PHYSICS TODAY

March 2021 • volume 74, number 3

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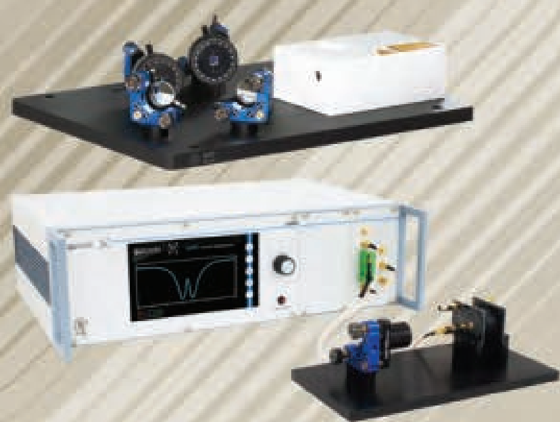
QUANTUM INFORMATION

Kevlar-inspired nanoribbons

COVID's toll on mental health

Topology meets biology



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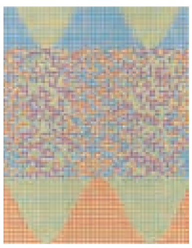
FEATURES



ON THE COVER: Placing an atom in one arm of an interferometer destroys the sinusoidal pattern that photons ordinarily produce. But, as artist Geraldine Cox depicts here, overlapping measurements of the atom's spin and the photon states reveal a hidden pattern. On **page 28**, Harrison Ball, Michael Biercuk, and Michael Hush discuss robust manipulation of information in quantum computing, and on **page 36**, Marcos Curty, Koji Azuma, and Hoi-Kwong Lo describe how to encode it for quantum cryptography. (*Illumination*, by Geraldine Cox, oil on canvas, 182 x 146 cm; http://www.findingpatterns.info.)

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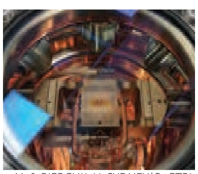

M. J. BIERCUK, U. SYDNEY/Q-CTRL

Quantum computers 101

The article on page 28 delves into quantum firmware, a crucial component for effectively manipulating qubits in a quantum computer. As described by PHYSICS TODAY's Christine Middleton, it's one of multiple layers of software abstraction that connect the physical qubit hardware and the user interface.
physicstoday.org/Mar2021a

SUSAN COLLINS

Science & society

Sociologist Harry Collins has long specialized in studying scientists. He talks to PHYSICS TODAY's Toni Feder about his early work tracking the transfer of knowledge among scientists, his shift to studying the role science plays—and should play—in society, and his current focus on remote meetings.
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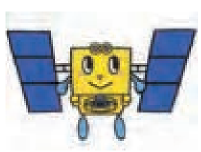

JAXA

SciComm in Japan

The sharing of science in Japan revolves around press clubs, clearinghouses through which most news in the country, scientific or otherwise, gets filtered, writes Amanda Alvarez. She also describes the whimsical side of Japanese science dissemination, which uses mascots and manga to make research accessible.
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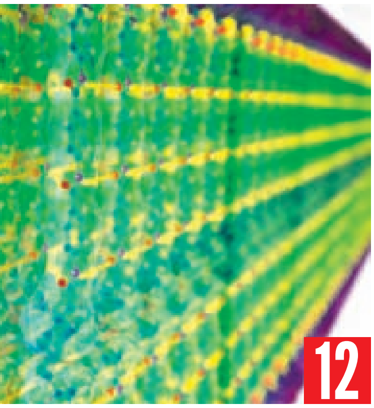

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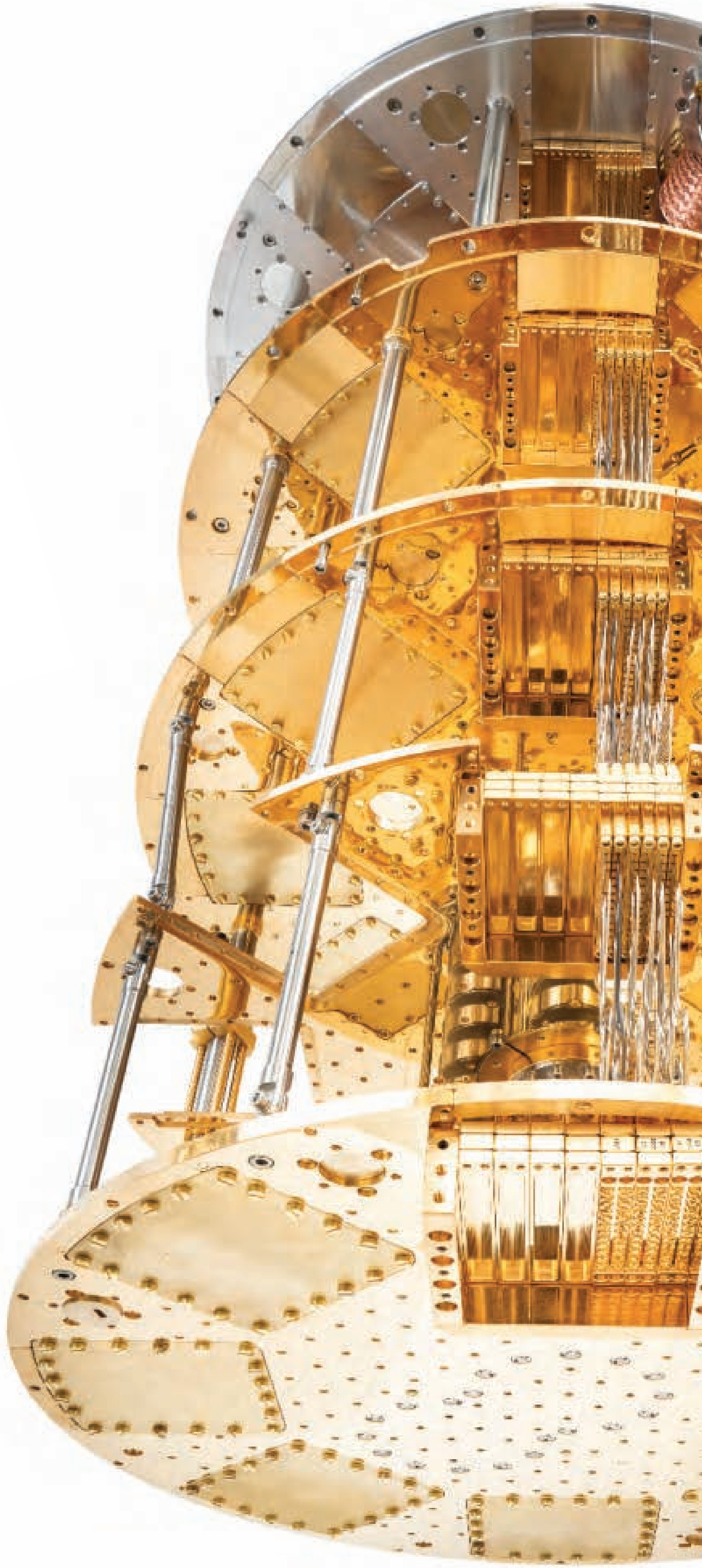

Quantum information is exciting and important

Charles Day

For the March–April 2007 issue of *Computing in Science & Engineering*, I wrote an essay entitled "Quantum Computing Is Exciting and Important—Really!" The essay's inspiration came from a sardonic disclaimer that Rolf Landauer (1927–99) proposed be added to papers about quantum computing:

> This proposal, like all proposals for quantum computation, relies on speculative technology, does not in current form take into account all possible sources of noise, unreliability and manufacturing error, and probably will not work.

Fourteen years ago I argued that even if Landauer's skepticism remained valid, the quest to build a quantum computer had already paid off. As supporting evidence, I cited the work of David Wineland and his collaborators at the NIST lab in Boulder, Colorado. Having developed logic gates based on trapped ions, they repurposed the technology to make new, entanglement-based clocks of unprecedented precision (see PHYSICS TODAY, October 2005, page 24).

I also cited the work of Princeton University's Jason Petta. In developing quantum dots as a platform for quantum computing, he and his collaborators at Harvard University measured the puny fluctuating magnetic field of 10^6 gallium and arsenic nuclei inside a quantum dot (see PHYSICS TODAY, March 2006, page 16).

Theorists were just as productive, I noted. The work of Caltech's Alexei Kitaev and others on topological quantum computation has spawned rich and fruitful explorations of the mathematical similarities of field theory, knots, and the fractional quantum Hall effect (see PHYSICS TODAY, October 2005, page 21). Princeton's Robert Calderbank applied the theory of quantum error correction to understand radar polarimetry.

Physicists continue to advance the field of quantum information. Perhaps the most spectacular recent feat is that of Jian-Wei Pan of the University of Science and Technology of China (USTC) and his collaborators. In 2017 their experiment aboard the satellite *Micius* beamed down pairs of entangled photons to the Chinese cities of Delingha and Lijiang, which are 1200 km apart. "Never has the spooky action of quantum mechanics been observed at so great a distance," wrote Ashley Smart in his news story (PHYSICS TODAY, August 2017, page 14).

This past summer, the team known as Google AI Quantum and collaborators reported the use of a quantum processor in combination with a classical computer to calculate the binding energy of chains of 6, 8, 10, and 12 atoms of hydrogen and the cis–trans isomerization energy of a diazene molecule, HNNH.

The Google team's calculations are not beyond the abilities of a classical computer. However, in October 2019 the Google team published a report in *Nature* that described achieving so-called quantum supremacy: Its 53-qubit device made of Josephson junctions took 200 seconds to solve a sampling problem that would take a classical system 10^4 years. This past December, USTC's Pan and his collaborators reported a similar feat in *Science*: Their 76-qubit device based on entangled photons solved a sampling problem 10^{14} times faster than a classical device could.

If Landauer were alive today, would he concede that a quantum computer probably will work? That's hard to say. The sampling problems tackled by the Google and USTC teams were expressly devised as benchmarks of quantum supremacy. They fall short of a universal quantum computer capable of, say, proving that the Hubbard model is sufficient to account for high-T_c superconductivity or the particles that result when protons and antiprotons collide at 14 TeV in an upgraded LHC.

Despite his skepticism about quantum computing, Landauer was a pioneer in investigating the quantum limits of information. One of his most cited papers is his 1961 derivation of the minimum about heat that is dissipated when one bit of information is erased: $kT \log 2$. PT

FOR MORE ON QUANTUM INFORMATION, TURN TO THE FEATURE ARTICLES ON PAGES 28 AND 36.

Visual similarities, micro and astronomical

Like many astronomy instructors this past autumn, I have been forced to teach my classes online. That means re-creating PowerPoint presentations, inasmuch as communicating visually on a small screen is different from doing so on a large one. In the process I came to see an old acquaintance in a new way.

The remnant of Tycho's supernova, SN 1572, appears in the left image, taken by the *Chandra X-Ray Observatory*. On the right is a computer model, derived from an electron microscopy image, of SARS-CoV-2. NASA puts the supernova remnant at 45 light-years in diameter; the virus is 0.1 µm across, according to the National Institutes of Health. So the objects differ in size by a factor of 4×10^{24}.

Yet the two share aspects in common. Both are young with respect to the Milky Way, and both evoke dread in those nearby.

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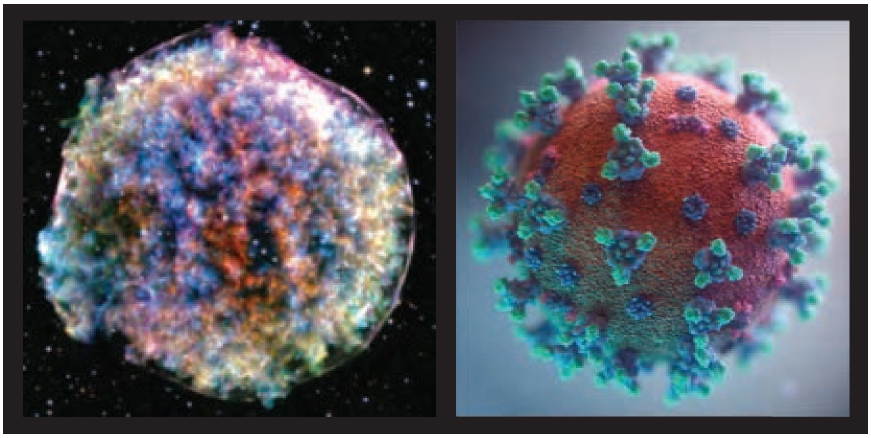

Tycho's supernova (left) imaged by the *Chandra X-Ray Observatory*. (Courtesy of NASA/CXC/RIKEN & GSFC/T. Sato et al.) SARS-CoV-2 virus (right) from a 3D computer simulation. (Courtesy of Fusion Medical Animation.)

Tools for a diverse college faculty

Physics departments that want to increase the diversity of their hiring pool (PHYSICS TODAY, October 2020, special careers issue) need to provide clear guidance to candidates, since some of the most interesting aspirants may lack mentors who can advise them on preparing applications. Colgate University has a website, www.colgate.edu/P&A/hiring, that offers help in writing statements on teaching, research, and diversity and inclusion for applicants to liberal arts colleges.

For example, we offer specific prompts for the teaching statement: Tell us what you learned from previous teaching experiences. How would you tailor a course to help students achieve their goals? What courses do you feel best prepared to teach? What have you learned about teaching from your experience as a student or from reading the science education literature?

We also specify what information we're looking for in a research statement. What will your lab look like? How will undergraduates contribute to it? And most importantly, we ask applicants to convince faculty from outside their research area that they've identified an exciting area of study where they can make contributions in an undergraduate environment.

We encourage other departments to think carefully about what they seek to learn from applications and to use their websites to share that information. Applicants who receive clear guidance can write more effective applications, which should increase equity in the hiring process.

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A picture's worth the right words

The October 2020 issue of PHYSICS TODAY included an item (page 26) by David Kramer entitled "The Great Lakes are filled to their brims, with no signs of receding." Kramer writes, "Water levels have always fluctuated on the Great Lakes, but the recent extreme seesawing, particularly on the upper lakes—Superior, Michigan, and Huron—is unprecedented in the century that records have been kept. . . . Michigan and Huron, which are linked and share the same level, stood at record highs in August, 84 cm above their historic average."

The article is interesting, and I do not dispute its general theme. However, the above quoted statement is misleading in that it is not a sound interpretation of the accompanying charts. They clearly show that the "record high" in August 2020 was matched by a similar high around 1987, and fluctuations do not appear significantly greater in recent years than those over the century since 1918. In fact, in 2000–2014, the levels were consistently below the long-term average.

Data presented in a scientific report should be seen to support the arguments and conclusions made. That is particularly important now, when the reliability of "the science" is under sharp scrutiny in disputes about such matters as climate change and epidemiology.

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Towcester, UK

Correction

February 2021, page 26—The image should have been credited to Point Designs, Lafayette, CO, https://pointdesignsllc.com. PT


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Evolutionary insights into shape-shifting proteins

Over millions of years a protein that now folds into two stable structures likely favored first one configuration, then the other, before settling on both.

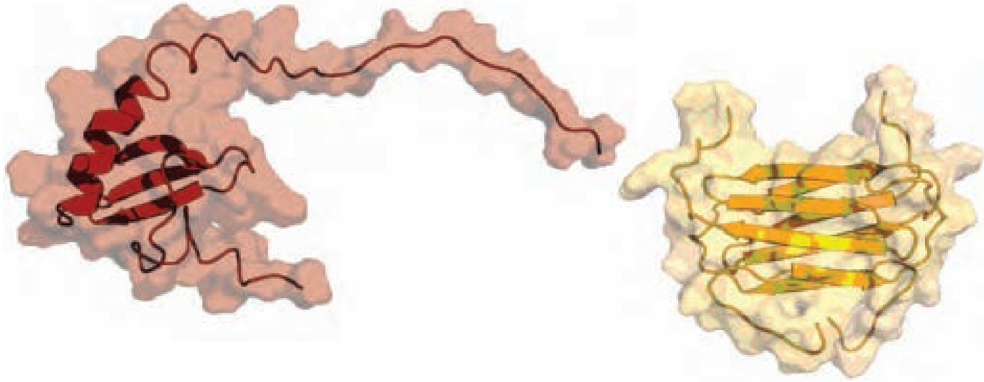

FIGURE 1. IMMUNE PROTEIN XCL1 switches between two different folded configurations that are equally stable under physiological conditions. In the chemokine fold (red), characterized by a helical structure and shared by the 50 proteins in the class, the protein binds to a receptor on a white blood cell and traffics the cell toward an infection site. In the alternative fold (gold), characterized by multiple sheet structures indicated by thick arrows, the protein directly attacks a virus or bacterium. (Courtesy of Acacia Dishman/Medical College of Wisconsin.)

According to biological paradigm, every protein has a unique stable three-dimensional structure, dictated by the specific sequence of its constituent amino acids. Through their interactions with each other, the amino acids form a well-defined, folded protein whose configuration is key to its function. Once folded, a protein may undergo conformational changes in response to environmental conditions such as temperature or pH: Subunits may rotate or hinge relative to one another to allow a channel in a cell's wall to open or close, for example. Nonetheless, the basic network of hydrogen bonds that holds the protein's shape remains unchanged.

But not all proteins follow the rules. In 2008 Brian Volkman (Medical College of Wisconsin) and colleagues reported one of the first glimpses of a human immune protein that appeared to switch seamlessly between two different folded conformations.[1] Under unchanged physiological conditions, the rule-breaking protein folded, unfolded, and refolded in equally stable structures that were held together by different hydrogen-bonded networks. How did that metamorphic behavior arise? How widespread is it? And why does it happen?

By reconstructing the likely family tree of a metamorphic protein, Volkman, graduate student Acacia Dishman, and their colleagues now identify molecular shifts that led from an ancestor that folded into a single conformation to a so-called fold-switching version that favored multiple conformations.[2] The finding suggests that metamorphic properties are not an evolutionary accident. Rather, fold switching could be a widespread adaptive trait among proteins, and the molecular sequences that encode it could offer a design strategy for engineering dual-function proteins.

Tracking a shapeshifter

The human immune system protein XCL1 was one of the first metamorphic proteins discovered. It operates mainly in the spleen and the lymph nodes and belongs to the family of 50 proteins, called chemokines, that together orchestrate the human immune response. In the chemokine fold conformation, common to all chemokines and characterized by a helical component as shown on the left in figure 1, the protein directs white blood cells to infection sites. In the alternative conformation, shown on the right, it directly kills viruses, bacteria, and fungal cells. Similar modern chemokines perform both of those functions in just one structure.

Most proteins, according to Volkman, undergo structural changes that nonetheless render them recognizable as the same protein—like an automobile whose roof opens but that still looks like a car in either state. In contrast, the two folded conformations of XCL1 don't even look at all alike. "It's like a Transformer toy, that goes from a robot back to a car," he says. In an aqueous solution, the protein switches its folding once every second, spending half its time in each conformation.

The researchers involved in XCL1's fold-switching discovery hypothesized that the protein could be an evolutionary artifact, caught in the act of changing from one version to another. As of 2020 the specific structures of six other metamorphic proteins had been examined in detail, but estimates suggest that thousands of other proteins could exhibit similar metamorphic traits.[3,4]

To investigate how a single amino acid sequence could encode two different structures and whether the shape-shifting behavior was a passing anomaly or a long-lived feature, Dishman and Volkman investigated XCL1's evolutionary history. They used software that predicted XCL1's likely ancestors based on 457 amino acid sequences from the protein's modern relatives in the chemokine family across species. The software compares amino acid sequences from different modern proteins known to share a family history and determines the sequences that are statistically most likely to have existed at different points going back in time.

How historical amino acid sequences folded, however, was still a mystery. (See PHYSICS TODAY, October 2008, page 20.) Dishman says, "If we reconstruct those ancestors, are they even going to look like a chemokine as we think of it today?" To find out, she produced the amino acid sequences in the lab and probed how they folded—something that cannot be predicted from first principles calculations. NMR spectroscopy revealed information about the arrangements of the amino acids in each protein after it folded into its final structure.

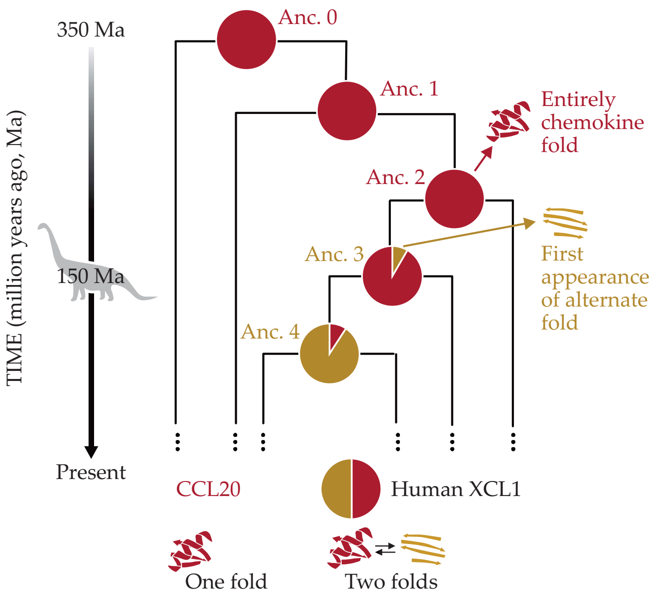

FIGURE 2. XCL1'S ANCESTORS evolved to favor an amino acid sequence that folded into the chemokine fold (red) and an alternate fold (gold). The fractional abundance of each arrangement adopted by the human immune protein shifted over time, first favoring one and then the other as represented by the pie charts, before arriving at XCL1's modern 50-50 split. Another modern protein, CCL20, retained the single fold of a 350-million-year-old Ancestor 0 (Anc. 0). Metamorphic folding may have evolved via a subset of key amino acid sequence changes that evolved from Ancestor 2 to Ancestor 3 around 150 million years ago (Ma). (Adapted from ref. 1.)

From the NMR fingerprints, the researchers found that an ancestor of XCL1, expected to have originated 350 million years ago, had just one stable structure—precisely that of a chemokine. NMR spectra of an XCL1 ancestor thought to have existed 150 million years ago contained strong peaks corresponding to the original chemokine structure, along with weak peaks indicating that 10% of molecules folded into an alternate structure. A more recent ancestor adopted mainly the novel second structure, and the modern human version, a 50-50 mixture, suggests that the dual-structure offered an evolutionary advantage.

The most exciting part, according to Dishman, is that XCL1 appears not to have evolved from one structure to another; rather, it evolved from preferring one fold to preferring a different fold and then settled on both. The fact that XCL1 folds and refolds repeatedly means that its thermodynamic stability is lower than most known proteins but not so low that it doesn't fold at all.

Family tree

After pinpointing when in the past the protein started to shift between two shapes, the researchers then deciphered the amino acid sequence that first led to XCL1's metamorphic properties. Figure 2 charts the path from the postulated oldest common ancestor shared by all chemokines, Ancestor 0, to the modern XCL1 version. In that family tree, Ancestor 2 was the last specimen to adopt just one fold, and Ancestor 3 was the first to adopt two folds. "We asked what changes in the amino acid sequence led to that shift in behavior," says Dishman.

Out of 67 amino acids that made up each of those two ancestors, 26 of them differed between the two sequences. To uncover how those sequence changes led to metamorphic behavior, the researchers analyzed the hydrogen-bond networks that formed between amino acids in each folded protein and in several other intermediate ones between Ancestors 2 and 3. The sequence changes that led from Ancestor 2 to Ancestor 3 corresponded to three structural constraints that needed to all be met for the second fold to be possible.

In one constraint, the original chemokine form of Ancestor 2 needed to incorporate new amino acids with nonpolar or sticky regions that allowed the alternate fold to arise in Ancestor 3. In another, the unfolded version needed more flexibility in some areas and more rigidity in others in order to bend into the alternate fold. Finally, the 3D chemokine fold had to be less tightly packed: The amino acids that fit together like a perfect jigsaw puzzle had to be replaced with others that meshed less well, lowering the energy barrier to structural rearrangement. If all three of those changes happened together, the protein became metamorphic; if one was missing, the metamorphism disappeared.

The ability to create artificial proteins with specific functions has opened new possibilities in drug delivery, vaccine design, functional nanomaterials, and more. Amino acid sequences that encode metamorphic proteins provide a new design strategy for researchers who want to create proteins that change their structure and function in the lab. For example, a fold-switching protein could be designed to fluoresce for use as a sensor or to serve as a moving part in a molecular machine. The sequences could also guide the search for additional metamorphic proteins in nature.

Whether metamorphic proteins are actually rare, or just rarely observed because humans have not been actively looking for them, remains to be seen. Most metamorphs have been discovered serendipitously, rather than sought out on purpose. Finding that they provide an adaptive advantage suggests that the Protein Data Bank, a global database of known proteins and their properties, could be littered with metamorphic proteins that are masquerading as monomorphs.

Rachel Berkowitz

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2. A. F. Dishman et al., *Science* **371**, 86 (2021).
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4. L. L. Porter, L. L. Looger, *Proc. Natl. Acad. Sci. USA* **115**, 5968 (2018).

Sturdy nanoribbons are a cross between a soap bubble and a bulletproof vest

A new strategy for molecular design takes self-assembled materials where they've never gone before.

Oil and water famously don't mix. Water molecules are polar—the shapes of their electron wavefunctions give them an uneven distribution of electric charge—and they energetically favor associating with other polar molecules to compensate. Nonpolar oil molecules don't qualify.

The immiscibility can be overcome with the help of an amphiphilic substance, whose molecules have polar, hydrophilic heads and nonpolar, hydrophobic hydrocarbon tails. With their tails pointing in and heads pointing out, amphiphilic molecules—such as emulsifiers, detergents, and other surfactants—surround droplets of oil and disperse them into the water. Even with no oil around, amphiphilic molecules can arrange themselves in water into intricate, orderly structures to protect their own tails from the surrounding polar medium.

Biology makes use of that self-assembly capability all the time. Every cell in your body is enveloped by a membrane made of two layers of amphiphilic molecules. Mimicking biology's powers of self-assembly is a goal of materials researchers who strive to make new engineered biointerfacing materials. (See, for example, the article by Simone Aleandri and Raffaele Mezzenga, PHYSICS TODAY, July 2020, page 38.)

But structures assembled through hydrophobic interactions almost always require the presence of water for their continued existence. The amphiphilic molecules in a self-assembled bilayer are held to one another only through weak van der Waals interactions. When the water dries up, the structure falls apart.

