PHYSICS TODAY

March 2022 • volume 75, number 3

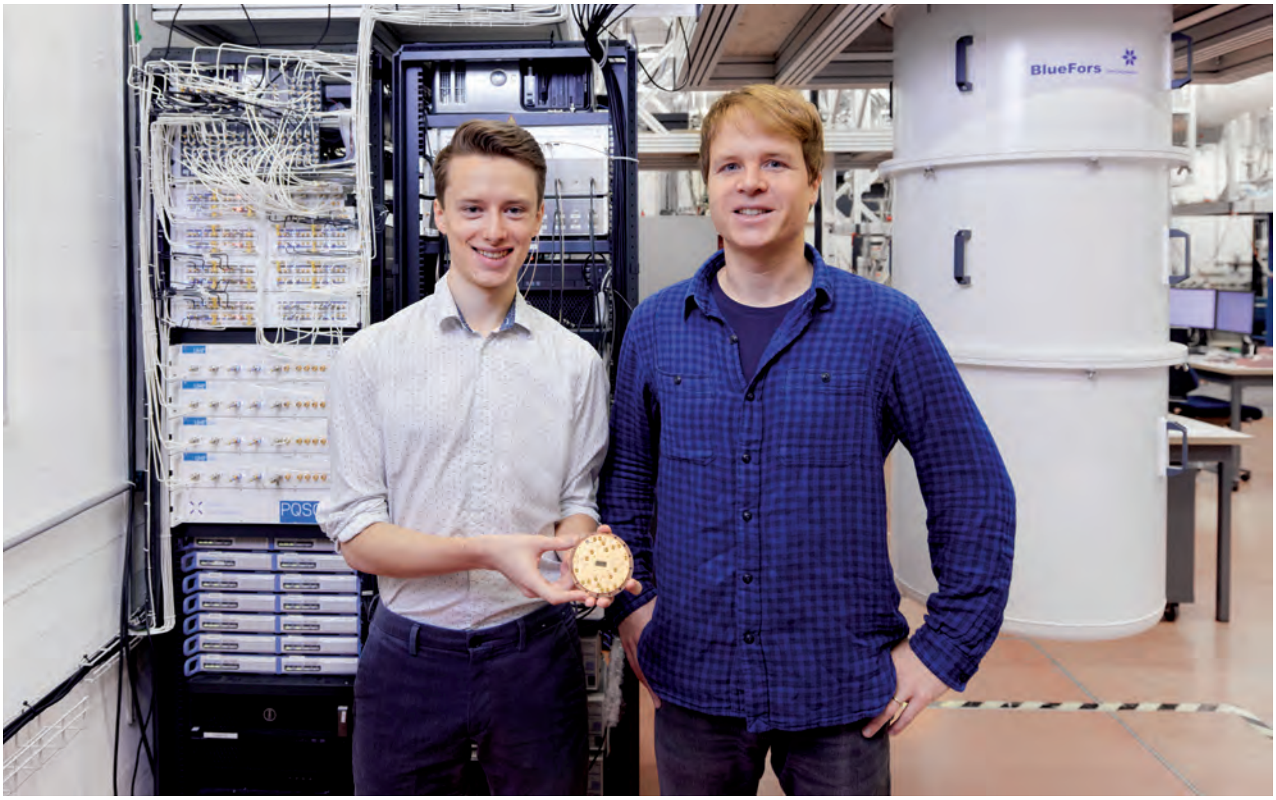
A publication of the American Institute of Physics

