieving those documents.) When the Alsos team arrived in Haigerloch in late April 1945, the scientists working on the experiment were arrested and interrogated to reveal the location of the reactor materials. Heisenberg had escaped earlier by absconding east on a bicycle under cover of night with uranium cubes in his backpack.[7]

On 27 April 1945, the remaining 659 uranium cubes were dug up from the field (see figure 5) and shipped, along with the heavy water, to Paris and later to the US under the control of the Combined Development Trust.[8] The CDT was a collaborative organization established earlier by Groves between the US and the UK to prevent adversarial countries such as the Soviet Union from obtaining enough nuclear material to develop a nuclear program of their own.[9]

If those cubes were shipped to the US, what happened to them after they arrived, and how did one end up in Koeth's hands? The most obvious use for large amounts of natural uranium metal at that time was weapons enrichment at Oak Ridge National Laboratory. However, given the pristine condition of our cube, something else must have happened. Perhaps after arriving in New York, some cubes found their way into the hands of one or more Manhattan Project officials as paperweight spoils of war. Trying to determine who might have distributed our cube and others like it led us to the National Archives at College Park, Maryland, where we unearthed another facet of the story.

There were more cubes

Many scholars have long thought that the German scientists could not have possibly created a working nuclear reactor because they did not have enough uranium to make the B-VIII reactor work. In Heisenberg's own words, "The apparatus was still a little too small to sustain a fission reaction independently, but a slight increase in its size would have been sufficient to start off the process of energy production."[10] That statement was recently confirmed using Monte Carlo N-particle modeling of the B-VIII reactor core.[11] The model showed that the rough analyses completed by the Germans in 1945 were correct: The reactor core as designed would not have been able to achieve a self-sustaining nuclear chain reaction given the amount of uranium and its configuration. But the design might have worked if the Germans had put 50% more uranium cubes in the core.

In looking for information on where the 659 Haigerloch cubes went, Koeth came across a box at the National Archives labeled "German Uranium." Rather than containing information on the whereabouts of the cubes in the US, the box had hundreds of recently declassified documents discussing other uranium cubes in Germany. Approximately 400 additional cubes of the exact size and shape of the Haigerloch ones were in Germany as part of another, later abandoned reactor experiment led by Kurt Diebner of the Gottow experiment group.[12] The combined inventory would have been more than enough to have achieved criticality in the B-VIII reactor.

Many contributing factors were likely involved in the resulting sequence of events, yet the revelation of the existence of the additional cubes makes it clear that if the Germans had pooled rather than divided their resources, they would have been significantly closer to creating a working reactor before the end of the war.

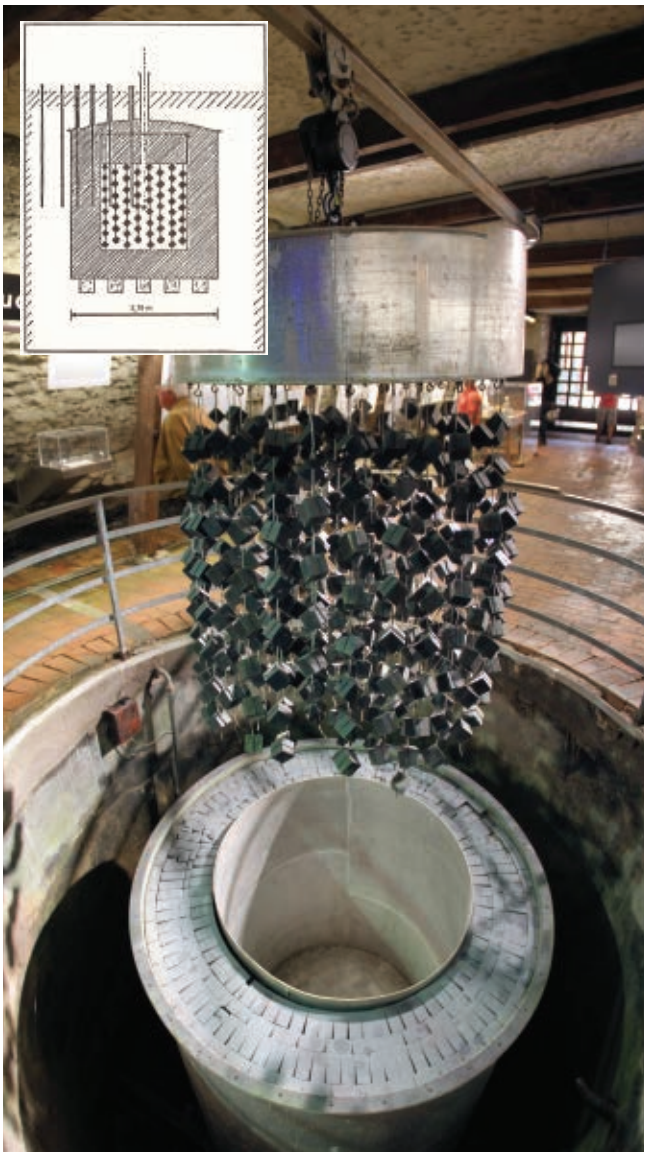


FIGURE 2. A DIAGRAM AND PHOTO showing the construction of the B-VIII reactor. The 664 uranium cubes were strung in chains using aircraft cable. The distances between the cubes in each chain and the chains themselves were precisely calculated, and in the final reactor design the entire apparatus was lowered into a pit filled with heavy water. (Diagram from ref. 4; photo from LepoRello, CC BY-SA 3.0.)

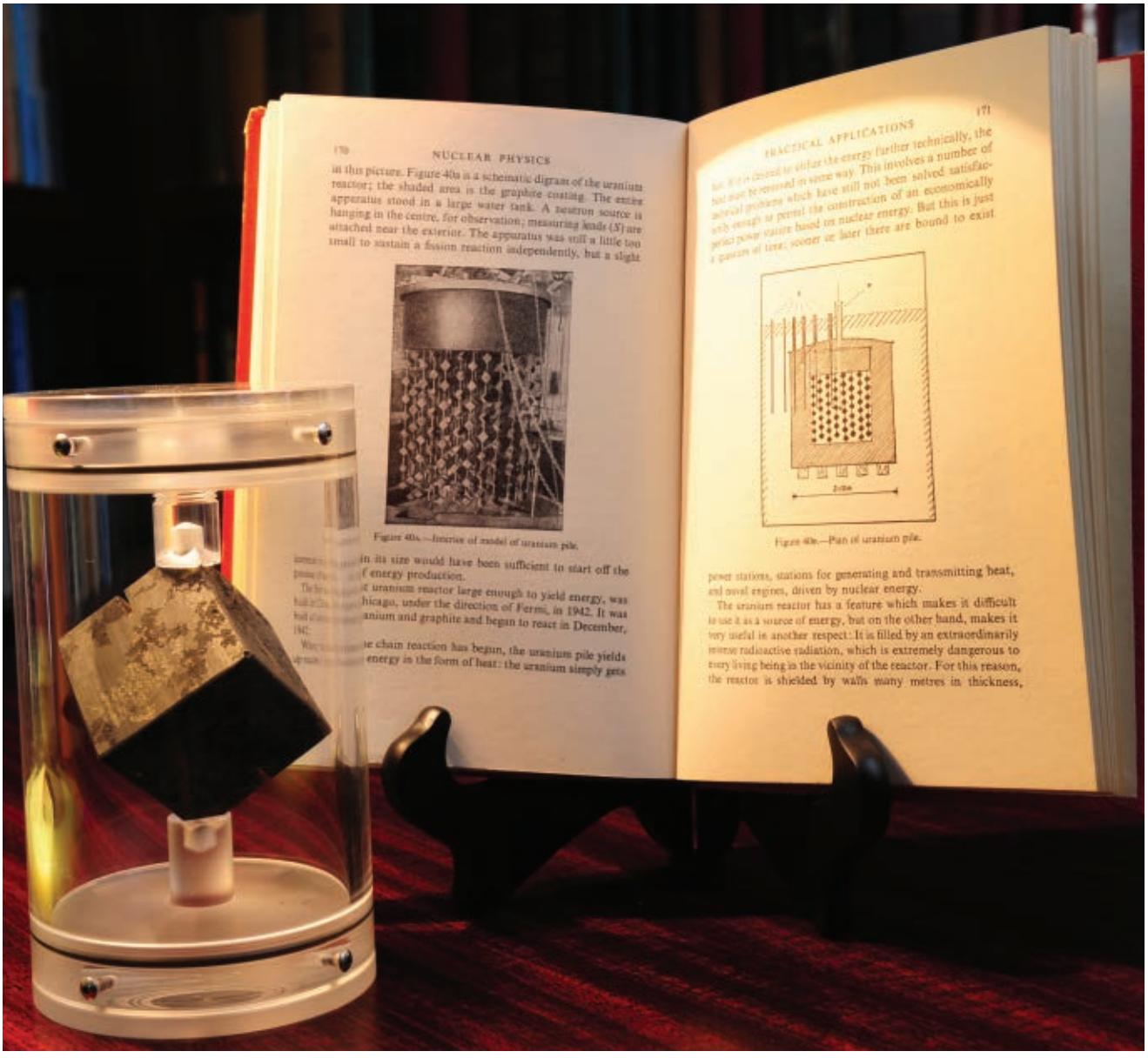


FIGURE 3. OUR URANIUM CUBE shown here weighs five pounds and measures two inches on a side. None of its faces are perfectly parallel. The large voids likely formed from bubbles made during the rough casting characteristic of early uranium-metal-processing methods. (Courtesy of Timothy Koeth, University of Maryland.)

The cubes fueled a black market in uranium throughout Eastern Europe after the war, peddled by what intelligence officer Joseph Chase described in a 16 March 1951 communiqué as a "ghostly gang" of profit seekers.[13] Since the Allied Control Commission prohibited German citizens from possessing any amount of uranium, the black-market dealers assumed the cubes were a rare commodity and took considerable personal risk in attempting to sell them.[14] Documents show that every few months, US officials received sinister letters, like one to the head of the Atomic Energy Commission, David Lilienthal, presenting opportunities to purchase a quantity of cubes for hundreds of thousands of dollars each, lest they be sold to entities "not considered over-friendly to the United States."[15] As the US was in no short supply of uranium ore by that time because of the work of the CDT, the US countered those offers with the going price of raw uranium metal, which was about six dollars per pound. The communications in the National Archives are replete with fantastic stories of con artists and smugglers trying to make a windfall profit and of scientists desperate to get their hands on small amounts of materials with which to continue their research.

In one such story, German citizens Helmut Goltzer and Gisela Nitzke were arrested and sentenced to life in prison in 1952 for the possession of a cube of uranium.[14] In the photographs accompanying the newspaper article about the arrest, the uranium taken from their apartment looks nearly identical to the cube in our possession. Upon hearing of the confiscated uranium during the trial, none other than Max von Laue wrote a letter to a Mr. Bierman imploring that he be given pos-

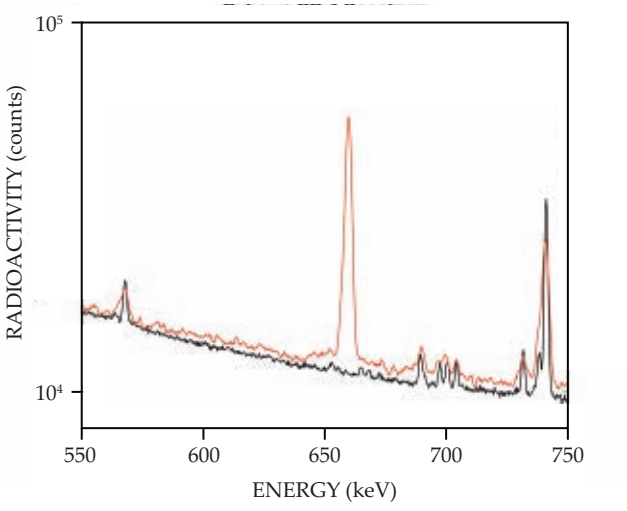


FIGURE 4. IN GAMMA-RAY SPECTROSCOPY, a peak at 662 keV indicates the presence of cesium-137, a ubiquitous fission product of uranium-235. The peak is present in the red spectrum obtained from a piece of the Chicago Pile-1 reactor, which achieved criticality; the piece is part of a collection of the Smithsonian National Museum of American History. However, the peak's noticeable absence in the spectrum obtained from our cube (black) confirms that it was never part of a critical chain reactor.

session of the cube for his research as it represented "irretrievable value since uranium, as you know, [could] not be bought in Germany."[16]

The documents at the National Archives also suggest that the majority of the cubes eventually ended up in the Soviet Union. Gordon Arneson, special assistant to the secretary of state, explained in a 1953 communication that every so often as "an offer is made to us of a kilogram or two of U-235 for a million dollars or so, a threat is delivered that the materials will be sold to the USSR unless the US purchases it. It seems that at last such a threat has materialized."[17] What happened to the cubes on their arrival in the Soviet Union is unknown.

Cubes in the US

Questions remained about our cube. If it wasn't processed at Oak Ridge, where was it for the intervening 70 years, and are there more out there? The second sentence on the note that was

THE PHYSICS OF A NUCLEAR REACTOR

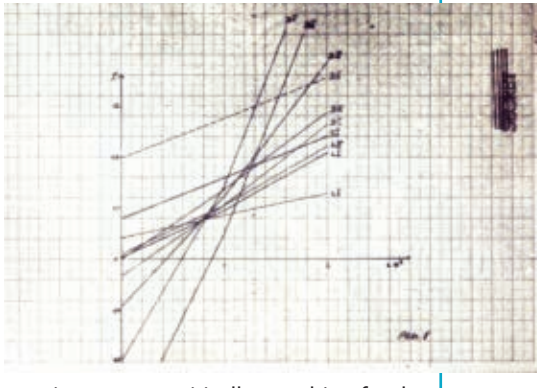
A nuclear reactor is at once both simple and complex. Once it is assembled, the only moving parts required are control rods that are moved in and out of the core to modulate its power output. However, choosing the appropriate number and orientation of a reactor's various components requires a detailed understanding of nuclear fission physics.

Fission readily occurs in a few isotopes of certain elements–for instance, uranium-235 and plutonium-239–when a neutron is absorbed into the nucleus. Because the nuclei of those fissile isotopes lie close to the edge of stability, the addition of a single neutron splits the nucleus into two smaller pieces called fission fragments, which are lighter elements such as barium and cesium. Along with those fission fragments, two or three neutrons are also ejected, and a large amount of energy is released that can be used for power generation. Since a single neutron leads to fission that produces more neutrons, the newly generated neutrons generate subsequent fission reactions, producing the famous nuclear chain reaction. The self-sustaining cycle perpetuates until all the fissile material is consumed. The process is the fundamental operating principal of a critical nuclear reactor.

A minimum quantity, the so-called critical mass, of fissile material is required to create a self-sustaining chain reaction. In a simplified model of the assembled pile of fissile uranium, two competing effects determine the neutron's outcome: The neutrons released from fission can lead to new fission or can escape the surface of the uranium pile and not participate in further fission. In practice, there are many other opportunities for neutrons to go unused, but with careful design, the neutron losses are surmountable, and self-sustaining reactors are possible. To quantify that condition, physicists talk in terms of an overall neutron multiplication factor, k_{eff}, which equals the number of neutrons in generation $n+1$ divided by the number of neutrons in generation n.

The self-sustaining status of a pile can then be placed into three categories. For a subcritical pile, k_{eff} is less than 1, the number of neutrons lost is greater than the number produced by fission, and the neutron population decreases with time. In a critical pile, where $k_{eff} = 1$, the population of neutrons remains constant from generation to generation. Finally, in a supercritical status, where k_{eff} is greater than 1, an increasing number of neutrons is produced each cycle. Steady-state operation of a nuclear reactor at $k_{eff} = 1$ requires continuous fine-tuning of the pile's geometry, typically by inserting or withdrawing one or more of the neutron-absorbing control rods, analogous to pressing on a car's accelerator or brake to maintain a constant speed.

In their experiments, the German scientists were empirically searching for the optimal geometry and minimum quantity of uranium needed. Placing a neutron-generating radium–beryllium mixture at the center of their pile as the initial source of neutrons, the German scientists measured the neutron population near the periphery as they added increasing amounts of natural uranium, which contains approximately 0.7% fissile ^{235}U.



The graph shown here was obtained by an Allied reconnaissance mission during World War II and shows the criticality calculations for each of the reactor experiments. (Image courtesy of the AIP Niels Bohr Library and Archives.) Each line plots the subcritical multiplication factor for an experiment. As the amount of uranium was increased with each experiment, the slope of the line will approach infinity. With each successive experiment, the slope of the line increases, showing that the German scientists were approaching, but never achieved, criticality.

FIGURE 5. THE CUBES FROM THE B-VIII REACTOR experiment during World War II were buried in a field near the underground laboratory. Members of the US Alsos mission to Germany found them and dug them up. Michael Perrin (far left), Samuel Goudsmit (third from left), and others are shown here retrieving the cubes from the ground. (Photograph by Samuel Goudsmit, courtesy of the AIP Emilio Segrè Visual Archives, Goudsmit Collection.)

included with our cube, "Gift of Ninninger," provided some hints but few substantial answers. In a bizarre stroke of luck almost too good for scientific minds to believe, Koeth was poking around a used-book store days after receiving the cube when he came across *Minerals for Atomic Energy* by Robert D. Nininger, published in 1954.

Despite the apparent misspelling of the name, Koeth decided the author had to be the man referenced in the note. Although Robert Nininger died in Rockville, Maryland, in 2004, a brief phone call with his widow confirmed our suspicions that he was likely the correct man. Nininger had apparently given the cube to a friend, and it changed hands once again before it got to Koeth. In March 1945, just a month before the Alsos seizure of materials at Haigerloch, Nininger was appointed interim properties manager for the Manhattan Project's Murray Hill Area in New York City.[18] The Murray Hill Area oversaw the uranium procurement efforts of the CDT. So Murray Hill was likely where the cubes were shipped to from Europe.

Ten other cubes, in private and public collections, have been identified around the country. Each has a different story for how it arrived at its current location, though most of the stories are incomplete at best. We hope to eventually trace all the cubes and their stories back to a common source. The Smithsonian Institution has one in its collection alongside a slug of uranium from the Chicago Pile-1 reactor. (Both are stored in the Washington, DC, area in a massive facility that calls to mind an Indiana Jones movie.) The cube was donated to its collection by Merril Eisenbud of New York University

Medical Center. In the letter he wrote to the curator of the physics collection at the time, he mentioned that he believed the cube was the only such one in existence. Harvard University also has a cube in its possession, donated by professor and Alsos mission participant Edwin Kemble. That cube is apparently passed among students in introductory physics courses: Its density makes it surprisingly heavy. There is no telling how many more cubes might be in university museums, private collections, and basements across the country. If interested readers have any information pertaining to one, the authors want to hear about it.