Now MIT's Julia Ortony, her graduate student Ty Christoff-Tempesta, and their colleagues have developed a new self-assembled nanomaterial inspired by Kevlar, the stuff of bulletproof vests. The nanoassemblies hold together even in a water-free environment, and they can be made into a dry, solid material.[1]

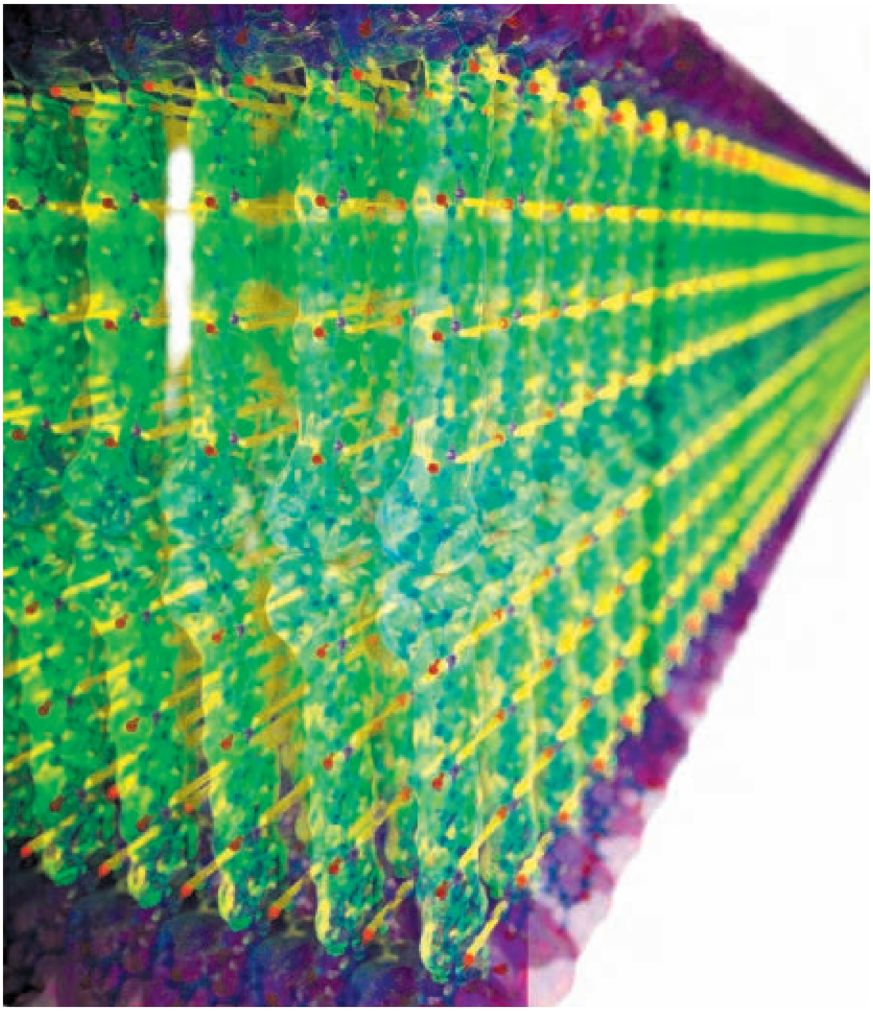

FIGURE 1. SMALL MOLECULES in water self-assemble into the bilayer nanoribbon structure shown in this computer rendering. The assembly is guided by the molecules' hydrophilic heads (purple) and short hydrophobic tails (bluish green). Between head and tail, three units of a monomer inspired by Kevlar (bright green and yellow) hold the molecules in tight formation, so the nanoribbon retains its structure even when the water dries up. (Image by Peter Allen and Ryan Allen.)

Amphiphiles assemble

Kevlar, an ultrastrong polymeric material, was developed in the 1960s and is used today in body armor, protective clothing, and many other applications. It derives its extraordinary strength from the interactions between adjacent parallel polymer chains. In one direction, the chains connect via intermolecular hydrogen bonds; in the perpendicular direction, they cling together through the stacking interactions between rigid benzene rings. Relative to most polymeric molecules, which are squiggly and floppy, Kevlar polymers are poker straight. Their inflexibility helps them line up and form interactions with their neighbors.

As a postdoc at Northwestern University in the mid 2010s, Ortony was interested in the effects of conformational dynamics on self-assembled nanomaterials.[2] Even a small change in molecular structure, she found, could make a big difference in material properties, if it affected how fluidly the molecules could move around. When she joined MIT as a new faculty member in 2016, she decided to

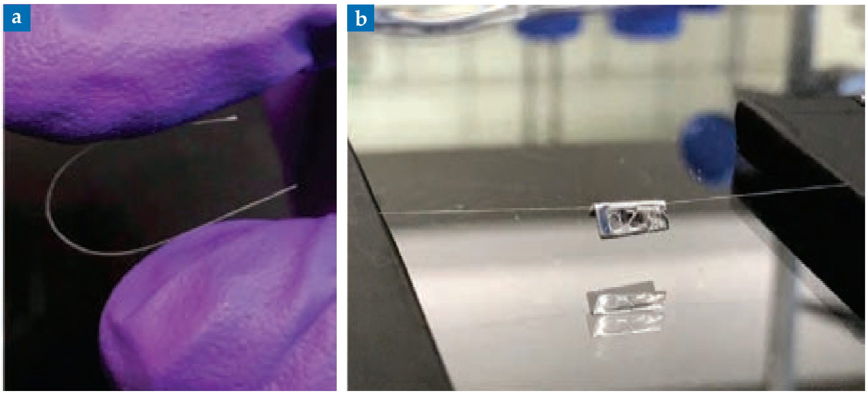

FIGURE 2. MACROSCOPIC THREADS made of aligned nanoribbons can **(a)** be bent and handled easily and **(b)** support up to 200 times their own weight: The metal fragment is a 20 mg mass, and the 5 cm thread it hangs on weighs just 0.1 mg. (Adapted from ref. 1.)

look at incorporating Kevlar's chemistry—and its conformational rigidity—into a hydrophobically assembled structure. Her goal: to create a hierarchically organized nanofiber that's stable without water.

To do that, however, she would need to venture beyond the existing understanding of what amphiphilic molecules are and how they behave. The dynamics of self-assembly are complicated; amphiphilic molecules can assemble not just into bilayers but into several other structures, depending on their size, shape, and interaction energetics. The foundational predictive theory, presented in a 44-page paper published in 1976, assumes that amphiphilic molecules' only components are their hydrophilic heads and hydrophobic tails.[3]

A snippet of Kevlar incorporated into such a molecule would be neither head nor tail but a distinct third domain. "We had no fundamental understanding of how that addition would affect the self-assembly," says Ortony. Too hydrophilic a molecule would dissolve in the water, and too hydrophobic a molecule would just precipitate out of solution. The ideal balance for creating complex structures had been identified for two-component molecules; finding it again for three-component ones would require trial, error, and iterative design.

Ortony and colleagues eventually hit upon a molecular recipe that yielded self-assembled nanoribbons: like bilayer membranes, but up to 4000 times as long as their 5 nm width. Surprisingly, the hydrophobic tails—the small bluish-green bulbs in the middle of the structure in figure 1—are short: just six carbon atoms as opposed to the 16 or so in a typical amphiphile. Between the head and tail are three units of a Kevlar-like monomer. "We tried two and we tried four," says Ortony. "Three is definitely the right number."

Tiny and tough

The nanoribbons are so much longer than they are wide because the intermolecular interactions are anisotropic: In the ribbon's long direction, the molecules are held together by hydrogen bonds between the chemical groups shown in yellow; in the short direction, by the less powerful stacking interactions between the benzene rings shown in bright green. To maintain that anisotropy, the hundreds of thousands of amphiphilic molecules in each nanoribbon must all be oriented the same way. That degree of order is unusual among hydrophobically self-assembled materials, which usually see their molecules drift and wiggle around one another and even diffuse in or out of a bilayer on time scales of hours.

To see if the ribbons' spatial order translated into temporal stability, the researchers mixed two batches of nanoribbons, one made of molecules tagged with a fluorophore and the other made of molecules tagged with a quencher. The quencher disrupts the fluorophores' fluorescence only when the molecules are in close contact—or part of the same nanoribbon. But even after two months, the mixture showed almost no change in fluorescence. Almost no molecules were moving from one nanoribbon to another.

The nanoribbons maintained their rigidity and integrity while just drifting in water, but what about under harsher conditions? Although it's not easy to rigorously measure the tensile strength of such small objects, one way to do it is to blast the material in a sonicator and analyze their fragmentation patterns. When Ortony and colleagues tried that, they found that their ribbons were stronger than steel, but Ortony cautions not to infer too much from that comparison. Most solid materials are stronger at the nanoscale than they are in bulk (see PHYSICS TODAY, November 2013, page 14). "What's most striking is that we could make this measurement at all," she says. "Other self-assembled structures would just have immediately fallen apart."

What happens when the nanoribbons are removed from water? To find out, the researchers filled a pipette with a nanoribbon suspension, drew out thin filaments, and allowed them to dry. Instead of collapsing like a soap bubble, the nanoribbons bundled together into resilient solid threads that could be handled and flexed, as seen in figure 2a, and support significant loads, as shown in figure 2b. Although not as strong as Kevlar, the threads constitute a truly solid-state self-assembled material.

The appeal of amphiphilic bilayers is that they always expose the same part of the molecule—the hydrophilic head—to the surrounding environment. Because the exact chemical identity of the head groups isn't critical for holding the structure together, they could be designed to perform tasks like pulling trace impurities out of the surrounding medium, releasing a cargo molecule, or catalyzing a surface reaction.

Furthermore, although the threads are tens of microns—or thousands of nanoribbon widths—thick, the spacing between ribbons is large enough to let atoms and small molecules in and out, so even the ribbons in a thread's interior can contribute to its chemical functionality. And because the nanoribbons are so thin, they pack a lot of active surface area into a small volume: The ribbons that make up a 0.1 mg thread, like the one shown in figure 2b, have a total surface area of some 200 cm^2. Ortony and colleagues are now exploring ways of putting their threads to work in places water can't go.

Johanna Miller

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Topological phases emerge in an ecological model

An exotic phenomenon in condensed-matter systems illuminates the behavior of a one-dimensional model akin to the game rock-paper-scissors.

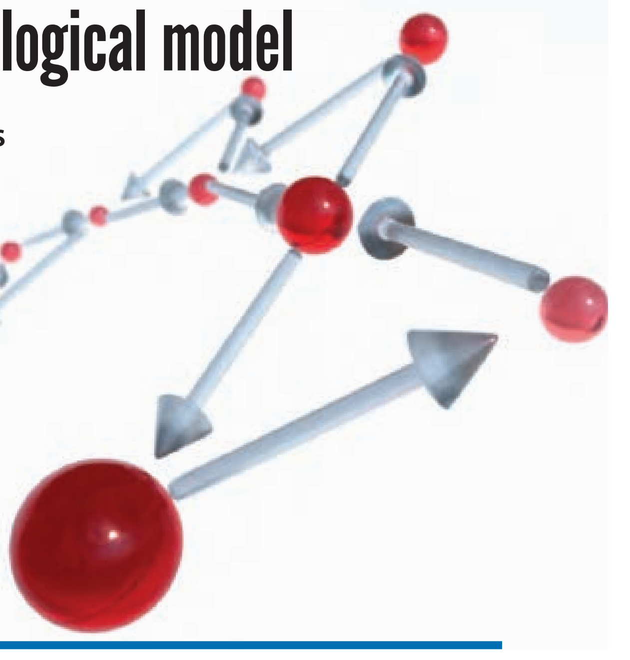


FIGURE 1. ROCK-PAPER-SCISSORS model for population dynamics. Population dynamics models incorporate interactions (arrows) between different species (red spheres). Similar to other nonlinear models, they typically show extreme sensitivity to small changes in their parameters, such as the initial population size of each species. But in the rock-paper-scissors model depicted here, Erwin Frey and his students found predictable behavior regardless of parameter tweaks. That behavior derives from the topological nature of the system's states. (Image by Cris Hohmann.)

Topology manifests itself in some of the major discoveries in condensed-matter physics of the past 50 years, including the quantum Hall effect (see the article by Joseph Avron, Daniel Osadchy, and Ruedi Seiler, PHYSICS TODAY, August 2003, page 38), topological insulators (see PHYSICS TODAY, April 2009, page 12), and the research honored by the 2016 Nobel Prize in Physics (see PHYSICS TODAY, December 2016, page 14). In topological phases of matter, the material's behavior derives from the connectedness of the band structure rather than the material's symmetries, which explain most states of matter.

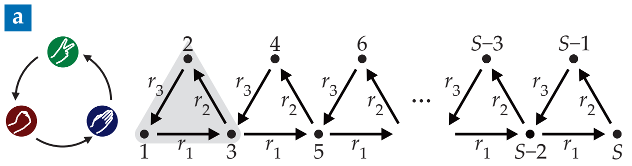
When a wave—for example, an electron wavefunction—travels around a topologically nontrivial path, it gains a phase after completing a closed loop rather than returning to its initial state. Although the results of the band structure's topology are complicated to understand in detail, an essential feature is the emergence of dynamic excitations localized at the system's boundary that are stable even in the presence of defects, a property known as robustness.

Researchers have recently started to study topological effects in systems outside hard condensed matter—for example, in liquids composed of self-propelled particles[1] and some atmospheric and ocean waves.[2] Now Erwin Frey and his group members at Ludwig-Maximilians University Munich in Germany have identified topological phases in an ecological model,[3] illustrated in figure 1. The work points to the potential application of topology to other dynamic biological systems.

Rock-paper-scissors

Johannes Knebel, one of Frey's graduate students, started the project in 2015 after he attended the Boulder School for Condensed Matter and Materials Physics in Colorado. While there, he was inspired by talks on topological phases in mechanical metamaterials by the University of Pennsylvania's Tom Lubensky and the University of Chicago's Vincenzo Vitelli and William Irvine.

One mechanical metamaterial is a lattice of gyroscopes coupled by springs (see "Topological insulators: from graphene to gyroscopes," PHYSICS TODAY online, 27 November 2018). Such a system supports a mechanical compression wave that propagates only along the edge and only in one direction, similar to the currents around the edges of topological insulators.



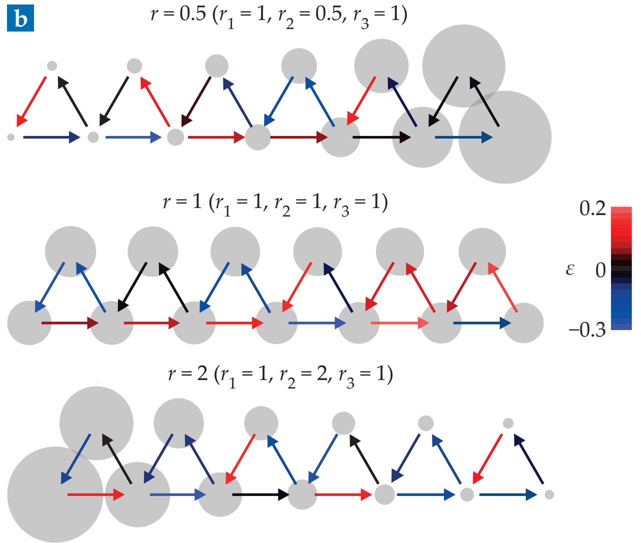


FIGURE 2. MASS POLARIZATION emerges in a one-dimensional evolutionary game-theory model inspired by the game rock-paper-scissors. **(a)** The model predicts the competition between S species (black points) through the mass-transfer rates r_1, r_2, and r_3 of linked individual rock-paper-scissors cycles (gray shaded triangle). **(b)** Different values of the skewness $r = r_2/r_3$ yield distinct behaviors. For $r = 1$ the time-averaged mass distribution (gray circles) keeps its initial distribution, in this case evenly spread out. But for $r < 1$ the average mass gathers on the right, and for $r > 1$, on the left. Those topological states, in which one species dominates, manifest even with rate perturbations ε, indicated by the color of the arrows. (Adapted from ref. 3.)

Knebel wanted to explore what other systems, in particular those described by nonlinear models, might host topological states.

Knebel and Philipp Geiger, another of Frey's graduate students, had been studying one such model, the antisymmetric Lotka–Volterra equation. The ALVE is a toy model used for many different dynamic systems. In ecology, for example, it's most often used for calculating population dynamics: how predator–prey interactions influence population growth. The Frey group recently employed it to predict the formation of Bose–Einstein condensates with species' populations swapped for the particle population in each energetic state.[4]

The ALVE can also describe an element of game theory known as a rock-paper-scissors cycle. If you picture the three moves in the game rock-paper-scissors as the points of a triangle, as seen in figure 2a, you can draw arrows to indicate which move wins. In a rock-paper-scissors cycle, each move wins or loses at some rate. For population-dynamics calculations, each point of the triangle represents a species, and the arrows become the rate at which mass moves in that direction—that is, the rate at which one species becomes more numerous at the expense of another. Each cycle is a local oscillator with mass shifting between the three sites.

Individual cycles, such as the first one, highlighted in gray, can be assembled in different geometries, with one site for each of the S species. The mass starts in some initial configuration, and through the nonlinear interactions between the sites, it rearranges over time. The mass transfer models the system's population dynamics.

When Frey and his students started looking for manifestations of topology in a two-dimensional lattice of rock-paper-scissors cycles, they observed chiral edge states, similar to the topological modes in 2D cold-atom lattices (see PHYSICS TODAY, September 2020, page 14). But rigorously connecting their observations to topology proved complicated. The researchers first needed to distill the essential elements of topology from the literature, which largely focuses on condensed-matter systems. So they turned to a simpler system: a 1D chain.

Polarizing behavior

Figure 2b shows an example of the researchers' numerical results for a 1D chain of rock-paper-scissors cycles. They start with the total mass evenly distributed over the whole chain and normalize the calculations such that the transfer rate $r_1 = 1$ for all trials. The researchers then vary the value of the skewness $r = r_2/r_3$ in terms of the other two rates.

When $r < 1$, the time-averaged distribution of the mass (gray circles) gathers on the right, and when $r > 1$, the average mass gathers on the left. Although the mass averages are stable, the system is not in a rest state and remains dynamic and fluctuating about that average. The researchers call the behavior mass polarization: The average mass becomes localized and drops off exponentially with the distance from the chain's edge. (From an ecological perspective, one species dominates the habitat.)

The skewness alone determines the mass polarization; the value of r_1 and the specific values of r_2 and r_3 alter the quantitative but not qualitative mass distribution. What's more, polarization states emerge regardless of the initial mass distribution and regardless of random perturbations ε to the rates, as shown by the color of the arrows in figure 2b. Even the addition of coupling between the top nodes of the chain doesn't change the qualitative behavior. The behavior is robust.

When $r = 1$—the transition between left and right polarization states—no one species dominates, and the time-averaged mass distribution doesn't concentrate in one spot in the chain. In figure 2b, the average mass distribution keeps its initial configuration evenly spread over the chain. If instead the mass is initially a packet confined to a few sites, the average mass remains spatially confined in the same shape as it moves along the chain. Two such mass packets on the chain retain their shape and speed after they interact, a behavior similar to solitons.

Those characteristics of the polarization states and transition state are topological in nature, which surprised Frey and his team. In most nonlinear dynamic models, the system's behavior depends sensitively on the parameters and typically dissipates or becomes chaotic, essentially the opposite of the behavior they observed.

The underlying structure

To clinch the case that topology explains their observations and to relate the ALVE to condensed-matter physics, the researchers calculated the equivalent of an energy band structure for their 1D rock-paper-scissors chain. First, they formulated the interactions in terms of an S-by-S antisymmetric matrix, which served as the basis for a Hamiltonian. Frey and his students then found the eigenvalues, eigenvectors, and from those, the band structure.

Because of its Hamiltonian symmetry, the rock-paper-scissors model is related to a model Alexei Kitaev devised for 1D superconductivity.[5] Just as in the Kitaev model, an invariant characterizes the topology of the band structure. An example of a topological invariant is the genus, which classifies the number of holes in a surface. A donut has the same genus as a coffee cup and can thus smoothly deform from the one shape to the other. But a donut can't smoothly deform into a sphere, which has a different genus.

The two skewness regimes, $r < 1$ and $r > 1$, have different values for the topological invariant and are thus topologically distinct phases. Those topological differences manifest in the mass-polarization states at the system's boundary, an illustration of the so-called bulk–boundary correspondence that underlies topological phases.

Whether topological states will show up in real-life biological or ecological systems remains to be seen. Promising candidates are gene-regulatory networks, which consist of a collection of molecules that govern gene expression in a cell. If topological states exist, then a network would regulate selected genes unaffected by external disturbances and noise.

Frey and his students plan to apply their approach to other dynamic systems, in particular stochastic ones. Frey says he wants the important ideas of topological phases to be available to the broad readership of biological and soft condensed-matter physics. He explains, "I believe that the transfer of methods from one field of physics to a different one remains one of the most inspiring sources of innovation."

Heather Hill

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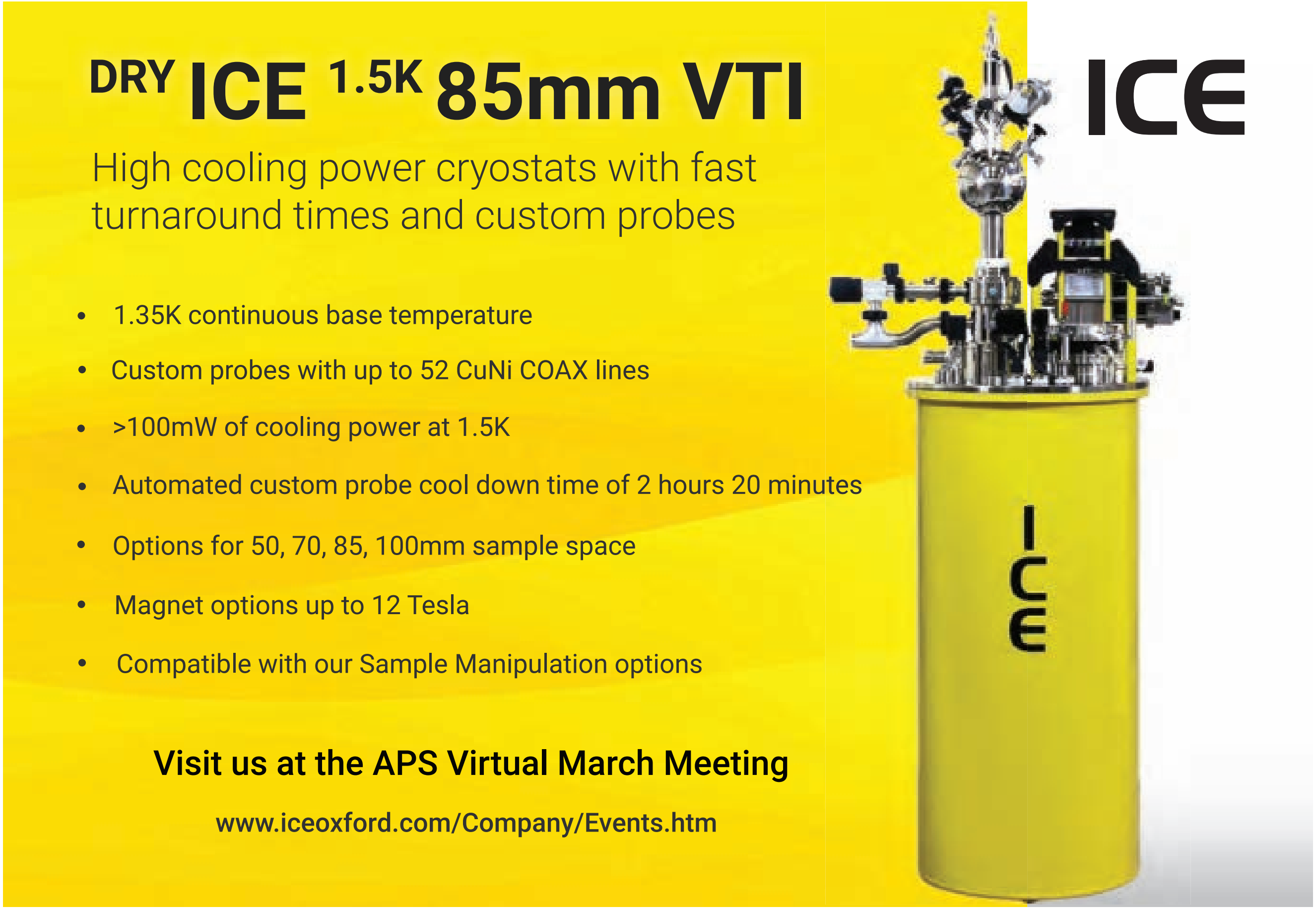
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• Custom probes with up to 52 CuNi COAX lines
• >100mW of cooling power at 1.5K
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• Options for 50, 70, 85, 100mm sample space
• Magnet options up to 12 Tesla
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PHYSICS TODAY

Stressed? Depressed? You are not alone

Many physicists find that establishing work–life balance is crucial to battling the COVID-related stresses of isolation, low productivity, and despondency.

VASHTI SAWTELLE

COMBINING CHILDCARE with remote work is a huge stress for many people. Vashti Sawtelle, a physics professor at Michigan State University, says she got two hours' notice to switch to remote teaching last March. Her children, ages 2 and 5, took care of themselves—sort of.

"Maybe I am a failure. Maybe I don't belong in academia. What is wrong with me?" wondered a postdoc in theoretical physics. Her research had stalled. The pandemic had her—along with much of the world—confined and isolated. The fact that she had a job and was not burdened with childcare responsibilities added to her feelings of guilt. "I was ashamed of myself for feeling depressed. I could barely get out of bed," says the postdoc, who requested anonymity.

The virus, the isolation the pandemic requires, and decreased productivity are for many people intertwined sources of anxiety and depression. Jacqueline Baeza-Rubio is a physics major at the University of Texas at Arlington. In January she, her siblings, and her parents were sick with COVID-19; she was administering nebulizers to her parents every six hours around the clock while continuing her work on NEXT, a neutrinoless double beta decay experiment, and preparing for a new semester of coursework. Baeza-Rubio says she had depression before the pandemic and "being alone in a room all day is not good. I became paralyzed with stress and didn't feel like working."

The effects of the pandemic have been exacerbated by economic uncertainty and unemployment, racial unrest, political upheaval, and wildfires, tornadoes, and hurricanes, says Roxane Cohen Silver, a professor of psychological science, medicine, and public health at the University of California, Irvine. She sums up these events as "cascading collective traumas." The effect on people varies by individual and circumstance and runs the gamut from making them short tempered to suicidal.

The impact on physicists mirrors the impact on society at large, says Daniel Lathrop, a physicist at the University of Maryland in College Park. "Without spontaneous meetings in my office and the hallway," he says, "I feel disconnected from my peers." Research group leaders are on the front line in counseling, he adds, for which they have no training.

For a few physicists, work has improved due to the pandemic. "The travel was a large strain on my mental health, and not having it is a huge quality-of-life enhancement," says a professor at the University of California, San Diego. "I'm kind of dreading going back to normal."

Even those in good circumstances feel the strain. "I have enormous privilege—a great job, the ability to work and teach remotely, a nice house to be confined to, grown kids so childcare is not an issue, and on and on," says Yale University astrophysicist Meg Urry. "I know it's a hundred times worse for younger scholars and parents with young children," she adds. "Yet I'm quite worn out. I find Zoom sessions valuable but much more tiring than in-person meetings."