QUANTUM MATERIALS

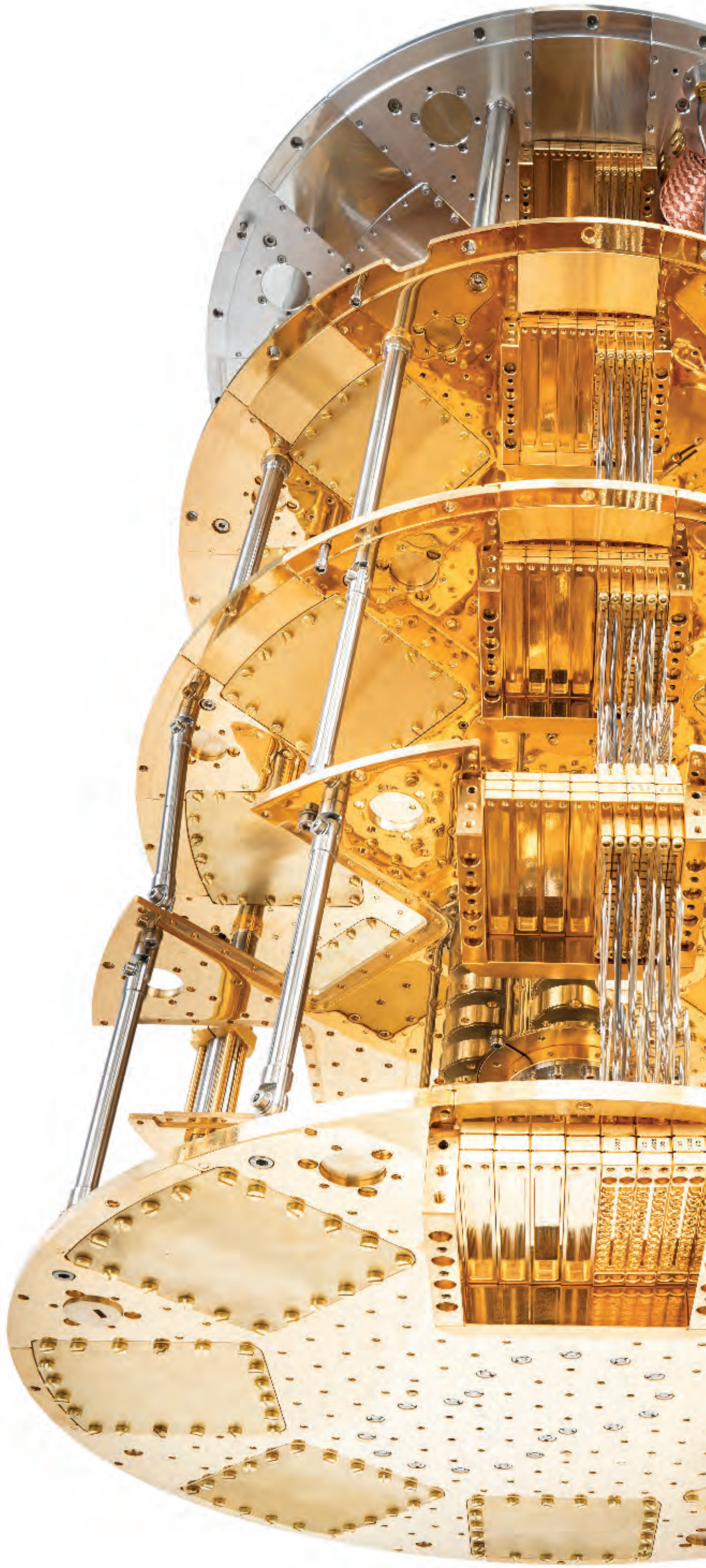
COVID-19's impact on K–12 physics

Diamond semiconductors

Krypton isotopes and early Earth



Nathan Lacroix and Sebastian Krinner, ETH Zurich



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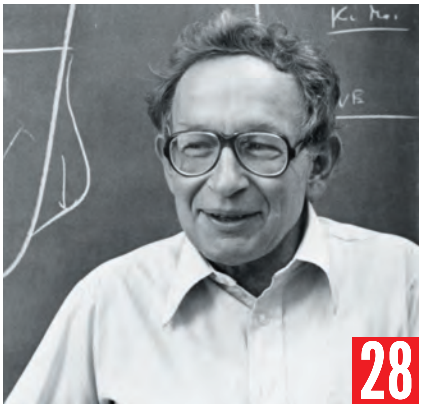

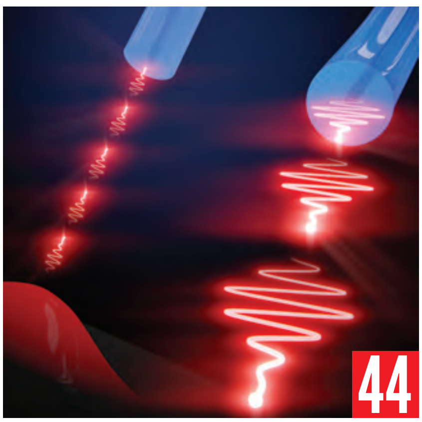

FEATURES

ON THE COVER: Kazimir Malevich's *Tochil'schik Printsip Mel'kaniia*, or *The Knifegrinder* (1912–13), exemplifies the fragmentation of forms characteristic of futurism and echoes the superposition of states characteristic of quantum mechanics. On **page 36**, Tim Langen describes dipolar supersolids, a class of quantum materials that are simultaneously solid and superfluid. On **page 44**, Peter Lodahl, Arne Ludwig, and Richard Warburton describe how advances in quantum materials are leading to new applications in quantum computation. (Image courtesy of the Yale University Art Gallery.)

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H. T. BENNETT

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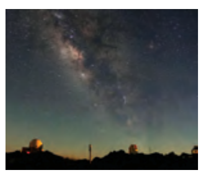

NOIRLAB

Dark skies

Artificial lighting and satellites can interfere with ground-based astronomical observations and impede humanity's ability to enjoy the night sky. Rachel Berkowitz reports on astronomers' efforts to reduce light pollution through legislation, education, and working with companies.

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FROM THE EDITOR

When we could be diving for pearls

Charles Day

My December 2021 editorial elicited an unusually high number of emails sent directly to me: three. The first to arrive came from Samantha Holland, who is the audio–video archivist at the American Institute of Physics's Niels Bohr Library and Archives. (AIP publishes PHYSICS TODAY.) Holland asked me if the editorial's title, "It's all too much," was an allusion to the Beatles' song of the same name. Yes, I confirmed.

The editorial was inspired by a paper by Johan Chu of Northwestern University and James Evans of the University of Chicago.[1] Having analyzed 1.8 billion citations of 90 million papers in 10 scientific fields, the pair concluded that as the number of papers in a field increases, researchers find it harder to recognize innovative work and scientific progress slows.

My second email correspondent, retired particle physicist Dick Land, told me about a past instance of innovative work that failed to achieve recognition: John James Waterston's 1845 paper "On the physics of media that are composed of free and perfectly elastic molecules in a state of motion." Rejected by the *Philosophical Transactions of the Royal Society*, the paper languished in the society's archives until Lord Rayleigh, having encountered a reference to it, retrieved it. He grasped its significance. In his view, the failure to publish it promptly retarded the development of the kinetic theory of gases by 10–15 years. An engaging account of the rediscovery of Waterston's paper appeared in John Howard's From the Editor column in the May 1969 issue of *Applied Optics*.

Judy Lamana's email to me acknowledged that Chu and Evans's predictions "seem inevitable." Nevertheless, she went on to propose a way to forestall them: Each paper should come with a concise table that identifies whether the paper describes a method, furthers existing ideas, or intends to be disruptive. She would also like papers to include a declaration about how they were reviewed. For example, "blind as to an author's gender, and affiliations," as she put it.

I like Lamana's idea of an at-a-glance way to evaluate a paper's novelty. Some journals already offer something somewhat similar. Papers in the *Proceedings of the National Academy of Sciences* include a distinctive blue box on the first page that outlines a paper's significance in more or less plain English. Papers in *Geophysical Research Letters* include not just a lay-language summary but also a bulleted list of key points.

But such an approach, however helpful, has two drawbacks. First, the summary and key points are generated by authors and are therefore not impartial. Second, although they make it easier to decide whether to read the whole paper, you still have to read each summary. An ideal system for identifying innovative research would be unbiased and automatic. Is such a system possible?

A portent of a truly automatic method came my way recently in the form of a paper by Brian Thomas and others.[2] They evaluated the feasibility of using machine learning to identify research priorities in astronomy. Specifically, they applied natural language processing to evaluate the prevalence of topics in two sets of bibliographic data: the abstracts of papers published in 1998–2010 in 10 top astronomy journals and the chapters of the 2010 decadal survey of astronomy and astrophysics that were devoted to the frontiers of astronomical science.

Thomas and company found a significant but modest correlation. Evidently, the priorities identified by the survey for the upcoming decade reflected the topics that astronomers most actively published on in the previous decade.

But are those topics of lasting impact or are they merely fashionable? For each paper in their data set, Thomas and company estimated its mean lifetime citation rate. The rate was modestly correlated with the prevalence of topics, as you might expect. But it did not correlate with topics in the decadal survey, from which Thomas and company conclude: "This result suggests that the Decadal Survey places significant emphasis on established research and may under-emphasize new, growing research topic areas."

Because machine learning works on existing data, the approach could indeed struggle to identify truly revolutionary science. But what if that's a feature, not a bug? Maybe the value of algorithms like Thomas and company's lies in identifying research that, as Lamana put it, furthers existing ideas. What's left could be the game-changing new work.