Lessons learned

The cubes represent a bygone era in science when researchers were just beginning to discover the subatomic world. We hope that by finding the cubes and piecing together what happened to them we will return a small amount of context to forgotten objects that have played a monumental role in human history. The cubes and the science they represent still shape modern life decades later.

Perhaps most importantly, the story of the cubes is a lesson in scientific failure, albeit a failure worth celebrating. The experiment they were part of, designed by some of the greatest scientific minds of the time, did not work. Thankfully for us all, the competitive approach and limited scientific resources of the German nuclear research program may have been what foiled Heisenberg and his colleagues in their pursuit of nuclear power. In science, as in other fundamentally human pursuits, we would do well to remember that we are only truly at our best and most equipped to tackle grand challenges when we put our differences aside and work together.

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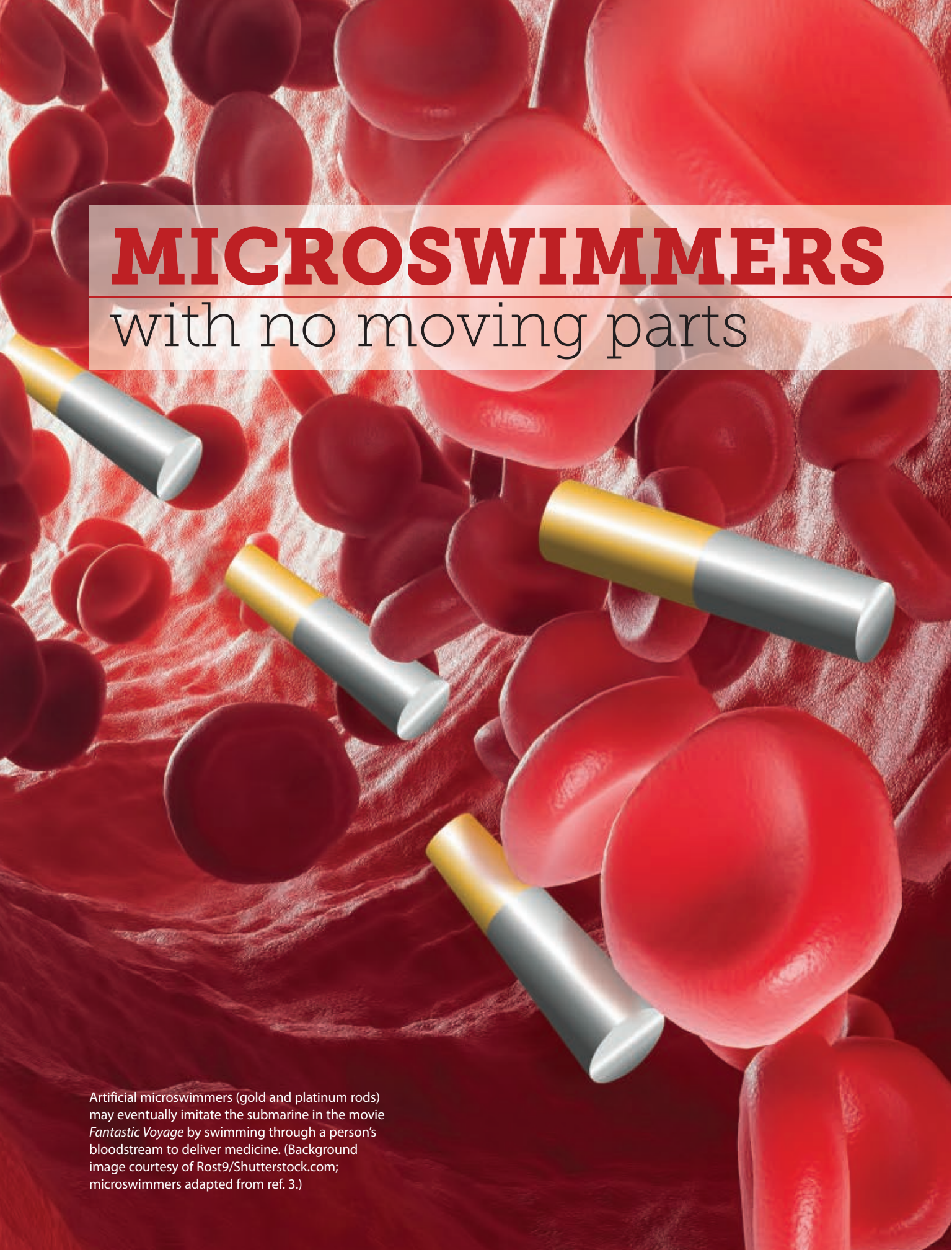
PT

MICROSWIMMERS
with no moving parts



Artificial microswimmers (gold and platinum rods) may eventually imitate the submarine in the movie *Fantastic Voyage* by swimming through a person's bloodstream to deliver medicine. (Background image courtesy of Rost9/Shutterstock.com; microswimmers adapted from ref. 3.)

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Jeffrey Moran and Jonathan Posner

Microscopic self-propelled particles could one day be used to clean up wastewater or deliver drugs in the body.

Swimming is a ubiquitous task performed by a broad range of creatures. Large animals, like whales or humans, generally swim by imparting backward momentum to the fluid, which results in forward motion of the animal through momentum conservation. The same strategy works even for relatively small animals, such as fish and tadpoles.

Microscopic organisms, such as bacteria, that are one-tenth to one-hundredth the size of tadpoles must also swim to find nutrients and avoid predators. However, the macroscale strategy of imparting momentum to the fluid is ineffective for them because of the low Reynolds number associated with the microscopic regime, in which viscous dissipation overwhelms the effects of fluid momentum. Picture a human trying to swim in molasses: Any effort to push fluid backward and thus generate forward motion would be stifled by the fluid's viscosity. Bacteria and other microorganisms face an analogous situation because they are so small that even water's viscosity is enough to overwhelm their negligible inertia. Despite that challenge, evolution has equipped microorganisms with a range of efficient swimming strategies that have enabled microscale swimming for millions of years.

Since the turn of the 21st century, scientists and engineers have begun to develop artificial analogues to natural microswimmers. Artificial microswimmers are colloidal particles, comparable in size to bacteria and typically 1–10 μm, that can propel themselves through liquids. Whereas naturally occurring microswimmers move by actuating appendages such as cilia or flagella, artificial microswimmers usually have no moving parts and instead generate propulsive forces by interacting with their environment through chemical reactions. The particles have been designed to perform complex behaviors and tasks, so they are being actively researched for various important practical applications from water treatment to drug delivery.

People have long been fascinated by the idea of microscopic self-propelled vehicles moving inside the body. In his 1959 lecture "There's plenty of room at the bottom," Richard Feynman spoke of one day being able to "swallow the surgeon." He challenged the scientific community to design a tiny motor that moves on its own and fits inside a cube 1/64 of an inch on each side. Nonscientists have been similarly enamored with the idea. The 1966 science fiction film *Fantastic Voyage* portrays a group of scientists who shrink themselves and their submarine, *Proteus*, to the size of a cell and are able to enter the bloodstream of a colleague and remove a blood clot from his brain.

Nanotechnology took several decades to catch up to that vision; not until the early 2000s were researchers able to successfully create artificial microswimmers. Through clever micro- and nanofabrication strategies, approximately a dozen designs for self-propelled particles have now been demonstrated.

Motion at the microscale

In 1956 biochemist Peter Mitchell proposed that some microorganisms might propel themselves through nonmechanical means without using any moving parts. He postulated that if a bacterium could pump ions across its membrane asymmetrically, such that ions would be pumped out of the cell on one end and back in at the other, an electrical circuit would form,[1] as shown in figure 1. Ions would flow from the rear of the bacterium's body to the front and in the opposite direction through the fluid adjacent to the surface of its membrane. In that way the organism would be propelled forward "much as a tread is used for the locomotion of a tank," as Mitchell put it. Using asymmetric ion pumping, an organism could, at least in principle, swim without flagella.

Phoresis is the motion of cells or particles due to a gradient of a specific quantity, such as electric potential (electrophoresis), solute concentration (diffusiophoresis), temperature (thermophoresis), or another quantity. It is a common mode of transport at the micrometer scale. Phoretic self-propulsion occurs when a particle or cell generates a motion-inducing gradient on its own and then moves in response to it. Mitchell dubbed his proposed bacterial swimming mechanism "self-electrophoresis."

Since Mitchell's proposal, several scientists have sought to determine whether any microorganisms move by self-electrophoresis. In the 1980s a marine cyanobacterium called *Synechococcus* was discovered to move in seawater despite having no visible appendages. Some scientists hypothesized that *Synechococcus* swam by self-electrophoresis; however, experimental measurements later showed that the organism lacks an appreciable surface charge and therefore cannot move under the influence of an electric field, either external or self-generated. The active propulsion mechanism driving *Synechococcus*'s motion remains an open question.

Although no conclusive evidence has been found—at least, none yet—that any microorganisms use self-electrophoretic propulsion mechanisms, self-propulsion can and does occur through electrophoresis, diffusiophoresis, and thermophoresis in engineered systems. Artificial microswimmers are microscale particles that generate chemical, electric, or thermal gradients in their vicinity through chemical reactions on their surfaces. Asymmetry in at least one quantity—such as electric potential, temperature, or concentration—is required to generate motion, and that asymmetry is typically generated through a nonuniform patterning of the particle surfaces. Most phoretic artificial microswimmers have opposite-facing sides with different chemical properties and are referred to as Janus particles, after the two-faced Roman god of beginnings and endings (see the Quick Study by Steve Granick, Shan Jiang, and Qian Chen, PHYSICS TODAY, July 2009, page 68).

Motion of microbatteries

Although it has yet to be definitively observed in nature, self-electrophoresis was the first mechanism realized in artificial microswimmers. In 2004 Walter Paxton, Ayusman Sen, Thomas Mallouk, and their colleagues at the University of Pennsylvania introduced autophoretic bimetallic rods.[2] The cylindrical particles were 2 μm long and 200 nm in diameter and consisted of two connected metal segments. Typically, the metals in such swimmers are gold and platinum, although other metal combinations can also be used. Each rod acts like a tiny battery, with platinum acting as the anode and gold as the cathode. When the bimetallic rods are placed in aqueous hydrogen peroxide solutions, electrochemical reactions on each surface create an electron current through the rod from the anode to the cathode and a complementary ionic current in the electrolyte. The oxidation reaction on the anode injects positive ions into the solution, and the reduction reaction on the cathode consumes positive ions. The reaction scheme is thus similar to the one Mitchell proposed, which is depicted in figure 1.

The reactions drive the locomotion of the rods. The products from those reactions, shown in figure 2, cause the fluid surrounding the Pt end to be positively charged and the fluid surrounding the Au end to be negatively charged, which generates an electric dipole and an associated electric field in the fluid.[3] The particle is ultimately propelled by the self-generated electric field because the field exerts a force on the positive charges in the electric double layer that surrounds the rods, and on the negatively charged rod itself. The positively charged fluid flows backward toward the cathode and the negatively charged rod moves with the anode facing forward. Like batteries, the rods convert chemical energy stored in the H_2O_2 molecules into electrical energy; unlike batteries, they then convert that electrical energy into kinetic energy.

When it comes to creating a self-electrophoretic particle, there is nothing special about platinum or gold. Rods fabricated from other metal pairs also self-propel in H_2O_2, and in each case the metal with less affinity for electrons is the one that faces forward during the motion.[4] For the gold–platinum rods, the platinum end always leads. Also, a greater difference in electron affinity between the two metals results in a greater driving force for the electron transfer and a faster swimming speed. Thus, electrochemical measurements can predict the direction and speed of a bimetallic rod's self-propelled motion.

Self-electrophoresis has been observed in other engineered systems using the same physical principles but different sources of energy. For example, the same mechanism underlies the self-propulsion of carbon fibers (roughly 1 cm long and 7 μm in diameter) in glucose solutions.[5] The anode end is coated with a

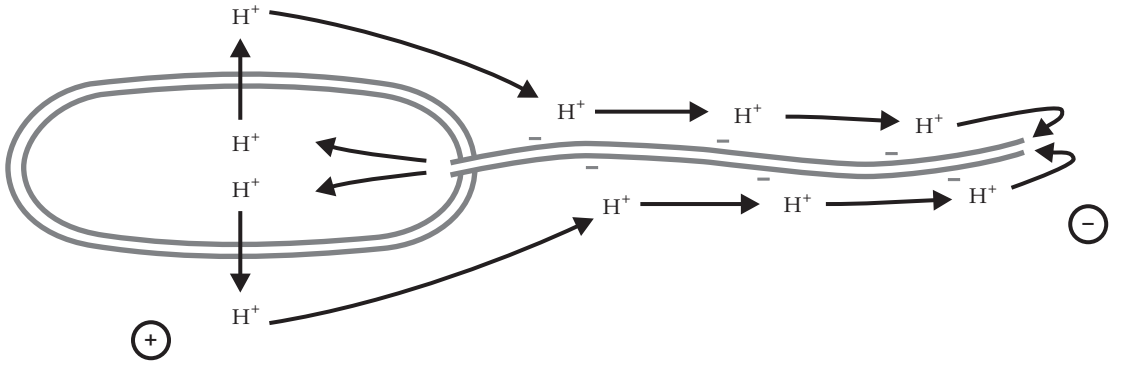

FIGURE 1. AN ELECTROKINETIC MECHANISM by which a bacterium could swim was proposed by biochemist Peter Mitchell. By pumping positive hydrogen ions out of its body and consuming them at its tail, the organism generates a stream of ions that moves alongside the outside of its body and in the opposite direction inside its body through the flagellum, completing an electrical circuit. The self-propelled motion occurs from right to left due to the negatively charged outer surface of the flagellum. (Adapted from ref. 1.)

catalyst that breaks down glucose. Electrons conduct through the fiber, and hydrogen ions migrate from the anode to the cathode end, which is coated with a different catalyst. At the cathode, oxygen combines with hydrogen ions and electrons to form water. If the electrical connection between the two ends is interrupted, the motion stops, which lends support for the self-electrophoresis mechanism.

Water and UV light can also be used as energy sources for self-electrophoresis. Titanium dioxide microspheres with one half coated in gold propel themselves in pure water under UV, with the TiO_2 end facing forward.[6] When TiO_2 is irradiated with UV, electron–hole separation occurs. The electrons that move to the TiO_2 conduction band have a high energy relative to what they would have in gold, so an electron current flows from the TiO_2 to the gold. Meanwhile, electrochemical charge transfer reactions occur on the TiO_2 and gold surfaces and produce a self-generated electric field that drives self-propulsion.

Artificial microswimmers, including self-electrophoretic ones, can be engineered to swim at greater than 1 mm—more than 100 body lengths—per second. By comparison, a Ferrari 488 sportscar traveling at its top speed of 205 mph moves only at about 20 body lengths per second. The speed of the particles generally increases with fuel concentration because the reactions driving the motion proceed faster. At high enough fuel concentrations, the velocity begins to level off, for two main reasons: First, there are a finite number of available sites on the metal surfaces for the reactions to take place; second, most of the reactions produce bubbles of molecular oxygen or hydrogen that can occlude the particle's reactive surface at fast reaction rates.

One drawback of self-electrophoretic microswimmers is that they must be operated in aqueous systems with very low salinity. Experimentally, even small concentrations of dissolved salts will substantially decrease the swimmers' velocity. Computer simulations at various salinities show that dissolved salts reduce the magnitude of the self-generated electric field, the reaction rate, and the particle surface charge. The particle velocity is roughly inversely proportional to the electrical conductivity of the solution.[7,8] Above a relatively modest salt concentration of 1 mM, the motion of platinum–gold rods is nearly indistinguishable from passive Brownian motion. Still, self-electrophoretic microswimmers are being considered for some low-salinity applications, such as motion-based contaminant sensing and removal in water samples.

A more neutral power source

Phoretic motion requires a gradient, but the gradient need not be in electric potential. Diffusiophoresis occurs when an object moves in response to a gradient in chemical concentration. When the object generates the gradient itself, the motion becomes self-diffusiophoretic. Unlike electrophoresis, diffusiophoresis can occur in gradients of neutral and charged solutes; however, most studies have focused on neutral solutes. Diffusiophoresis is thought to occur naturally in the locomotion of the bacterium *Listeria monocytogenes* and of some cells that crawl by using asymmetric polymerization of the protein actin.[9]

Self-diffusiophoresis requires that the swimmer induce a nonuniform concentration of a solute, typically through asymmetric surface reactions, as depicted in figure 3. The asymmetry in the solute concentration around the particle leads to imbalanced interaction forces between the solute and the particle. Common interaction forces between the solute and the particle stem from steric repulsion, hydration forces, van der Waals forces, and electrostatics. Those forces tend to be relatively weak, so self-diffusiophoretic swimmers typically move significantly more slowly than self-electrophoretic particles.

Swimming by self-diffusiophoresis was first proposed in 2005, around the same time research was beginning on the motion of self-electrophoretic platinum–gold rods. Ramin Golestanian and coworkers at the University of Sheffield proposed that a spherical particle could generate a neutral solute gradient if a single reactive site on its surface continually produced uncharged product particles or molecules. They calculated the resulting swimming speed as a function of the reaction rate.[10] Soon after the mechanism was proposed, a candidate system for self-diffusiophoresis was identified that used insulating microspheres, half-coated in platinum, that self-propelled with the insulating hemisphere forward and platinum-coated end backward in hydrogen peroxide solutions.[11] The dominant interaction mechanism for those swimmers is steric repulsion between the particle and the oxygen molecules generated in the peroxide decomposition reaction on the platinum surface. Since the particle–solute interaction is repulsive, the particle moves toward lower solute concentration.

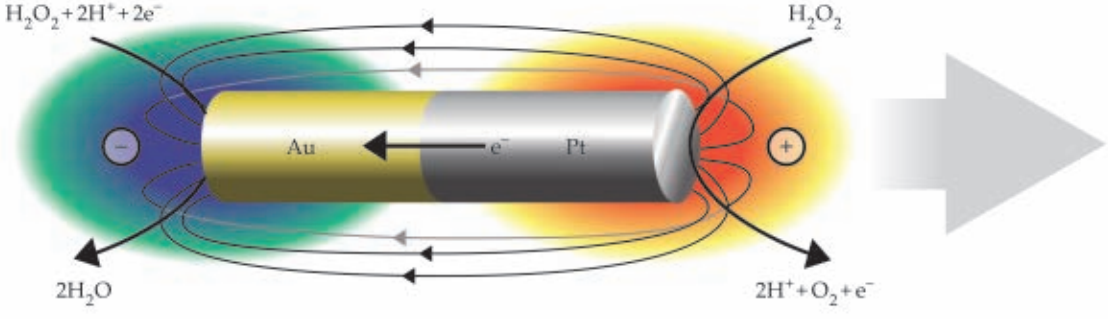

FIGURE 2. A PLATINUM–GOLD ROD UNDERGOES SELF-ELECTROPHORESIS in a hydrogen peroxide solution. The rod functions as a short-circuited electrochemical cell, with platinum acting as the anode and gold as the cathode. Oxidation and reduction reactions on the Pt and Au surfaces, respectively, lead to the establishment of dipolar charge clouds. The clouds form an electrical dipole, and an associated electric field, which then exerts a propulsive force on both the positively charged fluid surrounding the rod and the negatively charged rod itself. The result is self-generated motion of the rod from left to right. (Adapted from ref. 3.)