Among physicists who are particularly at risk are those who are most isolated or overwhelmed by taking care of dependents and other responsibilities. Students and academics often live far from their hometown friends and families; international scholars can be especially isolated. Graduate studies and the quest for tenure are notoriously stressful even in normal times. "There is layer upon layer of things people have to deal with that contribute to mental-health issues," says Lance Cooper, director of physics graduate studies at the University of Illinois at Urbana-Champaign (UIUC). In terms of solutions during the pandemic, he adds, "We are making it up as we go along."

Normalizing mental-health issues

People think that theorists can do things on their computers or scribble in their notebooks, says University of Pennsylvania theoretical physics professor Andrea Liu, whose research focuses on soft and living matter. "But it's really a social activity. We are used to interacting all day long. And the casual interactions where you talk about work with people in the office or hallway are incredibly important for both science and mental health." For those holed up at home, she notes, "maintaining focus and productivity is really hard. I am not worried about [my group's] productivity, I'm worried about them."

In 2017 Andrea Welsh, now a postdoc who works on nonlinear dynamics of

VIVA R. HOROWITZ

VIVA HOROWITZ finds she can work better when she has Zoom open with a friend. Horowitz is a condensed-matter experimentalist at Hamilton College in Clinton, New York. "My advice for mental health?" she says, "Block your self-view on Zoom. Don't stare at your own face all day."

biophysical systems at the University of Pittsburgh, founded an online support group for physicists with mental illness. At the time, she was part of the American Physical Society's Forum on Graduate Student Affairs and, having personally dealt with depression, was seeking ways to improve the climate for graduate students. Before the pandemic, the group had about 90 members. It's jumped to 198, purely by word of mouth.

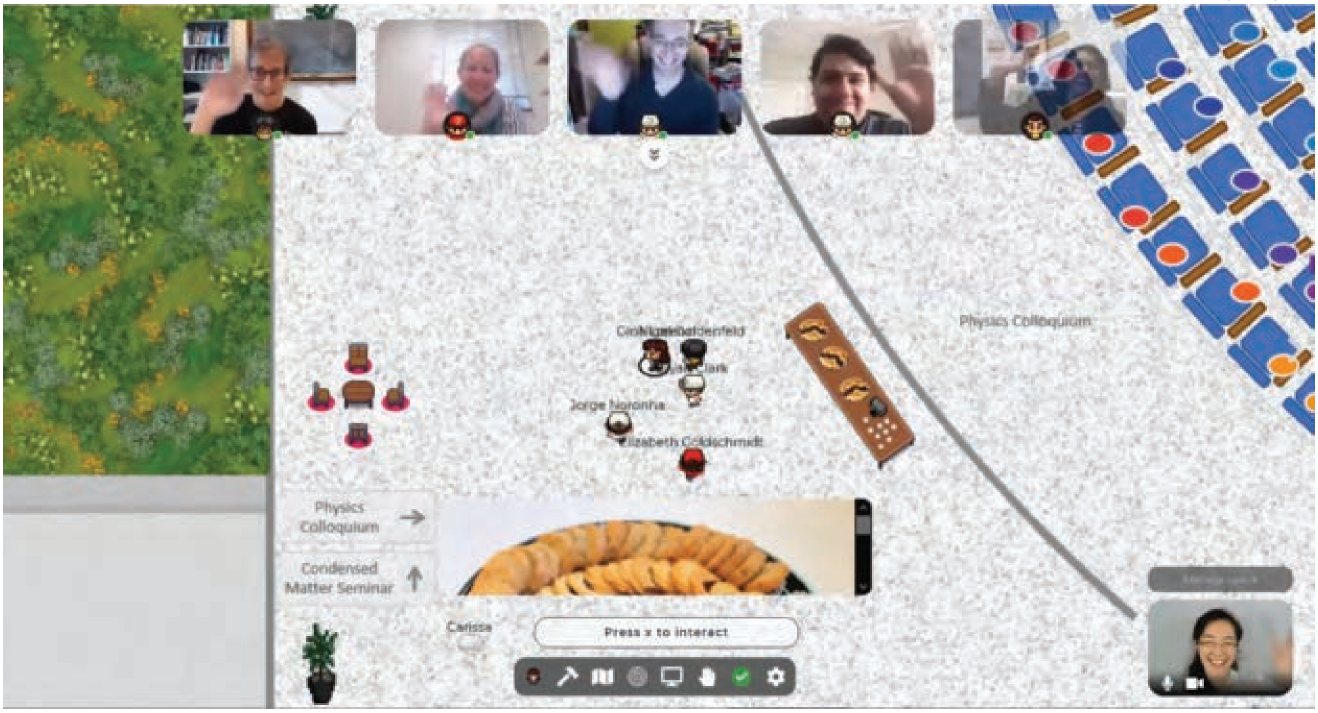
"My main concern," Welsh says, "is that a lot of people are falling through the cracks. They feel forgotten about. The community they had before is gone for now." The support group members interact on a Slack channel, where they share goals and report on their progress, seek advice on difficult and delicate academic and nonacademic situations, and discuss the effects of poor mental health on their day-to-day lives. Welsh also gives talks on mental health to physics departments, at conferences, and to experimental collaborations.

Since the start of the pandemic, the number of physics graduate students at UIUC who report struggling with their mental health has increased considerably, says Cooper. He has spoken with 75 or so of the department's 320 PhD students, and he checks in every week or two with about 15 of them. When research is not going well, many graduate students find teaching to be a confidence booster, he says. But with the pandemic it's harder to engage a class online, and graduate students feel their teaching is ineffective. They also tell Cooper they aren't learning as much themselves, in part because they can't study in groups. And they worry about the job market. "It's a big feedback loop." One of the hardest things is convincing students to tell their advisers when they are struggling, he continues. "They want to seem superhuman to their advisers."

The postdoc who requested anonymity eventually told her advisers about her depression and feelings of incompetence. "It was a big help," she says. She also posted about it on social media. "That led to an unexpected number of people writing to me that they felt the same way. It lifted the guilt." One adviser told her about her own struggles, and another suggested she take a real break. She had been taking a day off here and there, but that didn't help her mood or productivity. Because of visa issues and the travel ban imposed by President Trump (see "Revised travel restrictions drive scientists away from US," PHYSICS TODAY online, 10 March 2017), the postdoc, who is in the US from Iran, hadn't seen her family in seven years. In September 2020 she was able to travel to Iran after she received her green card. "I came back feeling like my old self," she says. "Now I am as productive as I was before the pandemic."

Grant Parker is a graduate student at the University of Texas at Arlington who is based in Madison, Wisconsin, where he works on the IceCube experiment. He has felt both self-pressure to be more productive and paralysis, he says. "It's taken a

VIRGINIA LORENZ



VIRTUAL REALITY is catching on for socializing and poster sessions. Here, faculty members at the University of Illinois at Urbana-Champaign are engaging in pre-seminar "cookie time" on gather.town. As your avatar approaches other avatars, you can hear and see the video of the corresponding people increasingly clearly and then join their conversation; it provides a simulation of reality that allows for some of the spontaneity people miss with Zoom. Visible at this meeting from 23 September 2020 are, from left, physicists Nigel Goldenfeld, Elizabeth Goldschmidt, Bryan Clark, Jorge Noronha, Vidya Madhavan, and Virginia Lorenz.

while to figure out how to beat the feelings of isolation." He and fellow graduate students schedule online chats and coffee breaks and in-person, masked, socially distanced walks. The pandemic is prompting discussions about work–life balance, he says. "Having these conversations is important, because otherwise we overwork or let guilt get to us."

Hidden impacts

Physics students and faculty tend to be high achievers who are good at carrying on despite impairments, says Walter Freeman, who teaches physics and astronomy at Syracuse University. "Mental-health impacts do not always show up in our work, but that doesn't mean the impacts are not there."

"When we went remote, my job got harder," says Freeman. "I sat in front of five monitors at home—with classes, a department Slack channel, a Zoom tutoring monitor, a stylus to write with." Sitting in front of a bank of flashing monitors for 14 hours a day "was not good for my own mental well-being," he says.

Freeman teaches more than 1000 students a year. He faces competing demands of engaging good students, helping weaker ones, dealing with the increasing numbers of cheaters, and responding to students' personal problems. "I get a ton of email that is some variant of 'I'm having personal problems and have not turned in my work,' " he says. "I want to be supportive, but I also have to figure out what to do with them academically."

The university doesn't want student suicides on its watch, says Freeman. "They tell faculty to send students to mental-health professionals." But students' issues often lie at the nexus of mental health and academics, he says. "What I desperately need from my institution is support in figuring out what accommodations are appropriate for students who say they have personal problems, many of which are subacute mental illness. I need support in building connections between people doing academics and people doing counseling."

"We need more compassion"

Like so much of the pandemic response in the US, remote teaching and advising is ad hoc and left to individuals or indi-

Getting help

- US National Suicide Prevention Lifeline: 1 (800) 273-8255
- Thrive Lifeline: 24/7 support from qualified crisis responders in STEMM; https://thrivelifeline.org. Text anytime: 1 (313) 662-8209
- Grad Resources, National Grad Crisis line: 1 (877) GRAD-HLP and more at https://gradresources.org
- Active Minds: Mental health resources during the COVID crisis, https://www.activeminds.org/about-mental-health/be-there/coronavirus/
- 7 Cups: Caring listeners for free emotional support, www.7cups.com/

MONIKA PAULAVICIUTE

LACK OF MOTIVATION and stress are both exacerbated by the pandemic. Mateus Carneiro and his girlfriend never intended for their small apartment in Brooklyn to double as their offices. Brookhaven National Laboratory, where Carneiro is a postdoc, supplied the chair he is seated on. When one of them needs to make a phone call without disturbing the other, they go out to the balcony.

vidual departments. Remote teaching and learning leads to detachment on both sides, says Maryland's Lathrop. Grades are down, and more students are withdrawing and failing. "The students' lack of engagement and their anxiety causes me stress," he says. "I hadn't realized how much the person-to-person contact meant to me as an educator. Interacting with students energizes me. I want them to succeed."

While many instructors are understanding toward their students, others expect business as usual. That's been Baeza-Rubio's experience with some of her classes. Due to an ulcer in her eye last fall she wanted to turn in work late, but her instructor said no, and told her to wear an eye patch. Baeza-Rubio knows of students who lost family members to COVID-19 and were told to produce an obituary to be granted deadline extensions. "We need more compassion," she says.

Similarly, Mateus Carneiro says he has observed international students stuck in dormitories being given little support related to COVID-19 while being pushed to be productive. "It boils down to the individual adviser," he says. "But academic culture generally is not very supportive toward graduate students. And COVID-19 has made it worse."

Carneiro, who is from Brazil, is a postdoc at Brookhaven National Laboratory. Before the pandemic, he went to Brookhaven a couple times a week. Other days he worked on calculations of neutrino cross sections in cafés near his Brooklyn apartment. Being cooped up with his girlfriend in an apartment never intended for 24/7 living, with social and work interactions limited to Zoom, is stressful, says Carneiro. "Not having spontaneity is a big loss." Work responsibilities have become "ethereal," he says. "Everyone is stressed and productivity is low, so my colleagues didn't notice I wasn't doing much. It made me feel guilty." The COVID-19 virus itself is also a source of anxiety, he says. "I cannot afford to get sick." When he realized he was depressed, he consulted a doctor. Medication seems to be helping, he says.

"I've had graduate students simply vanish; they stop communicating," says astrophysicist Angela Speck, chair of the University of Texas at San Antonio physics and astronomy department. "We have to take a holistic view of what's going on."

Official measures

Most US universities reopened experimental labs last summer with reduced capacity (see "University researchers get back to their experiments," PHYSICS TODAY online, 16 July 2020). That doesn't necessarily lead to increased social interactions, though. Pepijn Moerman is a postdoc at Johns Hopkins University who works on orchestrating self-assembly of microparticles using genetic regulatory networks. He goes into the lab two or three times a week. "I see people in the lab, but because we all know the time [for experiments] is limited, there is much less interaction than before the pandemic." For theorists, going onto campus likewise doesn't increase interactions, says Penn's Liu, "but it does offer a quiet workplace for some people."

COVID-19 testing is the key to staying open for many universities. At UIUC, for example, entry to campus requires being tested twice a week. The University of Arizona introduced testing with saltwater gargling samples, which is more sensitive and comfortable than the nasal swab. Through wastewater monitoring, last August that university also discovered two positive cases in a dormitory with several hundred residents. At Hamilton College in upstate New York, condensed-matter experimentalist Viva Horowitz says she feels less stress about going to campus because everyone is tested regularly. As for the students, she says, "they may be more afraid of being quarantined than of catching the disease." Horowitz says the "darkest moments" of the lockdown came when she realized she was afraid to spend the holidays with her mother and grandmother and was upset not to.

Horowitz studies diamond nitrogen–vacancy centers and two-dimensional materials. She was supposed to go up for tenure this year but has accepted her institution's offer to delay by a year. "The pandemic slowed down my research because of lack of lab access and for emotional reasons," she says. It also interrupted existing and new collaborations with colleagues around the country. "I don't know if a tenure delay or anything could make things fair," she says. "The university can't make it right that I was making research plans that I can no longer carry out."

Most institutions are offering an option to pause the tenure clock. Other measures campuses have taken to help faculty and students include inviting them to submit a statement with their promotion and tenure applications about how COVID-19 has affected their work, skipping student course evaluations (see PHYSICS TODAY, January 2020, page 24), extending deadlines for dropping courses, and installing improved air filters. The University of Arizona's College of Science created an emergency committee to guide graduate students and postdocs in campus reentry during COVID-19, says physicist Elliott Cheu, the college's interim dean. "Some teaching assistants were worried about teaching in person. It was getting dicey," he says. The college decided case by case whether in-person teaching was necessary.

Vashti Sawtelle is on the faculty at Michigan State University, where her research focus is physics education. She has two small children and shares childcare with another family; her husband is an essential worker. The university has done nothing to help with childcare, she says, but it did conduct a survey, and just telling the college how the pandemic affected her work life was "a big deal." One thing that has been hard on her mental health is that "it seems everyone expects you to have sorted things out by now, without any formal acknowledgment of what each family is dealing with. Academia wants you to keep doing what you usually do."

Money is another source of uncertainty. Institutions have allocated funds for COVID-related expenditures; testing alone can cost millions of dollars. UIUC is making funds usually used for travel available to students to cover insurance copays for off-campus counseling visits, says Cooper. At the University of Arizona, some departments have hired additional graders for large classes. At the same time, many institutions have frozen hiring and are being forced to cut budgets. Speck at San Antonio, for example, had to cut spending in her department by 15%. "We combined large online introductory classes and cut about seven adjunct faculty," she says.

Individual principal investigators have mostly continued to pay their graduate students and postdocs. NSF and other funding agencies have largely permitted "no-cost extensions," which allow researchers more time to spend existing awards. Although there was some talk about "cost extensions," which would have provided more money to existing grants, that hasn't materialized. Given people's lower productivity, PIs are concerned about accomplishing what they promised and winning future grants.

James Pennebaker, a social psychology professor at the University of Texas at Austin, has studied a decade's worth of language in Reddit comments. "COVID has had an unbelievably big effect in the degree of anxiety that people express," he says. One marker, he explains, is that people's comments have become "stupider and less logical." For some individuals and groups, the pandemic is especially tough, he says, pointing in particular to people who live alone and to young people "who are at an age where they need to network." In the academy, he says, "everyone is a bit terrified about the implications of the economy and funding for basic research."

Toni Feder

The undermining of science is Trump's legacy

The past four years saw interference in the scientific process, inaction on climate change, and a weakened federal science workforce. Artificial intelligence and quantum information science benefited.

"It's fair to say that in the scientific community, the four years of the Trump administration are going to be remembered as an intense moment of searing pain, one that is best forgotten as soon as the damage is repaired," says Representative Bill Foster (D-IL), Congress's sole PhD physicist.

"It would have been hard to imagine a president doing as much damage to science and Americans' trust in science and the application of science to so many problems this country faces," echoes Neal Lane, science adviser to President Bill Clinton and a former NSF director. "We've been through four years of hell."

"At the broadest level, on discussion of the issues in our body politic, [the Trump

OSTP

MICHAEL KRATSIOS, the Trump administration's chief technology officer, visited Fermilab in October 2019 to learn more about the lab's quantum research efforts.

administration] did terrible harm to any fact-based discourse," says Richard Moss, a visiting researcher at Princeton University and director of the US Global Change Research Program in the Clinton and George W. Bush administrations. He laments "the corrosive effect it's had on discussion of all manner of issues, from climate to COVID-19 . . . where facts no longer matter."

Nowhere did fact-based discourse suffer more than on climate change; Donald Trump not only denied the existence of a threat, famously calling it a "hoax," but actively undid the steps taken by his predecessor Barack Obama to mitigate greenhouse gas emissions. In addition to withdrawing the US from the 2015 Paris Agreement, Trump encouraged the increased consumption of coal and replaced the Obama administration's Clean Power Plan, which had tightened limits on carbon emissions from power plants, with greatly relaxed standards. A federal appeals court threw out Trump's plan on 19 January, effectively reinstating the Clean Power Plan.

Trump also eased Obama's vehicle carbon emissions caps and took legal action to overturn California's and 14 other states' authorities to continue adhering to the Obama-era tailpipe limits. The controversy confused and divided the auto industry on which limits it should follow. Litigation on those issues continues.

Trump appointed emeritus Princeton University physicist William Happer, an outspoken climate skeptic, to a White House advisory post. And Trump's advisers seriously considered former Department of Energy undersecretary Steven Koonin's proposal to conduct a "red team–blue team" debate that would pit the views of the small cadre of climate deniers and skeptics against those of the vast bulk of climate scientists. The idea, which was supposed to produce a consensus on the seriousness of the climate issue, was ultimately dropped.

"Policymakers' understanding of climate science suffered greatly by the president's denial of the problem," says Alice Hill, a senior fellow at the Council on Foreign Relations (CFR) and a National Security Council staffer in the Obama White House. "We saw the disappearance of the term 'climate change' from key strategic documents like the national security strategies and FEMA's [Federal Emergency Management Agency's] annual report on the preparedness of the nation for natural hazards." FEMA, she notes, "carries a heavy burden of responding to climate disasters."

But Kelvin Droegemeier, the director of the Trump White House Office of Science and Technology Policy (OSTP), points out that climate research continued at NSF, the US Geological Survey, DOE, and NOAA throughout the Trump years. "Was it a high priority of the administration? Clearly not as much as other administrations. That doesn't mean there wasn't scientific progress.

"Science is not the only thing that informs policy," says Droegemeier, noting that national security, economics, and politics are other considerations. "My job as director of OSTP was to make sure that science was at the table and that we were ensuring we had the best quality science results available."

Lane empathizes with Droegemeier. "You had people in the OEOB [Old Executive Office Building, where OSTP is housed] trying to do important things, while across the parking lot in the West Wing it was chaos, with anti-science, anti-truth, anti-everything. I've got to hand it to the career people at OSTP and other agencies who stuck it out. I can imagine how excited they are that science is again going to be listened to in the West Wing."

Droegemeier, who's returned to the University of Oklahoma as a meteorology professor, lists budget increases for artificial intelligence (AI) and quantum information science (QIS)—with a goal to reach $10 billion annually within five years—among the administration's science and technology accomplishments.

Droegemeier notes that AI quickly proved its usefulness in the pandemic, after he and science ministers of other nations called on journal publishers to immediately open up their coronavirus-related content in machine-readable format. "People brought their AI tools from around the world to bear on COVID publications that were coming out at a fire-hose pace," he says.

Foster acknowledges the White House achievements in AI and QIS, but he notes that "a lot of it was forced by increased competition from China and the rest of the world. Any administration would have done that. To their credit, people in the trenches at DOE and elsewhere made those programs happen."

Funding improves

To be sure, the nation's federal and academic basic research apparatus enjoyed funding increases throughout the Trump years—despite the president's intentions. "Every February, Trump would propose horrific cuts across the board, and to the credit of Republicans and Democrats in the House and Senate, they stood up and said, 'No, this will do damage to the country,' " says Foster.

Federal R&D appropriations rose to $165 billion in fiscal year 2021, from $118 billion in FY 2018, according to estimates from the American Association for the Advancement of Science. Those numbers don't include emergency spending related to the coronavirus, for which numbers aren't yet available.

The largesse was widely spread, led by the National Institutes of Health, where funding rose over the four years from just below $37 billion to $43 billion, according to FYI, the American Institute of Physics's science policy news source. NSF-sponsored research increased from $6.3 billion to $6.9 billion, while DOE basic R&D (excluding weapons and applied research programs) made similar gains, from $6.3 billion to $7 billion, according to FYI.

NASA's budget rose from $20.7 billion to $23.3 billion, with most of the growth devoted to human spaceflight. Trump countered Obama's agenda by ordering the return of astronauts to the Moon, but his goal of a lunar landing by 2024 was unrealistic, especially given Congress's refusal to provide anything close to the agency's budget requests for the Moon program. Critics of the selection of conservative representative Jim Bridenstine (R-OK) for NASA administrator were pleasantly surprised with his competent and largely apolitical management of the agency.

SHOREZONE, CC BY 2.0

THE ALASKAN VILLAGE of Kivalina on the Arctic Ocean is threatened by sea-level rise from climate change. Interior Department scientist Joel Clement was removed by Trump administration appointees from his job helping Arctic communities adapt to their shifting environment. He was reassigned to an office that collects royalties from oil and gas leases.

Research security

Critics acknowledge that in sensitive fields such as AI, QIS, and biotechnology, the OSTP made headway in balancing two priorities: maintaining international scientific openness in academia and protecting US intellectual property and research assets from foreign adversaries such as China. A three-year process that involved Droegemeier's own input gathering from universities around the country culminated in the issuance of a national security presidential memorandum in the waning days of the administration. The document spells out uniform guidelines to the federal agencies for vetting sponsored researchers on their involvements with foreign organizations.

Lane credits those efforts with helping defuse "crazy" threats by some lawmakers to ban all foreign students and international scientific cooperation.

The COVID-19 pandemic brought about an unprecedented rapid scale-up and redirection of research into vaccines and other therapeutics at several federal agencies. "I coordinated with NIH, DOE, NSF, and NIST to make sure we were getting money out the door quickly," Droegemeier says. Scientific computing and physics instruments at the national laboratories were directed to finding treatments for the disease (see PHYSICS TODAY, May 2020, page 22).

At Droegemeier's urging, NSF lifted the $200 000 cap on Rapid Response Research grants for coronavirus-related R&D. The funding mechanism allows accelerated review and award of funding for research addressing urgent needs.

But scientific progress against the pandemic was repeatedly undermined by Trump's endorsements of ineffectual treatments and his rejection of scientific advice. In particular, Trump sidelined Anthony Fauci, director of the National Institute of Allergy and Infectious Diseases, and Deborah Birx, the White House coronavirus response coordinator. In their place, he installed Scott Atlas, a radiologist who argued that the virus should be allowed to spread largely unimpeded.

Legacy of interference

An indisputable legacy of the Trump administration was an unparalleled level of political interference with science—data disappeared, scientists were silenced, and science-based policy was ignored or compromised. Perhaps the most far-reaching example of attempted interference was at the Environmental Protection Agency; an initiative, originally proposed by then administrator Scott Pruitt, sought to change the agency's process of setting individual exposure limits to harmful or toxic substances by excluding scientific studies for which raw data cannot be disclosed. Although the rule was due to take effect in January, it was vacated by a federal judge on 1 February.

The nonprofit organization Union of Concerned Scientists (UCS) documented 187 cases of political interference with science during Trump's four years. By comparison, the group counted 22 instances over Obama's eight years and 98 during George W. Bush's two terms.

Joel Clement, who catalogs episodes of political interference, was a high-ranking scientific career official in the Department of the Interior who had been working to assist Alaskan native communities in mitigating the impacts of climate change. Soon after Trump took office, he was reassigned to lead the department's office that collects royalties from oil and gas leases on federal lands. He resigned a few months after becoming a whistleblower and authoring a July 2017 op-ed in the *Washington Post*.

"It felt like being bullied in a schoolyard," Clement says. Political appointees in the agency had broken long-standing rules on reassigning senior career executives, he says, and had done so "in retaliation for my work telling them we've got to address these climate issues." He continues to work on Arctic issues as a senior fellow at Harvard University's Belfer Center for Science and International Affairs.

Jacob Carter worked on an EPA project to mitigate climate-change-caused flooding at the 1000 or so Superfund sites along the East Coast. Should a site be inundated by rising sea levels or heavy rains, toxic contaminants would leak into surrounding communities that are disproportionately communities of color and low income. Carter's research was aimed at assisting EPA site managers in determining the risk to particular cleanup sites and whether that risk warranted accelerating a cleanup or making a site more resilient. Carter, whose contract with the EPA expired days after Trump took office, says his peer-reviewed work was buried by the agency.

A UCS analysis released in January said that from a peak of 11 647 in early 2017, the scientific workforce at the EPA had fallen by 672 positions by 2020. The Interior Department's Fish and Wildlife Service lost 231 jobs during that period, and the US Geological Survey had 150 fewer scientists. On the other hand, 91 scientist positions were added at NASA and 79 at NSF, according to the UCS.

Droegemeier disavows any part in political meddling. "I was never directly aware or involved in incidences of political interference in science. They happened at the agency level," he says. "I said in my confirmation testimony that science needs to speak in an unfettered way and scientific results should be as they are."

Undoing the damage

Although the new administration rejoined the Paris Agreement on day one, reversing or rescinding all the Trump administration's environmental rules in such areas as clean air and wetlands could take years. "The Biden administration has a lot of digging out to do. I wouldn't trivialize that it's going to happen quickly," says Princeton's Moss. Adds CFR's Hill, "It takes time, it's complex, and it involves many experts to determine how to get back to where we were."

Trump's executive orders also can't always be reversed instantly by issuance of another order. "You've got to bring in lawyers to look at an order, you've got to agree on the right action, and you have to ensure it's an area that requires presidential attention," notes Hill.

Rejoining the Paris Agreement ensures that the US will be influential once again in the international response to the warming climate, says Lane. "But the world knows that in four years, it's possible someone will come in and go back to the dark ages," he warns. "They'll be hesitant to get too far out and assume we'll be a reliable partner for the next 20 years."

Myron Ebell of the libertarian Competitive Enterprise Institute sees another impediment to President Biden's climate change and environmental agenda. "The Biden administration will be up against what the Obama administration was at the end of its term: They have a very skeptical Supreme Court." He points to the court's 5–4 overturning in 2015 of the Obama-era rule that set emissions restrictions on mercury and other toxic pollutants by power plants and the court's blocking by the same margin of Obama's Clean Power Plan in 2016. "We have a new and improved Supreme Court now," Ebell says, referring to the three conservative justices appointed by Trump.

Rebuilding the scientific workforce at the agencies also will take time. Many of the scientists who left the administration have moved on to other jobs, and federal hiring authorities are cumbersome, says Hill. "It's not like once somebody leaves, they can jump back into their position."