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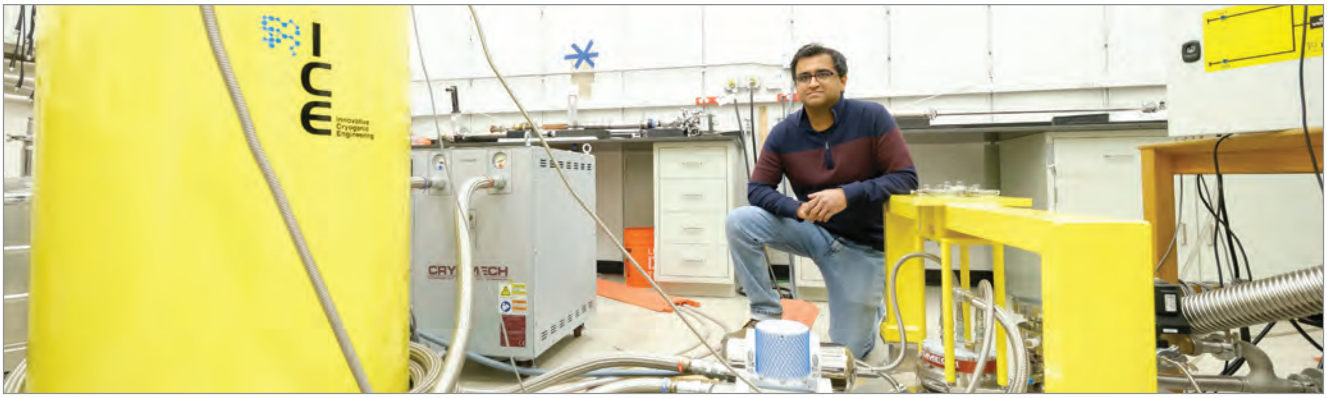
PT



Vikram Deshpande of the University of Utah uses an ICEoxford cryostat to probe the behavior of electrons moving inside long carbon nanotubes. (Credit: Matt Crawley/University of Utah)

Long carbon nanotubes reveal subtleties of quantum mechanics

Phil Dooley

Vikram Deshpande had a hunch that carbon nanotubes held a lot of promise as a building block. He suspected that their unusual electrical and thermal properties and extraordinary strength could be modified for specific purposes by adding nanofabricated structures.

Working with nanotubes more than a micron long, the University of Utah physicist and his team found that the nanotubes held surprises even without being adorned with those structural bells and whistles. "We started seeing all this richness in the data and had to investigate that before making the experiment more complicated," Deshpande says. "Because they are only a nanometer or so in diameter, they are excellent playgrounds for studying the quantum mechanics of electrons in one dimension."

But thin walls also mean little shielding. Impurities on the surface scatter electrons in the nanotube, and that initially prevented Deshpande from getting clean data.

His solution was to both clean the nanotubes and run his experiments in a DRY ICE 1.5K 70 mm cryostat made by ICEoxford. The UK-based company's cryostat allows him to suspend nanotubes between supports and run a current through them. The nanotubes heat up to several hundred degrees, and the impurities are knocked off the surface.

The setup is cooled by pumped helium-4 at around 1.5 K, which is important, says Deshpande. "A lot of cryogenic equipment is vacuum based, but the heat injected into the nanotube has no way out except along the tube, which is very ineffective." Another boon is the fact that the cryostat is top loading so it's easy to access. Within 12 hours of installing a new sample, the entire system is cooled and ready for testing.

With a good nanotube in place and thoroughly clean, Deshpande applies voltage to inject electrons and explore their quantum behavior.

A major influence on electron behavior inside the nanotube is the quality of the end contacts. The electrons travel unimpeded within the tube, known as the ballistic regime. But the ease at which they can escape the tube affects their behavior radically.

Using low-conductivity contacts, Deshpande's team measured the energy required to add individual electrons to the tube. Subtle changes in the energy showed that the electrons were falling into an ordered pattern called a Wigner crystal—effectively a solid made of pure electrons—which occurs only at very low density. "Lower electron density is obtained with longer lengths, which make our experimental signature possible," Deshpande says. His team reported their results in *Physical Review Letters* (volume 123, page 197701, 2019).

Last year the team published another paper in *Physical Review Letters* (volume 126, page 216802, 2021) with results from high-conductance contacts. They found the electrons' wavefunctions spread along the tube, creating quantum interference, analogous to light in an interferometer. There was not only interference similar to the Fabry–Perot effect between electrons bouncing back and forth, but also a more subtle interference caused by slight variations in the nanotubes, such as chirality. "These are exquisite measurements of delicate quantum effects that we can only see because our long nanotubes accumulate measurable phase difference between these modes," Deshpande says.

He has also made use of the DRY ICE cryostat's ability to apply magnetic fields up to 9 tesla. "If you thought the data so far were rich, you should see what happens in a magnetic field!" he says.

Phil Dooley is a freelance writer and former laser physicist based in Canberra, Australia.

Commentary

The rule of information

I recently hiked a snow-covered trail renowned for its lack of cell service. Yet somehow, as I passed from one bend to another, a radio signal leaked into my almost-dead smartphone. Torn out of my reverie in the frigid air and under blue skies, without thinking I began scrolling through my messages. I'd received an urgent work entreaty, so I trudged back to my car and fired up my computer-controlled, hydrocarbon-combusting engine, and then I plugged in my 10-billion-transistor device and let it vigorously shuttle electrons. Only afterward, back on the trail, did I question why on earth a few hundred bytes of data were worth all of this.

It's no big news that human technology has many of us by the scruff of the neck. Our machines and algorithms serve us, but we serve them too. With its duplicitous nature, social media provides connectivity and opportunity with one hand while it drains our attention and resources with the other. You pay for every Facebook post, Instagram story, and tweet with your own neural activity and investment in hardware and energy.