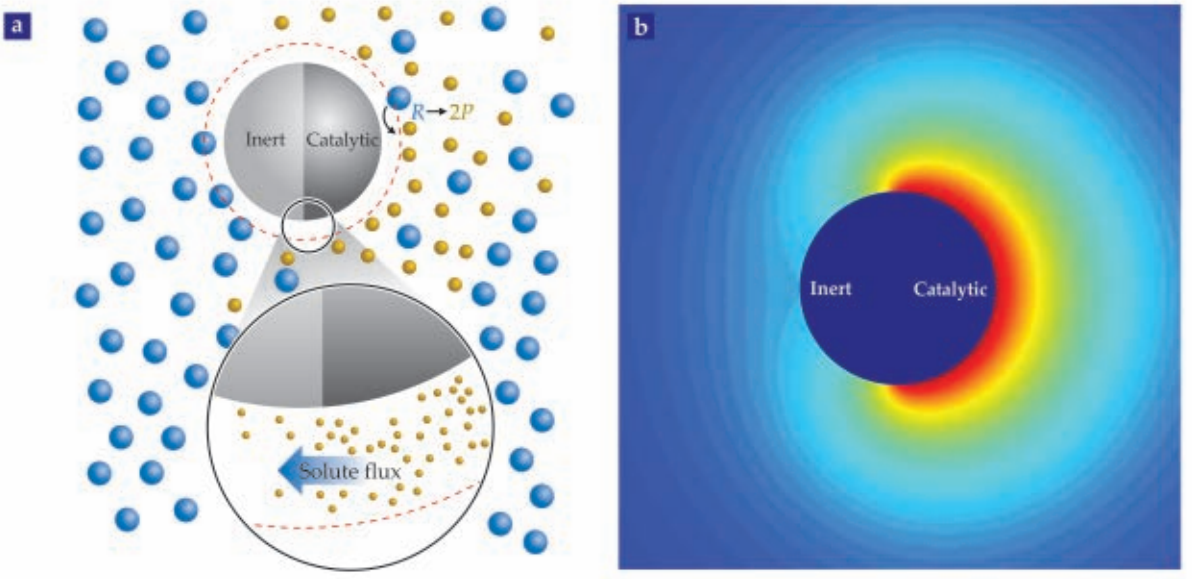

FIGURE 3. SELF-DIFFUSIOPHORESIS can propel particles in neutral solute gradients. **(a)** A Janus particle with two distinct sides is immersed in a solution containing a solute *R* (blue dots), which reacts when it contacts the catalytic half of the spherical particle, forming two product molecules *P* (orange dots). If the particle and the product molecules experience a mutually repulsive interaction force, the particle feels a net force from right to left. (Adapted from ref. 3.) **(b)** Solute molecules are asymmetrically distributed around a swimming particle. The solute molecules simply dock themselves on the catalytic hemisphere, and the repulsive interactions between the solute molecules and the inert side of the particle cause the particle to move from left to right. The colors represent the solute concentration, increasing from low (red) near the particle to high (blue) farther away. (Adapted from ref. 3 and U. M. Córdova-Figueroa, J. F. Brady, *Phys. Rev. Lett.* **100**, 158303, 2008.)

Other types of active particles have since been developed that appear more definitively to move by self-diffusiophoresis. One system uses gold–silicon dioxide Janus spheres with a catalyst on the SiO_2 hemisphere.[12] When the swimmer is immersed in a solution of monomer, the catalyst causes the monomer to form polymer chains on the catalytic SiO_2 surface and, in turn, decreases the local concentration of monomer on that side of the particle. The asymmetric polymerization results in a concentration gradient of monomer surrounding the swimmer, which causes the swimmer to propel away from higher concentration toward the polymerized end, again through repulsive steric interactions.

Some like it hot

Self-thermophoresis is the autonomous analogue to thermophoresis, the motion of particles or cells due to temperature gradients. In gases, thermophoresis is relatively straightforward. When a particle is immersed in a gas with a temperature gradient, the high-temperature gas molecules on the hotter side of the particle collide with the particle surface more frequently and with greater momentum, so that they propel the object in the direction of decreasing temperature.

In a liquid, particles typically move toward lower temperatures, as in the gaseous case; however, changing the environment by increasing the overall average temperature or by adding salt or a surfactant can cause particles to go toward warmer temperatures. The exact mechanism of thermophoresis in liquids is a topic of active research. Like other processes that occur spontaneously, it must be driven by a decrease in the Gibbs free energy of the system. Two main contributions to that energy of suspended colloidal particles are hydration forces and ionic shielding at the surface. At low temperatures and high electrolyte concentrations, the hydration entropy dominates, and motion toward warmer regions becomes thermodynamically favorable. At room temperature and in less-concentrated electrolytes, ionic shielding plays a greater role, and the particle tends to move toward lower temperatures.[13]

Like other forms of phoretic self-propulsion, self-thermophoresis typically occurs with an asymmetrically patterned colloidal particle. The prototypical self-thermophoretic system is a gold–insulator Janus particle driven by IR laser light. The particles are fabricated by taking silica or polystyrene microspheres and sputter-coating gold on half of the surface of each sphere.[14] The metallic side preferentially absorbs the IR radiation and becomes warmer than the insulating side; the temperature difference generates a temperature gradient in the surrounding solution and causes the particle to move.

The speed of laser-powered self-thermophoretic microswimmers increases with the intensity of the IR light and stops when the light is turned off. In that way, stop-and-go motion is achievable in pure water. Another advantage to not using chemical fuel is that the motion can essentially continue indefinitely as long as IR light is provided.

Complex and collective behaviors

Under a microscope, swimming particles behave similarly to microorganisms, such as motile bacteria. They change their swimming direction at regular intervals and interact with both solid surfaces and each other. Also, like some bacteria, artificial swimming particles respond to nonuniform solute concentrations, temperatures, and electromagnetic fields. Because of those apparent similarities, researchers have put significant effort into studying the complex and collective motion of artificial swimmers.

All micron-scale suspended particles undergo Brownian motion, which causes them to translate and rotate randomly due to thermal fluctuations. Self-propelled particles undergo

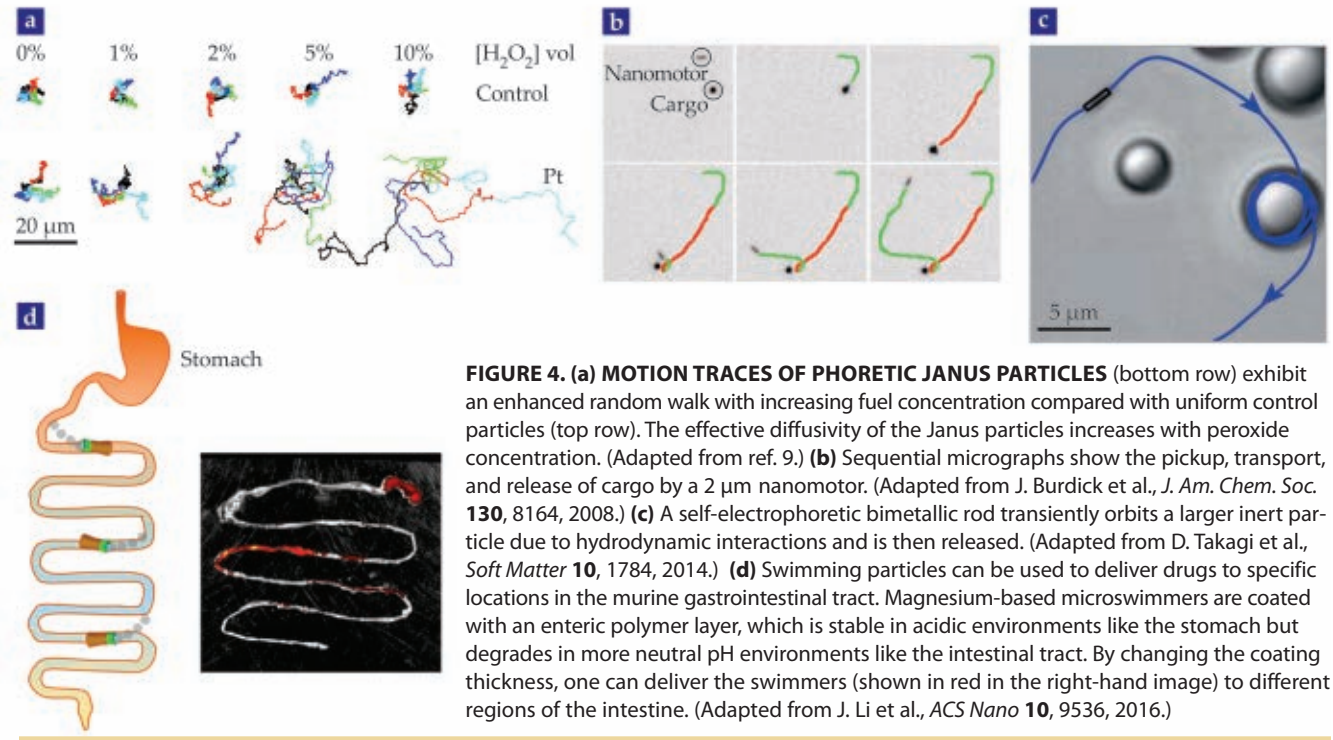

FIGURE 4. (a) MOTION TRACES OF PHORETIC JANUS PARTICLES (bottom row) exhibit an enhanced random walk with increasing fuel concentration compared with uniform control particles (top row). The effective diffusivity of the Janus particles increases with peroxide concentration. (Adapted from ref. 9.) **(b)** Sequential micrographs show the pickup, transport, and release of cargo by a 2 μm nanomotor. (Adapted from J. Burdick et al., *J. Am. Chem. Soc.* **130**, 8164, 2008.) **(c)** A self-electrophoretic bimetallic rod transiently orbits a larger inert particle due to hydrodynamic interactions and is then released. (Adapted from D. Takagi et al., *Soft Matter* **10**, 1784, 2014.) **(d)** Swimming particles can be used to deliver drugs to specific locations in the murine gastrointestinal tract. Magnesium-based microswimmers are coated with an enteric polymer layer, which is stable in acidic environments like the stomach but degrades in more neutral pH environments like the intestinal tract. By changing the coating thickness, one can deliver the swimmers (shown in red in the right-hand image) to different regions of the intestine. (Adapted from J. Li et al., *ACS Nano* **10**, 9536, 2016.)

an additional linear motion that is superimposed onto their translational and rotational Brownian motion. That superposition causes swimming particles to move persistently, but in randomly varying directions, exploring a much larger area than a freely diffusing particle would. Comparing the trajectories for Brownian particles and swimmers in figure 4a shows that the swimmers have a larger diffusivity. Over a 10-minute period, a passive particle may diffuse over a region of 35 μm^2, whereas a similar swimming particle may explore a region greater than 1 mm^2. That capability could be used for, say, delivering a drug to one region of the body with the goal of broadly distributing it.

Although most reports suggest that artificial microswimmers move in relatively straight lines with random perturbations, the particles have also demonstrated the ability to swim in tight circular patterns. They swim in circles due to an asymmetry, either unintentional or deliberate, in their geometry. As the particle swims, the asymmetry causes a larger viscous drag on one side versus the other, so the particle turns persistently in one direction. For short times circle-swimmers exhibit the large diffusivity of a swimmer, but for long times they show a reduced effective diffusivity because they swim back almost to their original position after a full revolution.

The swimming direction of a particle can be controlled using externally applied fields. A swimmer with an embedded magnetic segment will align itself in an external magnetic field. The microswimmer still generates a propulsive force on its own but moves in a direction aligned with the magnetic field. By combining those two mechanisms, a swimmer can be directed into predetermined patterns like microfluidic channels, reminiscent of when *Proteus* travels through Jan Benes's capillaries in *Fantastic Voyage*.

The swimmer could also use the same magnetic segment to pick up a paramagnetic particle and drop it off in another location, as demonstrated in several studies and shown in figure 4b. Like ants, artificial microswimmers can carry cargo more than 30 times their size. Because the swimmers are at low Reynolds number, it's the size, not the weight, of the cargo that determines its viscous drag. The cargo delivery capability has been used for purposes such as sorting cells or delivering drug-impregnated polymer particles.

Swimmers interact with surfaces and other particles through hydrodynamic, electrostatic, and phoretic forces. Long-range hydrodynamic forces can drive swimmers toward microscopic features, causing them to move along the boundaries of submicrometer-scale ledges and in intermittent circles around larger, immobilized spheres, like the rod in figure 4c. The chemical and electrical fields generated by swimmers have shorter ranges, so they can affect only interactions with nearby surfaces or particles. Interparticle interactions can be attractive, causing particles to cluster, or repulsive, causing particles to disperse, and the type of interaction can depend on the relative alignment of the particles and their associated fields.

Experiments have shown that autophoretic particles can exhibit taxis, which refers to the ability of an organism to sense an external stimulus, often light or the presence of a nutrient, and to move toward or away from it. Like some fish, engineered swimmers can exhibit positive rheotaxis, migrating against the current in a fluid flow.[15] Their upstream swimming originates from a viscous shear-flow-induced torque that persistently aligns the particles' swimming direction against the flow. Phoretic particles have also exhibited positive gravitaxis, upward swimming against the direction of gravity.[16] In that case, the particles are either geometrically or chemically anisotropic. In both cases the asymmetry leads to the displacement of the center of mass and results in a torque that aligns the particle with the gravitational field. Such behaviors could be used to design particles that can swim upstream in the circulatory

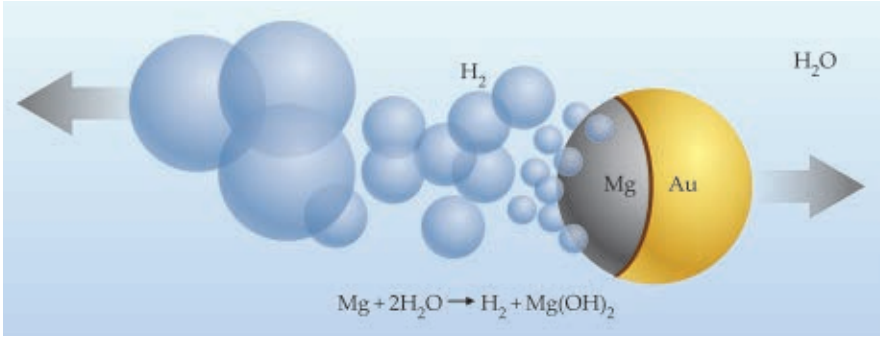

FIGURE 5. BUBBLE-PROPELLED MICROSWIMMERS generate hydrogen gas bubbles to push themselves forward. A sacrificial metal—in this case, magnesium—on one side of the particle reacts with water to form the bubbles. The gold on the other side of the particle does not react with the water. The particle experiences a recoil force on its left side from the separating bubbles and is pushed from left to right. (Adapted from ref. 18.)

system to deliver drugs or to the surface of a body of water to remediate toxic spills.

Applications in medicine and the environment

Artificial microswimmers are now being developed for biomedical applications. The *in vivo* environment poses challenges because it is often less hospitable to the mechanisms that drive swimmers' motion than pristine *in vitro* environments. Many swimmers require fuel, such as hydrogen peroxide, which would not be well tolerated by most animals at the concentrations needed for swimming. Additionally, *in vivo* conditions are typically salty—the average salt concentration in biological media is roughly 0.1 M—which precludes self-electrophoresis as a swimming mechanism.

An alternative mechanism is needed to propel microswimmers in those environments. Zinc, aluminum, and magnesium microswimmers dissolve in weakly acidic aqueous conditions and generate hydrogen gas bubbles that propel swimmers forward, as shown in figure 5. They are not phoretic, but instead are propelled forward by recoil forces generated by separating bubbles. Unlike phoretic microswimmers, bubble-propelled particles are not susceptible to dissolved salts, a major advantage for applications in organisms.

Several proof-of-concept studies from Joseph Wang's group at the University of California, San Diego, have demonstrated *in vivo* use of acid- and water-propelled bubble swimmers to deliver therapeutic payloads in mice. They use magnesium particles propelled by gas bubbles that form as the particle dissolves in stomach acid. The particles are coated with the antibiotic drug clarithromycin, which is used in humans to fight a *Helicobacter pylori* infection in the stomach and upper small intestine. In addition, microswimmers have been used to deliver drugs in the murine gastrointestinal tract (figure 4d). The process relies on clothing the swimmer with an acid-resistant enteric coating that degrades in the more neutral pH of the intestinal tract. The swimmers pass through the stomach unaltered but become motile once the enteric coating wears off; the point where the coating wears off and the swimmer becomes motile is determined by the thickness of the coating.

Christian Kastrup and coworkers at the University of British Columbia used other self-propelled microswimmers to deliver blood coagulants to severe hemorrhages in mice and pigs.[17] The particles, made from carbonate and tranexamic acid, used bubble propulsion to deliver thrombin, a blood clotting agent, several millimeters into the vasculature of a wound. When loaded with active thrombin, the particles halted severe hemorrhage in multiple animal models of intraoperative and traumatic bleeding.

Engineering swimmers to address environmental challenges, such as remediation of oil spills, may also be possible. When placed together with micron-scale oil droplets dispersed in seawater, magnesium particles asymmetrically covered with a hydrophobic coating swam through the suspension, and the oil droplets adsorbed onto the swimmers' hydrophobic surfaces.[18] The particles are propelled by breaking down seawater and generating hydrogen bubbles, similar to the gastric-acid-propelled swimmers mentioned above. The particles can be directed, collected, and reused, if they have a ferromagnetic metal incorporated into them.

Microswimmers can also clean up chemical pollutants by using them as fuel. Palladium-based swimmers in water can turn toxic nitroaromatic compounds—persistent, nonbiodegradable pollutants from industrial production of dyes and pesticides—into nontoxic by-products using a catalytic reduction reaction. Similarly, in the presence of light, TiO_2 particles use a photocatalytic reaction to destroy *Bacillus globigii* spores—a simulant of anthrax—thereby degrading an organophosphate chemical warfare agent into harmless by-products.