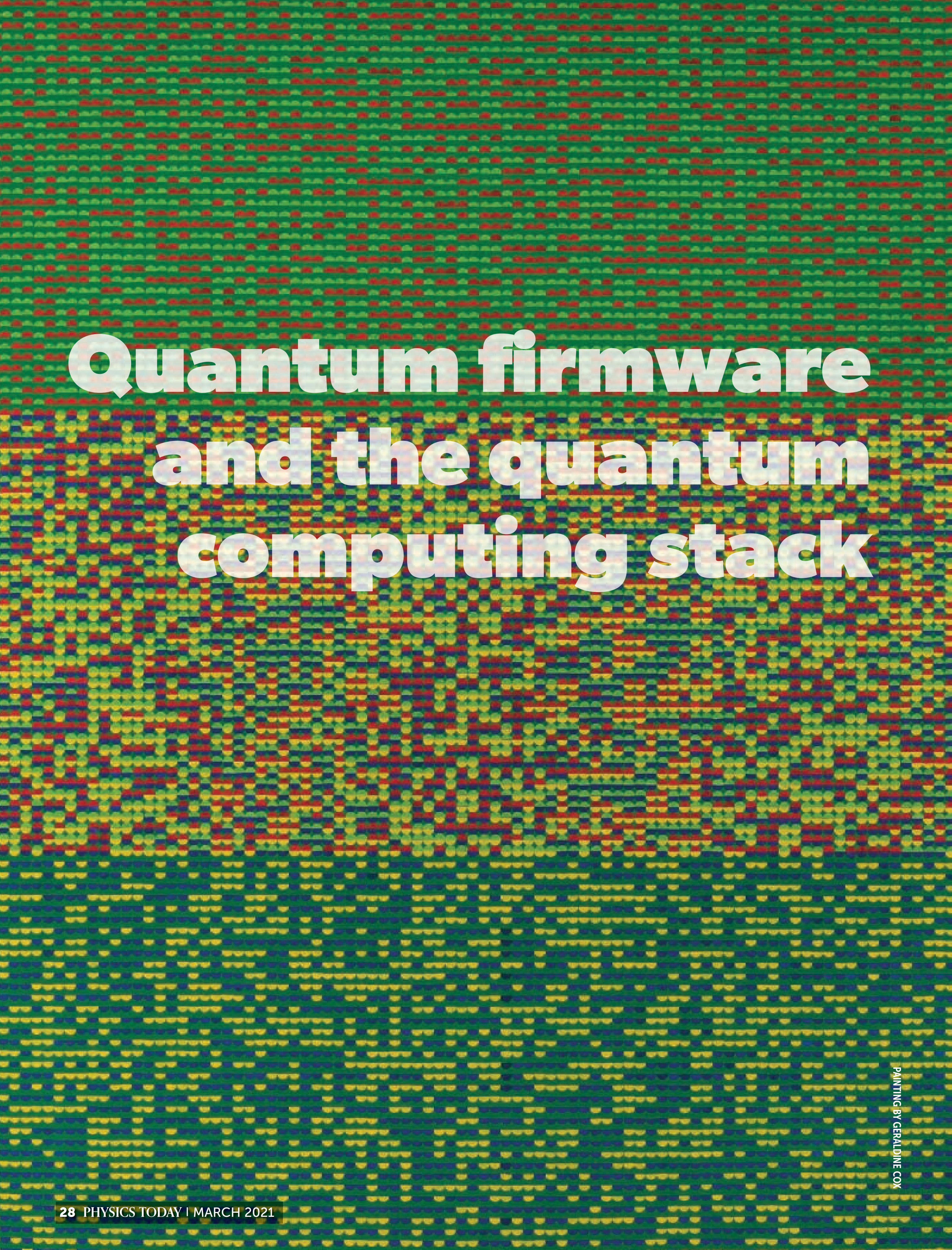
Droegemeier acknowledges much unfinished business. Maintaining global competitiveness will require figuring out how to quickly scale up newly developed technologies and bring them to commercialization, he says. That will require much stronger interactions between federal agencies, national laboratories, universities, and the private sector. "We learned from the pandemic that we can do things much faster and much more effectively in the midst of a crisis. Let's take those lessons learned and apply them to day-to-day business," he says.

Addressing competition from China will require far more than incremental increases to the agency budgets, warns Lane. "The idea that there are fields that are overfunded and we can just move money around, forget about that."

While expectations are high, Biden supporters see better times ahead. "Most scientists I talk to love the fact they can turn on the TV or radio in the morning and not have a feeling of dread at some anti-scientific proposal being floated or implemented by the administration," says Foster. He and Lane agree Biden's appointment of trusted experts, notably Eric Lander, who will be the first OSTP director with cabinet rank, sends a strong signal about the high value the president will have for science.

David Kramer PT

Quantum firmware and the quantum computing stack



PAINTING BY GERALDINE COX

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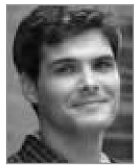


Harrison Ball, Michael J. Biercuk, and Michael R. Hush

Integrated quantum-control protocols could bridge the gap between abstract algorithms and the physical manipulation of imperfect hardware.

Quantum computers have rapidly advanced from laboratory curiosities to full-fledged systems operating with dozens of interacting information carriers called qubits. In 2019, researchers at Google became the first to demonstrate quantum supremacy[1]—a quantum computer capable of calculations that are impossible for conventional devices—by using just over 50 qubits.

Researchers are now on the threshold of being able to deploy quantum computers to solve a host of critical problems ranging from pharmaceutical drug discovery and industrial chemistry to codebreaking and information security. (For more on quantum cryptography, see the article by Marcos Curty, Koji Azuma, and Hoi-Kwong Lo on page 36 of this issue.) Because of ongoing developments in computational heuristics and approximate quantum algorithms, quantum computers may well be able to solve commercially relevant problems with some computational benefit, reaching what's known as quantum advantage, within the next decade.

Realizing useful computations using quantum systems requires scientists to recognize that performance is limited predominantly by hardware imperfections and failures rather than just system size. Susceptibility to noise and error remains the Achilles' heel of quantum computers and ultimately limits the algorithms they can run. Researchers are working to improve their devices' performance through passive means like circuit design, but they're also pursuing active measures; mitigating hardware errors through quantum error correction (QEC) has driven research for decades. The complexity and resource intensity of QEC—the set of algorithmic protocols necessary to ensure errors are identified and corrected—has motivated consideration of complementary techniques that enable augmented performance without that computational overhead.

Quantum firmware is a generalized designation for a set of protocols that connect quantum hardware with higher, more abstract levels in the quantum computing stack (see figure 1). More specifically, quantum firmware stipulates how physical hardware should be manipulated to improve stability and reduce various error processes—in essence, "virtualizing" the underlying imperfect hardware. Higher abstraction layers in the quantum computing stack then interact with qubits whose performance is different than that of the qubits in the bare hardware.[2] (For more on quantum computing architectures, see the article by Anne Matsuura, Sonika Johri, and Justin Hogaboam, PHYSICS TODAY, March 2019, page 40.)

The choice of the term "firmware" reflects the fact that although the routines are usually software defined, they reside just above the physical layer in the stack and are effectively invisible to higher layers of abstraction. That approach to low-level control resembles other forms of firmware in computer engineering, such as DRAM (dynamic random-access memory) refresh protocols that stabilize classical storage hardware against degradation caused by charge leakage. Such protocols are responsible for scheduling, defining relevant control and measurement operations, executing logic for actuation, and the like. A user employing DRAM has little awareness of its presence or activity except in the small effects its execution has on, say, memory access latency.

So that's the "what." But what about the "how?"

The underlying technology

Underpinning quantum firmware's functionality is quantum control,[3] a discipline that addresses the question, How can systems that obey the laws of quantum mechanics be efficiently manipulated to create desired behaviors? Ultimately, quantum control is concerned with how the classical world interacts with quantum devices. It guides researchers in gaining information about system dynamics through measurements and enables useful performance in computing, sensing, and metrology. (For more on quantum control see the article by Ian Walmsley and Herschel Rabitz, PHYSICS TODAY, August 2003, page 43.)

The field of quantum control largely owes its existence to decades of research in nuclear magnetic resonance and electron paramagnetic resonance, in which semiclassical magnetizations formed from nuclear or electronic spins are manipulated by pulses of resonant RF or microwave radiation. In those disciplines, hardware imperfections limited the ability to spectroscopically characterize molecules. Then, in 1950, Erwin Hahn demonstrated that a dynamic-control protocol now known as the Hahn echo could mitigate the impacts of magnetic field inhomogeneities on spectroscopic resolution. His discovery led to the development of average Hamiltonian theory, which is used to analyze the temporal evolution of spin systems, and of dynamical decoupling, a technique for canceling the impacts of unwanted spin interactions in molecules.[4]

Beginning in the 1980s, a parallel research discipline emerged that sought to adapt the concepts and numeric tools from control engineering to the strictures of quantum-coherent devices. That included both the treatment of linear systems, such as quantum harmonic oscillators,[5] and the development of numeric techniques for using imperfect hardware to effectively manipulate spin systems.[6] More recently, quantum optimal-control methods have been extended to more general Hilbert spaces and Hamiltonians[7] and have become powerful tools for optimizing quantum experimental system performance.[8]

Much like NMR, quantum computing hardware—whether trapped ions, neutral atoms, superconducting circuits, or another technology—generally relies on precisely engineered light–matter interactions to enact quantum logic. (For more on qubit technology, see the article by Lieven Vandersypen and Mark Eriksson, PHYSICS TODAY, August 2019, page 38.) Those operations constitute the native machine language; a timed

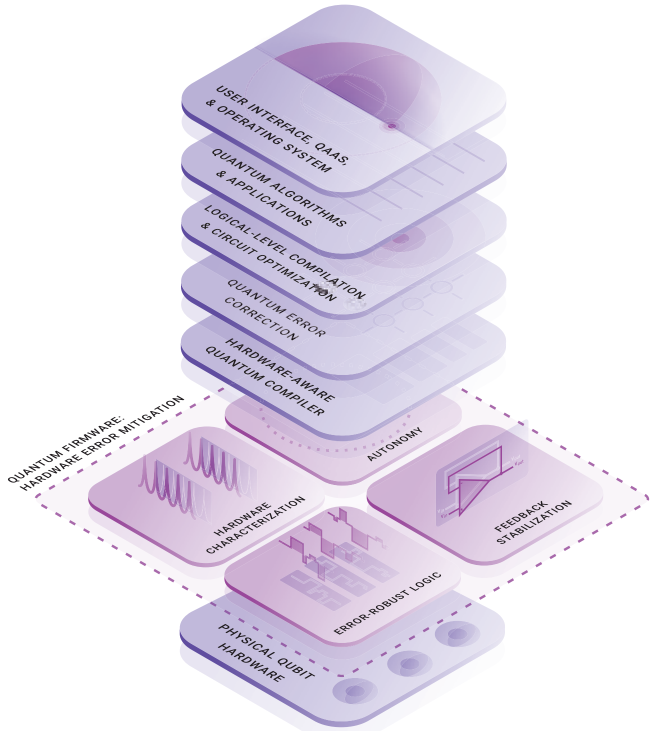


FIGURE 1. THE STACK in a fault-tolerant quantum computer is made of layers that correspond to levels of software abstraction. At the top sits Quantum As A Service (QAAS), which represents functions a user might interact with through, for instance, a cloud service. Below that are quantum algorithms and applications that are coded using developer tools that permit high-level abstraction. The algorithms and applications are compiled on the third level to enact circuits on encoded blocks. In fault-tolerant computing, that enaction is performed on logical qubits encoded using quantum error correction (QEC), although realizing the QEC code and other associated tasks occupies a dedicated layer. Physical connectivity between devices and compensation for any stray couplings are accounted for in a hardware-aware compiler. The quantum firmware layer, which is responsible for minimizing hardware error, resides between that layer and the physical hardware. It handles all tasks necessary for hardware calibration, tune-up, characterization, stabilization, and automation. (Image courtesy of Q-CTRL.)

Gaussian pulse of microwaves on resonance with a superconducting qubit can act as an X operation, the quantum equivalent of a NOT gate on a single qubit, whereas another pulse may implement a controlled-NOT operation on a pair of qubits, similar to a classical exclusive OR. An appropriately constructed temporal and spatial composition of such electromagnetic signals makes up a quantum algorithm.

The physical correspondence between spin-½ systems and qubits builds a natural bridge for transferring quantum-control techniques into quantum information in order to improve algorithmic success despite hardware imperfections and ambient decoherence. One of the clearest efforts to explicitly incorporate quantum control into quantum computers was articulated[2] by N. Cody Jones and coworkers at Stanford University in 2012. They introduced a so-called virtual layer that sat between quantum hardware and higher-level algorithmic abstractions in the quantum computing stack and leveraged

NMR-inspired composite pulsing.[4] Their foundational work inspired the quantum firmware layer described here. Researchers now have greater clarity about both the utility of quantum control and the structure of higher-level software abstractions with which the quantum firmware layer interacts.

Technical aims

Contemporary quantum firmware is charged with implementing the following functionality:

▶Error-robust quantum logic operations that are supported by measurement-free open-loop control.

▶Measurement-based closed-loop feedback stabilization at the hardware level.

▶Microscopic hardware characterization for calibration, noise identification, and Hamiltonian parameter estimation.

▶Machine learning–inspired approaches to realize autonomy for the above tasks in large systems.

Open-loop control refers to feedback-free actuation akin to a timed irrigation system that maintains a healthy lawn without information on soil moisture or rainfall. It's resource efficient and has proved to be remarkably effective in stabilizing quantum devices, both during free evolution and during nontrivial logic operations.[9] When open-loop error suppression is used in quantum computers, the instructions for quantum hardware manipulation are redefined such that they execute the same mathematical transformation, but in a way that is robust against error-inducing noise, such as fluctuations in ambient magnetic fields. The suppression is typically realized by temporally modulating the incident control fields that manipulate the physical devices (see the box on page 32), and the modulation patterns may be derived from Hamiltonian models or even machine-learning techniques. Thus the control solutions defined by quantum firmware constitute an effective error-robust machine language for manipulating quantum hardware.

In closed-loop feedback control, actuation is determined by measurements of the system. Its use is constrained by the destructive nature of projective measurement in quantum mechanics. Several strategies may nevertheless be employed for hardware-level feedback-based stabilization; they all are designed to gain sufficient information about the underlying system without destroying encoded information needed in a computation. In fact, QEC—the gold-standard approach for large-scale quantum computers—is a form of closed-loop feedback that employs indirect measurement through ancilla qubits. The direct integration of hardware-level feedback stabilization remains an ongoing area of exploration with some exciting results.[10]

Hardware characterization, known as system identification in the control-theoretic literature, has benefited from a large body of experimental and theoretical developments.[11] The underlying techniques complement external benchmarking routines that quantify the hardware's overall performance by focusing on the determination of actionable microscopic information for system optimization and tune-up. Noise spectroscopy, which is widely used as a complementary capability to noise suppression, provides information

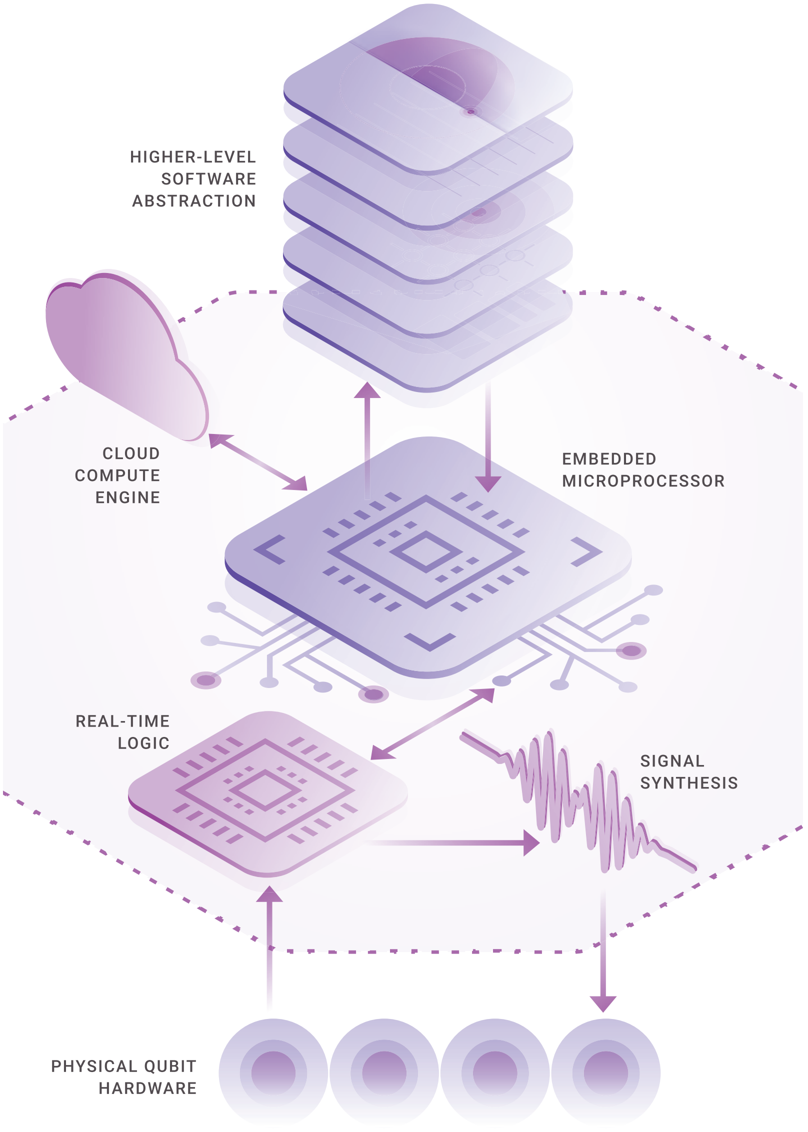


FIGURE 2. QUANTUM FIRMWARE is an abstract layer of the computing stack whose actions are orchestrated by an embedded microprocessor. The microprocessor accesses cloud-computing resources for computationally intense tasks such as open-loop-control optimization and virtualizes the hardware for its interaction with higher layers of the software stack. In the conception shown here, the microprocessor sends commands to programmable logic devices, such as field-programmable gate arrays. Those devices are responsible for processing measurement results in real time for physical-layer feedback stabilization, measurement-based decision making, and other tasks. They also provide instructions to other hardware elements such as direct digital synthesizers and arbitrary waveform generators. Arrows indicate communication pathways between elements. (Image courtesy of Q-CTRL.)

OPTIMIZED GATES FOR SINGLE-QUBIT LOGIC OPERATIONS

Existing medium-scale superconducting quantum computers provide an ideal platform for studies of quantum control because they allow for cloud access to advanced hardware. Using one such platform—a cloud-based IBM quantum computer—the research team at Q-CTRL, a quantum computing startup with facilities in Sydney, Australia, and Los Angeles, California, has explored the efficacy of quantum-control optimization in real systems. They employed specialized analog-layer programming that permits direct control of physical signals.

As an example, we demonstrate how to make an effective machine language that defines quantum logic operations that are resilient against the typical sources of hardware instability. In the illustration here, we show different techniques to produce gates that perform a Pauli X "spin-flip" operation,

$$\sigma_x = |0\rangle\langle 1| + |1\rangle\langle 0| = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix},$$

which is the quantum mechanical analog of a classical NOT gate. In each of the Bloch spheres shown, the quantum state—represented by the locus of a unit-length vector on the sphere's surface—follows a path from the sphere's north pole to its south pole. However, the qubit subject to a default implementation (panel a) takes a substantially different path from those of the two qubits subject to error-robust pulses (panels b and c).

The Pauli X operation is implemented using a pulse of microwave radiation that enacts a control Hamiltonian

$$H_c(t) = \tfrac{1}{2}\,(\Omega(t)e^{i\varphi(t)}\hat{a}).$$

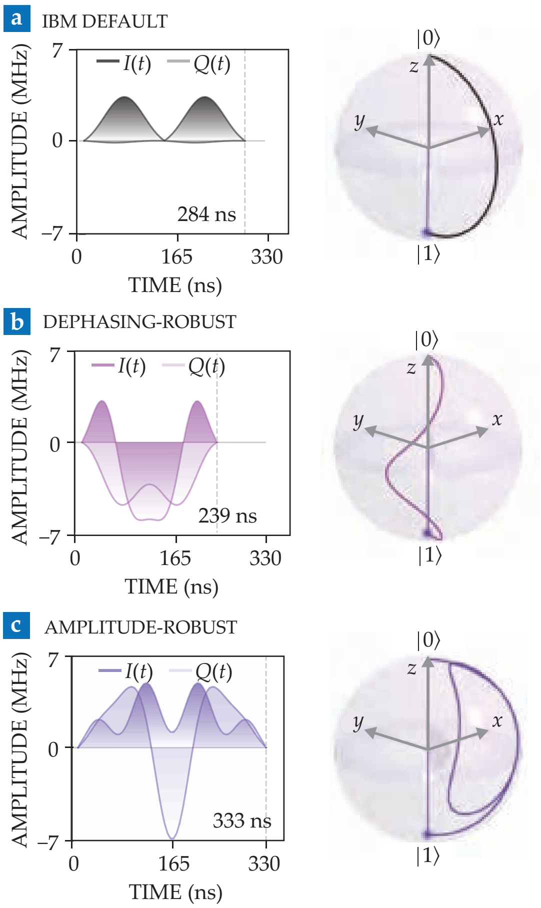
Here $\hat{a}$ is a function of a and $a^\dagger$, the lowering and raising operators for the state of the superconducting qubit. (We treat only the two lowest levels as an effective qubit.) The coupling term $\Omega(t)e^{i\varphi(t)} \equiv I(t) + iQ(t)$ represents the control-pulse waveform, and the functions $I(t)$ and $Q(t)$ therein represent user-adjustable controls.

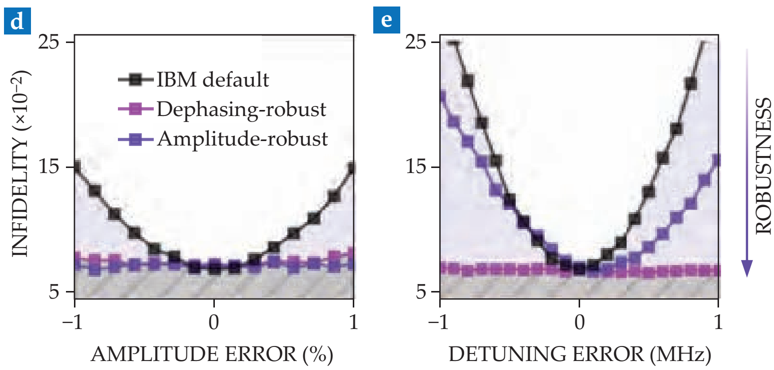
In the default implementation of the X operation (panel a), $I(t)$ is composed of two sequential pulses that are approximately Gaussian, with only a small component in $Q(t)$. Those pulses largely drive the qubit state along a meridian of the Bloch sphere. In a quantum firmware protocol, the simple physical definition for X is replaced with a new one that parameterizes the gate in terms of $I(t)$ and $Q(t)$.

Numeric optimization is used to minimize a cost function that ensures that the quantum logic gate is implemented correctly, even in the presence of noise. The controls applied in panels b and c are derived using $H_c(t)$ and take into account smoothing functions that ensure pulses can be faithfully transmitted from room-temperature electronics into a dilution refrigerator where the qubits are housed. Because of the error reduction incorporated into the control waveforms, qubit states subject to optimized controls take paths along the Bloch sphere that are more complex than those taken by the default qubit. Enacting those complex paths often requires a longer pulse.

The optimized controls described here are designed to implement the X operation in a manner that is robust against either errors in the amplitude $\Omega(t)$ or in the driving frequency that implements the pulses. To test the control's performance, it is repeatedly applied in the presence of either quasistatic pulse-amplitude errors or pulse-frequency (detuning) errors, and the gate's infidelity—the probability that a qubit state evolves to the wrong target—is measured (see panels d and e). Even when large amplitude or detuning errors were added to the applied pulse, each optimized solution shows a flat response, which is a signature of robustness. The control designed to be robust against dephasing (panel b) is indeed flat in the presence of dephasing errors (panel e). Likewise, the amplitude-robust control response (panel c) is flat despite amplitude errors (panel d).

The shaded areas in panels d and e indicate the overall improvement achieved through the choice of appropriate optimized pulses. Additional controls designed to exhibit robustness to both error processes simultaneously have also been demonstrated. (For a full explanation of the experiment described here, see reference 9.)





used in the design of open-loop controls. To implement it, a qubit can serve as a sensor that when subjected to appropriately designed time-domain control, probes noise at different frequencies.

Hardware imperfections can be identified through various techniques generally classified as Hamiltonian parameter estimation. A simple implementation might allow for the determination of the coupling rates between physical devices and control fields and reveal transmission losses experienced by signals en route to the qubits. More complex routines are commonly employed to determine the frequencies of unwanted energy levels in a device or to characterize unknown couplings between qubits. The information obtained from such protocols informs open-loop error-suppressing controls and dynamic models for feedback-based stabilization.

Artificial intelligence–enabled autonomy, the final class of techniques in quantum firmware operation, represents one of the most exciting exploratory areas of research in quantum information. Scaled-up systems will require high-efficiency routines that can tune up, calibrate, optimize, and characterize the underlying hardware with minimal user intervention. An interdisciplinary effort integrating machine learning, robotic control, and data inference is showing how adaptive measurement routines may be deployed to reduce the number of destructive measurements required[1,12] and to enable rapid autonomous system bring-up and operation.

Integration strategies

Any practical implementation of quantum control must be tailored to the needs of a hardware system; each scheme will require a particular subset of the functions described above. But the control techniques have much in common, and they are increasingly being used in state-of-the-art experimental and commercial-grade quantum computers. (See PHYSICS TODAY, November 2020, page 22, for more about the commercialization of quantum computers.) Researchers have thus been motivated to organize the relevant functionalities into an identifiable abstraction layer. Creating that organizational structure, however, is distinct from determining how quantum control should be integrated into real systems.

One approach involves integrating the control functions into their own encapsulated layer in the quantum computing stack. In that conception, quantum firmware is responsible for defining and executing all actions that bridge the gap between high-level abstractions, such as compilation or application programming, and the many low-level quantum-control routines customized for particular hardware systems. Firmware can be embedded into appropriate computational hardware to virtualize the underlying quantum-coherent hardware. That is, the firmware changes the behavior and performance of the hardware such that high-level abstraction layers have no visibility into the "bare" performance of the underlying hardware.

The implementation of a dedicated quantum firmware layer brings several potential benefits. First, the development of efficient high-level programming frameworks such as Cirq, Quil, and Qiskit has led to an explosion of capability at the application and algorithmic level. Building a framework to standardize quantum-control integration may also encourage the quantum-control and machine-learning communities to develop more diverse technical solutions for efficient hardware manipulation.