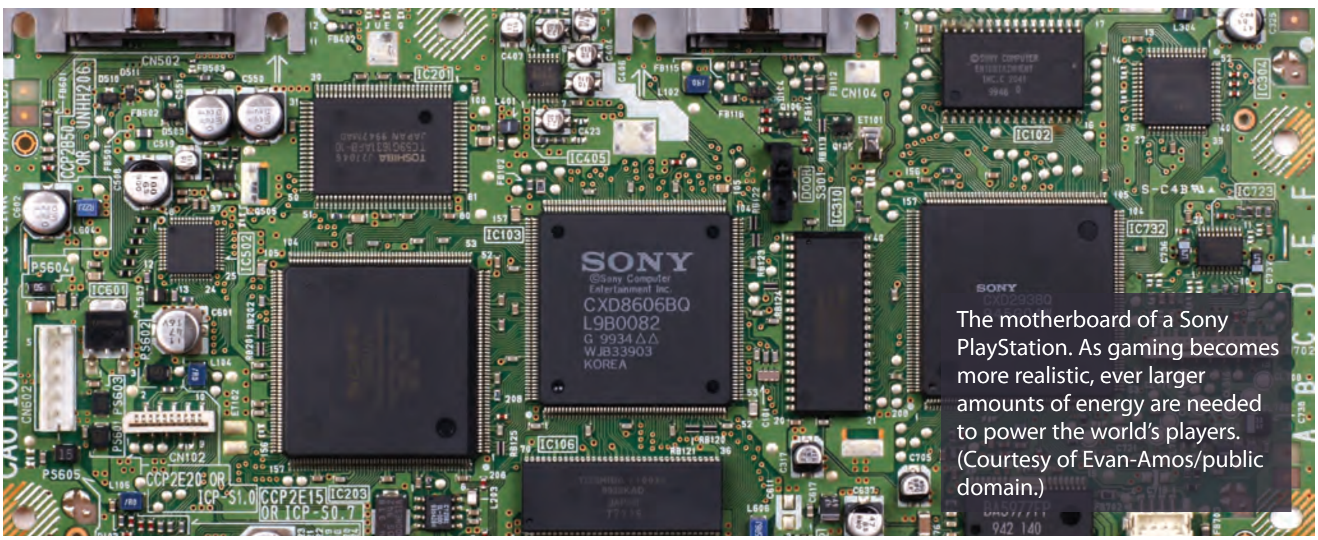
We keep inventing more of such hidden burdens. Crypto enthusiasts expound on the democratic possibilities of decentralized, secure data and currencies derived from blockchain technologies. Yet those technologies can be voraciously resource hungry; it's inherent to how they work. Other dubious inventions, like non-fungible tokens, rely on those same structures, and machine learning and streaming services consume energy resources as well. Some applications are profoundly useful, yet many appear utterly frivolous for a civilization teetering on the brink of planetary disaster brought on by unthinking resource use.

Part of the energetic overhead for all those activities originates in the fundamentals of how we handle information. A modern microprocessor features tens of billions of transistors—structures that represent an extreme reduction of local entropy, which takes a lot of work to accomplish. A much-cited study from back in 2002 introduced the phrase "the 1.7 kilogram microchip," which references the approximate mass of hydrocarbon fuel and chemicals then required to assemble a single DRAM chip a mere 2 grams in mass. Fabrication also required 32 kilograms of water and about 700 grams of elemental gases.[1]

Of course, the actual running of digital computation is getting more efficient over time. Some improvements come from greater miniaturization; others come from a trend to hardware specialization rather than generalization. The catch is that the tasks we give devices are growing exponentially. Take the example of deep-learning systems: A 2019 study showed how training an all-bells-and-whistles version of the Transformer natural-language processing model, working with over 210 million parameters, can gulp down an amount of energy equivalent to the emission of more than 284 metric tons of carbon dioxide, about the same as the lifetime emissions of five gasoline automobiles.[2]

An investigation of global data in 2011 found a two-decade trend of about 60% growth per annum in our species' total computing capacity. That outpaced what continues to be a roughly 20–30% annual growth in data-storage capacity.[3] It's unclear which growth drives which, but perhaps sheer necessity is contributing to computing growth. Still, it's easy to see that a large proportion of our informational world—including reams of mundane financial data, social media posts of lunchtime sandwiches, and promulgations of false information—has questionable importance for the survival of our species. We don't really know what the total semantic quality is of the more than 2.5 quintillion bytes of data generated each day by our civilization. Consequently, we wind up expending ever more effort to find benefits.

One projection suggests that by 2040 computing will necessitate more energy than the world currently produces.[4] Simultaneously, the total "anthropogenic



The motherboard of a Sony PlayStation. As gaming becomes more realistic, ever larger amounts of energy are needed to power the world's players. (Courtesy of Evan-Amos/public domain.)

mass"—all of the matter embedded in inanimate solid objects made by humans—is estimated to already exceed the total biomass.[5]

The implications of such ideas are both fascinating and concerning. We know that if the resources demanded by our global civilization are not balanced against their environmental impacts, we'll suffer. At the same time, the vast, externalized informational world that we generate and sustain—an entity that I have dubbed the "dataome" in my 2021 book *The Ascent of Information: Books, Bits, Genes, Machines, and Life's Unending Algorithm*—has helped make us one of the most successful and sophisticated species Earth has ever seen. We've engineered an astonishing amplification of biological traits by off-loading memory, communication, and problem-solving to other places, outside of our cells and genes.

Maybe we can innovate our way out of informational meltdown. Some people pin (perhaps unrealistic) hopes to the realization of more generalized quantum computing. But while qubits use little energy to compute, their environmental conditions require significant power. As of 2015 the hardware of a D-Wave Systems machine consumed about 25 kilowatts of power, much of which was used to maintain refrigeration.[6] It's still unclear how that will scale further. But no matter what, the infrastructure and exponential growth of data storage and retrieval required will remain a burden.

Humans may have catalyzed the rise of a dataome and a world increasingly structured and restructured in service of information, but it's not obvious that the extraordinary benefits we enjoy will continue to outweigh the burdens. The big question is where that problem takes us.

Explaining biological evolution has benefited from the concept of the selfish gene, whose ability to propagate relies not on the advantage it bestows but on its ability to enhance its own transmission. The dataome suggests that those resource-seeking informational forms can spill like a tsunami into other domains and follow thermodynamic imperatives that are indifferent to parochial human needs, dissipating energy until our planet's contents are once again in equilibrium with the rest of a cold cosmos.

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LETTERS

Reviewing Trump's relationship with science

The criticisms by Wallace Manheimer, Christopher Barsi, and Joseph Moody (Physics Today, June 2021, page 10) of David Kramer's excellent, entirely fact-based report, "The undermining of science is Trump's legacy" (March 2021, page 24), demand a response. The writers attack Kramer and imply that he wrote a political opinion piece. Nothing could be further from the truth. Kramer's report is good science journalism, focused on what highly respected scientists and former presidential advisers have said about Donald Trump's impact on science, particularly with respect to the role of facts and fact-based decision making. It illustrates each issue with facts and examples.

Kramer accurately describes Trump's handling of the pandemic as an example of his undermining of science. Trump did in fact sideline Anthony Fauci and Deborah Birx, a well-documented fact attested to by both doctors. Moody asks, "Has there ever been a more aggressive effort to impede the spread of a virus?" Such a question is ludicrous on its face. Trump, who at one point admitted to downplaying the pandemic, was the loudest voice in the nation denying the effectiveness of masks and pushing back against social distancing.

Moody says that "most any unbiased individual would applaud Trump for seeking a variety of opinions." But seeking a variety of opinions on a scientific or medical subject shouldn't entail amplifying the opinions of those with no background or training in the area, as Trump did with Scott Atlas, a radiologist with no expertise in infectious disease, virology, epidemiology, or statistics.

Barsi claims that Kramer conflates science with "his personal preference for the government planning of scientific research." But the story does no such thing. Kramer reports on a public issue—namely, Trump's legacy in science. He does not advocate for government funding of scientific research. Barsi accuses Kramer of imposing his views of the 2015 Paris Agreement, but the piece does not do that either. Rather, it straightforwardly reports on the fact that Trump's climate actions were not based on facts and science, thus illustrating how Trump damaged the position of science in the nation.