Engineered, self-propelled, microscopic particles that can autonomously interact with their local environment to perform useful functions sound like the basis for a hit science fiction movie. Researchers have made great strides in understanding the physics that drives them and in developing swimmers that operate in a wide range of real-world conditions. However, there are still many unanswered questions about the self-propulsion mechanisms. As the variety of artificial microswimmers grows and their general principles are better understood, the number of applications to people's health and the environment will expand rapidly.

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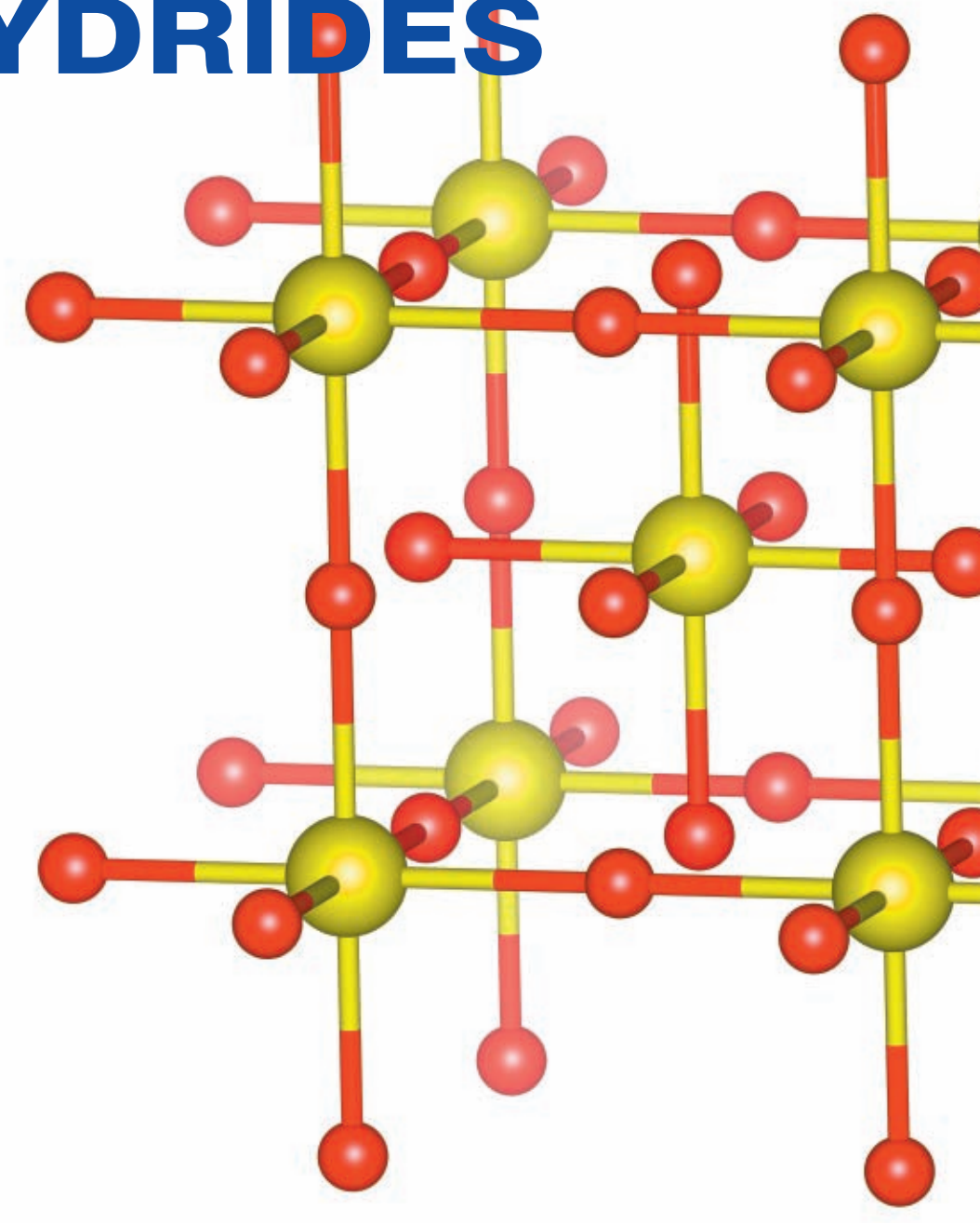
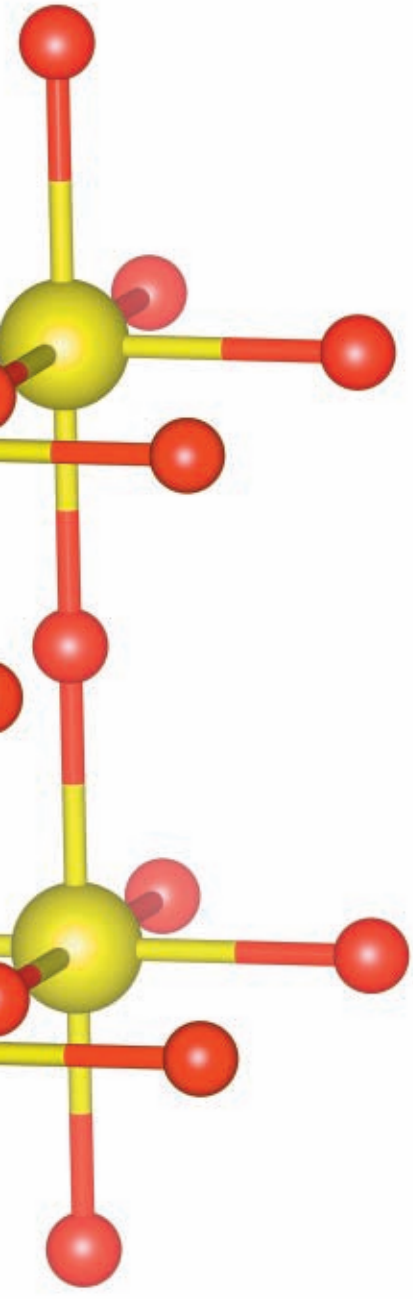
THE QUEST FOR ROOM-TEMPERATURE SUPERCONDUCTIVITY IN HYDRIDES

Warren Pickett and
Mikhail Eremets



Whereas previous discoveries of superconductors were largely serendipitous, the latest advances have emerged from the close coupling of theoretical predictions and high-pressure experiments.

Warren Pickett is a distinguished professor in the department of physics at the University of California, Davis.
Mikhail Eremets is a research physicist at the Max Planck Institute for Chemistry in Mainz, Germany.



When a material becomes superconducting below some critical temperature T_c, its electrical resistivity drops abruptly to zero. That complete loss of resistance may seem impossible because current-carrying electrons scatter from atomic vibrations, impurities, and crystal imperfections of the lattice. Electrons also ordinarily repel each other because they have the same negative charge. But two electrons in a metallic lattice can experience an attractive interaction through polarization of the positive ionic lattice, as explained in box 1. Because of that interaction, pairs of electrons with opposite momenta and spin angular momenta can bind together. Those Cooper pairs coalesce into a coherent wavefunction known as the superconducting condensate.

First observed soon after helium was liquefied in 1908 (see the article by Dirk van Delft and Peter Kes, PHYSICS TODAY, September 2010, page 38) and today open to simple tabletop demonstrations, the superconducting condensate holds a unique standing in physics. Rather than being a normal metal in which even small electric voltages drive conducting charge carriers, a superconductor exhibits an energy gap—the energy 2Δ required to split a pair out of the condensate—that is explained in box 2. In BCS theory, developed by John Bardeen, Leon Cooper, and J. Robert Schrieffer in 1957, the gap directly relates to the critical temperature T_c at which electrons no longer scatter from vibrations or impurities: $2\Delta = 3.52\ k_B T_c$, where k_B is Boltzmann's constant.

An energy bandgap, which provides zero conductivity, is the *sine qua non* that distinguishes insulators such as silicon, diamond, and sodium chloride from normal metals. The superconducting gap is far different. It provides, via the underlying condensate, an infinite conductivity. That characteristic reflects the counterintuitive property that superconductors conduct electricity in the absence of any applied electric voltage.

The tabletop demonstrations of a supercurrent include zero resistance and the exclusion of an applied or existing magnetic field. The conduction of electric current without resistance—and thus without heat dissipation or power loss—forms the basis of most applications developed for superconductors. Magnetically levitated trains, for instance, now operate in a few parts of the world, and superconducting magnets are common in hospitals worldwide for MRI machines.

A larger goal is long-range power transmission without energy loss. If industrially applicable materials could be designed, discovered, or engineered, the savings in electrical power would be tremendous. (See PHYSICS TODAY, March 1996, page 48, and January 2008, page 30.) The full story is more complicated, but superconducting power transmission, if it were produced at room temperature, would constitute a transformative technology. The achievement would not be free of complications—even the best material candidates would suffer some dissipation under large current loads. The challenge would be to design an optimal system.

For physicists, chemists, and materials scientists, the challenge is to achieve the superconducting state at increasingly higher temperatures. The primary task in reaching that goal is to understand the theoretical and practical limitations of the superconducting critical temperature. That kind of materials challenge, broadened to applications in clean energy,

national security, and human welfare, was behind the 2011 introduction of the Obama administration's Materials Genome Initiative (www.mgi.gov). The motivating idea was to integrate the rapidly expanding capability of computational simulations of materials with experimental synthesis to speed products' time to market and to stimulate the design and discovery of new materials—for instance, ones that will superconduct at higher temperatures. Therein lies a parable.

In June 1973 PHYSICS TODAY published a letter to the editor (page 11) that included the maximum known values of T_c versus time. The data from 1911 to 1973, presented in graphical form (figure 1), fit well into a straight line of slope three degrees per decade. Its author, Bruce Friday, joked that room-temperature superconductivity was within sight, as long as one's sight extended to the year 2840.

The letter's implied conclusion could hardly have been more discouraging. In 1973 the maximum T_c was a mere 23 K. Fortunately, the outlook improved. Little more than a decade later came the announcement and rapid confirmation that layered copper oxide compounds provided superconductivity near 100 K. With applied pressure, that critical value rose to 160 K. The achievement vitalized the field. The 1987 March Meeting of the American Physical Society featured a marathon session—now known as "the Woodstock of physics"—of about 50 presentations on the superconducting cuprates.

Although some impressive and serendipitous developments have emerged, the 160 K maximum stood for 25 years. A recent article celebrating the history of *Reviews of Modern Physics* observed that "progress in discovering new superconductors has always been linked to the clever performance of making the correct material" (Art Hebard and Greg Stewart, PHYSICS TODAY, February 2019, page 44).

In this article we illustrate how that paradigm is shifting. Computational theorists and experimentalists are currently partnering to design and discover new superconducting hydrides with the highest critical temperatures ever found. Three years ago, one of us (Eremets) found that pressurized sulfur hydride superconducts at 203 K (see PHYSICS TODAY, July 2016, page 21). And more recently, reports have emerged that lanthanum hydride superconducts at temperatures as high as 280 K (see "Pressurized superconductors approach room-temperature realm," PHYSICS TODAY online, 23 August 2018.)

Progress in context

BCS theory provides an understanding of superconductivity as arising from the pairing of electrons via quantized lattice vibrations, or phonons. A primary result was an expression for the critical temperature in the form $T_c \sim \Omega \exp[-1/(\lambda - \mu^*)]$, where Ω is the characteristic phonon vibration frequency, λ the electron–phonon coupling constant, and μ^* the Coulomb pseudopotential—a measure of the Coulomb repulsion between electrons.

The BCS expression is valid for when the coupling λ is weak. In the late 1960s William McMillan of Bell Labs extended the BCS analysis to moderately strong coupling. His equation for T_c was extrapolated beyond its regime of validity to fortify claims that 30 K would be the upper limit for electron–phonon coupling. But rigorous analysis of strong-coupling theory in 1975 by Philip Allen of Stony Brook University and Robert Dynes of Bell Labs demonstrated that T_c continues to increase (rather strongly) with increasing coupling strength, everything else being equal.

Although substantial experimental searches persisted, no superconductors with T_c higher than 23 K were found over a 15-year period. In 1986 Georg Bednorz and Alex Müller, of IBM Zürich, discovered an entirely new class of superconductors, the magnetic copper oxides. The initial values of T_c were around 30 K, but shortly thereafter they were extended by other researchers to 160 K under pressure. What's more, the magnetism found in those cuprates rendered conventional BCS theory inapplicable.

Aoyama Gakuin University's Jun Akimitsu's 2001 discovery of BCS superconductivity at 40 K in magnesium diboride (MgB_2)

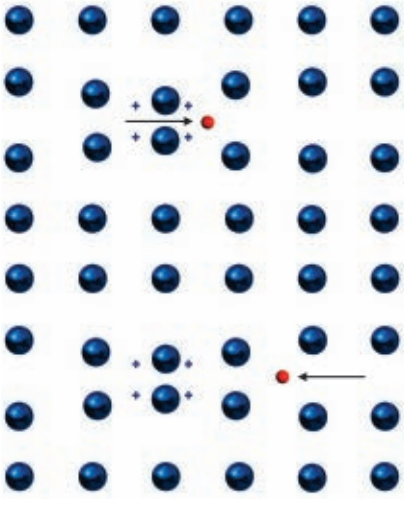
Box 1. Superconducting pairing of electrons

BCS theory—named after its authors John Bardeen, Leon Cooper, and J. Robert Schrieffer—established the two features underlying the superconducting state: the pairing of electrons and subsequent coalescence of those pairs into a coherent superconducting wavefunction. Each pair has an energy within a range of 2Δ of the Fermi energy (the highest energy of occupied electronic states), has equal and oppositely directed momenta **k**, and has oppositely directed spin angular momenta σ, conventionally called up and down.

The pairing is a consequence of the effective interaction strength λ between electrons. Although the direct Coulomb interaction is repulsive, an effective interaction due to lattice vibrations or magnetic fluctuations may become attractive. The electron–phonon coupling term λ is then defined as positive, and larger λ leads to a higher critical temperature T_c, at which a material starts superconducting. (See the article by J. Robert Schrieffer, PHYSICS TODAY, July 1973, page 23.)

Fast-moving electrons become coupled to heavier, slow-moving atomic cores. As shown here, a negatively charged electron (red) with quantum numbers **k** and σ careens through the lattice, distorting positively charged ions in its wake. Traveling in the opposite direction, the pairing electron with $-\mathbf{k}$ and $-\sigma$ feels the attraction of the deformed lattice and becomes bound—in energy if not in real space—to the initial electron. Although the interaction occurs over a long time, the electrons are spatially close for only a short time, and the repulsive Coulomb interactive assumes a minor role.

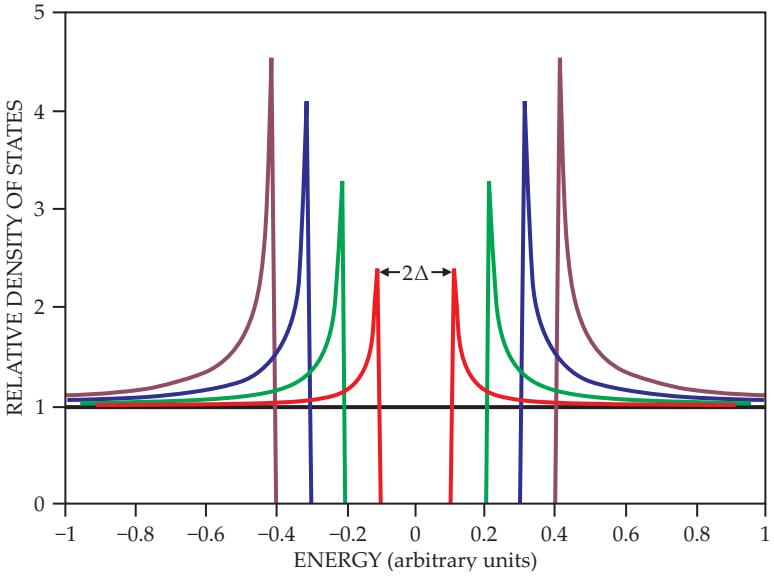
COURTESY OF AMBER CRENNA-ARMSTRONG



Box 2. Metals versus superconductors

The defining property of a metal is that it conducts electricity in response to an imposed electric field. The microscopic quantum mechanical description invokes the electron's dispersion relation, energy $E_{\mathbf{k}}$ versus wavevector $\mathbf{k}$. Although $E_{\mathbf{k}}$ is quantized at each $\mathbf{k}$, crystalline solids have energy bands in which momenta are continuous and the bands can be measured. Those bands are crucial for extracting charge and heat-transport coefficients, but much electronic behavior can be described by a density of states function $N(E)$, whose value at energy E is obtained from all bands where $E_{\mathbf{k}} = E$. States are occupied by accommodating all the electrons in the crystal up to an energy maximum, the Fermi energy E_F. Electrical and thermodynamic properties at and below room temperature are determined by states near E_F, with a relative concentration of states being the density of electron states at zero energy, $N(0)$.

Superconductors are metals that are cooled below their superconducting transition temperature T_c. (Note that many metals never superconduct, no matter how cold they become.) At and below T_c, electrons bind with each other in pairs and condense into a single coherent superconducting wavefunction Φ. The state described by Φ possesses a finite energy gap 2Δ. The gap, centered at E_F, is an energy range in which no states exist; the states that fall in that energy range above T_c have been repelled into regions just above or just below the gap. The number of such states that are affected is $2\Delta\, N(0)$. The larger the density of states $N(0)$, the larger the number of pairs, the larger the value of 2Δ, and the higher T_c becomes.



The figure illustrates the density of states of a superconductor. A metal has a constant value, normalized to unity here, drawn as the horizontal black line. The red, green, blue, and brown curves show the superconducting $N(E)$ for progressively larger energy gaps 2Δ of 0.2, 0.4, 0.6, and 0.8, respectively, as temperature is lowered.

brought to light yet another new class of superconductors—those in which strong covalent bonds are driven metallic by chemistry.[1] (See PHYSICS TODAY, April 2001, page 17, and the article by Paul Canfield and George Crabtree, PHYSICS TODAY, March 2003, page 34.) That event also energized the field but did little to alter entrenched opinions about the limit of T_c.

In 2014 Eremets and colleagues at the Max Planck Institute for Chemistry reported[2] yet another major achievement: the discovery of superconductivity in sulfur hydride at a T_c of approximately 200 K at 150 GPa. The H_3S discovery was also the first time that a previously unknown material was predicted to be superconducting and, at roughly the same time, experimentally confirmed to be so.