A dedicated firmware layer could autonomously orchestrate quantum-control tasks that span different classical computational hardware. Those processes could exploit local processing to support automated scheduling and unsupervised stabilization, distributed computing infrastructure to execute computationally intensive optimization tasks, and low-latency programmable logic to conduct real-time processing. For example, a local microcontroller can, on a schedule, initiate a cloud-based numeric optimization of a multiqubit gate (see figure 2). That solution can be used to seed a hardware-executed tune-up of the final control waveform, which is then written to embedded memory. Slaved to the microcontroller is a field-programmable gate array that both directs signal-synthesis hardware to output the waveform used to manipulate the qubits and also processes measurement results from the qubits. (A logically distinct "embedded operating system" always remains that defines and enables the functionality of the classical electronics in use.)

For the near term, researchers are exploring how the distinctions between layers in the emerging stack could be blurred to deliver maximum performance. For example, it's possible to pursue a hardware–firmware co-design strategy to directly integrate certain critical tasks into the classical electronics[13] while others remain in the experimental software.

Opportunities may also arise to fundamentally rethink the organization of quantum computer software stacks based on the functionality provided through exploitation of quantum control. The potential value of such approaches is evident in hardware-aware compilation, in which optimal control is used to efficiently produce high-fidelity hardware-optimized logical blocks. Quantum algorithms may then be compiled into a library of numerically optimized "analog" control sequences that would replace a smaller but more general set of universal gates.[14]

System-level impacts

Regardless of how quantum firmware is realized, recent experiments have made clear that the quantum-control functionality encompassed therein could affect or even reshape higher abstraction layers. That's because the virtualization produced by quantum firmware fundamentally transforms the behavior of the underlying hardware, especially as it pertains to the characteristics of hardware errors.

Open-loop control strategies are broadly used to suppress errors in state-of-the-art quantum computer hardware; for example, in certain settings, DRAG (derivative removal by adiabatic gate) pulses—an example of open-loop control—have been shown to reduce gate errors in superconducting qubits by approximately an order of magnitude compared with conventional Gaussian pulses. More recent results demonstrate that numerically optimized gates can mitigate the effects of hardware imperfections in cloud quantum computers, thereby suppressing pulse-amplitude, off-resonance, and cross-talk errors. Those demonstrations are particularly powerful because the error processes effectively addressed by quantum firmware often generate far larger effects than one would expect from best-case-scenario benchmark routines.

In both research-grade systems and publicly available cloud systems, best- and worst-case qubit error rates across a device often differ by more than an order of magnitude. Those errors can arise from fabrication variances and coupling inhomogeneities between qubits and the ambient electromagnetic environment. Quantum firmware homogenizes hardware performance in space and time. Optimized quantum-control operations implemented in real systems have brought error rates for all qubits close to the best-case performance; likewise, drift-robust controls can extend typical calibration windows on cloud and laboratory hardware from 6–12 hours to more than five days.[9]

Why do those improvements matter? To start, current algorithmic compilers can improve performance by trading an increase in compiled-circuit complexity for the ability to avoid poorly performing devices. But in large-scale systems with substantial performance variation, that compilation process can become quite complicated, and shuttling information around the worst-performing devices may require many more gates and time steps. By homogenizing device performance in space and time, quantum firmware can simplify higher-level compilation protocols,[15] thereby reducing the complexity and duration of the implemented algorithm.

Quantum control will also have a long-term impact on the performance of QEC. Both the hardware-level feedback stabilization and open-loop control found in firmware exploit the fact that noise processes often vary slowly in space and time; those methods provide little benefit for truly stochastic errors. On the other hand, QEC formulations generally assume statistically independent error models. Thus quantum firmware works in concert with QEC to correct for a broad range of error types and effectively preconditions the properties of the residual errors to be compatible with QEC.[16] But more than that, the way in which quantum firmware closes the gap between the best and worst performing qubits and reduces statistical correlations in the residual errors[17] actually reduces QEC's resource intensity. It's a win–win combination.

The future of quantum firmware

Quantum computing is complex, so algorithm designers and end users need a framework through which they can efficiently exploit quantum computers without having detailed technical knowledge of the underlying hardware. They expect high-performance quantum hardware to be stable and provide consistent outputs irrespective of small changes in an algorithm's structure. Quantum firmware enables those capabilities.

Quantum-control demonstrations have confirmed improvements of about a factor of 10 in the performance of quantum logic operations relative to naive gate implementations.[9] Similarly, dynamic memory stabilization has extended qubit lifetimes to time scales measured in minutes. In those settings, the performance gains have been limited by either incoherent processes or the capabilities of classical electronics, but both are showing steady gains with time and specialization for the quantum computing market. We therefore expect that control systems and device performance will improve in parallel with quantum firmware protocols.

The effect of using quantum-control technologies such as error-robust open-loop control on algorithmic performance can be quantified with benchmarks. One such benchmark is quantum volume, a metric that accounts for architectural features, including hardware connectivity, and device-level parameters, such as the one- and two-qubit error rates across the device.[18] Honeywell has claimed a quantum volume of 128 with just a handful of qubits compared with approximately 64 from IBM's larger systems; the results demonstrate that hardware performance is the primary bottleneck.

Improving both one- and two-qubit error rates by more than a factor of 10, as has been demonstrated experimentally, would have a massive impact on system-level performance. Those impacts would be largest in devices with weak connectivity, where the spatial rearrangement of qubit data requires many multiqubit swap operations. Device sizes are increasing rapidly—Google and IBM have each released a road map to 1000-qubit systems—and quantum control provides a means to ensure system utility at the algorithmic level tracks with system size.

Ultimately, we believe that building and operating large-scale quantum computers is effectively impossible without integrating advanced quantum-control techniques into a quantum firmware abstraction layer. Autonomous vehicles, walking robots, and advanced avionics systems have all demonstrated the importance of dynamic control and automation. Similarly, in quantum computing, advanced control-theoretic strategies were instrumental in the calibration and tune-up of devices used to achieve quantum supremacy. Many techniques from the fields of machine learning and robotic control are likely to improve performance and increase autonomy, thereby allowing future quantum developers to confidently abstract away the details of a computer's underlying hardware.

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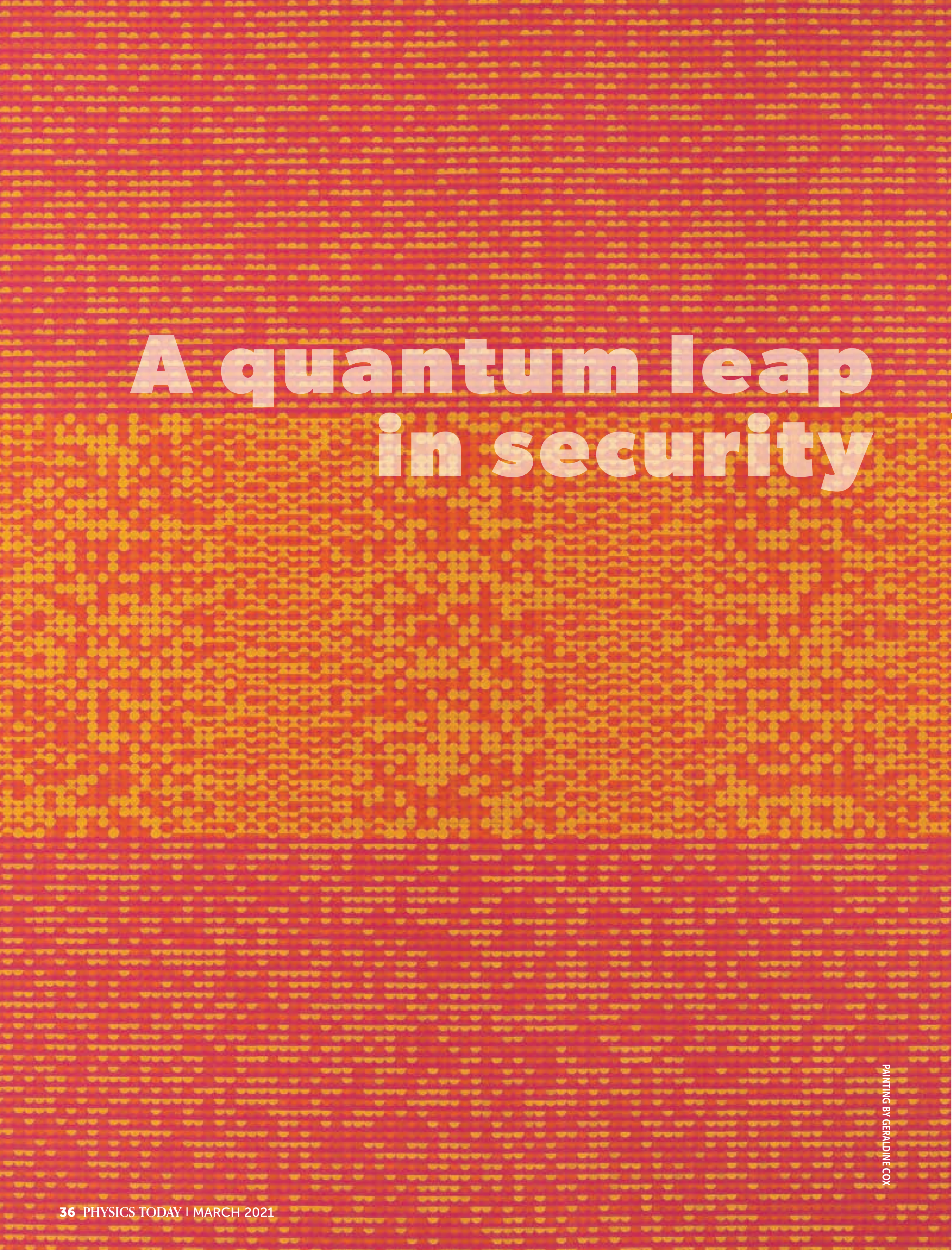

A quantum leap in security

PAINTING BY GERALDINE COX

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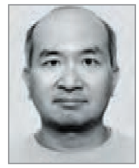

Marcos Curty, Koji Azuma, and Hoi-Kwong Lo

One-photon and two-photon interferences have recently led researchers to develop new classes of quantum cryptographic protocols.

We all send sensitive data such as credit card information over the internet daily. Internet security currently relies on several computational assumptions. For example, the security of a well-known public-key encryption scheme—the so-called RSA cryptosystem—hinges on the belief that no efficient algorithm for performing prime factorization of large integers will appear in the next decade on conventional computers. But a quantum computer could efficiently factor large integers and thus break the most widely used public-key encryption schemes, including the RSA and elliptic curve cryptosystems.[1] Put simply, when a fully functioning quantum computer is built, much of conventional cryptography will fall apart.

Motivated by that eventuality—and by the many potential future applications of quantum computers in biomedicine, chemistry, artificial intelligence, and other fields—researchers have recently made tremendous progress toward constructing a large-scale, universal quantum computer. (To learn about how quantum hardware is becoming increasingly accessible, see the article by Harrison Ball, Michael Biercuk, and Michael Hush on page 28 of this issue.) Technology giants Alibaba, Google, IBM, and Microsoft are in the race. In 2019 Google claimed to have achieved the first experimental demonstration of quantum supremacy—a quantum computer capable of solving a problem unfeasible for a conventional computer.[2] Rapid developments have spurred the US National Security Agency, which spearheads code-making and code-breaking in the country, to start planning for a transition to quantum-safe cryptosystems over the next decade or so.

There are two main approaches to quantum-safe cryptography. The first one, post-quantum cryptography, relies on conventional public-key cryptosystems that experts believe are resistant to existing quantum algorithms. Its security against future advances in classical or quantum algorithms, however, has yet to be established. The second approach, quantum key distribution (QKD),[3] relies on the quantum no-cloning theorem, which states that any attempt to copy an unknown quantum state, or even try to obtain information about it, disturbs the original state. With that theorem, QKD securely distributes a common string of secret bits, called a cryptographic key, between two distant parties, typically named Alice and Bob.

The security of QKD holds even if a potential eavesdropper—say, Eve—has computational capabilities that reach the limit allowed by quantum mechanics. The security is achieved by sending nonorthogonal quantum signals through an open channel, such as an optical fiber or a free-space link. Any eavesdropping attempt to access the transmitted information can be caught because it introduces detectable errors.

If the established secret key is combined with a one-time-pad cryptosystem, Alice and Bob can communicate in absolute privacy through an untrusted channel (see the article by Daniel

Gottesman and Hoi-Kwong Lo, PHYSICS TODAY, November 2000, page 22). In the one-time-pad cryptosystem, to create the ciphertext that she sends to Bob, Alice applies bitwise XOR operations between her message and the key. The XOR operation outputs a bit value of 1 only if the two input bits differ from each other. On the receiving side, Bob decrypts the ciphertext by using bitwise XOR operations with his copy of the key. The length of the key needs to coincide with that of the message, and the key must be discarded once used.

To generate a secret key using QKD, Alice and Bob must first distribute a (possibly virtual) bipartite quantum-entangled state through a quantum channel. A bipartite quantum state is entangled precisely if it exhibits stronger than classical correlations (see the article by Reinhold Bertlmann, PHYSICS TODAY, July 2015, page 40). For example, suppose that Alice's and Bob's systems are prepared in the entangled state $|\psi^-\rangle_{AB} = 1/\sqrt{2}\,(|0\rangle_A\,|1\rangle_B - |1\rangle_A\,|0\rangle_B)$, called a Bell state. Here, $|0\rangle$ and $|1\rangle$ form an orthonormal basis termed Z. If Alice and Bob measure their individual systems in the Z basis, the measurements will produce opposite results: If Alice obtains $|0\rangle$, Bob generates $|1\rangle$.

That property holds for any common measurement basis selected by Alice and Bob. Most importantly, their results are totally random and unpredictable for Eve. If Alice and Bob associate the bit value 0 to the result $|0\rangle$ and the bit value 1 to the result $|1\rangle$, they obtain a secret key, and Bob needs to flip only his bit values to match those of Alice. Therefore, if they share many Bell states, they can perform secure communication by means of the one-time-pad cryptosystem.

In practice, channel loss, channel noise, device imperfections, and a possible attack by Eve might prevent Alice and Bob from sharing perfect Bell states. Still, quantum mechanics allows them to verify if the shared states are sufficiently close to Bell states. If they are, Alice and Bob can distill a smaller fraction of perfect Bell states from the original states using local operations and public, classical communication. That fraction determines the length of the secret key that Alice and Bob can extract from their shared systems.

Progress and challenges

Researchers have developed high-speed QKD systems with repetition rates of up to 10 GHz; implemented long-distance, fiber-based, point-to-point QKD links as far as 421 km apart; and enabled the multiplexing of quantum and classical signals in the same fiber, which is necessary for QKD to be compatible with conventional optical communication systems. QKD networks are now being deployed worldwide for secure communication in metropolitan and suburban areas.

Quantum-repeater technology would enable entanglement distribution over arbitrarily long distances, but it has yet to be developed. Currently, QKD networks typically rely on a trusted-node architecture to overcome the distance limitation imposed by channel loss.[4] For that setup, QKD only protects the communication between adjacent nodes in the network, and a copy of the key is available at all trusted nodes. In China, a 2000 km QKD backbone with about 30 trusted nodes connects Beijing and Shanghai, and a ground-to-satellite QKD network has recently enabled a secure video conference between Beijing and Vienna, 7600 km apart. Likewise, Europe and the US are developing blueprints for building continental-scale QKD networks this decade.

Despite such tremendous achievements, some fundamental challenges remain. The most pressing one is to guarantee the security of real-life QKD implementations. Because of device imperfections, real devices could, for example, leak electro-

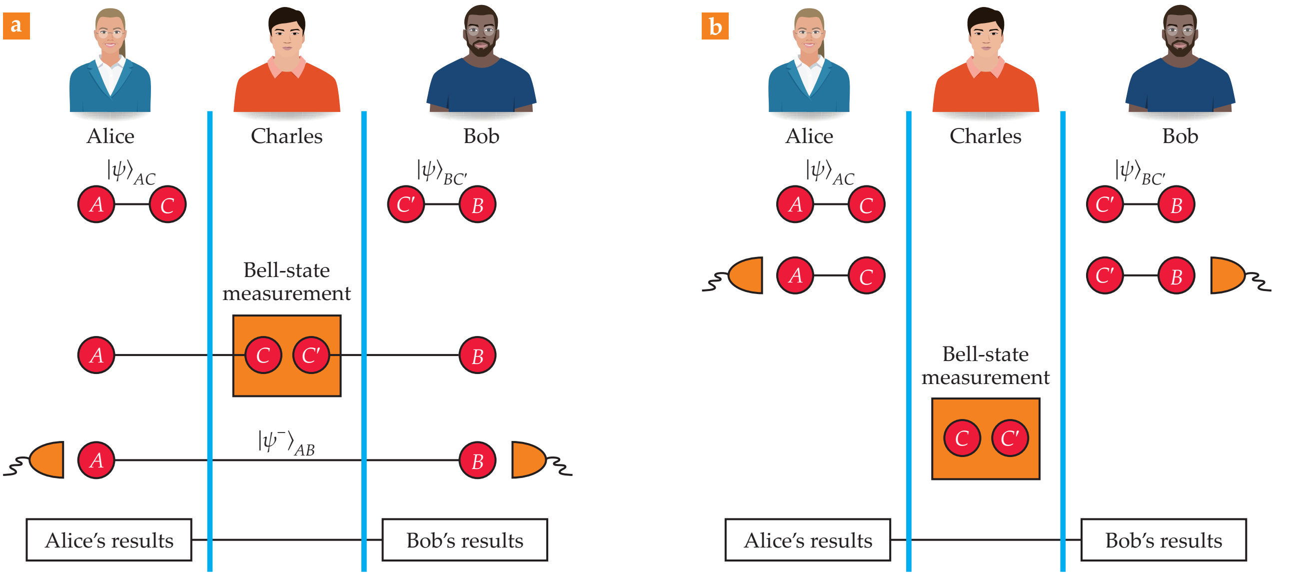

FIGURE 1. QUANTUM KEYS can be distributed via entanglement swapping. **(a)** Two parties, Alice and Bob, who wish to communicate information, prepare entangled states $|\psi\rangle_{AC}$ and $|\psi\rangle_{BC'}$ and send the particles C and C′, respectively, to a third person, Charles. If Charles's Bell-state measurement is successful, particles A and B become entangled in a Bell state, such as $|\psi^-\rangle_{AB}$. Alice and Bob can verify the entanglement by measuring their particles A and B in the Z and the X bases at random and then comparing their results. **(b)** Because Alice's and Bob's measurements commute with those of Charles, they could measure the particles A and B before they send him C and C′. That approach is equivalent to a prepare-and-measure scheme in which they send Charles the states that would result from such a process without actually preparing entangled states. (Adapted from F. Xu et al., *IEEE J. Sel. Top. Quant. Electron.* **21**, 6601111, 2015.)

magnetic or acoustic radiation, or behave differently from what is typically assumed in security analyses. The deviations could open security loopholes, or so-called side channels, which Eve might exploit. Single-photon detectors at a receiver are particularly sensitive to quantum hacking attacks. Researchers have demonstrated that by injecting strong light into the receiver, Eve could control which of Bob's detectors observes a signal each time and thus obtain the secret key.[5]

One possible approach to bridge the gap between theory and practice is QKD that is device-independent (DI),[6] though no experimental implementation has been realized so far. The solution uses a Bell inequality to verify if Alice and Bob share an entangled state, and it thus does not require them to characterize the internal functioning of the apparatuses. Despite its theoretical beauty, DI QKD is impractical with current technology: It demands a nearly perfect single-photon detection efficiency and yet would provide only a low key rate—the number of secret bits obtained per transmitted signal—at short distances of about 40 km. In addition, ensuring that the measurement apparatuses do not leak any information to Eve might be challenging for uncharacterized devices. For example, certain single-photon detectors emit backflash light that reveals which detector observes a signal each time.

The performance of QKD in terms of key rate versus distance still needs improvement. In point-to-point QKD configurations, the key rate scales at most linearly with the transmittance of the quantum channel, which is the probability that a one-photon pulse emitted by Alice reaches Bob.[4] For typical optical-fiber channels, the transmittance decreases exponentially with the distance and thus so does the key rate. Whereas quantum repeaters are the ideal solution, researchers can increase secret-key rates via multiplexing techniques.

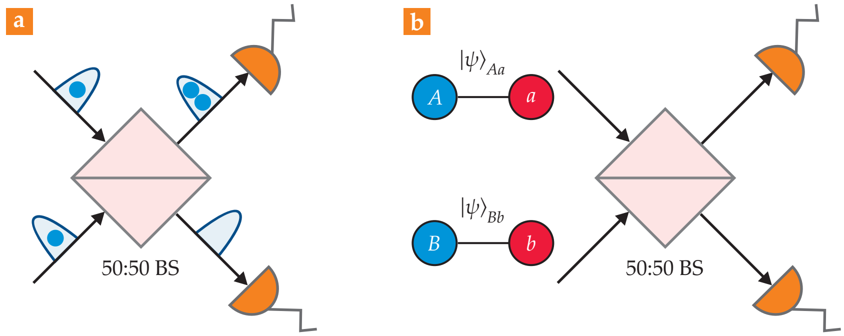

FIGURE 2. GENERATING INTERFERENCE with a two-photon and one-photon approach. **(a)** Due to the Hong-Ou-Mandel effect, if two indistinguishable photons (left) enter through different input ports of a 50:50 beamsplitter (BS), both photons exit the BS through the same randomly chosen output port (orange, right). If the photons do not overlap perfectly in time, the probability that they exit the BS through different ports increases with the time delay between them, up to a value of 0.5. **(b)** Alice prepares the entangled state $|\psi\rangle_{Aa} = \sqrt{p}|0\rangle_A\,|0\rangle_a + \sqrt{1-p}\,|1\rangle_A|1\rangle_a$ where p is an arbitrary nonzero probability, $|0\rangle_A$ and $|1\rangle_A$ are an orthonormal basis, and $|0\rangle_a$ and $|1\rangle_a$ represent a vacuum and a one-photon state, respectively. Bob prepares an analogous state $|\psi\rangle_{Bb}$. If the photonic systems a and b interfere at the BS and the detectors at its output ports observe precisely one photon, then the particles A and B become a Bell state because of one-photon interference. (Figure by Marcos Curty, Koji Azuma, and Hoi-Kwong Lo.)

Network distribution

To distribute an entangled state and protect the QKD setups from side-channel attacks, researchers have developed an alternative solution called entanglement swapping. It relies on a third party called Charles, who holds the measurement unit and forms a small quantum network with Alice and Bob. Each of them prepares an entangled state locally and sends one half of the entangled pair of particles to Charles and keeps the other half in their respective lab. At the receiving side, Charles detects the arriving signals with a measurement that projects them into a Bell state. Remarkably, if Charles's measurement is successful in the ideal noiseless scenario, the local particles at Alice's and Bob's labs become entangled in a Bell state even though they have not interacted with each other. Figure 1a represents the process.

Alice and Bob can verify that they actually share Bell states, or states sufficiently close to them, independently of the method used to distribute the states. To complete the verification, they measure their local systems in two conjugate bases Z and X and then compare a randomly chosen subset of the results. Here, the X basis is defined by two orthonormal states $|+\rangle = 1/(\sqrt{2})(|0\rangle + |1\rangle)$ and $|-\rangle = 1/(\sqrt{2})(|0\rangle - |1\rangle)$. If they share states sufficiently close to Bell states, they proceed with the key generation phase; otherwise, they abort. To generate a key, Alice and Bob then process their data by performing error-correction and privacy-amplification steps, the second of which removes any information that Eve could have learned about the data. Privacy amplification requires Alice and Bob to apply a particular hash function to the corrected data, which maps a bit string to a shorter bit string. The result is an almost perfectly secure key.

Alice and Bob can then verify that Charles behaved honestly by confirming that they share entangled states. Because all of the detectors are within Charles's station, Alice and Bob are protected from all possible side-channel attacks that target the measurement unit.

From a practical point of view, the setup in figure 1a can be simplified further as illustrated in figure 1b. Because Alice's and Bob's local measurements commute with Charles's, the measurement order is irrelevant. Alice and Bob could each measure one half of the entangled pair before they send the other half to Charles. More importantly, the procedure is equivalent to a so-called prepare-and-measure scenario in which Alice and Bob directly prepare the states of the signals that are sent to Charles without first generating entangled states. In practice, the arrangement means that Alice and Bob do not need to distribute real entanglement between them. They merely need to share virtual entanglement or, to be more precise, to confirm that they would have shared real entanglement if they had prepared and sent real entangled states.

The essential ingredient that enables entanglement swapping is the Bell-state measurement performed at Charles's station. Remarkably, researchers can make such a measurement by using a simple interferometric setup with standard, linear optical components based on two-photon or one-photon interference. Both effects, each resulting in a different QKD protocol with its own merits, are illustrated in figure 2.

The scenarios that have been considered thus far assume that Alice and Bob can prepare perfect entangled states. In a prepare-and-measure setup, that assumption corresponds to generating photon-number states, which have a well-defined number of photons. But those states are challenging to prepare with the experimental capabilities currently available. Instead, researchers typically prefer to implement QKD using attenuated laser sources that emit weak coherent pulses (WCPs). Although Alice and Bob could still run QKD protocols with that experimental setup, they would need to estimate certain quantities related to the photon-number states. Fortunately, they can estimate those quantities with the decoy-state method.[7] It requires Alice and Bob to randomly vary the photon-number statistics of the respective signals they each generate. If Alice and Bob generate phase-randomized WCPs, the decoy-state method requires them to simply change the laser's intensity setting.

Measurement-device-independent QKD

An important, recent research direction builds QKD networks with untrusted relays using QKD that is measurement-device-independent (MDI).[8] It's currently the most popular and effective solution to counter quantum hacking because of its practicality and high key-generation rate at long distances. Indeed, numerous experimental demonstrations of MDI QKD have been reported in recent years that have achieved 1 Mb/s secret-key rates[9] and transmission distances of 404 km with telecommunication fibers.[10] The successes would be enough, for example, to encrypt a high-quality video call with the one-time-pad cryptosystem or to distribute secret keys between the Canadian cities of Toronto and Ottawa.

MDI QKD builds on the entanglement-swapping protocol that uses a Bell-state measurement based on two-photon interference and is implemented in a prepare-and-measure fashion using WCPs and decoy states. Secret bits are distilled from the one-photon contributions emitted by Alice and Bob and successfully detected by Charles, who could be the QKD network provider.

A schematic diagram of MDI QKD is shown in figure 3a. Alice and Bob each send Charles phase-randomized WCPs independently prepared in one of the four polarization states employed in 1984 by Charles Bennett and Gilles Brassard.[3] The previously introduced orthonormal states $|0\rangle$ and $|1\rangle$ may now be defined as the horizontally polarized one-photon state $|H\rangle$ and the vertically polarized one-photon state $|V\rangle$. Generating the QKD signals is then equivalent to having Alice and Bob each prepare the Bell state $|\psi^-\rangle = 1/\sqrt{2}\,(|H\rangle|V\rangle - |V\rangle|H\rangle)$ and then measure the first particle in either the Z or X basis selected at random.