Certainly, COVID-19 vaccines were developed extraordinarily quickly during the Trump presidency, as Manheimer notes. But that has nothing to do with the damage Trump has done to science and the respect for science in the US, through multiple instances of his refusal to acknowledge facts and the role science must play in public policy, no matter how uncomfortable that may be. Kramer is to be congratulated for his straightforward, fact-based account of that damage.

H. Joel Jeffrey
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David Kramer's powerful report "The undermining of science is Trump's legacy" (PHYSICS TODAY, March 2021, page 24) elicited responses like Wallace Manheimer's letter in the June 2021 issue (page 10). Manheimer complains that Kramer's story was too political, but then he launches into a highly politicized and inaccurate portrayal of Donald Trump's legacy.

The letter touts a rise in R&D funding that occurred during Trump's presidency. But that increase was the result of repeated congressional actions to reject draconian cuts that the Trump administration attempted to impose on critical R&D funding. Recall the outrageous efforts by Trump's Health and Human Services secretary Tom Price (before he was forced to resign because of corruption) to reduce the National Institutes of Health budget by almost $6 billion through cutting funding for universities' and research institutions' overhead expenses.

With regard to the vaccine achievement that Manheimer says Trump "spearheaded," the former president's lasting legacy is unfortunately his politicization of the vaccine development process in an effort to influence the outcome of the 2020 presidential election. While heroic scientists across the US and the world were working around the clock to achieve extraordinary results with COVID-19 vaccines, Trump was busy mocking the wearing of masks, promising without any basis that the virus would disappear, and pitching ineffective and dangerous therapeutics.

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Corrections

January 2022, page 17—The report incorrectly described Earth's distance from Messier 51. It is more accurate to say that it is about 400 times as distant as the far edge of the Milky Way's disk.

January 2022, page 37—In figure 2, the legend should indicate that the blue circle represents Earth's orbit and the red circle represents Mars's. A corrected figure can be found online. PT

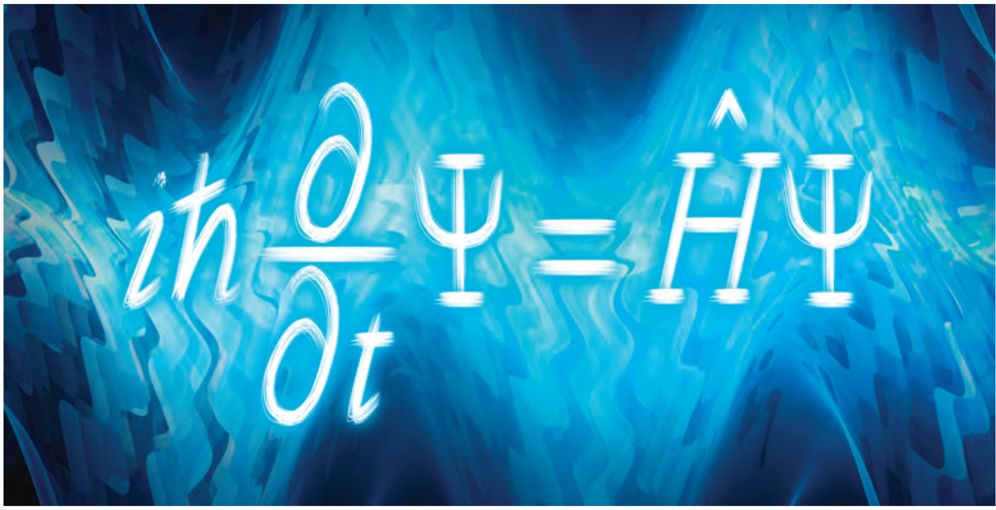
Does quantum mechanics need imaginary numbers?

A newly proposed experiment rules out a class of real-valued quantum theories.

The square root of negative one doesn't correspond to any physical quantity, but that doesn't mean it has no place in the physical sciences. For example, putting an imaginary number in an exponent changes the behavior of the exponential from rapid growth or decay to a steady sinusoidal oscillation. The result is a useful description of the physics of waves. (See, for example, the Quick Study by Iñigo Liberal and Nader Engheta on page 62 of this issue.)

In electromagnetism and most other fields of physics, imaginary numbers are merely a mathematical convenience. All the relevant phenomena can still be described using nothing but real numbers. Quantum mechanics is an exception: The observable quantities and probabilities are by necessity all real, but the underlying quantum states and governing equations involve imaginary numbers, and there's no simple way to remove them. But are they just an artifact of the way the theory was written down, or do they really need to be there?

In their new theoretical work, Miguel Navascués of the Institute for Quantum Optics and Quantum Information in Vienna and colleagues shed some light on that question.[1] They find that, subject to some postulates about how a quantum theory must be mathematically structured, no real-valued version of quantum theory can duplicate all the predictions of the familiar complex-valued formulation. Moreover, they designed an experimentally feasible test capable of ruling out real-valued quantum theories. In the time since their proposal was made public in January 2021, two groups carried out the experiment—and both found results in favor of standard complex-valued quantum theory.[2]



UNLIKE MOST physics equations, the time-dependent Schrödinger equation features the imaginary unit *i*. Purging the imaginary numbers from quantum mechanics would require major changes to the theory's mathematical structure. (Image by iStock.com/sakkmesterke.)

By any other name

Ever since its advent a century ago, the quantum world has challenged classical intuitions in many ways, with even prominent physicists bristling against quantum weirdness. A quantum state, for example, doesn't contain enough information to prescribe the outcome of every possible measurement on the state; rather, for most measurements, it offers only a probability distribution among the possible outcomes.

Could it be that the theory's pioneers unluckily happened on an incomplete description of the quantum world, just waiting to be supplemented by a system of local hidden variables that do, in fact, preordain every measurement outcome?

Thanks to the work of John Bell and others, that idea has been laid to rest. An experiment can be designed in which quantum mechanics and any possible theory of local hidden variables predict different results. The description of the experiment alone is enough to establish that no complete set of local hidden variables could possibly be lurking beneath the veneer of quantum theory. But when the experiment is actually performed, quantum mechanics emerges triumphant every time.

The question of the necessity of complex numbers has a lot in common with the question of quantum theory's inherent uncertainty, but it's much more subtle. One can always devise new mathematical constructs that behave in all the same ways as complex numbers even though they're called something else. As early as 1960, Ernst Stueckelberg did essentially just that with his real-valued formulation of quantum mechanics.[3] For the question to make sense, it's therefore necessary to establish some ground rules that exclude real-valued quantum theories that restate the standard complex-valued theory by other names.