The history goes back decades. In the late 1960s Neil Ashcroft of Cornell University and Vitaly Ginzburg of the P. N. Lebedev Institute in Moscow proposed, at about the same time, that the critical temperature of metallic hydrogen should be high because its lattice vibrations are high,[3] even while the material retains a high λ. Metallic hydrogen is tremendously difficult to study, though. For one thing, it requires pressures of the order of 500 GPa, or 5 million atmospheres, to make measurements in the superconducting state.

In 2004 Ashcroft proposed focusing on hydrogen-rich materials,[4] namely methane and its silicon-based cousin, silane (SiH_4), under pressure. The materials' solid forms can be considered chemically "precompressed" hydrogen—the important atomic nature of hydrogen is achieved at much lower pressure than it can be in elemental form. The metallic yet covalent hydrides have the potential to superconduct at high T_c for the same reasons that hydrogen does at extreme pressures.

Although precompressed, the hydrides still require 100–200 GPa to be driven into the metallic state. Such pressures are generated by confining a sample (typically tens of square microns in size) within a gasket compressed by two opposing diamond anvils, as illustrated in figure 2. Such tiny samples can be probed with various experimental techniques, including resistivity measurements, optical absorption, reflection spectroscopy from the IR to the UV, Raman scattering, and x-ray diffraction. Magnetic-susceptibility measurements are also possible on tiny samples at high pressure.

Ashcroft's focus on hydrides opened a broad and abundant class of materials to study. However, initial experimental searches were largely unsuccessful. Some materials, such as methane, ammonia, and water, resist transforming into metals even at the highest available pressure. Fortunately, theory was coming to the rescue: Computational developments based on density functional theory were making realistic first-principles predictions of stable new materials and calculations of their critical temperatures.

In the late 1980s, researchers began making *ab initio* predictions of new high-pressure phases of Si. Those predictions became more relevant following Ashcroft's 2004 proposal.[4] (See references 5 and 6 for reviews of the literature.) Once the most stable structure at a given pressure was found computationally, the electron and phonon spectra, the material's coupling constant λ, and T_c could be calculated. Many such calculations

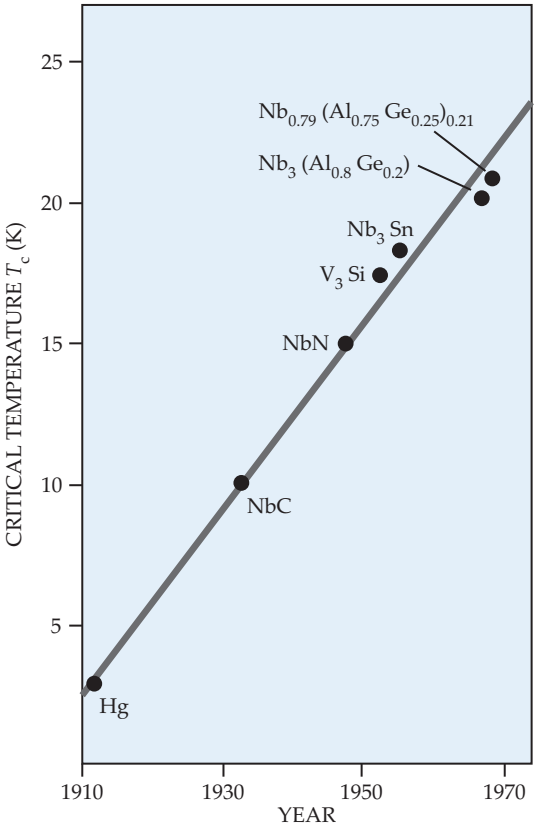


FIGURE 1. BRUCE FRIDAY'S 1973 GRAPH of maximum transition temperature T_c of all known superconductors as a function of time. A linear extrapolation of the plot suggested that not until the year 2840 would experimentalists be likely to discover a room-temperature superconductor. (Adapted from PHYSICS TODAY, June 1973, page 11.)

predicted that several hydrogen-rich compounds superconduct between 100 K and 300 K. But at the time, several of the results struck researchers as implausibly high.

From H_2S to H_3S

Early experimental attempts to verify the calculations were discouraging. Although predicted to have a critical temperature of 166 K at 200 GPa, SiH_4 was found to superconduct at a modest 17 K. Five years ago Yanming Ma of China's Jilin University and his colleagues published a computational study of hydrogen sulfide (H_2S) under high pressure.[7] Their predicted T_c of 80 K at 160 GPa was twice as high as the best BCS superconductor at the time, MgB_2. Previously, H_2S had not seemed particularly promising because of its small atomic fraction of hydrogen.

Experimentally, the material is attractive because the sample can be prepared from commercially available gas by direct condensation in the diamond anvil cell. The outlook improved as signals of T_c at 50–60 K were detected. Those values were at least comparable to predictions and would be record breaking for conventional superconductors.

The sulfur hydride (H_3S) discovery came on the heels of a surprising realization: During the usual pressure and temperature cycling used to prepare the sample for testing, H_2S transforms into H_3S at high pressure, and it stabilizes at 200 K after the material is first heated to room temperature. The H_2S sample used by the researchers decomposed into sulfur particulates and a phase richer in hydrogen. The hydrogen's higher content in the new phase was thought to be responsible for the increase[2] in T_c. Subsequent testing—in particular, x-ray measurements consistent with cubic H_3S as the superconducting phase—bore out that suspicion.[8]

The superconductivity in H_3S was supported by several measurements: zero resistance; a large susceptibility swing at T_c, which signals a superfluid response; a reduction in T_c due to an applied magnetic field that acts to align spin directions of pairing electrons; and a large, downward "isotope shift," shown in figure 3. When deuterium is substituted for hydrogen, its mass (twice that of hydrogen) reduces the phonon frequency and T_c with it. (For an early description of the effect, see the article by Emanuel Maxwell, PHYSICS TODAY, December 1952, page 14.)

One crucial measurement, the Meissner effect—the exclusion of a magnetic field by the onset of the superconducting state—required a new technique in diamond anvil cells. The effect had been measured previously in materials only at more modest pressures, one-tenth the pressure required for H_3S. The expulsion of a magnetic field from a superconductor can be measured with a sensitive magnetometer such as a superconducting quantum interference device. A new pressure cell that could accommodate a SQUID less than 9 mm in size was built within two months and applied successfully. Other experiments determined the superconducting gap from IR spectroscopy.[9] (For a detailed history, see M. I. Eremets, A. P. Drozdov, *Physics Uspekhi* volume 59, page 1154, 2016.)

At roughly the same time the experimental discovery was published,[2] Ma's paper was followed by the stunning prediction[10] from Tian Cui's group, also at Jilin University, of superconductivity in H_3S. Cui and colleagues calculated its T_c to be around 200 K at 200 GPa pressure. The stable structure, pictured on page 52, is cubic, one of the simplest possible structures for a binary compound with a 3:1 composition. Several theoretical groups quickly confirmed the new predictions of the material's structure and T_c.

Superconductivity in H_3S can be understood as atomic hydrogen driven to a superconducting state by the hybridization of hydrogen's 1*s* orbitals with the 3*p* orbitals of sulfur.[11] The effect of sulfur is to preclude the formation of molecular H_2 in favor of atomic hydrogen, for which electron–phonon coupling is maximized. Researchers subsequently established computationally that the dominance of vibrations of hydrogen has important consequences for H_3S. Among other things, the hydrogen's light mass leads to anharmonic vibrations and quantum zero-point motion effects in sulfur hydride.[12,13]

The success of the theory–experiment synergy bodes well for the future of superconductivity, as other hydrides will likely be studied in expectation of yet higher T_c or lower pressures. That synergy also points the way toward the next frontier: metallic atomic hydrogen.

The origin of high T_c

In BCS superconductors, as described above, T_c is set by a few materials parameters: the electron–phonon coupling strength λ, a representative phonon energy scale Ω, and a dimensionless Coulomb repulsion strength μ^*, which varies little from the range 0.10–0.15. For H_3S—and likely for most other potential

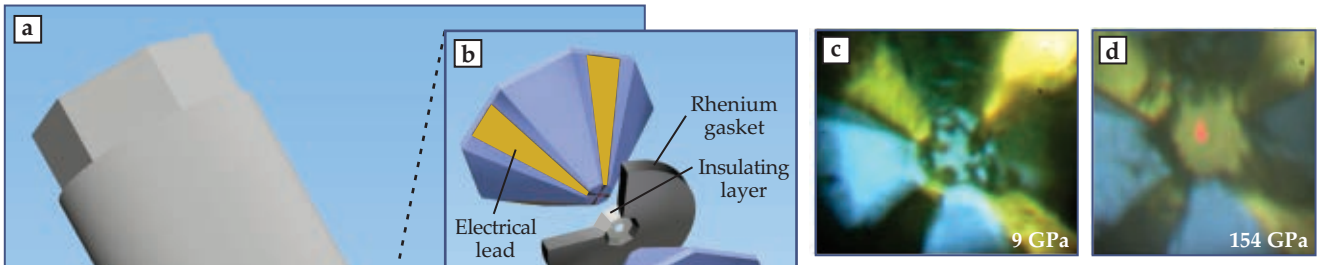


FIGURE 2. ANATOMY OF A DIAMOND ANVIL CELL. **(a)** This cell, made of nonmagnetic copper:titanium alloy, has an outer diameter of 8.8 mm and was designed for magnetometer measurements at pressures up to 200 GPa. **(b)** An expanded view shows the electrical leads on the surface of the diamond and contact points for the sample at the tiny, flat end of the diamond. **(c, d)** The hydrogen sulfide sample, photographed at the center of each image, is 25 μm wide. At 9 GPa, it is dielectric and transparent; at 154 GPa, it is metallic. The red spot at the center is a reflection of light from a helium–neon laser. (Panels c and d adapted from ref. 2, A. P. Drozdov et al., 2015.)

high-T_c hydrides—the contribution to T_c is dominated by hydrogen, as noted earlier. For an elemental superconductor (which H_3S approximates), one can express the coupling strength in terms of Ω and the atomic mass M as

$$\lambda = N(0)I^2/M\Omega^2.$$

The electronic density of states at zero energy, where electron pairs form, is $N(0)$, and I^2 is the square of the matrix element that describes the scattering of electrons by displacements of hydrogen.

The equation for T_c mentioned earlier involves the prefactor Ω and an expression involving λ and μ^*. Ashcroft reasoned that Ω would be large in hydrides under pressure.[3,4] That's because hydrogen is the lightest possible nucleus and thus promotes high vibrational frequencies and because pressing atoms together increases the force constants, which, in turn, enhance those frequencies. Calculations verify that the increase indeed happens; the maximum phonon frequency in H_3S is 2500 K in temperature units. That's an impressive prefactor for T_c, and it's produced by the high pressure and the small proton mass.

Modern electronic structure methods estimate λ at around 2.5 in H_3S. That's comparable to the electron–phonon coupling strength of strongly coupled conventional superconductors such as lead, for which $\lambda = 1.55$ and $T_c = 7$ K. Some lead alloys have λ that exceed 2. But the atoms in those alloys have large masses, roughly 180 times the proton mass. The alloys themselves are also soft, which means they have weak force constants and exceedingly low vibration frequencies, hence low T_c.

Why is H_3S so different from previously found conventional superconductors? The straightforward answer is that H_3S manages to retain a large λ in spite of a large increase in Ω, whose square occurs in the denominator of λ and thus tends to decrease it. The small mass of the proton certainly helps, but another key aspect is that the numerator in the expression for λ is relatively large (and increases under pressure). The density of states $N(0)$ is not exceptionally large; rather, the magnitude of the hydrogen scattering (I^2) is what's crucial. Obtaining an understanding, and thereby control, of I^2 is one of the most important remaining questions in researchers' quest to further increase T_c or to reduce the necessary pressure.

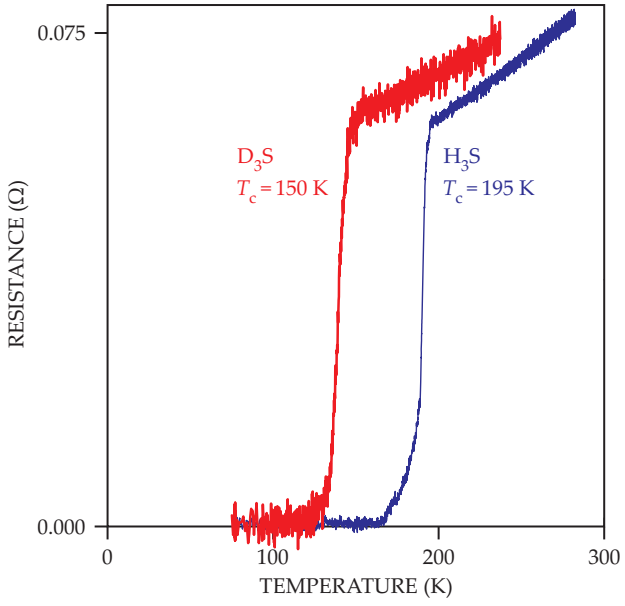


FIGURE 3. THE ISOTOPE EFFECT IN SULFUR HYDRIDE. A plot of resistance versus temperature in sulfur hydride (H_3S), the decomposed phase from a compressed sample of hydrogen sulfide (H_2S), shows the superconducting transition to zero resistance at 195 K. The onset of superconductivity shifts to 150 K in the deuterated D_3S compound. That downward isotope shift arises from the heavier isotope's lower vibrational frequencies and is a signature of electron pairing. (Adapted from ref. 2, A. P. Drozdov et al., 2015.)

The next challenge

Since the H_3S breakthrough, attention has returned to Ashcroft's original idea of superconductivity in metallic atomic hydrogen.[3] In that solid, T_c should be high for the same reasons

discussed for hydrides: The mean vibrational frequency Ω sets the scale for T_c, and yet hydrogen scattering remains strong. However, due to the large binding energy of the H_2 molecule, metallization has remained elusive. In 1935 Eugene Wigner and Hillard Bell Huntington estimated the pressure of metallization at 25 GPa. But it's actually at least 20 times as high, around 500 GPa according to calculations[14] and experiments.

Extreme pressure isn't the only requirement. Unless care is taken to mitigate the damage, the small hydrogen atom gets driven into the diamond anvils themselves. The defects introduced into the diamonds become cracks that eventually break the diamond lattice. What's more, the experimental signatures of superconductivity, listed above, become ever more challenging to measure as pressure rises.

In high-pressure experiments, H_2 becomes semimetallic, with a low density of electron and hole carriers. Further increasing the pressure increases the overlap of valence and conduction bands, and hydrogen becomes a good metal. With a sufficiently large density of states $N(0)$, it becomes a superconductor. Theoretical studies of superconductivity in molecular hydrogen predict that T_c might approach the temperature scale found in H_3S, whereas in atomic hydrogen, T_c should exist well above room temperature.

Researchers have been taking steps toward hydrogen metallization. But they are plagued by the material's dependence on the details of pressure–temperature cycling and other experimental complications. After some earlier reports, Eremets and coauthors obtained evidence of semiconducting dense hydrogen[15] at 360 GPa. In 2017 Ranga Dias and Isaac Silvera of Harvard University reported evidence of metallic atomic hydrogen at 495 GPa and 5 K from reflectivity data.[16] Several groups expressed reservations though. Hua Geng of the Institute of Fluid Physics in China offered an informal account of the issues at the time:[17] As pressures rise, determining those pressures accurately becomes increasingly difficult and measurements themselves become more challenging and less definitive.

More than just high T_c

The 2015 revolution in high-temperature superconductivity—the achievement of T_c above 200 K in H_3S at extreme pressure—has not received the acclaim that previous superconductivity advances have enjoyed. Nonetheless, it has reinvigorated the challenge to find ways to further increase T_c or, perhaps more importantly, to maintain the superconductivity at lower pressures.

There also remains the possibility that room-temperature superconductivity will be demonstrated in other metal hydrides rather than in metallic hydrogen itself. Calcium hydride, yttrium hydride, and lanthanum hydride have each been predicted to superconduct at or near room temperature around pressures of 300 GPa or lower,[6] and the precompression that the compounds offer may alleviate some of the experimental difficulties presented by squeezing hydrogen to such pressures.

In fact, those predictions are bearing fruit. Earlier this year two independent groups—one led by George Washington University's Russell Hemley, the other led by Eremets—found superconductivity[18] in LaH_{10} (shown in figure 4) in the reported temperature range of 250–280 K at pressures just below 200 GPa. That range includes the freezing point of water at temperatures common to human experience.

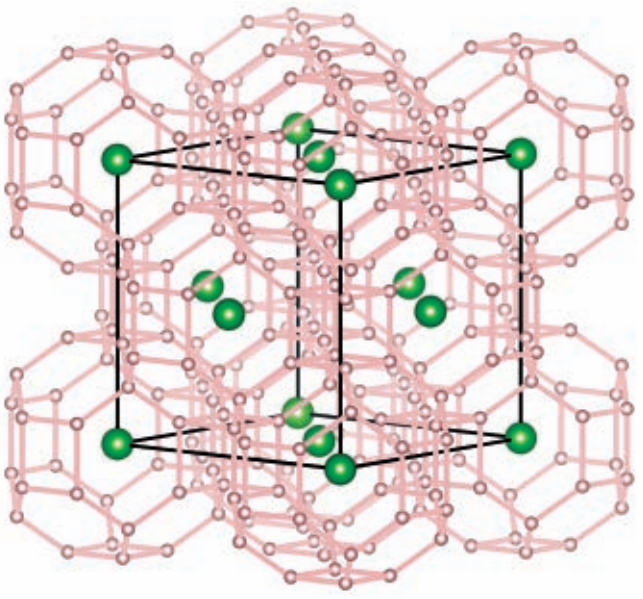


FIGURE 4. SUPERCONDUCTING LANTHANUM HYDRIDE (LaH_{10}) has a clathrate lattice structure. Each La atom (green) resides in the center of a cage of 32 H atoms (pink), each separated by 1.1 Å. (Adapted from Z. M. Geballe et al., *Angew. Chem.* **57**, 688, 2018.)

Computational prediction was combined with experiment to make the advance. Near-room-temperature superconductivity has been achieved eight centuries before the extrapolation of Bruce Friday's 1973 experimental plot. A room-temperature superconductor under such extreme pressure would be a fundamental extension of human understanding, even with no practical application. The hope is that it could offer a path to designing another material that behaves similarly at ambient pressure.

Warren Pickett appreciates support from NSF. Mikhail Eremets thanks the Max Planck community for its support and Ulrich Pöschl and Alex Drozdov.