Charles is supposed to measure the incoming signals with a Bell-state measurement and then announce his results. The setup exploits the Hong-Ou-Mandel effect to identify two of the four Bell states, which is enough to achieve secure QKD. Depending on the Bell states announced and the polarization bases used, Bob might need to bit-flip part of his polarization

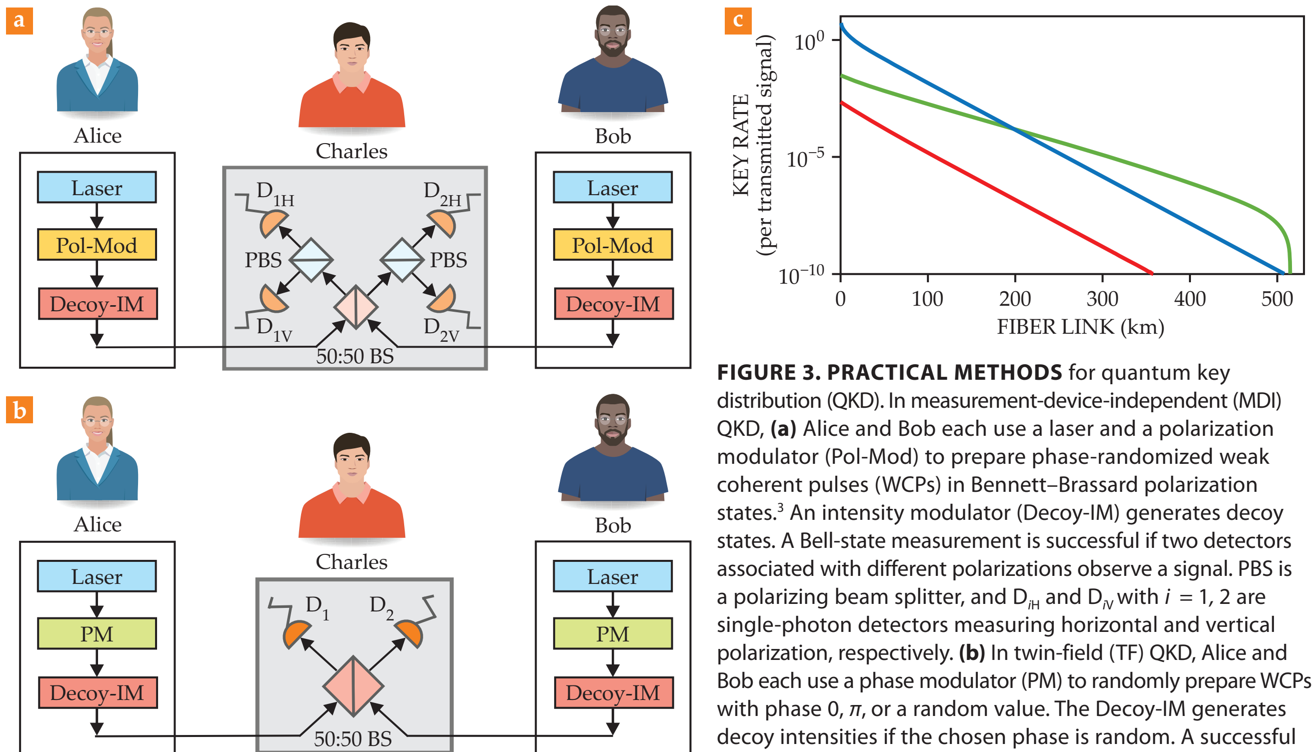

FIGURE 3. PRACTICAL METHODS for quantum key distribution (QKD). In measurement-device-independent (MDI) QKD, **(a)** Alice and Bob each use a laser and a polarization modulator (Pol-Mod) to prepare phase-randomized weak coherent pulses (WCPs) in Bennett–Brassard polarization states.[3] An intensity modulator (Decoy-IM) generates decoy states. A Bell-state measurement is successful if two detectors associated with different polarizations observe a signal. PBS is a polarizing beam splitter, and D_{iH} and D_{iV} with $i = 1, 2$ are single-photon detectors measuring horizontal and vertical polarization, respectively. **(b)** In twin-field (TF) QKD, Alice and Bob each use a phase modulator (PM) to randomly prepare WCPs with phase 0, π, or a random value. The Decoy-IM generates decoy intensities if the chosen phase is random. A successful Bell-state measurement corresponds to one detector observing a signal. **(c)** The asymptotic rate at which secret keys are generated for MDI QKD (red line) and TF QKD (green line) depends on the distance between Alice and Bob. The blue line is the private capacity of point-to-point QKD.[4] (Panels a and b by Donna Padian; panel c by Marcos Curty, Koji Azuma, and Hoi-Kwong Lo.)

data to match Alice's. The raw key is formed by the polarization data in which both Alice and Bob employ the Z basis, and Charles declares a successful result. Then they use the decoy-state method to estimate the number of bits in the raw key that have been obtained from their one-photon emissions. Alice and Bob use the X basis events and the decoy-state method to estimate how much information Eve could have learned about the raw key. A secure key is then made by applying error correction and privacy amplification to the raw key.

When compared with conventional QKD schemes that suffer from detection side-channels, the key advantage of MDI QKD is that Charles need not be trustworthy. He can only learn if Alice's and Bob's raw key bits are the same or different but not their particular values. The secret-key rate still scales linearly with the quantum channel transmittance because MDI QKD requires that two photons—one from Alice and the other from Bob—reach Charles. To overcome that limit, one can furnish MDI QKD with quantum memories[11] or quantum nondemolition measurements[12] or use another approach known as twin-field (TF) QKD,[13] shown schematically in figure 3b.

An alternative approach

The elegant idea of TF QKD replaces the entanglement-swapping operation based on two-photon interference with one based on one-photon interference.[9] The method, if successful, projects the incoming states into a Bell state $|\psi^{\pm}\rangle = 1/\sqrt{2}(|0\rangle|1\rangle \pm |1\rangle|0\rangle)$, whose orthonormal states $|0\rangle$ and $|1\rangle$ refer to the vacuum and a one-photon state, respectively. With that projection, only one photon from Alice or Bob sent to Charles is sufficient to generate a secret key. TF QKD doubles the transmission distance compared with MDI QKD and is robust to any possible side-channel attack because Charles can be untrusted. Figure 3c compares the key rates of the two QKD protocols.

Several recently introduced variants of TF QKD offer security against general attacks.[14,15] Most importantly, the ideal setup[15] can be well approximated with a prepare-and-measure scheme in which Alice and Bob each send Charles WCPs whose phase is randomly and independently selected as 0, π, or a random value. A phase value of 0 encodes a bit value of 0; π encodes a bit value of 1; and a random phase value corresponds to a decoy state. If a random phase is selected, the pulse intensity is also randomly chosen, usually from among three settings. With decoy states, the privacy amplification that needs to be applied to the raw key can be tightly estimated. The raw key is obtained from those instances that encode a bit value and result in a detection at only one of Charles's detectors.

The main experimental challenge of TF QKD is maintaining the phase stability between Alice's and Bob's signals, which is not required in MDI QKD. That demand means that TF QKD needs an auto-compensating technique, such as a Sagnac loop, or phase locking of the remote laser pulses. But despite the experimental difficulties, various research groups have already performed proof-of-principle demonstrations[16] and have achieved transmission distances longer than 500 km.[17]

Closing the gap

Quantum interference enables a family of novel protocols that offer unprecedented levels of security and performance for QKD. The protocols are particularly suited for an untrusted network setting with multiple users. Each user holds a low-cost, compact, chip-based QKD transmitter, and they all share the measurement unit that contains the single-photon detectors.

However, in real-life network settings, the symmetric scenario, in which the channel loss between Alice and Charles is the same as or similar to that between Bob and Charles, is not always true. Some researchers introduced efficient variants of MDI QKD and TF QKD for asymmetric configurations that allow Alice and Bob to use different intensity settings for their signals.[18] The protocols could prove useful in a general quantum network with vastly different channel losses. In such a network, users are dynamically added or deleted at any time without compromising network performance.

A fundamental question that remains unanswered is how to protect QKD transmitter hardware against quantum hacking. Protection will require the development of security proofs that can handle device imperfections in the transmitters and hardware countermeasures that prevent the manipulation of devices. Fortunately, those tasks are, in general, much simpler than protecting the measurement unit. Alice and Bob could use optical isolation, spectral filters, and monitor detectors to physically protect their transmitters from Eve. In addition, security proofs that include most transmitters' imperfections have been developed in recent years. When combined with the setups introduced in this article, the security proofs can close the gap between QKD theory and practice.

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The three PHYSICISTS

Chris DeWitt, José Edelstein, and Bayram Tekin

Since 1951, the Prize of the Three Physicists has been awarded by the École Normale Supérieure in honor of Henri Abraham, Eugène Bloch, and Georges Bruhat—successive directors of the university's physics laboratory. These are their stories.

As the daughter of two physicists, Bryce DeWitt and Cécile DeWitt-Morette, I was always aware of the profound impact of the Holocaust on the lives of 20th-century scientists. Countless Jewish physicists and mathematicians—Albert Einstein, Lise Meitner, Emmy Noether, Edward Teller, Victor Weisskopf, and Eugene Wigner among them—or those married to Jews, such as Enrico Fermi, had to abandon their native European countries with the rise of the Third Reich. Others, such as Nobel laureate Georges Charpak and Fields Medalist Alexander Grothendieck, were sent to concentration or internment camps—Charpak to Dachau in Germany and Grothendieck with his mother to the Rieucros Camp in southern France.

Many of the physicists who managed to find safe havens nonetheless suffered immeasurably. Nobel laureate Walter Kohn, for example, managed to get out of Austria as a teenager on a Kindertransport, but both of his parents were killed by the Nazis. Other Jews, such as French astrophysicists Évry Schatzman and Jean-Claude Pecker, survived the Holocaust by first fleeing Paris to the unoccupied zone in southern France, known as the "free zone," and then by assuming false identities. But Schatzman's father was killed in Auschwitz-Birkenau, as were both of Pecker's parents.


DÉCRET
DE LA
CONVENTION
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AN III
ECOLE NORMALE
SUPERIEURE

FIGURE 1. THE PHYSICS LABORATORY of the École Normale Supérieure. Built in 1937, it has undergone several renovations and an expansion. (Photo courtesy of Sébastien Balibar.)

There were also casualties of Nazi barbarism among the families of other prominent scientists. Max Planck's son Erwin was executed for attempting to assassinate Adolf Hitler, and Louis Cartan, the physicist son of Élie Cartan, was beheaded by the Nazis for being in the French Resistance. The tragic cases are countless.

Because of my mother's own experiences during World War II and the bombing of her family home in Normandy on D-Day, my sisters and I were raised on stories about the war and its aftermath. But some war stories are often forgotten, overlooked, or only told on certain occasions in hushed and somber tones. The story told here is one of them. I stumbled on it almost haphazardly because one of the protagonists was the father of my mother's close friend and coauthor, French mathematician Yvonne Choquet-Bruhat.

This is not a story to be relegated to a footnote. The shared tragic fates of French physicists Henri Abraham, Eugène Bloch, and Georges Bruhat deserve to be known. Passionate about their scientific endeavors and teaching—and committed to the future of France—the three men were betrayed by the Vichy government when the pestilence of fascism swept through France.

The three men were successive directors of the famous physics laboratory of the École Normale Supérieure, one of France's most prestigious institutions: The original entrance to the university is shown on page 43, and the facade of the physics lab is shown in figure 1. For more than three decades during the scientific revolutions of quantum mechanics and relativity, first Abraham, then Bloch, and finally Bruhat led the lab. They are known in the French physics community as *les trois physiciens*, the three physicists.[1,2]

Chris DeWitt

University under threat

On 4 August 1944 in Paris, the Gestapo burst onto the campus of the École Normale Supérieure (ENS).[3] Germany's defeat was inevitable at the time, but its leaders were still determined to carry out the "final solution"—the Nazi plan to exterminate the Jewish people—at any cost. They were looking for a literature student suspected of being part of the French Resistance, but the ENS's deputy director, Georges Bruhat, and secretary general, Jean Baillou, refused to divulge his whereabouts.

Five months earlier Bruhat, shown in figure 2, had already been arrested for defending several employees who were apprehended by the Gestapo for having sheltered Allied parachutists in the cellars of the ENS, but he was eventually released. This time the Germans were utterly brutal: They detained the men's wives, Berthe Hubert Bruhat and Aline Baillou, and threatened to kill the women the following day if their demands regarding the student's whereabouts were not met (reference 3, page 274; reference 4, page 71, French ed.). Yvonne Choquet-Bruhat pleaded with the Germans to allow her to take her mother's place, but they refused.

The Gestapo did not carry out its threats against the women, but Georges Bruhat and Jean Baillou were taken just south of Paris to the Fresnes Prison, which the Germans used to hold and torture captured British agents and members of the French Resistance. As the Allied forces approached Paris, the Germans hurriedly killed or transferred their prisoners. One of the last trains out of Fresnes embarked for Germany on 15 August. It was carrying Bruhat and Baillou. Paris was liberated the following week.

Bruhat had no self-pity. He resolutely supported the morale of other prisoners and taught them the physics of the Sun. He was transferred to the Sachsenhausen concentration camp, where the eldest of Joseph Stalin's children was murdered the year before, along with several tens of thousands of mostly political prisoners. Some survivors recounted that in Sachsenhausen, Bruhat gathered a group of students, engineers, and imprisoned officers eager for intellectual activity. But tragically, he became ill with bronchopneumonia and died in the camp hospital on

New Year's Eve when most of France was already liberated. Baillou, who was younger and stronger, managed to survive and return to Paris in the spring of 1945.

Once Bruhat entered the Gestapo's insane machinery, there was no way out. None of his captors knew that this man, weakened by the inhumane conditions of his detention, was a remarkable physicist, a professor revered by his students, and the author of four volumes of a colossal general-physics course— translated into several languages and an obligatory reference work in many European universities. But the story of Georges Bruhat and his fate cannot be told without beginning with those of two other French physicists: Henri Abraham and Eugène Bloch.

The great inventor

Abraham, shown in figure 3, was born in Paris on 12 July 1868; he was the fifth of six children in a Jewish family. He entered the ENS as a student in 1886. Like many French physicists of his day, Abraham began his career by teaching at a prestigious high school, Louis-le-Grand, which is a short walk from the ENS and counts among its alumni such giants as Henri Poincaré, Victor Hugo, and Jean-Paul Sartre. He also taught for a period at the secondary school where he himself had been a student—the Collège Chaptal, which also counts among its alumni Alfred Dreyfus, the French Jewish officer who was falsely accused of treason because of virulent anti-Semitism.

Abraham was interested in Heinrich Hertz's proof of the existence of the electromagnetic waves predicted by Maxwell's equations. In his doctoral thesis, he decided to verify another of Maxwell's predictions—namely, that the propagation speed of the waves must be equal to the ratio of units of electric charge defined in the two unit systems (electrostatic and electromagnetic) then in use. In 1892 Abraham obtained a precise result, within 1% of the results found by J. J. Thomson at the University of Cambridge. At the time, few knew the connection between electromagnetic waves and light. The overall agreement between the two measurements helped confirm electromagnetic theory and placed Abraham, at the age of 24, on the same level as the best experimental physicists of the era. The rest of Abraham's scientific career was devoted to verifications and applications of electromagnetic theory.

In 1912 Abraham became a tenured professor at the University of Paris, and he took over the management of the ENS physics laboratory. His career was interrupted by World War I, during which he was assigned to the military telegraph service with other high-caliber scientists such as Bloch, Bloch's brother Léon, and Léon Brillouin. Working from the ENS, they invented a series of new radio-transmission devices.

Abraham is credited with improving the US's three-electrode lamps by perfecting the technique used to obtain a high and durable vacuum; the lamps were provided to all the Allied armies. Shortly afterwards, he and Eugène Bloch built the first radio amplifiers that used the lamps. They later developed many electronic devices essential to radio-transmission and ultimately the success of the Allied war effort. In addition, Abraham was in charge of the "Walzer apparatus," a remarkable submarine sonar detector that he jointly developed with Charles Fabry and Paul Langevin. For his achievements, Abraham was decorated with membership in the military Legion of Honor.

Abraham was a prodigious inventor and respected teacher. He had a particular interest in recording rapid phenomena. His mastery of vacuum techniques and his use of the newly established intercontinental radio-wave-transmission system to obtain an even more precise value of the speed of electromagnetic waves made him vital to the French scientific community. He served as the secretary-general of the French Physical Society, expanded the ENS physics lab during his tenure, and kept it running during the Great Depression before retiring in 1937. The great inventor was so involved in designing the plans and technical layout of the new lab that the director of the ENS suggested adding an architecture certificate to the long list of Abraham's degrees.

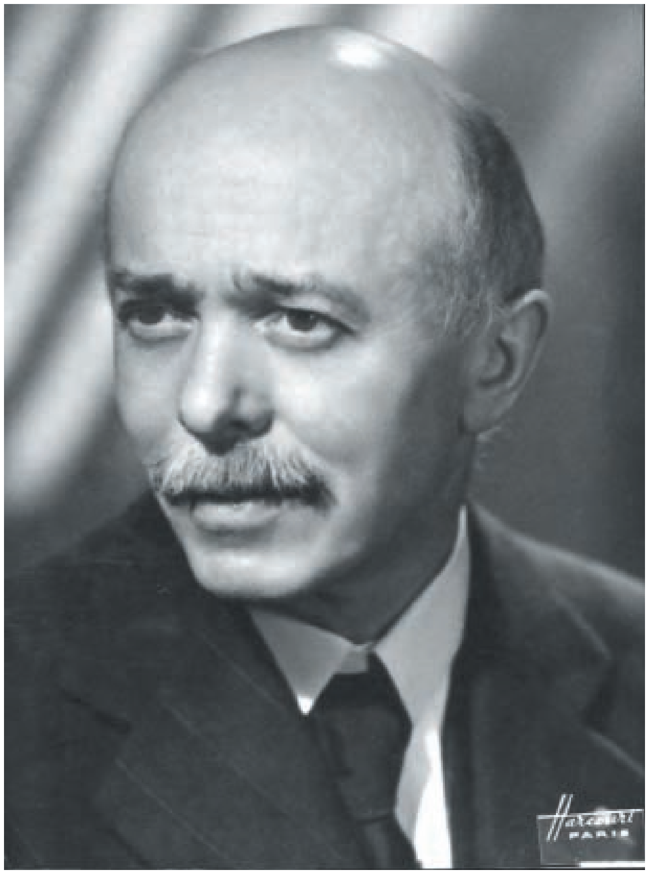

FIGURE 2. GEORGES BRUHAT (1887–1945). This portrait was taken at Studio Harcourt, Paris, circa the 1930s. (Courtesy of the École Normale Supérieure.)

On 1 September 1939 Nazi Germany invaded Poland, and on 10 May 1940 it attacked France and the Low Countries. Abraham left Paris, on orders to follow the technical section of the artillery to Bordeaux. After the June 1940 armistice between Germany and France, he joined his family in Aix-en-Provence. In 1942, German troops moved into the rest of France; Abraham was arrested on the night of 23 June 1943. He was taken to Marseille with his eldest daughter, who did not want to leave her sick father. They were transferred to Drancy, a town northeast of Paris with an internment camp through which most French Jews and other deportees passed before being sent to extermination camps in Germany and Poland. The father and daughter briefly stayed there before being transferred to Auschwitz. On arrival, Abraham was most likely sent directly to the gas chambers.

Under the spell of the quantum

Bloch, shown in figure 4, was born on 10 June 1878, two years after his older brother, Léon, in the small town of Soultz, in

FIGURE 3. HENRI ABRAHAM (1868–1943). This portrait was taken at Studio Harcourt, Paris, circa 1935. (Taken from ref. 1; available on Wikimedia Commons.)

FIGURE 4. EUGÈNE BLOCH (1878–1944). (Courtesy of the École Normale Supérieure.)

Alsace. They were born only a few years after the annexation of Alsace by Germany. Because their father wanted a French education for his sons, he sold his small silk weaving factory and settled in Paris. The two brothers excelled at Louis-le-Grand, the high school where Abraham taught, and they both later entered the ENS. They explored different fields, such as philosophy and botany, before devoting themselves to physics. After being a teacher at the Lycée Saint-Louis for more than a decade—in the middle of which he was assigned to the military telegraph service with Abraham—Eugène became a physics and chemistry professor at the ENS in 1920.

Bloch was a tremendous teacher. He prompted Alfred Kastler to study Arnold Sommerfeld's work in the then-nascent field of quantum mechanics. Bloch's classes were clear and clever. In a 10-year period he wrote four books: on the kinetic theory of gases, on thermionic phenomena, on his applied-physics experience in the military telegraph service, and, most notably, on quantum theory. His early book on quantum mechanics[5] was considered "the bible" among French physicists in subsequent decades.

Bloch carried out his first research in the flourishing arena of atomic physics, in which he focused on the connection between ionization and phosphorescence. That work spurred his interest in ionization produced by UV light—the photoelectric effect discovered by Hertz in 1887. Bloch was one of the first to demonstrate the importance of operating with monochromatic light. His publications of 1908 and 1910 lent support to the theoretical explanation of the photoelectric effect proposed by Albert Einstein in 1905; that theory ultimately earned Einstein the Nobel Prize.

Because of his background in handling UV, Bloch devoted the rest of his career to spectroscopy. Beginning in 1912, he worked to provide precise experimental data for the new quantum theory. With remarkable ingenuity, he developed the first spectrograph with a concave, reflective, and vacuum network that worked from the near-UV down to wavelengths of 20 nm. The tables of wavelengths, made with the spectrograph on 30 chemical elements and their variously charged ions, are still in use.

Bloch succeeded Abraham as director of the physics lab and oversaw the completion of its new building, on which they had both worked, in 1937. Three years later the Vichy regime decreed that Jews could no longer hold public office, and so Bloch had to leave. In October 1941 he and his brother, Léon, quickly abandoned Paris and managed to secretly cross the demarcation line and take refuge in Lyon, which was in the "free zone." They were warmly received by their colleagues in the University of Lyon's laboratory.

Léon wrote a satirical pamphlet addressed to Philippe Pétain, the head of state of the Vichy regime, for which he was arrested. The arrest ultimately saved his life. Eugène, meanwhile, took refuge in different places under a false identity. He unsuccessfully tried to cross the Swiss border and ended up hiding in the mountains. On 24 January 1944, Bloch was arrested by the

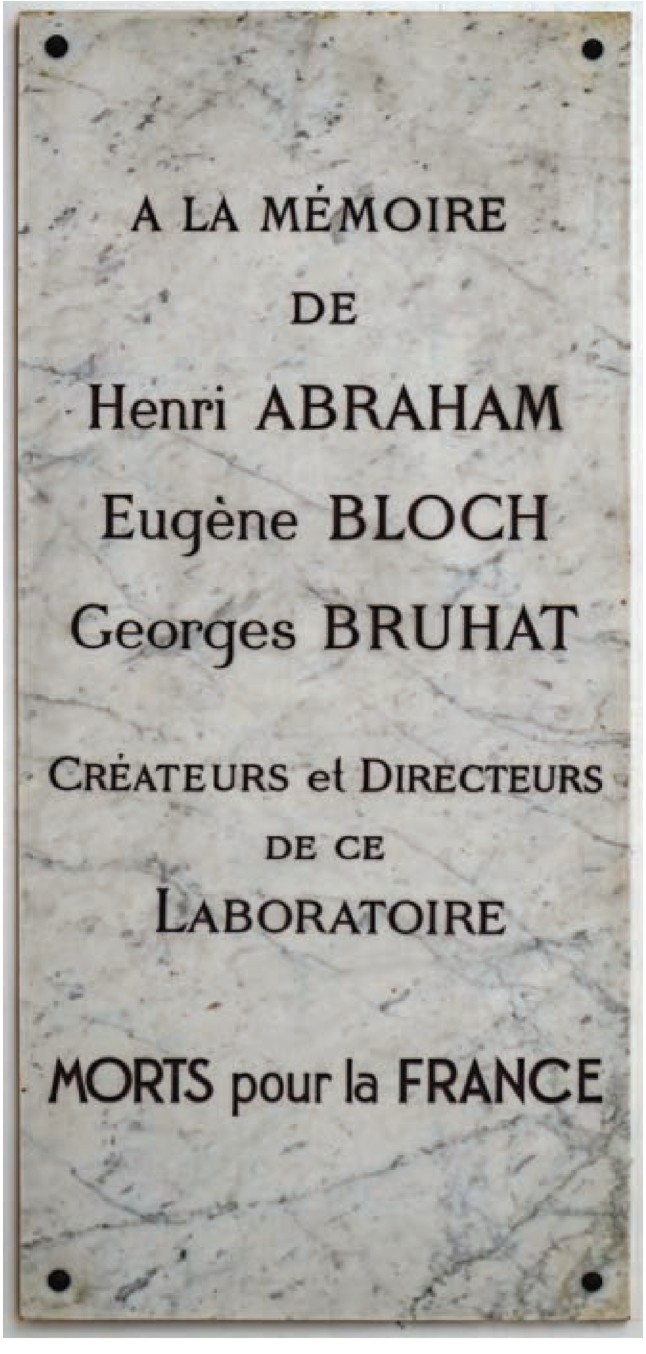

FIGURE 5. A MEMORIAL for the three physicists. The plaque resides at the entrance to the École Normale Supérieure physics lab. (Photo courtesy of Sébastien Balibar.)

Gestapo and sent to Drancy. A few weeks later, he was deported to Auschwitz, where he met the same fate as Abraham.

Master of light

The three founding directors of the ENS physics lab followed each other in age by about a decade. Bloch was born 10 years after Abraham, and Bruhat was born on 21 December 1887, nine years after Bloch. Bruhat entered the ENS in 1906 and completed his doctoral thesis in 1914, shortly before World War I began. While completing his thesis work on the anomalous dispersion of molecular rotatory power under Aimé Cotton, he taught at the Lycée Buffon on Paris's Left Bank. Bruhat entered the French Army in 1915 and received the Croix de Guerre for his contributions to the acoustic detection of cannons.

After the war, Bruhat was appointed to the University of Lille, a few hundred kilometers north of Paris, and he was promoted to full professor in 1921. Shortly thereafter, in 1922, his wife, Berthe, a philosophy professor, gave birth to their daughter Jeanne, and then in 1923 to Yvonne, who also became a physicist. It was not until 1927 that Bruhat obtained a chair in stellar physics in Paris at the Sorbonne. His preference for that area of astronomy led him to write two high-level popularizations, *Le soleil* (The Sun)[6] and *Les étoiles* (The Stars).[7] His son, the mathematician François Bruhat, was born in 1929. Soon after Abraham's retirement, Bruhat became the deputy director of the ENS physics lab under Bloch; and when Bloch was dismissed under the Vichy regime's anti-Semitic laws, Bruhat, who was not Jewish, became the lab's acting director.