Too many dimensions

A complex number, $a + bi$, can be described by an ordered pair (a, b) of real numbers—that is, a vector in the two-dimensional space of real numbers. But quantum states themselves are multidimensional vectors of complex numbers, and the compounding of dimensions on dimensions gets complicated. A spin-½ qubit is represented by a vector in two complex dimensions. It could also be written as a vector in four real dimensions, but those dimensions aren't naturally all equivalent.

The cracks start to show when one considers how to construct multiparticle states. One of Navascués and colleagues' ground rules, which they say they consider to be a fundamental mathematical property of a quantum theory, is that the combination of two quantum systems is represented by their tensor product. (Stueckelberg's formulation violates that rule.) For example, standard quantum theory says that the combination of two qubits, each with two complex dimensions, has $2 \times 2 = 4$ complex dimensions, equivalent to 8 real dimensions. But in a real-valued formulation, the same two qubits each have 4 real dimensions, and their tensor product has $4 \times 4 = 16$ real dimensions—twice as many as necessary to describe the system.

Having too many dimensions doesn't seem as though it would be a fatal problem for a theory—and it isn't. Previous work has shown that for all manner of Bell-like experiments, in which two or more entangled particles emerge from a central source and are measured by spatially separated observers, real-valued theories can be formulated to mimic all the predictions of standard quantum mechanics, even with the constraint of the tensor-product rule.

But what about when the number of dimensions is made to decrease, not increase? That can happen in an entanglement-swapping experiment, as sketched in the figure below. Rather than originating from a single source, two sets of entangled qubits are created by separate sources. One observer, Bob, receives one qubit from each pair (B_1 and B_2), and the other two, A and C, go to Alice and Charlie, respectively.

Bob then makes a joint measurement on his two qubits, with four possible outcomes. In complex-valued quantum mechanics, that measurement halves the number of dimensions of the system and cuts the number of entangled pairs from two to one. That is, it transfers the entanglement to qubits A and C. But in a real-valued formulation, Bob's four-outcome measurement doesn't cut the dimensionality by enough to fully swap the entanglement—he'd need an eight-outcome measurement to do that—so qubits A and C don't end up fully entangled.

The dimension mismatch still doesn't mean that the real-valued theory can't describe the system, especially if the extra dimensions didn't need to be there in the first place. And Navascués and colleagues spent a lot of time trying to make the real-valued description work before they turned to trying to prove that it couldn't.

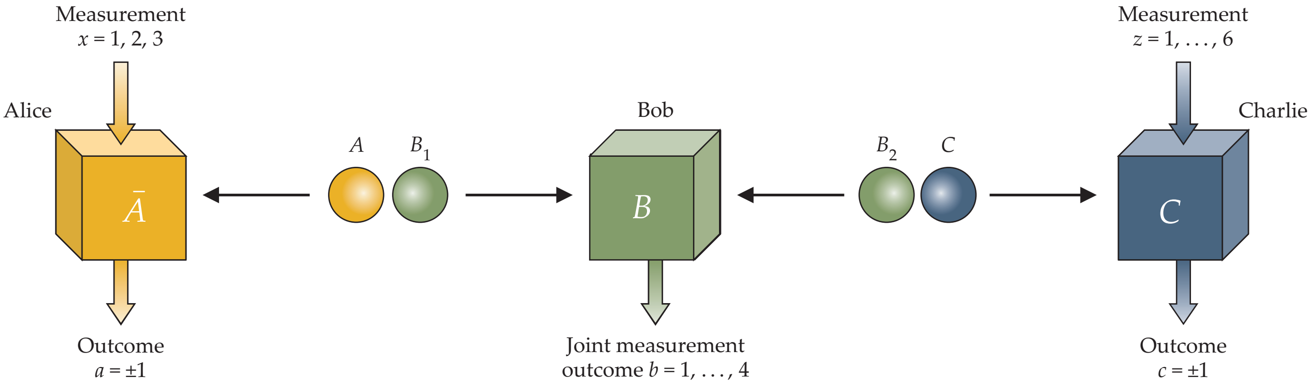
Real complex

Mathematical proofs of impossibility can be much more difficult than constructions of what's possible. To show that quantum mechanics (subject to the tensor-product rule) needs complex numbers, Navascués and colleagues had to prove not just that the most obvious real-valued formulation doesn't work, but that none of them do. Perhaps it's most natural to represent each complex dimension by two real dimensions, but real-valued theories need not be so limited. There could be three real dimensions per complex dimension—or four, or even infinitely many.

Accounting for all the possibilities was daunting. Help came in the form of a recent paper by Antonio Acín (also a coauthor on the new paper) and colleagues on certifying entanglement for quantum information networks.[4] By piggybacking on that work, Navascués and colleagues found a function of measurement correlations for the entanglement-swapping experiment that could reach $6\sqrt{2} = 8.49$ in standard quantum theory but that could never exceed 7.66 in a real-valued formulation.

That's not a lot of wiggle room, and Navascués suspects that the real-valued bound could be significantly improved. When the researchers first tried to calculate it numerically, their computer ran out of memory. In the end, they had to make some approximations that gave them a significantly looser bound than they'd hoped for.

Still, when Jian-Wei Pan and colleagues at the University of Science and Technology of China in Hefei carried out the experiment using superconducting qubits, they observed a value of 8.09, comfortably in the realm of complex quantum theory. And when Jingyun Fan (of Southern University of Science and Technology in Shenzhen, China) and colleagues



AN EXPERIMENT on entanglement swapping can distinguish real-valued from complex-valued quantum theories. Two pairs of entangled qubits (A and B_1; B_2 and C) are produced at separate sources. When an observer, Bob, makes a joint measurement on B_1 and B_2, he transfers the entanglement to a pair of qubits, A and C, that never interacted. Two other observers, Alice and Charlie, measure those qubits: Alice chooses from among three measurements to make on her qubit, and Charlie chooses from among six. The correlations between their measurements predicted by standard quantum mechanics—and observed when the experiment is performed—are inconsistent with real-valued theories. (Adapted from ref. 1.)

used photons to measure a related quantity, they too found a vindication for complex-valued quantum mechanics.[2]

Like Bell tests, the experiments are subject to some fine print. The measurements should be close enough to simultaneous to ensure that no classical information can pass between the observers that could influence their outcomes. And few enough of the measurement trials should go undetected to ensure that the correlation threshold is met not just by the detected trials, but by all of them. If either of those loopholes is not closed, it's possible for quantum-like correlations to be mimicked not just by a real-valued theory but by a classical one. (See PHYSICS TODAY, December 2011, page 20.) Closing the loopholes in Bell tests themselves was a decades-long effort that came to fruition only in 2015. (See PHYSICS TODAY, January 2016, page 14.)

Neither Pan's nor Fan's group has yet closed the loopholes in their experiments. Technically, therefore, the jury is still out on whether real or complex numbers are the better descriptors of the quantum world. Still, it seems likely that future students of quantum mechanics will have no choice but to continue to grapple with the mathematics of imaginary numbers.