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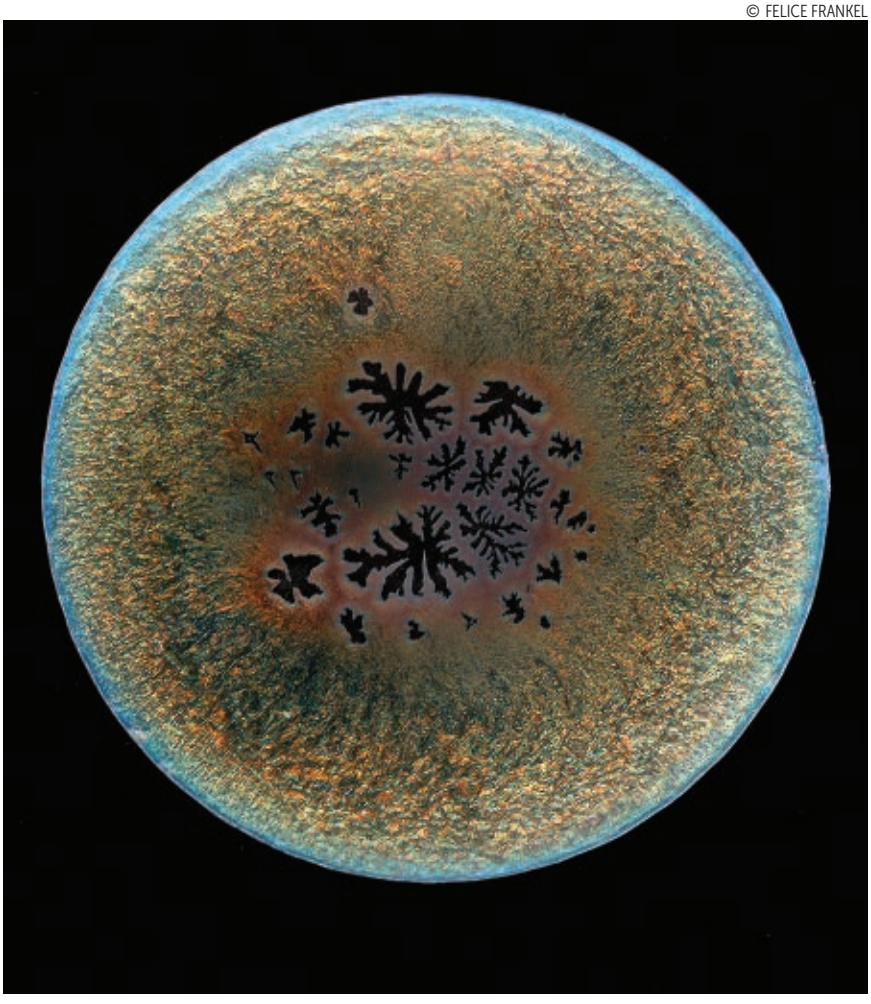

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Exploring scientific images with creativity and insight

Picturing Science and Engineering
Felice C. Frankel
MIT Press, 2018. $39.95

Felice Frankel's *Picturing Science and Engineering* is, in a word, remarkable. Despite its length—more than 450 pages—it took me only two days to read. It is a fascinating, wonderful volume that will encourage its readers to think about images, their role in science, and how the world sees science and technology. Creative and insightful, the book is an absolutely unique achievement.

Scientists work to discover new ideas and concepts. After testing those discoveries by experiment, they usually write a paper describing their observations. The resulting insights are often communicated through prose in scientific journals and conference talks.

But words are not the only way to disseminate science. Some of the most effective communication in those articles and talks takes place through images. *Picturing Science and Engineering* is targeted at readers interested in further exploring the visual communication of science.

The book consists of hundreds of images, each of which has something to show us about science, technology, and the world in which we live. Every picture is accompanied by a description, written by Frankel and her contributing colleagues, that explains the image and why it belongs in the book.

Each of the eight chapters in *Picturing Science and Engineering* are centered around one technology or theme: flatbed scanners, camera basics, light, phone cameras, microscopy, presentation, image adjustment and enhancement, and case studies. The book is very well devised—its combination of pictures, scientific studies, and writing clearly conveys information. The text is well matched with the striking photographs, which explore the book's themes by focusing on objects and on interactions between humans and machines.

After perusing sections of the book, readers become aware of how photographs can teach science differently than words or equations. Frankel contends that science is best done by trying to answer a question or make an observation and that it is often necessary to challenge our previous ideas. Readers are reminded that words and concepts are critical for human learning, but they must also critically examine their ideas by interacting with the physical world.

Many of the pages have several photographs of the same object, but the photographs differ in subtle ways to get readers to discern how camera settings and digital edits can affect the final outcome. Those comparisons deepen readers' understanding of both the photographs themselves and the objects in them.

I suggest that readers approach *Picturing Science and Engineering* with an open, inquiring mind; they may change their perspectives and ideas as they read, study, and enjoy it. The book presents both challenges and answers, and readers will feel happily rewarded.

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TONDA/ISTOCK/THINKSTOCK

The many uses of radio waves

Foundations of Radio for Scientists and Technologists
Christopher John Coleman
Cambridge U. Press, 2018. $89.99

Radio enriches many aspects of our daily lives, from personal communications to weather forecasts. But how does radio accomplish those feats? Attempting to answer that question in a meaningful way leads one to realize that even the basics of modern radio draw from various topics ranging from condensed-matter physics to information theory. The challenge of describing radio's impact is compounded by the rapid evolution of radio technologies, the incredible miniaturization of hardware, and the ever-tightening bond that now exists between radio and the ubiquitous computer.

In the past, the art of radio could be covered thoroughly in a single volume, such as the classic *Electronic and Radio Engineering* (4th edition, 1955) by Frederick Terman. Now textbooks are more specialized: Jack Smith's *Modern Communication Circuits* (2nd edition, 1998) covers circuitry, David Pozar's *Microwave Engineering* (4th edition, 2012) discusses high-frequency techniques, Simon Haykin and Michael Moher's *Communication Systems* (5th edition, 2009) focuses on information theory and signal processing methodologies, and Jeffrey Reed's *Software Radio: A Modern Approach to Radio Engineering* (2002) concentrates on modern digital techniques. For a practical viewpoint, *The Radio Amateur's Handbook*, published annually by the American Radio Relay League, is a wonderful resource.

In *Foundations of Radio for Scientists and Technologists*, Christopher Coleman introduces the interdisciplinary subject of modern radio to the nonspecialist. An associate professor of electrical and electronic engineering at the University of Adelaide in Australia, he takes the reader on an adventure of scientific discovery and engineering application. In a concise, articulate style, Coleman begins by providing the groundwork for electromagnetic theory, flowing smoothly from Gauss's law to the wave equation—with just enough mathematics for subject completeness without excessive detail—and guides the reader with historical milestones. That successful approach to the history and the math continues throughout the book.

From there, the challenges of selecting the right wave for a specific task give Coleman the opportunity to transition from field theory to passive circuits. In the course of that discussion, the reader learns about power transfer, the characteristics of tuned circuits, and the definition of the quality factor. A more advanced analysis of the frequency responses of both Butterworth and Chebyshev signal filters follows quite naturally.

Coleman emphasizes the need to impress information onto the radio wave and ultimately extract it in his discussion of active components. He uses examples of scientific discoveries to take the reader on a journey from basic vacuum tube theory to the operation of bipolar-junction and field-effect transistors that evolves into a review of operational amplifiers. The book covers the concept of noise and even mentions Shannon's maximum channel capacity. *Foundations of Radio for Scientists and Technologists* also discusses how circuits are folded into functional blocks for transmitters and receivers. It introduces feedback, negative resistance, and mixers, including single-diode and balanced configurations, superheterodyne receivers, and the various forms of modulation and demodulation.

The book next covers modern software-defined radio, beginning with the basic digital logic functions, sequential logic, and the discrete Fourier transform. It then presents the concepts of sampling, aliasing, windowing, and filtering, followed by discussions of data conversion, quantization noise, signal-to-noise ratio issues, and digital radio architectures.

The last several chapters cover wave propagation, starting with the transmission line and culminating in free-space propagation. Coleman addresses transmission-line theory quite extensively, along with resonators and coupled-line filters. Various types of antennas, including aperture antennas and arrays that describe sidelodes and grating lobes, are explored. A summary of the ionosphere covers the concepts of refractive index and plasma frequency. The Kirchhoff integral and the Huygens principle are used to analyze diffraction over a conducting screen, surface-wave propagation, and Bragg scattering.

The book concludes with a brief synopsis of modern radio applications. It introduces digital modulation modes and

channel capacity, followed by a short summary of spread-spectrum, cellular radio, and multiple-input multiple-output communications systems. Among the other applications of radio that are discussed are various radar systems and satellites for communications and navigation. A brief introduction to the natural sources of noise and radio astronomy is also included.

Coleman covers an incredible amount of material in this small volume. *Foundations of Radio for Scientists and Technologists* is presented in a concise, well-organized, physics-based manner. Although the author assumes that the reader has a thorough understanding of calculus and basic physics, the development of certain topics lacks the in-depth mathematical derivations that a reader or instructor might expect from a specialized textbook. The level of treatment is appropriate for advanced undergraduate and graduate students in a two-semester course given by an instructor well versed in the subject matter. The reader should keep in mind that the book does not contain any worked examples or exercises; those are presented in the book's online resources. Practicing scientists and engineers who simply want a thorough overview of the subject will also find the book quite gratifying, and they will appreciate the topical bibliography of additional information on selected subjects. Overall, this textbook is a pleasure to read and will serve as a comprehensive introduction to radio for the nonspecialist.

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GREG WEBB/IAEA

Inspectors at the Fukushima Daiichi power plant in 2013.

The past and future of nuclear regulation

Confessions of a Rogue Nuclear Regulator
Gregory B. Jaczko
Simon & Schuster, 2019. $26.00

Gregory Jaczko is a physicist who ventured into the political arena after he earned his PhD. In his subsequent career as a nuclear regulator, he had a rapid rise—and an equally sudden fall. In *Confessions of a Rogue Nuclear Regulator*, he tells his story and gives valuable insights into the inner workings of US nuclear regulation.

In 1999 Jaczko started as a congressional science fellow in the office of Representative Edward Markey (D-MA), a critic of the safety oversight of the US Nuclear Regulatory Commission (NRC). Jaczko then joined the staff of Democratic senator Harry Reid, who was focused on stopping the licensing of the Yucca Mountain radioactive waste repository that the US Department of Energy was building in his home state of Nevada.

In 2005 Reid succeeded in getting Jaczko a seat on the five-member Nuclear Regulatory Commission. Four years later President Barack Obama appointed Jaczko NRC chairman. While campaigning in the Nevada primary, Obama had pledged that, if elected, he would end the licensing process for the Yucca Mountain repository. The site had been selected by Congress in 1987, when Reid was a junior senator with little clout. After Obama's election, the two worked together to scuttle the repository and succeeded in 2011.

Jaczko's book is in large part a rebuttal to industry critics who attacked his decisions on a number of issues, including his recommendation that US citizens in Japan evacuate any area within an 80-kilometer radius of the Fukushima

Daiichi plant—far beyond the 20- to 50-kilometer distance ordered by Japan's government. He also defends himself against accusations from his fellow commissioners that he was on occasion abusive toward NRC staffers, berating them when he thought they were giving in to pressure from proindustry commissioners.

As a longtime observer of the US nuclear regulatory process, however, I was disappointed that Jaczko does not discuss the outcomes of the NRC's important decisions on post-Fukushima safety upgrades. Presumably that is because by the time the commission held its final votes on those upgrades in 2015, Jaczko had been forced out by his former boss Reid. Republicans planned to reappoint a proindustry and pro–Yucca Mountain NRC commissioner, Kristine Svinicki, to another five-year term. As Jaczko reports matter-of-factly, Reid, by then the Senate minority leader, wanted Jaczko out so he could appoint a Yucca Mountain critic to serve a full five-year term matching Svinicki's. Reid chose geologist Allison Macfarlane as NRC chair. Macfarlane stepped down after two and a half years, however, and in 2017 President Trump appointed Svinicki as chair.

The decisions on post-Fukushima upgrades put into stark relief the politics of nuclear regulation in the US at a time when nuclear power is failing to compete with cheap natural gas, wind, and photovoltaic energy. Because of its poor finances, the US nuclear power industry refuses to make any costly safety investments. According to the NRC, US nuclear utilities will spend an average of $40 million per reactor on post-Fukushima upgrades. In contrast, the estimated average per-reactor cost of upgrades required by regulators in France and Japan will be about $210 million and $640 million, respectively.

One investment the US industry deemed too costly was a heavy-duty filtration system to remove radioactivity from gases vented from an overpressurized reactor containment structure. European regulators began to require such filters after the 1979 accident at the US Three Mile Island plant, but US and Japanese regulators did not. The unfiltered gases released from three overpressurized Fukushima reactor containments resulted in land contamination that required the long-term relocation of about 100 000 people.

Since Fukushima, Japan's utilities are being required to install filters in all of their reactor containments. The NRC staff estimated that filtered vents would cost US nuclear utilities between $15 million and $20 million per reactor and recommended that they be installed in US reactors with the same small-volume containments as the Fukushima reactors. But US nuclear utilities opposed the idea of filters, and the NRC ultimately voted against requiring them.

As Jaczko explains, the NRC justifies rejecting safety upgrades through a probabilistic cost–benefit analysis, in which the cost of an upgrade is weighed against the increased losses from hypothetical reactor accidents in its absence, multiplied by the estimated probability of accidents occurring during the remainder of the reactor's currently licensed life. According to the memoir *A Brighter Tomorrow: Fulfilling the Promise of Nuclear Energy* (2004) by former senator Pete Domenici (R-NM), the NRC adopted that approach after Domenici, then chairman of the Senate appropriations subcommittee with oversight of the NRC's budget, threatened to cut the NRC's funding by one-third if he continued to hear complaints from the nuclear industry.

Between 2012 and 2016, I was a member of a National Academy of Sciences committee that studied the lessons the US could take away from the Fukushima accident. During that time, I examined two major NRC cost–benefit analyses and learned that such analyses are skewed by arbitrary probability assumptions—assuming a zero probability of a successful terrorist attack, for example—and by underestimates of accident consequences. In its analysis of the filtered-vent decision, for instance, the NRC staff estimated that the average off-site damage from a Fukushima-scale release of radioactivity in the US would be $2 billion. As of December 2016, Japan's official estimate of the off-site costs for decontamination and compensation for the Fukushima accident was ¥13.5 trillion, or about $125 billion.

Jaczko's book provides insights into the politics behind such skewed analyses and suggests that a reform-minded Congress might usefully look into the NRC's regulatory process.

Frank N. von Hippel
Princeton University
Princeton, New Jersey

Universe Sandbox

Giant Army, 2018 (Update 22.1). $24.99

If you have ever wanted to build your own universe from scratch, or see what would happen to ours if you flicked Mars out of its orbit, Universe Sandbox is the video game for you. This space simulator allows users to experiment with adding or removing planetary bodies from both our solar system and known exoplanet systems like TRAPPIST-1. You can replace our sun with a red dwarf, add asteroids or new planets, and—if you're really looking to cause trouble—throw in a black hole. You can also build your own system from scratch. Because there are so many options, the controls and menus are not always intuitive; players will benefit from spending time with the game's tutorials. An early-access version is currently on sale at Steam, and publisher Giant Army reports that more updates and features are coming. Available for Windows, Mac, and Linux operating systems. —MB

Apollo 11

Todd Douglas Miller

CNN Films/Statement Pictures, 2019

In this new documentary, director Todd Douglas Miller uses a massive cache of film and audio recordings from the US National Archives to tell the story of the 1969 Apollo 11 launch. The film has no narration but instead relies on the recordings from NASA's Mission Control to tell the viewer what is happening on-screen. Since the film footage itself is silent, matching that footage with the appropriate Mission Control recordings is an impressive technical feat. *Apollo 11* also uses background music to convey awe, tension, and beauty. In one particularly touching moment, as the crew is heading back Earthward, Buzz Aldrin says, "Let's get some music." "Mother Country" by John Stewart starts playing softly on a portable tape recorder, and viewers watch the recorder flip end-over-end inside the zero-gravity cabin. The film is a worthy monument to the people who made the Moon landing happen. *Apollo 11* opened in IMAX and cinemas in March, a 40-minute IMAX version will be released on 17 May, and CNN will air the film this summer. For a full review, see physicstoday.org/Apollo11. —PG

Alice and Bob Meet the Wall of Fire

The Biggest Ideas in Science from *Quanta*

The Prime Number Conspiracy

The Biggest Ideas in Math from *Quanta*

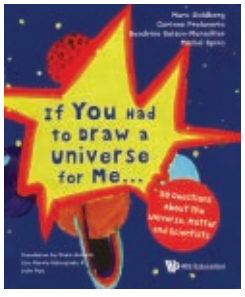
Thomas Lin, ed.

MIT Press, 2018. $19.95 apiece (paper)

These two companion volumes represent some of the best articles published in *Quanta Magazine* since its inception as an online publication seven years ago. The set, edited by *Quanta* founder and editor-in-chief Thomas Lin, presents the latest developments in theoretical physics, computer science, life sciences, and mathematics in a manner designed to be accessible to the general reader. Each book is divided into sections aimed at grabbing readers' attention by addressing some big questions of science: What is time? What is life? Why doesn't our universe make sense? —CC

If You Had to Draw a Universe for Me ...

50 Questions About the Universe, Matter and Scientists

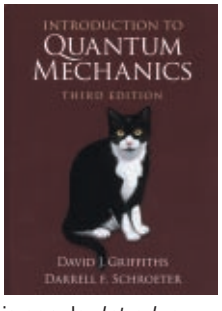


Marc Goldberg, Corinne Pralavorio, Sandrine Saison-Marsollier, and Michel Spiro

WS Education, 2019. $14.90 (paper)

The result of a competition organized by CERN in 2014, this book features the colorful artistic renderings of French and Swiss schoolchildren who were tasked with asking and illustrating fundamental physics questions, such as What's inside a black hole? Each question and drawing are accompanied by a scientific explanation and a literary quotation. CERN has a reputation for sponsoring programs to foster dialog between artists and scientists, and the book's four authors—a playwright, a CERN communications officer, an educational consultant, and a physicist—reflect that goal. —CC

Introduction to Quantum Mechanics



David J. Griffiths and Darrell F. Schroeter

Cambridge U. Press, 2018 (3rd ed.). $74.99

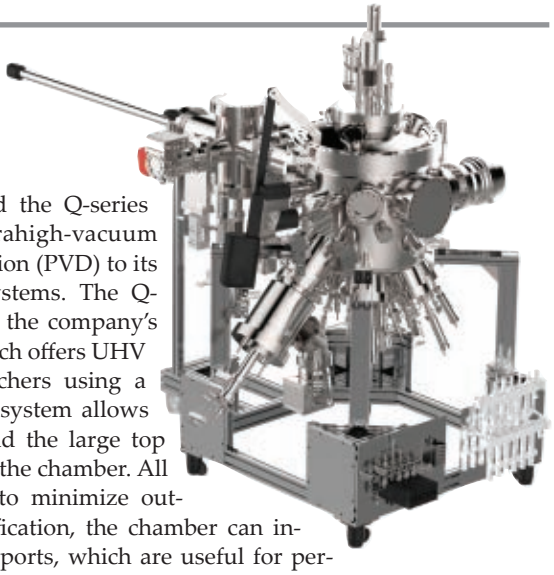
For the third edition of his popular *Introduction to Quantum Mechanics*, well-known textbook author David Griffiths brings aboard a new coauthor, condensed-matter theorist Darrell Schroeter. Changes include a new chapter on symmetries and conservation laws, more material on solid-state physics, and many new problems and examples. Students and instructors will appreciate the book's easy-to-follow layout and clearly labeled graphs and diagrams. —MB PT

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 the product description. For all new products submissions, please send to ptpub@aip.org.