Bruhat was a world-class expert in optics and specialized in anisotropic crystalline media, which became important to the development of solid-state physics after World War II. He prepared various experiments with circularly polarized visible and UV light and studied phenomena such as circular dichroism and birefringence by compression. Bruhat was interested in thermodynamics. And despite being an experimentalist, he was also an accomplished theorist. In 1926 he was awarded a prize from the Becquerel Foundation for his work in theoretical physics.

In addition to his important contributions to different fields of physics, Bruhat left a precious legacy to the scientific community. He was a prolific writer of textbooks, and in the span of a decade he wrote a four-volume treatise covering electricity (1924), thermodynamics (1926), optics (1930, with the sixth edition published in 1965 by Kastler), and mechanics (1934). Together, they constituted his course in general physics. The optics book, undoubtedly the most complete, continues to serve as a reference for many aspects of experimental optics. French physicists still regard those volumes as among the most important books in their education; they simply call them les Bruhats.

In the summer of 1944, ENS director Jérôme Carcopino, who had collaborated with the Vichy regime, decided to flee Paris in anticipation of the arrival of the Allied forces. He put Bruhat, then deputy director of the ENS, in charge of the ENS. And that's why Bruhat was confronted by the Gestapo about the whereabouts of the literature student. Bruhat's daughter Yvonne never got a chance to say goodbye to her beloved father (private communication with Chris DeWitt).

Bruhat's family held on to hope that he would eventually return home. Yvonne continued with her studies while trying to obtain information about her father's whereabouts. Because she was Catholic at the time, she turned to the chaplain of the ENS for assistance. The chaplain asked, "Your father, was he a practicing Catholic?" When Yvonne responded that he was not, the chaplain said, "Well then, I will pray for him" (reference 4, page 72, French ed.). It was not until the spring of 1945 that the new director of the ENS informed the family that Georges Bruhat had eventually succumbed to the filth and disease of the concentration camp.

Le prix des trois physiciens

In the first few years after World War II, the fate that had befallen the three physicists went virtually unmentioned. In particular, few acknowledged Bruhat's selfless and courageous refusal to cede to Nazi demands. The silence was due, at least in part, to the fact that in the war's aftermath, the French placed everyone into three categories: members of the Resistance; Jewish victims of the Holocaust; or reviled collaborators.

But Bruhat did not fit neatly into any of those categories, and some people even spread rumors that because he had not joined Charles de Gaulle in the UK, he must have been a Nazi collaborator. That was false, of course. He had felt a duty to remain in Paris to keep the lab running and to help students escape the Nazis and find jobs under assumed names. Like Abraham and Bloch, he paid with his life.

To rectify the void in history and to honor the three great physicists, Hélène Bloch, Eugène's widow, provided seed money for a prize known simply as le prix des trois physiciens, "the prize of the three physicists." Inaugurated in 1951, it is awarded annually (and primarily) to physicists affiliated with the ENS. For recipients, the prize is considered not only recognition that one's work has been of great value but also a treasured jewel within the ENS family. Indeed, the laureates regard the prize as more than an award of great respect; they see it as a legacy to carry forward in the fight against present-day elements of racism and fascism.

Beginning with Jean Cabannes in 1951, the laureates have included J. Robert Oppenheimer in 1958; Nobel laureates Louis Néel in 1963, Claude Cohen-Tannoudji in 1986, and Walter Kohn in 2002; Edith Falgarone in 2018; and, most recently, Vincent Hakim in 2019. (The full list is available at www.phys.ens.fr/spip.php?article2180.)

To commemorate the three physicists, the ENS has installed a plaque (see figure 5) at the entrance to the physics lab, which each of them had helped design or build. It is meant to remind ENS students that the three physicists represented the very best of France. The three men were united in death as they were in life. Their lab stands today as the product of their mutual accomplishments and as a reminder of the Nazis' brutal crimes against humanity.

The idea for this article originated from conversations one of us (DeWitt) had with Jean-Claude Pecker and Yvonne Choquet-Bruhat to whom this article is dedicated. We are grateful to Sébastien Balibar and Christophe Salomon, both physicists of the École Normale Supérieure, and to Daniel Choquet, the grandson of Georges Bruhat and son of Yvonne Choquet-Bruhat. Without their valuable assistance, this article would not have been possible.

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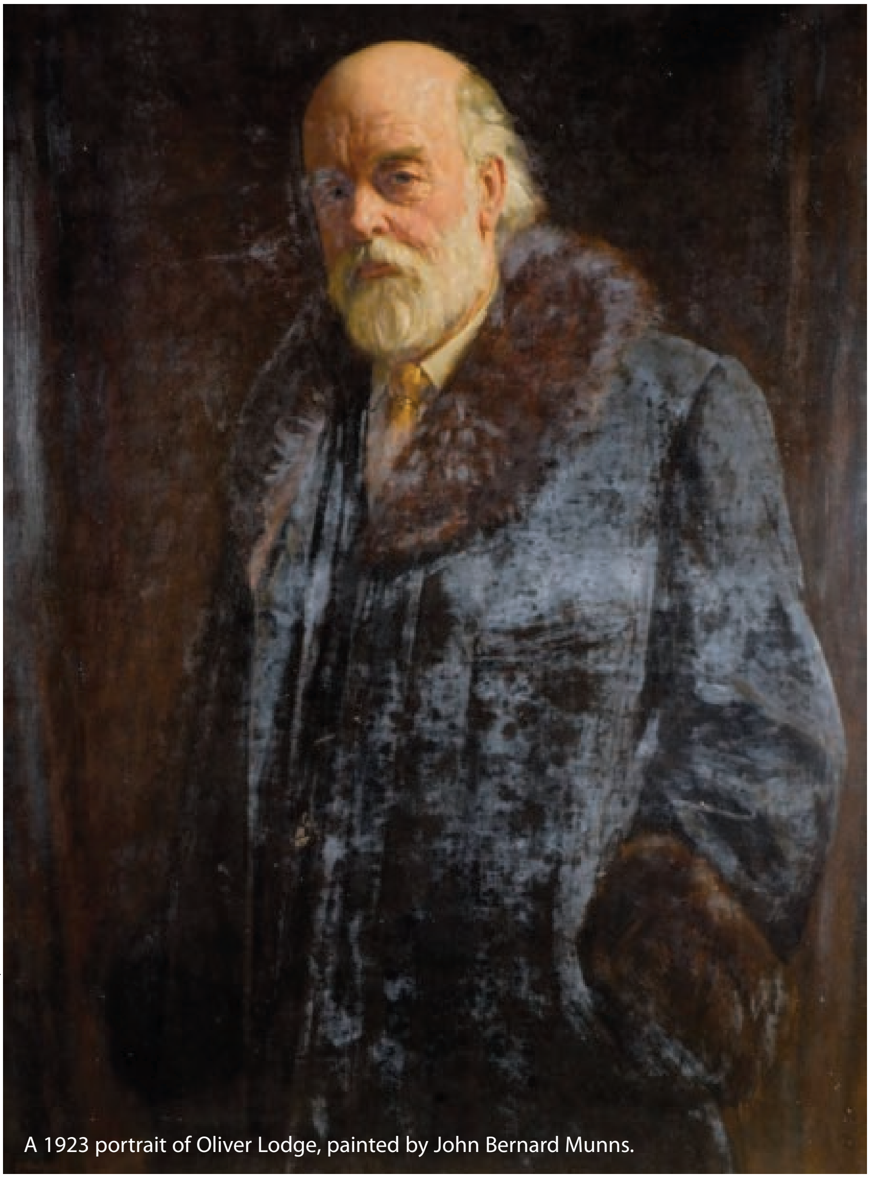

A 1923 portrait of Oliver Lodge, painted by John Bernard Munns.

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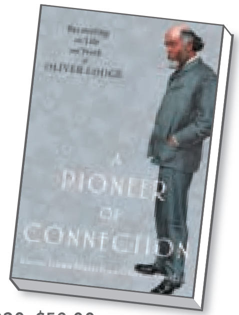
The quintessential Victorian scientist



A Pioneer of Connection
Recovering the Life and Work of Oliver Lodge
James Mussell and Graeme Gooday, eds.
U. Pittsburgh Press, 2020. $50.00

Physicist Oliver Lodge is probably best known for the apocryphal tantrum he threw over Einstein's theory of relativity. The outburst relegated Lodge, who repeatedly missed opportunities to become rich and famous, to the dustbin of history. *A Pioneer of Connection: Recovering the Life and Work of Oliver Lodge*, a collected volume edited by James Mussell and Graeme Gooday, shows that there was much more to his life and work than that singular event.

Lodge's career demonstrates that although history is often told by the proverbial winners, scientific knowledge is produced through a productive dialog between advocates and detractors. Lodge was one of only a few brave souls who dared to look at an accepted idea and say, "That's not right." Even when wrong, voices like Lodge's are invaluable because they push researchers to check their claims. Filling a notable gap in the scholarly literature, Mussell and Gooday's volume provides a welcome reminder of why hero worship does a disservice to our understanding of scientific progress.

Lodge was the patron saint of thankless scientific tasks. He repeated experiments countless times, showed lay audiences how science worked, edited journals and articles, and tirelessly advocated for science funding and education. He excelled at teaching physics, and his sensational lectures, often featuring lightning demonstrations, brought the general public's attention to otherwise esoteric laboratory research. Before radio became commonplace, for example, his lectures showed how electromagnetic waves could be detected by early receivers known as coherers. Those activities raised the public profile of science in the UK, but they brought Lodge little glory; he is a particularly tragic figure because he had the skills to achieve tremendous scientific renown but chose otherwise.

Nevertheless, his scientific work should not be underestimated. Today his discoveries are more important than ever because the fields in which he worked—most notably, the electrodynamics of wireless transmission—form the backbone of our modern technological universe. Among many other contributions, *A Pioneer of Connection* makes clear that it was Lodge who authored the first publication announcing the discovery of electromagnetic waves and who first published results verifying Maxwell's theory of electromagnetic radiation.

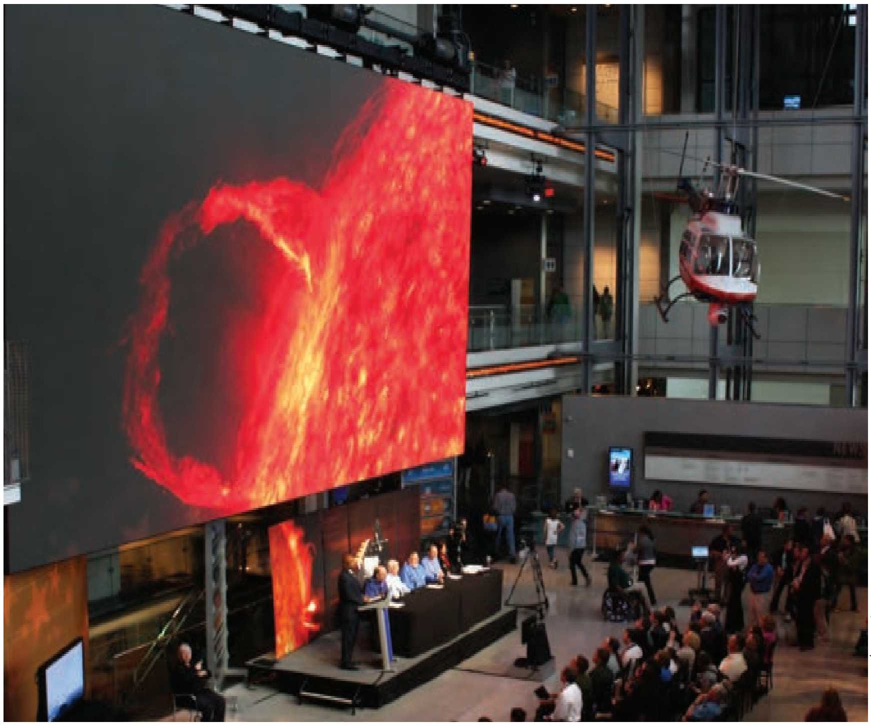
So why is Lodge not more celebrated today? One reason is because he criticized Einstein's theory of relativity. Ironically, as Bernard Lightman demonstrates in his chapter, Lodge's criticisms of relativity theory were valid—in fact, Albert Einstein himself agreed with them. A second reason stems from Lodge's research into psychic and spiritual phenomena, epitomized by his 1916 book *Raymond, or Life and Death*, which details communications beyond the grave with his youngest son, who was killed during World War I in 1915.

Here, too, we should celebrate Lodge, for despite his belief that communication with the deceased was possible, he nevertheless warned the public about how many mediums took advantage of people's vulnerabilities. During his day, it was commonplace even for educated people to hold spiritualist beliefs; it is largely due to Lodge that most everyone now tends to distrust those who allegedly communicate with the dead. Moreover, his advocacy of science education, his public lectures, and his willingness to test wild claims are key reasons why many spiritualist beliefs were checked against the best science of the era. Mussell argues in his chapter that Lodge's studies on psychic phenomena are as much a part of his scientific legacy as his research on telegraphic systems, loudspeakers, and microphones.

Setting himself apart from the scientific trends of his day, Lodge warned of the dangers of going off on a theoretical limb without experimental support. For him, physics was about "hands-on laboratory work," to be followed by a theoretical apparatus based on "tangible physical concepts, not symbols." Such knowledge would lead to a better, "full-blooded" understanding of the universe—one in which it was much easier to know why we should care about knowing. Lodge also played a key role in the successful struggle to incorporate science into the general curriculum at British universities; previously, it was relegated to polytechnical schools.

One of the most interesting claims in *A Pioneer of Connection* is that Lodge was self-conscious of his tendency to damage his own reputation. He left accolades for others to collect, just as many talented untenured lecturers, adjuncts, and laboratory scientists do today. His life demonstrates that second place in science should receive more attention. What use are first observations if they are not confirmed? In science, the inclusion of less prestigious lives matters.

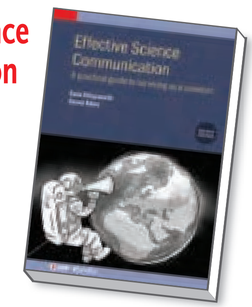
Jimena Canales
University of Illinois at Urbana-Champaign



NASA/GSFC, CC BY 2.0

THE FIRST IMAGES taken by NASA's *Solar Dynamics Observatory* are presented during a press conference in Washington, DC, in April 2010.

A researcher's how-to manual



Effective Science Communication
A Practical Guide to Surviving as a Scientist
Sam Illingworth and Grant Allen
IOP, 2020 (2nd ed.). $50.00

Even the most groundbreaking scientific research is of little use if it can't be communicated to the broader scientific community, and to the general public, in a cogent and timely manner. Nevertheless, many scientists struggle to disseminate their results successfully. *Effective Science Communication: A Practical Guide to Surviving as a Scientist*, by Sam Illingworth and Grant Allen, aims to help researchers do just that. Both authors are successful researchers, and they base their narrative on their extensive personal experience. Comprising nine chapters that work both independently and as a whole, *Effective Scientific Communication* is a useful handbook for anyone in the scientific world.

The book's introduction highlights the importance of scientific communication and offers advice on how to use the book. The authors then discuss how to prepare research findings for journal publication—the way in which most scientific results are disseminated to the broader community. They begin with tips for choosing an appropriate journal, advice on writing the manuscript, and explanations of the peer review process and metrics like impact factors and citations. According to Illingworth and Allen, when sitting down to write a journal article, authors should first identify the key message they wish to share. Additionally, they note that publishing more papers on a topic as opposed to fewer is not always advisable—the oft-quoted "publish or perish" can be a misleading mantra.

Chapter 3 details how to secure funding to establish and sustain scientific research. Gone are the days of Isaac Newton and Albert Einstein, who required little or no research funding. Nowadays, a successful research career requires continuous funding, so learning how to craft grant proposals is a vital skill for researchers. The authors give quality advice on conceptualizing a good research idea, detail the components of a grant proposal, and discuss how to select appropriate funding agencies.

Oral presentations to specialist audiences are the subject of chapter 4. The authors emphasize that crafting a clear message is key to presenting effectively, as are audiovisual elements like images and PowerPoint slides, which should be chosen carefully. They emphasize as well how important it is to respect the time limit when presenting and responding to questions. The chapter also offers practical advice on overcoming nervousness when presenting to unfamiliar audiences: Researchers should know their content, know their audience, and practice rigorously to develop confidence.

Although scientists are accustomed to speaking to technical audiences, in today's world that is not enough. Researchers also need to communicate their findings to the public at large, as evidenced by the COVID-19 pandemic and the global spotlight it has brought to epidemiology and vaccine science. Possible venues include press conferences, news articles, public lectures, panel discussions, and book clubs. *Effective Science Communication* describes how narratives must be sculpted with both the idea and target audience in mind. Engaging with the public requires extra preparation and training, but it also molds public thinking and creates a well-informed society.

The next two chapters cover how to communicate science in the mass media and online. Writing popular scientific works and giving radio and TV interviews remain viable methods for communicating with the public. But researchers today have the opportunity to develop an online presence using blogs, podcasts, and social media networks such as Facebook, Twitter, and ResearchGate. YouTube is a great platform for sharing laboratory demonstrations and live lectures. All of these options can be beneficial and even lead to unexpected collaborations—but, the authors warn, they can also be distracting!

Chapter 8 addresses how science shapes public policy and vice versa. Many researchers undoubtedly enter the scientific world out of a desire to improve our quality of life and to preserve the health of our planet. Ideally governments base their decisions on reliable scientific information and, in turn, promote good science by way of increased funding. In that scenario, regulators, governments, university presidents, and citizens all have collective ownership of science, which reduces the risk of forming policies based on skewed or one-sided viewpoints.

The final chapter discusses other components of a researcher's tool kit, such as time management, professional networking, teamwork, mentoring, and scientific integrity. Some discussion about managing stress would have been useful here.

The authors did a commendable job outlining effective writing and speaking techniques. I also enjoyed the quotations at the opening of each chapter—the cartoons included there are simply delightful! One gap that could be addressed in future editions is a discussion of listening and reading techniques, which take up much of a researcher's time and complete the circle of scientific communication. Nevertheless, this text is a solid manual for novice and established researchers alike.

Raj Chhabra
Indian Institute of Technology Ropar
Rupnagar, India

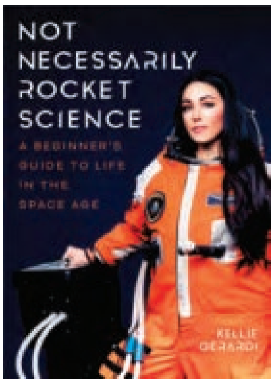
NEW BOOKS & MEDIA

Quantum Ethics

A Call to Action

The Quantum Daily
Teralon, 2021

As Peter Parker was famously warned by his Uncle Ben, "With great power comes great responsibility." That modern-day proverb is the theme of *Quantum Ethics*, a new minidocumentary about the moral issues surrounding quantum computers. It might seem like an idle concern, but the film compellingly argues that the machines' sheer strength will enable unprecedented technological developments that could prove dangerous, such as destructive weaponry, powerful artificial intelligence, and the breaking of seemingly secure encryption technologies. Even if those dire scenarios don't come to pass, quantum computers, if not allocated equitably, would likely concentrate more of the world's wealth in the hands of what one interviewee pithily terms a "bunch of really, really rich hedge fund people." *Quantum Ethics* cautions us to take heed before the genie is out of the bottle. —RD



Not Necessarily Rocket Science

A Beginner's Guide to Life in the Space Age

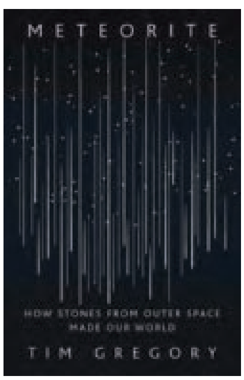
Kellie Gerardi
Mango, 2020. $19.95

Part history of space exploration, part memoir, *Not Necessarily Rocket Science* focuses on the development of the aerospace industry and the author's own part as a space-travel advocate and science communicator. Kellie Gerardi has trained for spaceflight, conducted research in microgravity, and made a career as a commercial spaceflight industry professional, working for such entities as the Commercial Spaceflight Federation, the Space Frontier Foundation, and Masten Space Systems. Her enthusiasm and passion for what she calls the new era in space exploration and for the brighter future for humanity it represents are evident throughout her narrative. —CC

Meteorite

How Stones from Outer Space Made Our World

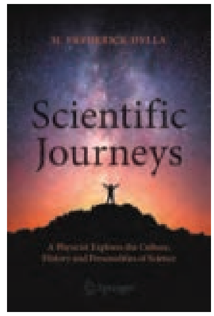
Tim Gregory
Basic Books, 2020. $30.00



The simplicity of the title *Meteorite* belies the vastness of the actual subject matter covered by cosmochemist Tim Gregory. In discussing "how stones from outer space made our world," Gregory explains how the unique chemistry of meteorites that have fallen to Earth has provided insights into the creation of not only our own planet but the entire solar system. Along the way, he covers various other topics, such as some of the earliest discoveries of meteorites—including one that hit the Chaco region of Argentina more than 4000 years ago—and the development of the field of cosmochemistry. Aimed at the general reader, Gregory's debut science book brings geology to life with his easy conversational style and nontechnical narrative. —CC

Scientific Journeys

A Physicist Explores the Culture, History and Personalities of Science

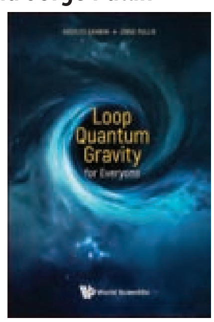


H. Frederick Dylla
Springer, 2020. $27.99 (paper)

A collection of vignettes about science, its history, and its intersection with the public sphere, *Scientific Journeys* was authored by H. Frederick Dylla, a plasma physicist and former CEO of the American Institute of Physics (publisher of PHYSICS TODAY). The anecdotes cover figures as varied as medieval botanist Hildegard of Bingen; electrical engineer Amar G. Bose, founder of the eponymous audio company; and particle physicist Jean Trân Thanh Vân, who helped rebuild ties between scientists in his native Vietnam and the international scientific community after the country's reopening in the 1990s. A self-described "Sputnik kid," Dylla was motivated to pursue a career in science by Cold War angst that the US was falling behind after the 1957 launch of the Soviet satellite. Some of the vignettes may seem naïve in our age of political polarization, but the author's infectious enthusiasm for science—and his evocative depiction of post–World War II optimism about the future—is inspiring. —RD

Loop Quantum Gravity for Everyone

Rodolfo Gambini and Jorge Pullin
World Scientific, 2020. $28.00



In this new book, physicists Rodolfo Gambini and Jorge Pullin take on the challenging task of explaining loop quantum gravity to a general audience in less than 100 pages. The result is an enjoyable read that will be accessible to students and scientifically curious laypeople. The authors begin with explanations of gravitation and quantum theory before moving on to loop quantum gravity and its applications, including black holes and spin foams. —MB PT

Focus on lasers, imaging, microscopy, and nanoscience

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

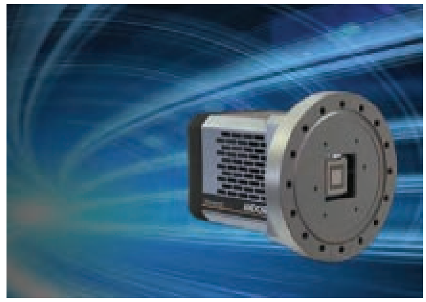
Andreas Mandelis

All-in-one single-frequency laser

Hübner Photonics has introduced its Cobolt 05-iE (integrated electronics) series of single-frequency lasers that cover the 457–1064 nm wavelength range. Because all the control electronics are contained in the laser head, the Cobolt 05-iE lasers do not need an external controller. With less complexity and fewer parts, the laser has a significantly reduced system footprint and is simpler to integrate into researcher and other user systems. The company's Cobolt Rogue 640 nm 1 W laser is also available with integrated electronics as a Cobolt Rogue iE. All Cobolt lasers are manufactured using proprietary HTCure technology. According to the company, the resulting hermetically sealed package protects the lasers from varying environmental conditions and ensures that they perform reliably in both laboratory and industrial settings. ***Hübner Photonics Inc****, 2635 N 1st St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com*

Tip-scanning atomic force microscope

Nanosurf designed its DriveAFM to allow researchers in materials science, life sciences, and nanotechnology to capture high-resolution images of large samples: It offers an imaging envelope of 100 μm × 100 μm × 20 μm, with an optional 150 μm z-axis extension. The DriveAFM comprises a low-noise, high-bandwidth controller; a low-noise, super-luminescent diode for feedback; and a direct-drive scanner. It features innovative CleanDrive technology, a photothermal method to actuate the cantilever. Photothermal excitation provides high stability and a high excitation bandwidth in both air and liquids, benefits that allow high-speed measurements at multiple frequencies. Laser and detector alignment, tip approach, and sample movement are all managed with the software. Such full-system motorization makes it easy to use and opens up new possibilities to fully automate the system. ***Nanosurf AG****, Gräubernstrasse 12, 4410 Liestal, Switzerland, www.nanosurf.com*



Camera for high-energy physics

Andor Technology, an Oxford Instruments company, now offers its Marana-X camera for ultrafast soft-x-ray and extreme-UV (EUV) tomography and high-harmonic-generation applications. According to the company, the camera's scientific CMOS (sCMOS) technology makes it significantly more advanced than slow-scan CCD cameras. With its fast frame rates, high sensitivity, and high dynamic range (up to 16 bits), the Marana-X overcomes the limitations of CCD technology in the soft-x-ray–EUV energy range. The Marana-X features what the company claims is the first uncoated 4.2 MP sCMOS sensor with greater than 90% quantum efficiency in the 80 eV–1 keV range at up to 74 fps full frame. That unique combination speeds up and improves sampling of dynamic phenomena such as large tomographic data sets. The Marana-X is deep cooled to −45 °C and offers a convenient USB 3 plug-and-play interface and a CoaXPress interface more suited to challenging high-energy-physics environments. ***Andor Technology Ltd****, 7 Millennium Way, Springvale Business Park, Belfast BT12 7AL, UK, https://andor.oxinst.com*

Lattice light-sheet fluorescence microscope

Zeiss developed its Lattice Lightsheet 7 instrument to observe processes in cells and small organisms in 3D over extended time periods at subcellular resolution, with minimal light. The Lattice Lightsheet 7 comes with a special structured light sheet, a so-called sinc3 beam, and provides flexibility in generating light sheets of different lengths and thicknesses. That generation is accomplished by a light-efficient beam shaping system that uses a spatial light modulator; only moderate laser powers are required. The illumination and detection optics are arranged perpendicular to each other and at an oblique angle to the surface of the sample carrier's cover glass, an arrangement that makes available the full numerical aperture of the detection objective. Resolutions of up to 290 nm × 290 nm × 450 nm can be achieved at an acquisition speed of up to 3 volumes/s. ***Zeiss Research Microscopy Solutions****, Carl-Zeiss-Promenade 10, 07745 Jena, Germany, www.zeiss.com*

Fast, high-resolution EMCCD camera

According to Raptor Photonics, its Kestrel ultrafast electron-multiplying (EM) CCD camera cost-effectively operates at 2000 fps, one of the fastest speeds available, and has a region-of-interest function. With its back-illuminated sensor, cooled to −20 °C, the camera provides ultrahigh sensitivity from 350 nm to 1100 nm and a peak quantum efficiency of 95% at 600 nm. The digital monochrome Kestrel features a resolution of 128 × 128 pixels, each of which is 24 μm^2; a scientific-grade 16-bit analog-to-digital converter; and a standard Camera Link output. It has high sensitivity from the UV to the near-IR, and with EM gain on, it offers less than 0.01 e^- read noise. Applications include wavefront sensing, adaptive optics, calcium signaling, fluorescence imaging, and space-debris and fast-object tracking. ***Raptor Photonics Ltd****, Willowbank Business Park, Larne, Co Antrim BT40 2SF, Northern Ireland, UK, www.raptorphotonics.com*

Confocal microscope

Leica Microsystems has launched its Stellaris confocal microscopy platform for capturing 3D images of living cells and tissues. The Stellaris 5 and the more advanced Stellaris 8 combine the company's new Power HyD detectors, White Light Laser, and sophisticated software to deliver brighter signals and images with more contrast and fine detail. The integrated TauSense imaging modes, based on fluorescence-lifetime technology, can help separate fluorophores even when their emissions fully overlap. The number of simultaneous detection channels can also be expanded by using lifetime-based information. According to the company, compared with other confocal systems, Stellaris offers enhanced sensitivity in the blue-green region, which improves detection limits and dynamic range for the most commonly used fluorophores. ***Leica Microsystems Inc****, 1700 Leider Ln, Buffalo Grove, IL 60089, www.leica-microsystems.com* PT

OBITUARIES

Noah Hershkowitz

On 13 November 2020, the plasma-physics community lost distinguished scientist and teacher Noah Hershkowitz, the Irving Langmuir Professor Emeritus of Engineering Physics at the University of Wisconsin–Madison (UW–Madison). Few have contributed so much and so broadly to the field of plasma science. Noah's work was foundational in nature, but it profoundly influenced applications spanning the gamut from materials processing to fusion. He guided generations of plasma physicists, probed theories and assumptions, and provided international leadership in the plasma-physics community. He was the founding editor in 1992 of *Plasma Sources Science and Technology*, which has become the premier venue for disseminating low-temperature plasma science.