Johanna Miller

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Krypton isotopes tell the early story of Earth's life-giving elements

Since its infancy, our planet has accumulated volatiles from more than one source.

The Galápagos Islands' extraordinary biodiversity famously helped inspire Charles Darwin to formulate his theory of the evolution of life on Earth. But the volcanic islands also offer a window into our planet's even deeper past. The volcanoes, including the one in figure 1, sit atop a mantle plume that channels deep-mantle material to Earth's surface. And the portion of the mantle tapped by the plume has been unusually stagnant over the planet's 4.5-billion-year history.

Over geologic time, Earth's crust and much of its mantle are in constant, albeit slow, motion, as tectonic plates are recycled from the crust to the mantle and back again. Like the churning of butter, the churning of the planet's thickest layer serves not to homogenize its components but to separate them based on their density, volatility, and chemical properties. As a result, almost nothing we encounter on Earth's surface bears any relation to the planet's average composition.

But some pockets of the mantle seem to have been immune to that mixing and have instead remained undisturbed by geological processes since at least the first 100 million years of the planet's history. (For more on the analysis that makes that conclusion possible, see PHYSICS TODAY, October 2010, page 16.) When bits of those primitive materials make their way to the surface—as they do in the Galápagos, Iceland, and a few other volcanic regions—they provide scientists with a valuable look back in time to reveal what the infant planet was originally made of.

FIGURE 1. FERNANDINA VOLCANO in the Galápagos Islands is one of several sites around the world where geoscientists can discern Earth's original composition. (Photo by tomowen/Shutterstock.com.)

Now Sandrine Péron (a postdoc at the University of California, Davis, at the time she did the work, now at ETH Zürich) and colleagues have used a newly developed technique to analyze some primordial mantle samples for their krypton, an element present only at the parts-per-trillion level.[1] The findings paint a picture not only of krypton itself but of carbon, hydrogen, nitrogen, and oxygen—all the building blocks of life.

Mantle fingerprints

Early Earth was a hot place, as the young planet was frequently enduring energetic collisions with the planetesimals that it

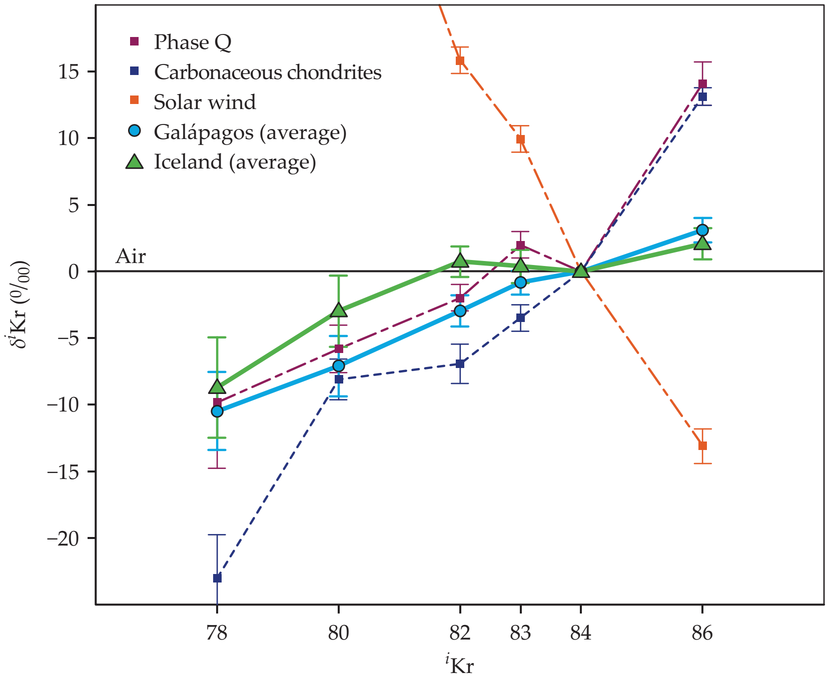

FIGURE 2. THE ISOTOPIC MAKEUP of krypton can be used to trace its source. The krypton found in mantle samples from Iceland and the Galápagos Islands differs from that of air. But the levels of five of the six isotopes closely match those of phase Q, a carbonaceous material found in meteorites. The deficiency of ^{86}Kr in the mantle follows a pattern of similar anomalies observed in other elements; it could be a sign that the protoplanetary disk that formed the solar system was not well mixed. (Adapted from ref. 1.)

hadn't yet cleared out of its orbit. The life-giving elements, on the other hand, tend to form compounds with low boiling points, such as methane, ammonia, and water. It wouldn't seem that those volatile substances would stick around long in such an environment—if they could even condense in the first place.

Clearly, Earth does have an abundance of volatile elements, and they had to have come from somewhere. They're not created in earthly nuclear reactions in appreciable amounts, so they must have either been part of the planet's original composition or been delivered later, perhaps by a comet. Knowing how Earth got its volatiles could help researchers understand how usual or unusual our planet's circumstances are—and perhaps how likely they are to have been replicated elsewhere in the universe.

That's where krypton comes in. As a gaseous element, it's physically similar to other volatiles, so it's likely to have condensed and degassed along with them. And its six naturally occurring isotopes are present in different ratios in different possible sources. If a particular sample of krypton has an isotopic composition matching what's found in the solar wind, for example, that's at least circumstantial evidence that the krypton came from the Sun.

The challenge in working with krypton is that there's so little of it. The element itself is rare enough, but its least abundant isotopes are two to three orders of magnitude rarer still: A typical 4 g sample of mantle material could have just a few hundred thousand atoms of ^{78}Kr. Moreover, it's subject to contamination. The gas entrained in volcanic rock could be bubbles of the original mantle gas, or it could be air that made its way into the lava after an eruption. Any given sample likely contains unknown amounts of both, and previous efforts to analyze mantle krypton have been stymied by the atmospheric contamination.

Péron developed a way around that problem.[2] She'd crush the sample a bit at a time, and she'd separately analyze the gas released at each step. If it showed signs of having been contaminated by air, she'd exclude it from the measurement. Otherwise, she'd keep it.

But Péron couldn't make that determination by looking at the krypton alone. Too little is released at each stage to separately analyze, and without knowing the mantle krypton composition, it's not possible to know how much, if any, atmospheric krypton is present. Instead, she turned to the more abundant neon. With only three natural isotopes, neon is less effective at distinguishing among many possible sources. But the isotopic composition of mantle neon and atmospheric neon are both well known, and they're significantly different. Only if the neon released at a crushing step matched the expected mantle composition would Péron keep the krypton released in the same step.