Andreas Mandelis

ConFlat chamber deposition system



Mantis Deposition has added the Q-series system for advanced ultrahigh-vacuum (UHV) physical vapor deposition (PVD) to its line of sputter deposition systems. The Q-series platforms are based on the company's QPrep system technology, which offers UHV performance for PVD researchers using a ConFlat flange chamber. The system allows true UHV to be achieved, and the large top flange provides easy access to the chamber. All joints are internally welded to minimize outgassing. Depending on specification, the chamber can include various *in situ* analysis ports, which are useful for performing ellipsometry, residual gas analysis, and differentially pumped reflection high-energy electron diffraction. Because the standard base ports are confocal, a greater number and variety of deposition sources can be used than with nonconfocal arrangements. ***Mantis Deposition Inc**, 10200 E Girard Ave, Denver, CO 80231, www.mantisdeposition.com*

Digital vacuum gauge

Thyracont Vacuum Instruments has added a digital vacuum transducer to its Smartline product family. Designed for load-lock applications, the VSL vacuum gauge offers a reaction time of 40 ms, accuracy of 0.3% from scale end, and measurement independent of gas type at atmospheric pressure. It measures absolute pressure in the range of 0.0001 mbar to 1200 mbar and relative pressure in relation to the environment in the range of −1260 mbar to +940 mbar. The calculation of the differential pressure signal guarantees the helium tightness of the sensor's metal-sealed setup. The gauge head uses multisensor technology that combines two piezo sensors with a Pirani. The piezo-resistive diaphragm sensors monitor the chamber during the pump-down and vent-up processes. To ensure the purity of the pump-down process, the Pirani sensor controls the low-pressure transfer between the load lock and process chamber. ***Thyracont Vacuum Instruments GmbH**, Max-Emanuel-Str 10, 94036 Passau, Germany, https://thyracont-vacuum.com*

Throttle valves for actuators

According to Nor-Cal Products, new-generation J-Lock actuation on its Intellisys IQ+ throttling butterfly valves allows for optimal pressure control and wide dynamic range. The tapered bore and dynamically energized, spring-loaded seal offer reliability and robust performance. Due to its lead-free circuit board, the on-valve integral control and drive unit complies with both the Registration, Evaluation, Authorisation, and Restriction of Chemicals directive and the Restriction of Hazardous Substances directive. User interfaces include a DeviceNet protocol and physical layer and standard RS-232, RS-485, and Ethernet communications. To achieve superior pressure control from 1 mtorr to 760 torr, patent-pending Intellisys throttling butterfly valves can operate singly or in multivalve installations. ***Nor-Cal Products Inc**, 1967 S Oregon St, Yreka, CA 96097, www.n-c.com*

Hybrid thermal interface material

Indium Corp has released m2TIM, a novel solid–liquid hybrid thermal interface material that provides reliable thermal conductivity for heat dissipation. A solid metal solder preform absorbs and contains the liquid metal alloys while improving thermal conductivity. The m2TIM is available in various alloys, including indium gallium and indium gallium tin. It exhibits a high wetting ability to metallic and nonmetallic surfaces and extremely low interfacial resistance. ***Indium Corporation**, 34 Robinson Rd, Clinton, NY 13323, www.indium.com*

Optical coating system

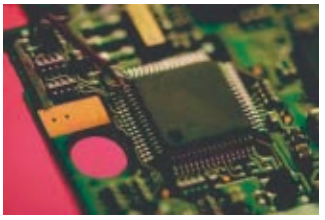
Intlvac Thin Film has announced its latest precision optical coating platform. The Nanochrome IV UV/Vis optical filter production system is designed to produce antireflective coatings, complex optical filters, and dielectric and UV-visible filters via e-beam evaporation with ion assist. Its *in situ* broadband optical monitoring system provides real-time reoptimization of film layers and automated process control in reflection or transmission mode. Because of its Smart technology, the Nanochrome IV can adapt quickly to different heat and gas loads. According to Intlvac, the new system is the world's first production platform with the latest-generation variable-speed cryopump from CTI, the largest cryopump currently available. ***Intlvac Thin Film Corporation**, 1401 Duff Dr, Unit 600, Fort Collins, CO 80524, www.intlvac.com*

High-compression turbopumps

Pfeiffer Vacuum has launched its very high compression HiPace 700 H turbopumps, which generate high and ultrahigh vacuum for research, analysis, and industrial applications. They feature a compression ratio of greater than or equal to 2×10^7 for light gases such as hydrogen. Due to the high compression ratio, a low residual gas spectrum—desirable for certain mass spectrometry applications—is created in the chamber. Advanced rotor designs enable an exceptionally high critical backing pressure capability of 22 hPa. That lets the pumps reach ultrahigh vacuum even when operating with high backing pressures that occur in combination with diaphragm pumps. If the backing pressure is insufficient, the HiPace H's intermittent-mode function turns on a connected backing pump, which reduces the system's energy consumption by up to 90% without loss of performance. ***Pfeiffer Vacuum Inc**, 24 Trafalgar Sq, Nashua, NH 03063-1988, www.pfeiffer-vacuum.com*

Cryogenic temperature controller

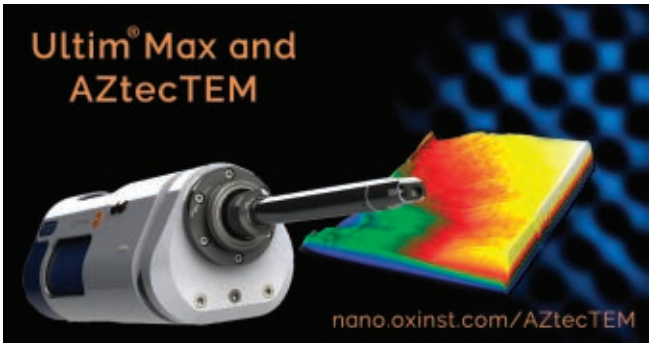
The model 26C cryogenic temperature controller from Cryogenic Control Systems combines the wide-temperature-measurement range of model 24C with the high-output-power control loops of the original model 26. With an appropriate sensor, model 26C operates from 100 mK to over 1500 K. Four inputs and four independent control loops provide a total output power of 150 W. Each of the four multipurpose input channels is enhanced with the negative-temperature-coefficient resistance sensors commonly used at ultralow temperature. The controller also supports general-purpose devices such as diodes and platinum resistance-temperature detectors. Applications include use in helium-3 refrigerators, probe stations, large cryocoolers, and superconducting magnets. ***Cryogenic Control Systems Inc**, 17279 La Brisa, Rancho Santa Fe, CA 92067, www.cryocon.com*



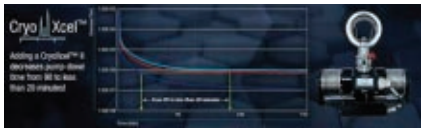
Thermally conductive underfill epoxy

Master Bond's EP3UF-1 is a single-component epoxy that is not premixed and frozen. Due to its low viscosity of 5000–15 000 cps, the heat-curable thixotropic compound is suitable for underfill and many bonding applications. EP3UF-1 delivers high bond strength and dimensional stability with a compressive strength of 18 000–20 000 psi and a tensile modulus of 450 000–500 000 psi. Its thermal conductivity of 1.30–1.44 W/(m•K) makes it an effective thermal interface material. The epoxy contains a special filler with a small particle size. That allows it to be applied in bond lines as thin as 10–15 μm, which imparts a low thermal resistance of 5–7 × 10^{-6} K•m^2/W. EP3UF-1 offers superior electrical insulation with a low dielectric constant of 4.5 at 60 Hz and a high dielectric strength of 1.77 × 10^5 V/cm (for a 1/8-inch-thick test specimen), both measured at 75 °F. ***Master Bond Inc**, 154 Hobart St, Hackensack, NJ 07601-3922, www.masterbond.com*

Microscope for elemental analysis



Oxford Instruments developed its AZtecTEM with Ultim Max technology to offer new capability and increased productivity for elemental analysis in areas such as biology, advanced materials, and *in situ* chemistry. Its high performance is achieved through the use of energy-dispersive x-ray spectroscopy (EDS) on the transmission electron microscope (TEM). According to the company, the Ultim Max detectors deliver a threefold increase in sensitivity compared with previous-generation silicon drift detectors and a fourfold increase in speed. With that high sensitivity and speed, AZtecLive EDS analysis software can be used in a TEM. AZtecLive combines live x-ray maps, electron images, and x-ray spectra and allows real-time feedback of chemistry changes in specimens exposed to heat, liquids, gases, and electrical fields. It quantifies elemental composition by mass thickness and delivers accurate quantification across the entire range of specimens analyzed in a TEM. ***Oxford Instruments Nanoanalysis**, Halifax Rd, High Wycombe HP12 3SE, UK, https://nano.oxinst.com*



Cryogenic water-vapor vacuum pumps

MDC Vacuum Products has released its self-contained and compact CryoXcel cryogenic water-vapor pumps. Its Stirling cryocooler design enables fast, simple pump-to-tool integration and reduces power and footprint space. The CryoXcel devices provide up to 50% faster pump-down times to high- and ultrahigh vacuum levels when they are paired in-line with more compact turbo and mechanical pumps whose pumping speeds are in the 70–12 000 L/s range. Single- and dual-stage water-vapor cryopump models are available in various Del-Seal flange configurations from DN40 to DN320, with cooling power and temperature range dependent on the model. In addition to water vapor, the units can pump sulfur dioxide, anhydrous ammonia, carbon dioxide, and other gases and vapors. ***MDC Vacuum Products LLC**, 30962 Santana St, Hayward, CA 94544, https://mdcvacuum.com* PT

PHYSICS TODAY PRODUCT PICKS

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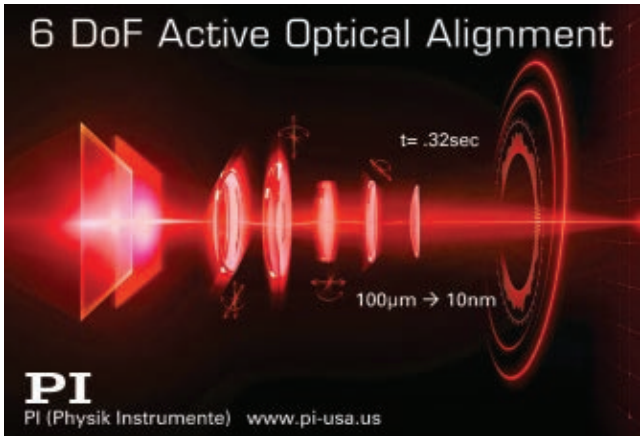
KNF Neuberger, Inc.



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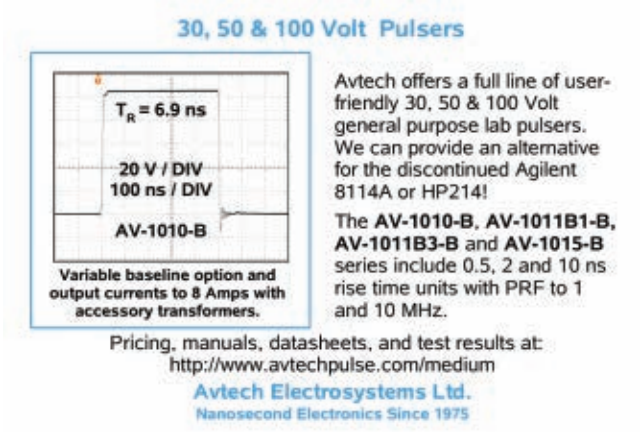

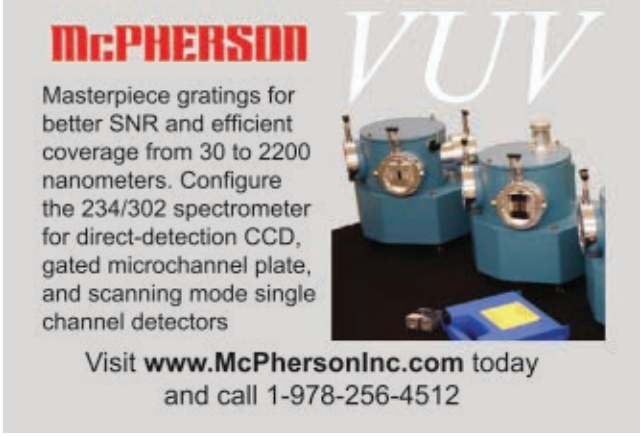

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OBITUARIES

John Wyllie Coburn

John Wyllie Coburn passed away peacefully in his home on 28 November 2018 in San Jose, California. A superb experimentalist, he designed and ran insightful, elegant, and groundbreaking studies that led to an understanding of plasma and ion-beam materials processing. Those developments have been crucial to the progress in nanoscience and nanotechnology that have transformed our lives in so many ways.

John was born on 9 November 1933 in Vancouver, British Columbia, and proudly maintained his Canadian citizenship throughout his life. He went to the University of British Columbia, from which he received a bachelor's of applied science in engineering physics in 1956 and his master's degree in theoretical physics two years later. At the University of Minnesota, under the guidance of William Peria, John earned his PhD in electrical engineering with a thesis on electron-stimulated desorption. During a postdoctoral year at Simon Fraser University, he studied Faraday rotation in europium-doped calcium fluoride.

In 1968 John joined the IBM Research Center in San Jose, where he worked for the next 25 years in close collaboration with Harold Winters and me. The order of the day was to gain better insight into key processes in the growth of sputtered elemental and compound thin films in low-density plasmas operated in different frequency and mean-free-path regimes. John's first invaluable contribution was in plasma diagnostics, which for thin-film growth was primitive at the time. John built an electrostatic-extraction and mass-spectrometry facility capable of measuring neutral and ionic species and their kinetic-energy distribution at the surface of a thin film growing on a room-temperature substrate in a relatively low mean-free-path plasma environment.

John's studies gave some of the first realistic insights of species that could participate in the nucleation, growth, and ultimate composition and structure of the sputtered films. Superimposing spatially defined diagnostic optical spectroscopies led to further understanding of the role of reactive, long-lived free radicals that arrived at the substrate. In the absence of meaningful data on many collisional processes in the plasma, those combined approaches proved to be invaluable in the context not only of elemental and compound inorganic thin-film growth but also of plasma etching and polymerization in halocarbon plasmas.

Undoubtedly, John's most influential technical contribution was the seminal ultrahigh-vacuum ion-beam experiments he conducted with Winters. In 1979 they demonstrated quantitatively the unequivocal role kinetically energetic inert-gas ions play in dramatically enhancing the chemistry of fluorine atoms that interact with silicon surfaces compared with silicon oxide, silicon nitride, and silicon carbide surfaces. That phenomenon, loosely called reactive-ion etching, and advances in high-resolution lithography remain the backbone of nanoscale materials processing of multilayer thin-film assemblies used in high-density magnetic information storage systems and semiconductor microcircuitry. His work on halocarbon plasma polymerization greatly clarified the role of dielectric plasma-polymerized films in selective, directional etching, which is critical in obtaining high-resolution etching features.

After retiring from IBM in 1993, John spent a year as a Senior Distinguished US von Humboldt Scientist at the Fraunhofer Institute in Freiburg, Germany, and studied dry etching of III–V heterojunctions. Subsequently, he worked part-time as a senior research associate with David Graves's group at the University of California, Berkeley. He continued to focus on plasma etching and reactive-ion etching mechanisms, with an emphasis on quantitatively measuring a more comprehensive set of discharge parameters simultaneously. That included, for example, determining the number density of all key species in the plasma, which led to a more realistic description of chemical reaction mechanisms.

John's collaborative work with Graves's group also led to a greater understanding of key surface processes encountered in many plasma-assisted etching environments—for example, the role of surface-catalyzed recombination of chemically active atoms or radicals to form relatively stable molecules on different surfaces.

John never seemed discouraged by the complexity of plasma systems; with rigorous, relatively straightforward approaches, he always managed to identify and experimentally clarify key dimensions of the problems at hand. Another dimension in which John excelled was his dedication to and effectiveness in relating advances in plasma and associated concepts in surface and thin-film science to broad audiences in the technology world.

John Wyllie Coburn

All John's areas of study are within the mission of AVS, originally the American Vacuum Society. John's deep involvement with AVS began when he joined as a graduate student. Over the years he held almost every office, including president in 1988. The work of John and his lifelong colleague Winters was recognized by AVS with the 1993 John A. Thornton Memorial Award and with the 1994 creation of the John Coburn and Harold Winters Student Award in Plasma Science and Technology.

John is remembered by family, friends, and colleagues as a warm and caring person to everyone around him. His wry sense of humor enhanced our lives. I am proud to have been his friend and colleague throughout his career. He is greatly missed.

Eric Kay
Saratoga, California PT

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PHYSICS TODAY | JOBS

Stephane Poulain is a graduate student and **Lydia Bourouiba** is an associate professor and director of the Fluid Dynamics of Disease Transmission Laboratory; both are at MIT in Cambridge, Massachusetts.

Disease transmission via drops and bubbles

Stephane Poulain and Lydia Bourouiba

Watery air bubbles covered with bacteria or viruses can live far longer than uncontaminated ones. And on bursting, they spawn orders of magnitude more droplets, each one a microbial grenade.

Seasonal influenza was responsible for nearly a million hospitalizations in the US in 2018, and tuberculosis killed more than a million people around the world. Those and other infectious diseases are spread by pathogens, such as bacteria and viruses. An important part of the pathogens' life cycle occurs in liquids, whose fluid dynamics influences transmission from one infected host or environmental reservoir to another.

A cough or sneeze, for instance, produces a turbulent cloud of hot, moist air and droplets, as shown in figure 1. That cloud and its droplet payload can span a room up to 8 m long in a few seconds. Droplets can also be spread from bursting bubbles or splashed from a wet, contaminated surface.