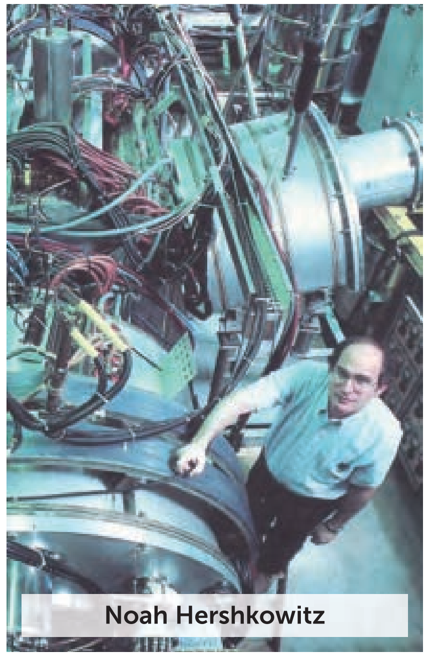
Noah was born on 16 August 1941 in Brooklyn, New York, and attended the High School of Music and Art. He earned his bachelor's degree at Union College in 1962. While taking an honors physics course there, he and another student fabricated a working ruby laser only two years after the first laser was built. Noah was 24 when he earned his PhD in physics from Johns Hopkins University; under adviser J. C. Walker, he worked on experimental Mössbauer spectroscopy. After teaching at the university for about a year, he joined the physics department at the University of Iowa.

Noah started out as a nuclear physicist. However, his fascination with a 1971 colloquium about electrostatic shocks in laboratory plasmas motivated his abrupt shift to plasma physics, despite his never having taken a single course on the topic. He thought it would be fun. His beginning foray included the study of solitons and double layers, and his results challenged the conventional wisdom regarding those curious structures. Noah always asked basic questions first—such as, How does plasma potential get from point A to point B?—to get to the core of the underlying science. His fundamental plasma-physics experiments led to his development and refinement of emissive probe techniques for measuring plasma space potentials. His work is now the basis for how emissive probe measurements are made in fields ranging from processing plasmas to Hall thrusters.

While on a sabbatical in 1980 at the University of Colorado Boulder, Noah was recruited to take charge of the large-scale Phaedrus tandem-mirror fusion program at UW–Madison, which he did later that same year. Noah steered Phaedrus in a new direction. The program conducted groundbreaking experiments that featured a simplified axisymmetric coil set and achieved magnetohydrodynamic stabilization through externally applied RF power, the first tandem-mirror machine to do so. The results from the Phaedrus-B tandem-mirror device continue to influence designs worldwide. Noah also served on many US Department of Energy mirror program committees, including the US/Japan Joint Planning Committee on tandem mirrors, and in 1989 he was a key participant in the DOE Office of Fusion Energy's US/USSR exchange program.

When DOE focused efforts on the tokamak fusion-confinement concept in the late 1980s, Noah built the Phaedrus-T tokamak, but he also began working on low-temperature plasma physics as the basis of semiconductor device manufacturing. His pioneering research helped to advance that critical technology at a time when it was responsible for maintaining Moore's law. Noah led the plasma-etch group at UW–Madison's Center for Plasma Aided Manufacturing for over a decade, and he was the center's director for more than a decade after that. His characteristic integrity and leadership helped the US regain competitiveness in the microelectronics industry.

Although he led thriving fusion energy and technology research programs, Noah never let go of the fundamental research he pursued at the beginning of his career. The sorts of questions that held a special fascination for him were those that challenged assumptions in plasma physics that dated back to Irving Langmuir's work in the 1920s but that had no definitive experimental benchmark. Noah's advances in probe- and laser-based diagnostics allowed him to make seminal measurements of the "sheath problem," which describes the electrostatic boundary layer responsible for mediating the interaction between plasmas and materials surfaces.



UNIVERSITY OF WISCONSIN–MADISON

Noah spent the last half of his career in a wheelchair, dealing with, and often just ignoring, primary progressive multiple sclerosis. His ability to work undaunted by the disease was an inspiration. A brilliant teacher and a kind and generous mentor, he cared enough to create an environment where everyone—a vast, diverse "everyone"—could thrive.

"Physics is like a jigsaw puzzle that's really old," Noah once said. "All the pieces are worn down. Their edges are messed up. Some of the pieces have been put together in the wrong way. They sort of fit, but they're not actually in the right places. The game is to put them together the right way to find out how the world works."

Noah is mourned by plasma physicists throughout the world.

Gregory Severn
University of San Diego
San Diego, California
John Foster
Scott Baalrud
University of Michigan
Ann Arbor

Stephan von Molnár

Stephan von Molnár, a Distinguished Research Professor Emeritus at Florida State University (FSU) and a trailblazer in the fields of magnetic semiconductors and spintronics, died on 17 November 2020 in Tallahassee, Florida. Stephan was a professor of physics at FSU from 1994 until his retirement in 2013 and was director of its interdisciplinary Center for Materials Research and Technology between 1994 and 2007.

Born on 26 June 1935 in Leipzig, Germany, Stephan spent much of his childhood taking shelter in the southern German countryside during World War II. In 1947 he immigrated to the US to be reunited with his mother, who was Jewish and had left Germany in 1938. At Stuyvesant High School in New York City and later at Phillips Academy in Andover, Massachusetts, Stephan developed an interest in theater acting and science. After getting his BS in physics from Trinity College in 1957 and his MS in physics from the University of Maine in 1959, he did a brief stint with DuPont's polymer division.

In 1960 Stephan decided on physics as his lifelong pursuit and entered the graduate program at the University of Chicago. A year later he moved with his adviser, Andy Lawson, to the University of California, Riverside. His dissertation focused on magnetic resonance study of the magnetic anisotropy in europium sulfide, an ideal Heisenberg ferromagnet and a model material of concentrated magnetic semiconductors.

After receiving his PhD in 1965, Stephan joined the research staff at the IBM Thomas J. Watson Research Center; he was manager of the cooperative phenomena group there in 1970–89 and senior manager of the novel structure physics group from 1989 until he left in 1993. When Stephan started at Watson, Frederic Holtzberg was leading the synthesis and magnetic studies of the europium chalcogenides EuX and their derivatives. Starting with those substances, Stephan began more than five decades of highly influential and far-reaching research into the magnetotransport properties of magnetic semiconductors. In many ways, his studies helped launch the field and were a harbinger of the field's remarkable progress into mainstream materials science and condensed-matter physics. The research also presaged the emergence of the field of spintronics.

SCOTT BAXTER/FLORIDA STATE UNIVERSITY

Stephan von Molnár

In 1967 Stephan, Leo Esaki, and Phillip Stiles made heterojunctions of metal-EuX-metal. In a clever move, they exploited the spin-splitting of the Schottky barrier height as the magnetic semiconductor entered the ferromagnetic state, and they observed greatly enhanced field emission current. That constituted a direct experimental demonstration of spin-filtered tunneling and control of the charge current through the semiconductor's magnetic state. Their work was broadly recognized as the first conceptual presentation of a semiconductor spintronic device.

That same year Stephan and his colleagues observed that a moderate magnetic field could reduce the resistance of gadolinium-doped europium selenide by orders of magnitude near the Curie temperature. He conceived the term "giant negative magnetoresistance" to describe the enormous resistance changes. Inspired by those magnetoresistance experiments, Stephan and Tadao Kasuya proposed the idea of the bound magnetic polaron. It offers a natural and physically appealing account of the giant magnetoresistance and associated magnetic and electronic phase transitions in those and many other material systems. In 1987 at IBM, Stephan and one of us (Awschalom) observed the magnetic polaron in diluted magnetic semiconductors by using novel time-resolved optical and magnetic measurements. Stephan became increasingly convinced that magnetic polarons could be found in numerous magnetic materials and could be a microscopic force behind electronic phase separation and associated percolative phase transitions.

Two years later Stephan, Hiro Munekata, another of us (Ohno), and colleagues at IBM set out to synthesize III–V magnetic semiconductors, and they identified ferromagnetism in phase-pure indium manganese arsenide. Ohno's group followed that work by synthesizing gallium manganese arsenide with high Curie temperatures. Those breakthroughs set off worldwide research efforts on the III–V materials, which quickly became a model material system for spintronics physics and device research.

Stephan moved in 1994 to FSU, where he embraced the intellectual freedom offered by academia and took great pleasure in mentoring graduate students and postdocs. While continuing his longstanding endeavors in nanomagnetism and spintronics, he quickly ventured beyond the physics department and initiated collaborations with colleagues in biology, chemistry, and engineering. He also turned his curiosity to bionanotechnology, particularly the use of solid-state devices for biomolecular activation and sensing.

Throughout his career, Stephan steadfastly believed in, promoted, and personified open scientific exchange and collaboration across disciplinary and national boundaries. His mentees and collaborators dotted numerous countries across several continents. Stephan's passion went far beyond his science. His interests ranged from music and theater to sports; he was not only a fan but also a skilled squash player. Stephan was a warm, gracious, and greathearted colleague who made a lasting impression on numerous researchers, especially those he mentored. His wise counsel, frank critiques, timely encouragement, and unwavering support early in their careers are fondly remembered by many.

David Awschalom
University of Chicago
Chicago, Illinois
Hideo Ohno
Tohoku University
Sendai, Japan
Peng Xiong
Florida State University
Tallahassee PT

QUICK STUDY

Oleg Gang is a professor of chemical engineering and of applied physics and materials science at Columbia University in New York City and a group leader at Brookhaven National Laboratory in Upton, New York.

DNA assembles nano-objects

Oleg Gang

A programmable one-size-fits-all method builds lattices of nanoparticles, proteins, and enzymes.

Nanoscale objects are fundamentally different from either their atomic components or their bulk counterparts. Those differences extend across their optical, electrical, catalytic, and magnetic properties. For example, semiconductor nanoparticles efficiently emit light whose wavelengths, unlike in bulk semiconductors, depend on the particles' sizes. To put those unique properties to use—for example, as nanoscale pixels in TVs that save energy and enhance performance by emitting only the desired wavelengths—researchers are establishing methods to build the nanoscale particles and biomolecules into two-dimensional and three-dimensional systems. With top-down construction methods (see the article by Matthias Imboden and David Bishop, PHYSICS TODAY, December 2014, page 45), such as nanofabrication and 3D printing, researchers struggle to integrate different nanomaterial types and to provide small-scale spatial control, particularly in 3D. A promising alternative is self-assembly, in which building blocks organize themselves to minimize free energy. Self-assembly has the advantage that billions of nanoscale blocks can simultaneously assemble into a particular structure.

But designing the self-assembly process and the resulting nanomaterial is challenging. Unlike atoms, which come in a limited variety, nano-objects can be highly tailored and custom-made, with varied shapes and compositions and with surfaces covered by a range of organic molecules. Biomolecules in particular have complex shapes and surfaces with heterogeneity in both charge and chemistry. The resulting nano-objects are extremely diverse and too large for atomic-level computations. Therefore, even predicting the structures formed by assembled nano-objects is tricky and can only be done by limited coarse-grain descriptions. The situation is even more challenging if the end goal is not only to predict the assembled structure but also to prescribe and control its formation. Given the diversity of nanoparticles, a single approach is unlikely to address the challenge of building every desired system.

A solution for the one-size-fits-all assembly problem may lie in nano-blocks composed of DNA. Almost four decades ago, New York University's Nadrian "Ned" Seeman realized that single-stranded DNA (ssDNA) can serve as a programmable nanoscale building material. DNA's constituent nucleic acids bind in pairs: adenine (A) with thymine (T), and cytosine (C) with guanine (G). So a region of a DNA strand with the sequence CAT will bond with a so-called complementary region of another strand with the sequence GTA. Writing DNA sequences can thus prescribe which regions bond to form double-stranded DNA chains. By selecting and coding their joined regions, researchers can connect multiple single- and double-stranded DNA chains to form nearly any target shape.

In the past decade, researchers have used DNA's programmability and selective bonding to construct primarily 2D and increasingly 3D DNA lattices. Those engineered DNA architectures can serve as scaffolds for organizing inorganic and biological nano-objects regardless of shape or properties.

Building blocks

The addition of a DNA shell controls how nano-objects interact. In previous studies, nanoparticles repelled one another when coated with sufficiently dense polymers that have a neutral electrical charge. Particles covered with oppositely charged polymers could overcome that repulsion and bind together. Instead of such binary interactions, nanoparticles covered with short ssDNA bind with variable strength determined by the number and length of their complementary DNA sequences.

Using DNA-sequence encoding, my research group

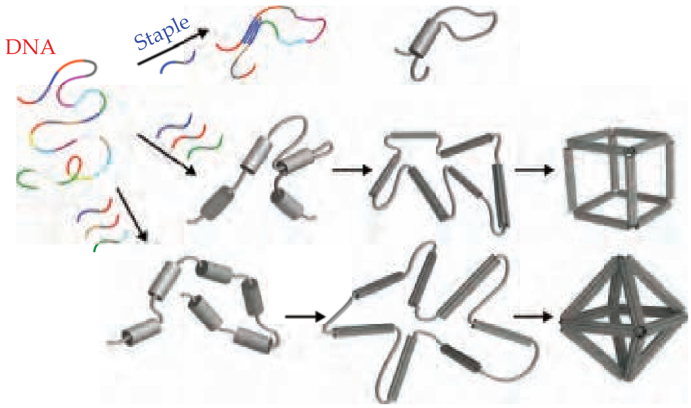


FIGURE 1. SINGLE STRANDS of DNA, left, bond to shorter DNA strands called staples in regions for which their nucleic-acid sequences are complementary (indicated by matching colors). The bonded regions fold the strand and form double helixes, indicated by the gray cylinders. With the right combination of staples, the double helixes bundle together and form a prescribed shape, such as a cube, shown at right. (Image by Oleg Gang.)

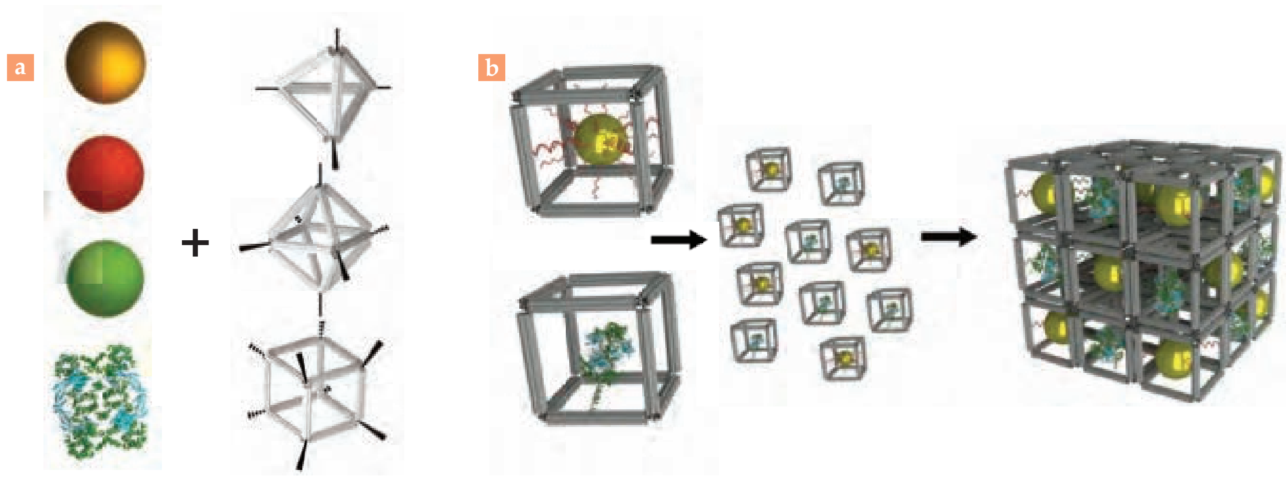


FIGURE 2. SELF-ASSEMBLY guided by DNA starts with a so-called voxel composed of **(a)** a nano-object—that is, one of the different types of nanoparticles (colored spheres) or biomolecules on the left—loaded into one of the DNA-origami frames on the right. (Adapted from Y. Tian et al., *Nat. Mater.* **19**, 789, 2020.) **(b)** The voxels (left) assemble into a lattice (right) as prescribed by DNA coding at each frame's vertices. The lattice's shape and symmetry are independent of the properties of the nano-object in the voxel. (Image by Oleg Gang.)

and others create a pool of particles in which only selected ones bond and the rest, without complementarity, repel. Such particles form various periodic organizations that mimic atomic phases, such as crystalline lattices, and that are determined by the particles' relative sizes and dynamic changes to the composition of their shells. But that assembly process is constrained by the nanoparticles' characteristics, such as their sizes, material types, shapes, and DNA shell properties.

Overcoming system specificity requires more complex DNA architectures and a technique called DNA origami, depicted in figure 1. Similar to traditional paper origami, the structure forms through folding. Using a long ssDNA chain, researchers can design short DNA strands, known as staples, that are complementary to two specific regions of the long ssDNA chain. Those staples bring together or fold the chain, and a specific set of staples folds the strand into a desired 2D or 3D shape.

Self-assembly

DNA origami shapes can encapsulate and assemble generic nano-objects, as depicted in figure 2. Although previous works used specific origami architectures to position nano-objects, my research group generalized the idea to different lattice symmetries and an array of nano-objects, including inorganic nanoparticles, proteins, and enzymes. In the approach, the lattice comprises what are called material voxels, a similar concept to the pixels that make up a TV screen. Each voxel has a 20- to 100-nm polyhedral DNA frame with one or more extra dangling strands inside. Those internal strands determine, through interactions with DNA attached to the objects, which inorganic or biomolecular nano-objects the frame carries. The frames also have external DNA strands that establish prescribed interframe bonds. Simple polyhedral frames—such as tetrahedral, octahedral, and cubic—with interframe DNA-encoded bonds located at their vertices self-assemble into diamond, simple cubic, and body-centered cubic lattices, as confirmed by x-ray scattering and computational methods.

Different kinds of nano-objects can organize using the same assembly platform. For example, an array of light-emitting quantum dot nanoparticles with two emission wavelengths could arrange with alternating colors through the lattice design. Because the voxels' dimensions were only about 1/10th the light's wavelength, the process patterned the nanomaterials at subwavelength scales. The same strategy forms, with nanoscale precision, a lattice of octahedral voxels loaded with six simple proteins called streptavidins. What's more, biomolecules preserved their biological functions. For example, when two enzymes arranged themselves in a specific order in a 3D lattice, they operated more efficiently because of their controlled spacing and mixing. The enzymes in question were a prototypical pair that demonstrate enzyme cascade, in which the products from one enzyme's reactions serve as the reactants for the next enzyme's reaction. The assembly approach enables a new class of chemically active nanomaterials that harvest their properties from the 3D organization of biomolecules.

The molecular-level programmability of DNA interactions opens opportunities for precision nanoscale manufacturing. DNA-guided self-assembly with billions of nanocomponents can form diverse material architectures with diverse functionalities. However, there's still work to be done to understand how to encode more complex structures through multiple DNA bonds and how to steer the assembly process through intricate thermodynamic landscapes.

Additional resources

▶ N. C. Seeman, "Nucleic acid junctions and lattices," *J. Theor. Biol.* **99**, 237 (1982).

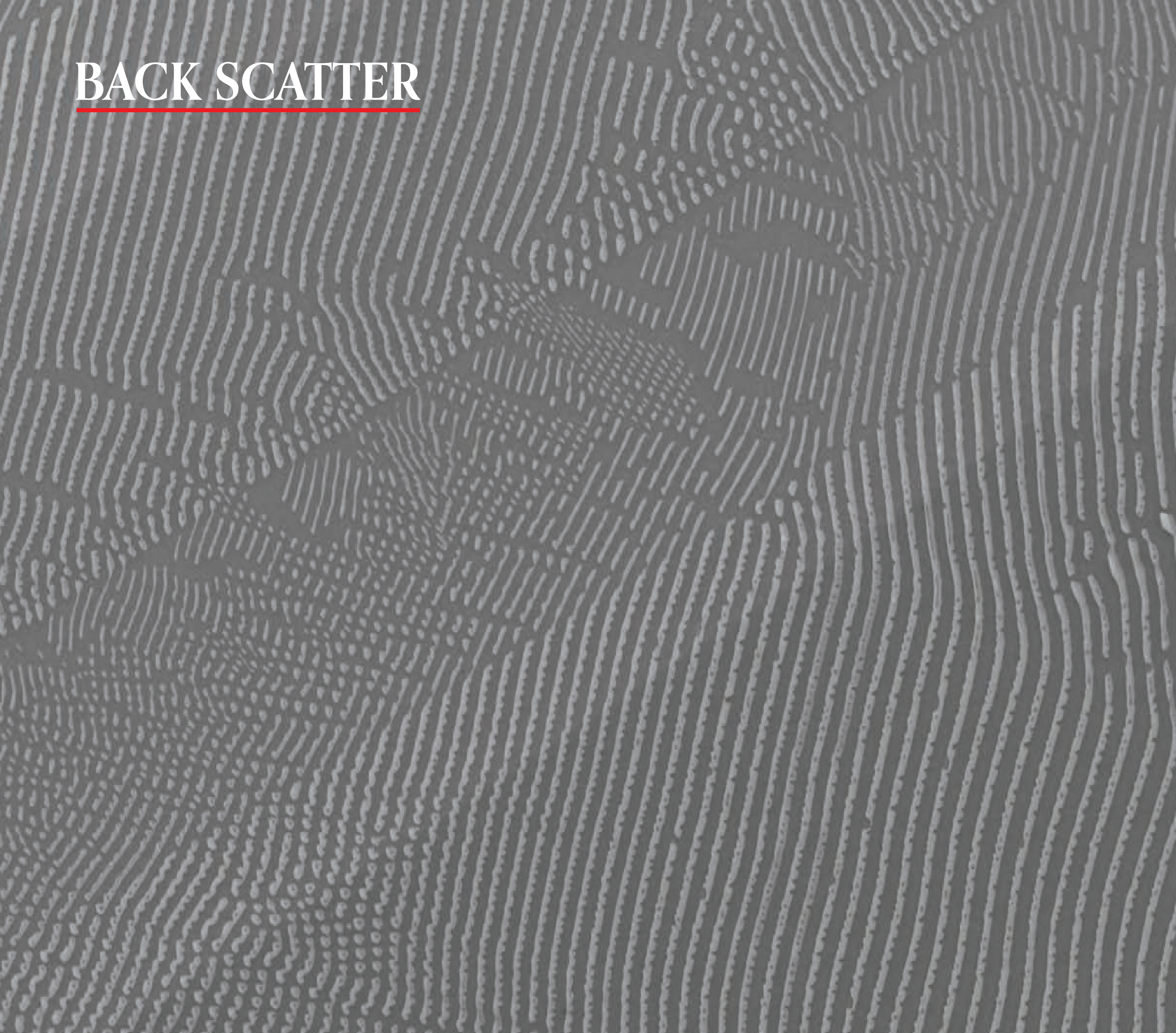
▶ P. W. K. Rothemund, "Folding DNA to create nanoscale shapes and patterns," *Nature* **440**, 297 (2006).

▶ S. Nummelin et al., "Evolution of structural DNA nanotechnology," *Adv. Mater.* **30**, 1703721 (2018).

▶ D. Nykypanchuk et al., "DNA-guided crystallization of colloidal nanoparticles," *Nature* **451**, 549 (2008).

▶ Y. Tian et al., "Ordered three-dimensional nanomaterials using DNA-prescribed and valence-controlled material voxels," *Nat. Mater.* **19**, 789 (2020). PT

BACK SCATTER



Prevailing surface patterns

Metallurgists, engineers, and others know that when a liquid metal mixture cools into a solid, its constituent elements often separate to form microstructures. An alloy's chemical formula and bulk structure don't necessarily indicate the patterns that form on the surface. Those patterns could be used in various nanomaterials and dynamic surfaces, for example. Jianbo Tang and Kourosh Kalantar-Zadeh (University of New South Wales), Stephanie Lambie and Nicola Gaston (University of Auckland), and their colleagues recently observed highly ordered patterns unique to the surface of a bismuth–gallium alloy. One such pattern is shown here: The light gray parallel lines are each a few micrometers wide.

By tracking the phase transition in real time, the researchers determined that the patterns formed as a solidification front propagated across the liquid alloy's surface at about 30 μm/s. Molecular-dynamics simulations indicated that the rate at which bismuth diffused from the interior to the surface was critical to explaining the observations. Other significant factors included the energetic barriers to crystal formation, the thickness of surface oxide layers, and temperature gradients in the alloy. Bismuth–gallium belongs to a group of alloys known as eutectics: Its melting point is lower than either of its constituents. That makes the alloy potentially useful for optics, electronics, and other applications. (J. Tang et al., *Nat. Nanotechnol.*, 2021, doi:10.1038/s41565-020-00835-7.) —AL

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