To predict and model disease transmission at both population and individual scales, and to develop efficient mitigation innovations and strategies against the spread of infectious diseases, understanding the role of the underlying fluid dynamics is critical. Yet little is known about the factors affecting the source, transport, and persistence of pathogen-bearing droplets. This Quick Study focuses on the example of bursting air bubbles to illustrate the rich physics and close coupling of biology and fluid dynamics in the context of disease transmission.

Bursting bubbles and droplets

Watery air bubbles are ubiquitous: They populate the surfaces of pools, rain puddles, and wastewater treatment plants, and an estimated 10^{19} bubbles are created every second in Earth's oceans and seas. As they burst under various conditions, each bubble can emit hundreds of water droplets. Those droplets are efficient vehicles for transporting what the water contains, including microorganisms, toxins, and even crude oil. Bursting bubbles from a flushing toilet can send droplets more than a meter into the air. They are also easily carried aloft by winds, over both short and long distances.

A surface bubble consists of a thin cap of water a few microns thick that entraps air. The curvature of the cap creates an overpressure relative to the bulk water below it. To first order, the pressure difference induces a flow resisted by viscosity at the base of the bubble. The cap drains into the pool of water it is connected to, and its thickness continuously decreases until the bubble eventually ruptures and ejects droplets.

Figure 2 illustrates an important factor governing the properties of those droplets: the thickness of the cap when it bursts. Thinner bubbles emit more, smaller, and faster-moving droplets than do thicker bubbles. It follows that older bubbles generate droplets that are particularly efficient at spreading contaminants because they are smaller and more easily transported longer distances.

During our experiments at MIT, we noticed that the bubbles on the surface of clean, distilled, bottled, or tap water burst quickly, typically within a couple of seconds; fewer than 5% survive up to 10 seconds. But even during that short lifetime, their interaction with the ambient air can control their thickness in a surprising and counterintuitive way. In addition to draining, the water in a bubble also evaporates. By cooling the bubble's cap, evaporation increases its surface tension compared with that of the bubble's base, which remains at ambient temperature.

The imbalance in surface tension drives water from the base (low surface tension $\sigma-$) toward the cap (high surface tension $\sigma+$), a phenomenon known as Marangoni flow. The upward flow counteracts the drainage and produces thicker bubbles of

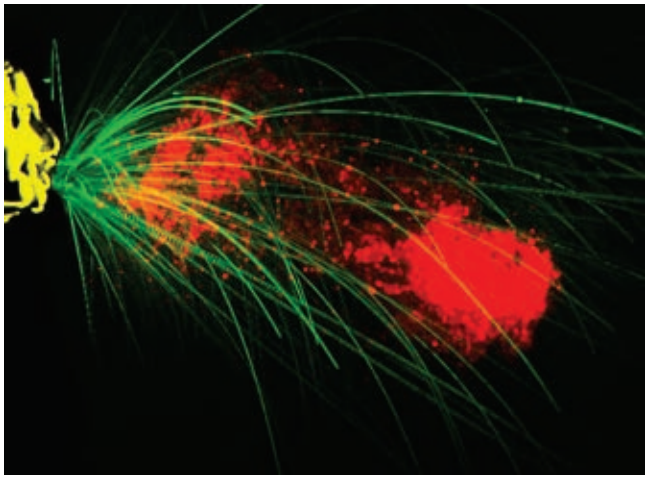


FIGURE 1. VIOLENT EXHALATIONS SUCH AS A SNEEZE release a turbulent cloud of hot, moist air and suspended droplets (red) that can travel the length of most rooms (up to 8 m). The cloud and its payload of saliva and mucus droplets can also linger in the air for as long as 10 minutes. The largest of such drops (green) shoot from the mouth and fall quickly. The gas-phase dynamics enhances the range of suspended droplets by delaying their exit from the cloud. (Image courtesy of Lydia Bourouiba, MIT, from HHMI's Image of the Week: The Anatomy of a Sneeze.)

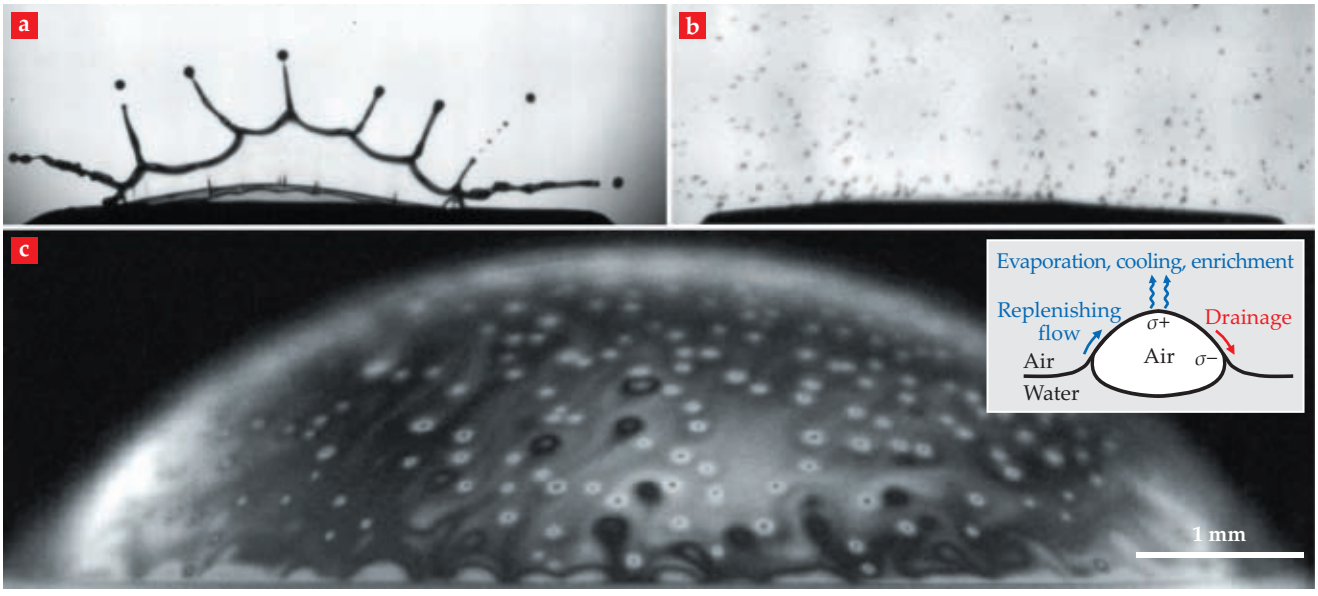


FIGURE 2. TWO BUBBLES BURST ON A WATERY SURFACE, one **(a)** after 3 seconds and the other **(b)** after 55 seconds. The longer-lived bubble, being thinner, spawns some 250 drops when it bursts, whereas the younger one emits less than a dozen. **(c)** An air bubble is shown laden with bacteria. The inset shows that when the surface tension σ of a bubble's apex is higher than that of its base, a replenishing Marangoni flow is established that counters evaporation. (Adapted from S. Poulain, L. Bourouiba, *Phys. Rev. Lett.* **121**, 204502, 2018.)

a given age. The thickening effect is, in fact, general. According to our recent research, any mechanism that produces a surface-tension gradient leaving the base with relatively lower surface tension can dramatically increase the thickness and lifetime of bubbles.

This replenishing effect of evaporation on watery bubbles is, in fact, ubiquitous. It is exacerbated by volatile compounds, such as alcohol (see the article by Roberto Zenit and Javier Rodríguez-Rodríguez, PHYSICS TODAY, November 2018, page 44). The addition of salt also leads to a dramatic illustration of the effect, with important implications for the ocean–atmosphere coupling. In that case, the evaporation enriches the local salt concentration at the apex of each bubble, which further increases σ. The result is bubbles that can stop thinning altogether!

Brimming with bacteria

Freshwater bubbles contaminated with bacteria live much longer than do clean-water bubbles. Indeed, some of them survive for minutes. In our experiments we discovered that bacterial secretions can stabilize those bubbles, which makes them resistant to perturbations that would otherwise pop clean bubbles at much shorter lifetimes. The effect is akin to adding surfactant molecules that stabilize liquid films and give soap bubbles their long lifetimes.

Altough replenishing via upward Marangoni flows is pervasive in clean bubbles, they still continuously thin. However, coated with secretions, bacteria-laden bubbles can reach lifetimes and thicknesses beyond those accessible to clean bubbles. And if such biologically contaminated bubbles survive beyond a critical lifetime, their thinning changes dramatically.

The direct removal of water by evaporation becomes more dominant than the replenishing of water by upward Marangoni flow. That is, in the short term, bubbles become thicker than expected. But beyond a certain age, evaporation thins them out faster than expected. Indeed, drainage-induced thinning is thickness dependent, whereas evaporation-induced thinning is not. Below a critical thickness, the rate of thinning by drainage-dominated dynamics becomes smaller than the rate induced by evaporation.

That subtle competition has important implications. Because they increasingly thin as they age, old and contaminated bubbles produce 10 times as many droplets as clean ones of the same age—potentially hundreds of them from a single bubble. And those droplets are themselves 1/10 as large—down to, on average, 10 μm in radius—and are emitted into the air 10 times as fast (up to 15 m/s) as those of clean bubbles.

Bacterial secretions are known to protect the microorganisms by forming a biofilm—a thick matrix of cells that stick together. But the secretion's effect on bubbles arises even in the absence of a biofilm, and even for common species such as *Escherichia coli*. Despite their tiny size, pathogens cannot be assumed to be passively transported in bubbles and droplets. Indeed, whether they evolved for this purpose or not, when the microorganisms reside on bubbles, they can, in effect, manipulate the underlying interfacial physics to optimize their own dispersal.

Additional resources

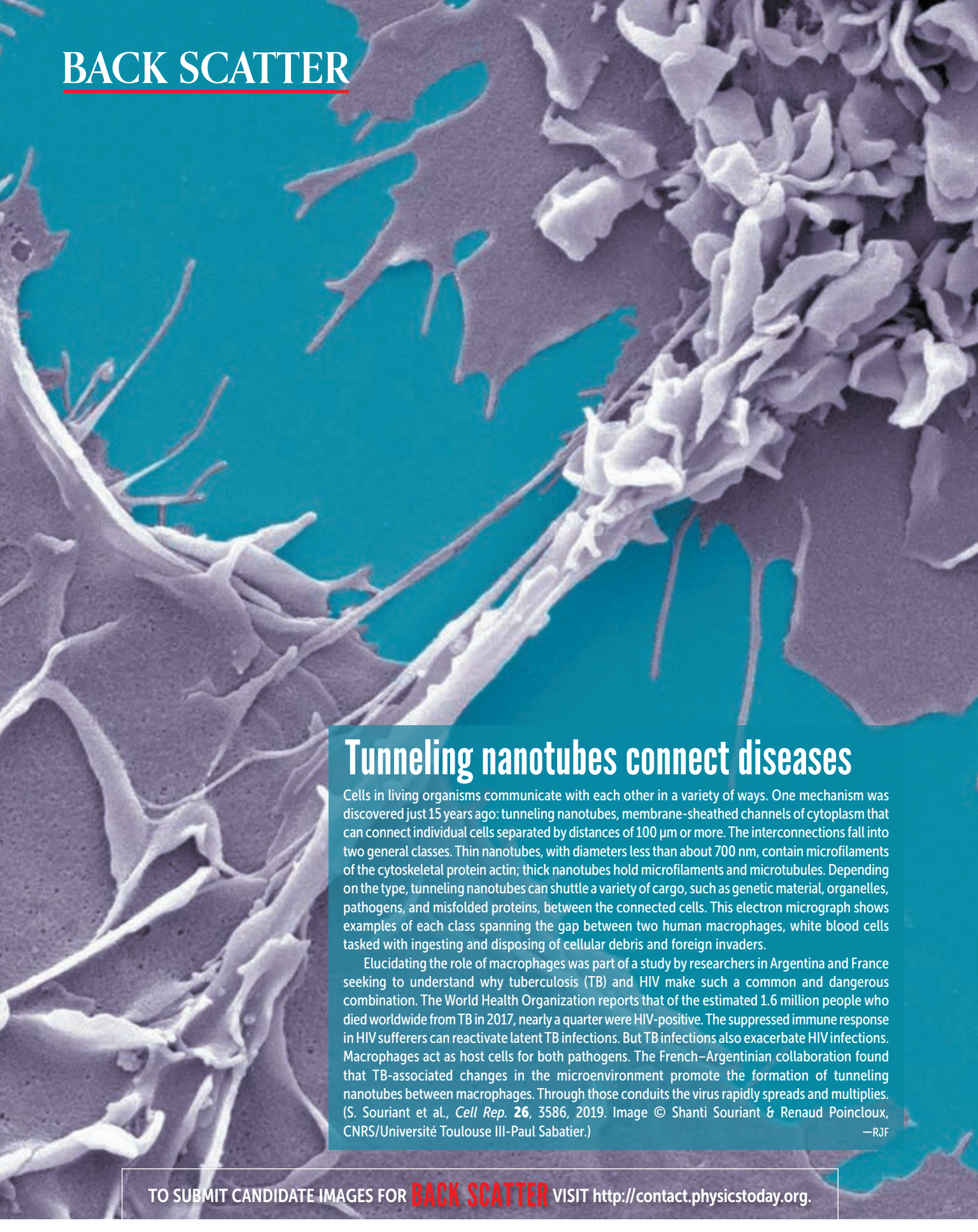
▶ L. Bourouiba, "Fluid dynamics of disease transmission and health," in *Research Trends in Biological Fluid Dynamics*, S. Jung et al., eds., US National Committee on Theoretical and Applied Mechanics (2016), p. 11.

▶ L. Bourouiba, J. W. M. Bush, "Drops and bubbles in the environment," in *Handbook of Environmental Fluid Dynamics: Overview and Fundamentals*, H. J. S. Fernando, ed., CRC Press/Taylor & Francis (2013), chap. 32.

▶ H. Lhuissier, E. Villermaux, "Bursting bubble aerosols," *J. Fluid Mech.* **696**, 5 (2012).

▶ S. Poulain, E. Villermaux, L. Bourouiba, "Ageing and burst of surface bubbles," *J. Fluid Mech.* **851**, 636 (2018).

▶ S. Poulain, L. Bourouiba, "Biosurfactants change the thinning of contaminated bubbles at bacteria-laden water interfaces," *Phys. Rev. Lett.* **121**, 204502 (2018). PT



Tunneling nanotubes connect diseases

Cells in living organisms communicate with each other in a variety of ways. One mechanism was discovered just 15 years ago: tunneling nanotubes, membrane-sheathed channels of cytoplasm that can connect individual cells separated by distances of 100 μm or more. The interconnections fall into two general classes. Thin nanotubes, with diameters less than about 700 nm, contain microfilaments of the cytoskeletal protein actin; thick nanotubes hold microfilaments and microtubules. Depending on the type, tunneling nanotubes can shuttle a variety of cargo, such as genetic material, organelles, pathogens, and misfolded proteins, between the connected cells. This electron micrograph shows examples of each class spanning the gap between two human macrophages, white blood cells tasked with ingesting and disposing of cellular debris and foreign invaders.

Elucidating the role of macrophages was part of a study by researchers in Argentina and France seeking to understand why tuberculosis (TB) and HIV make such a common and dangerous combination. The World Health Organization reports that of the estimated 1.6 million people who died worldwide from TB in 2017, nearly a quarter were HIV-positive. The suppressed immune response in HIV sufferers can reactivate latent TB infections. But TB infections also exacerbate HIV infections. Macrophages act as host cells for both pathogens. The French–Argentinian collaboration found that TB-associated changes in the microenvironment promote the formation of tunneling nanotubes between macrophages. Through those conduits the virus rapidly spreads and multiplies. (S. Souriant et al., *Cell Rep.* **26**, 3586, 2019. Image © Shanti Souriant & Renaud Poincloux, CNRS/Université Toulouse III-Paul Sabatier.)

—RJF

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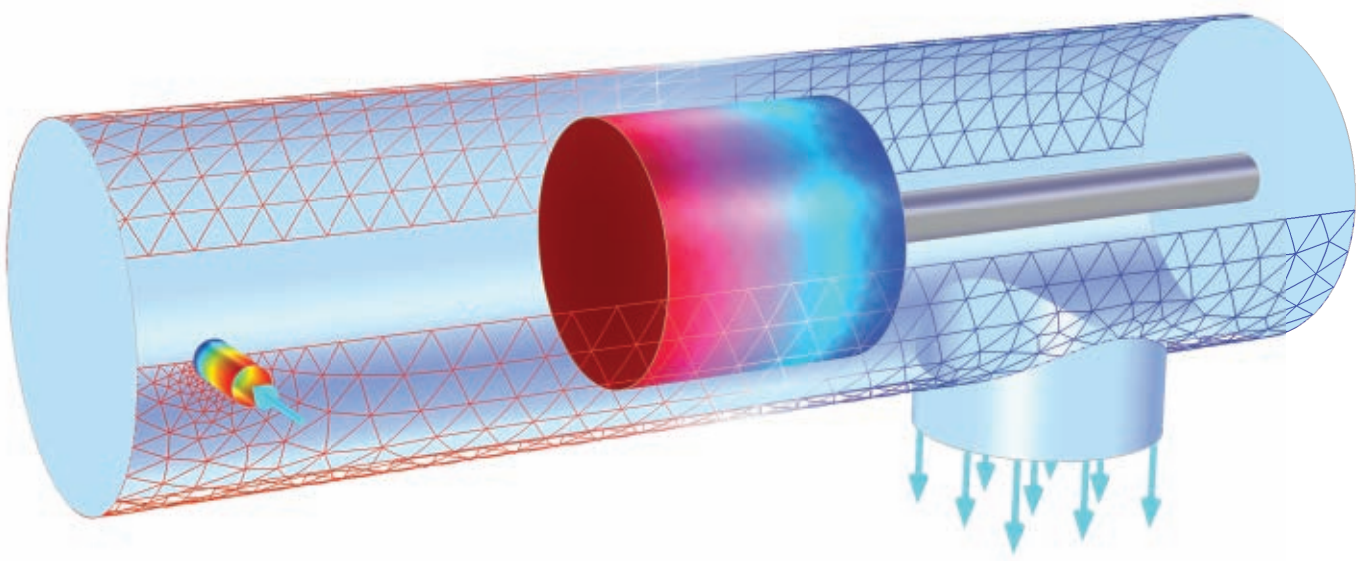

Visualization of the molecular flux of SiH_4 at the wafer cassette of an ultrahigh vacuum chemical vapor deposition system.

Ultrahigh vacuum chemical vapor deposition (UHV/CVD) is a popular process in the semiconductor industry for growing high-purity silicon on top of a wafer substrate. The growth is directly controlled by the chemical composition and the molecular flux arriving on the surfaces. This cannot be measured easily with experiments, so models are crucial for investigating the deposition process. To analyze and optimize the UHV/CVD process, engineers can use simulation.

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