Volatile two-step

The stepwise analysis takes a long time—about a week for a single sample—and requires throwing away half to two-thirds of the data. But it gives a better estimate of the primordial mantle's krypton composition than has been possible before.

The results of Péron and colleagues' measurements are shown in figure 2. Their Galápagos and Iceland measurements reassuringly match one another. On the other hand, the mantle krypton is distinctly different from that of air. The difference means two things. First, the krypton in the mantle definitely isn't just recycled atmospheric krypton. Second and conversely, the krypton in the air—and by extension, other volatiles—can't have come solely from the degassing of the primordial mantle. Later in its history, Earth must have received another delivery of volatiles from somewhere else.

In five of the six isotopes—all but ^{86}Kr—the new mantle measurements are a reasonable match to a class of meteorites called chondrites, which are thought to represent the original building blocks of the solar system. Figure 2 shows the krypton isotopic composition of two chondritic references: average carbonaceous chondrites (chondrites that originated from the outer solar system, where volatiles could more easily condense) and phase Q, a poorly characterized material that carries most of the heavy noble gases found in many types of meteorites.

But the krypton in Earth's mantle couldn't have come directly from either of those sources because the ^{86}Kr levels don't match. The discrepancy is a bit of a puzzle, but it's also a clue. Similar anomalies—specifically, a deficit in the mantle of an element's most neutron-rich isotope—have been observed for at least eight other elements, including calcium, titanium, and nickel. Krypton, however, is the first volatile element found to follow the pattern.

Neutron-rich isotopes form in stars mostly through the r-process, or rapid neutron capture, as opposed to the s-process, or slow neutron capture. The protoplanetary disk that formed the solar system likely drew on the remains of a few different stars—some with more vigorous r-processes than others. If the stars' contributions weren't well mixed, the part of the disk that formed into Earth could have been relatively enriched in s-process matter. Moreover, the fact that krypton shows the same anomaly as other elements seems to indicate that Earth acquired its early dose of krypton and other volatiles at the same time, and from the same source, as it accreted its nonvolatile elements.

If that explanation is right, then there should be some meteorites—remnants of the same part of the protoplanetary disk that formed Earth—that show the same ^{86}Kr deficit as the mantle does. None have yet been found, but data on krypton isotopes in meteorites are sparse. Péron's next plan is to turn her analysis technique to different types of meteorites to see whether she can find any with a krypton composition that matches Earth's in all six isotopes.

Johanna Miller

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Laser pulses probe quantum beats

States of nearly equal energy underlie physiological processes, but studying them directly has been a challenge.

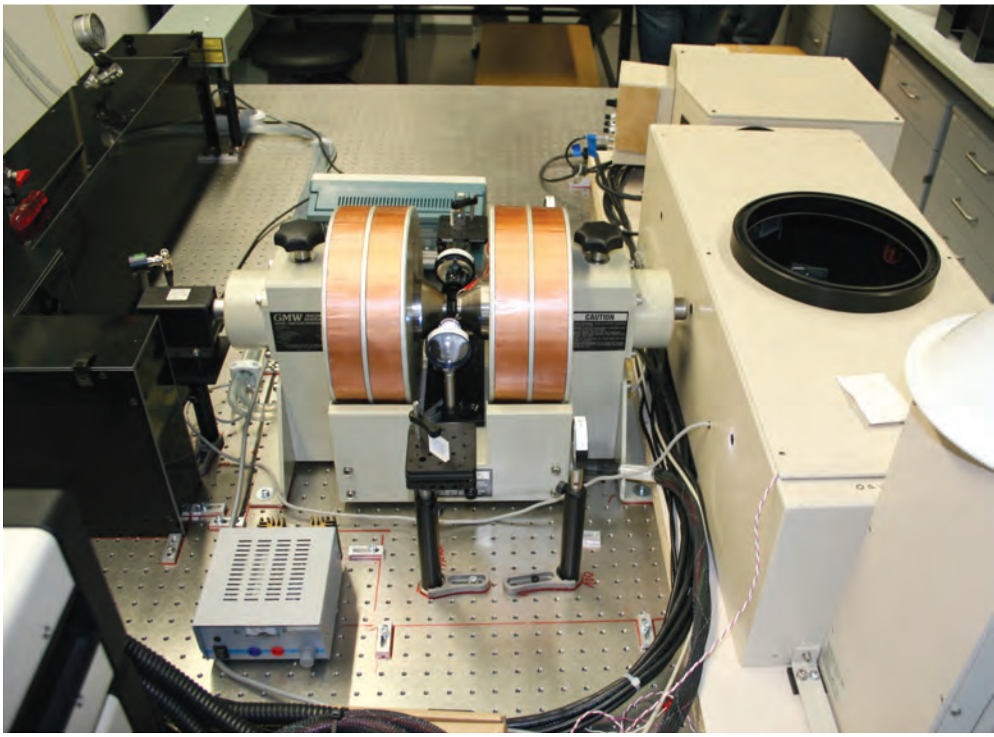

FIGURE 1. TWO ELECTROMAGNET COILS flank a sample chamber containing a solution of photoactive molecules. The surrounding optics direct a pair of laser pulses at the sample to manipulate the molecules' spin dynamics. (Courtesy of Michael Moos.)

Cryptochromes are a class of light-sensitive proteins found in many organisms. In animals, they're an integral part of the circadian clock: the collection of biochemical oscillations that align physiology with the day–night cycle.[1] A network of positive and negative feedback loops in gene expression and protein production couple those oscillations to downstream processes. For example, they link external light and temperature conditions to levels of hormones that stimulate hunger and sleepiness.

The involvement of cryptochromes in circadian clocks is well established; they're part of a negative feedback loop that suppresses transcription. But much about them remains poorly understood—for example, their structures are not well characterized, and the light-reactive proteins participate in cycles that don't have light as an input.

Cryptochromes are also the only biomolecules other than chlorophylls that are known to host so-called radical pairs. When a photon hits a cryptochrome, it can excite an electron that hops along the molecule from an electron donor to an electron acceptor—areas with low and high electron affinities, respectively. The mobile electron leaves behind another electron, but the electrons' spins remain entangled despite the separation.

The paired electrons exist in a singlet state before the excitation because they must have opposite spins per the Pauli exclusion principle. And they usually remain that way afterward. But when conditions are just right, the electrons undergo quantum beats: oscillations between singlet and triplet states. The frequency of the beats is determined by the electron spins' magnetic environment, which is dominated by the magnetic nuclei in the molecule, and the electrons' state can affect which reaction pathways are available to the molecule.

Unfortunately, the beats are tricky to study: The states' nearly equal energies make them indistinguishable by optical spectroscopy techniques. But Christoph Lambert and his graduate students David Mims and Jonathan Herpich (University of Würzburg, Germany), in collaboration with theoreticians Ulrich Steiner (University of Konstanz, Germany) and Nikita

Lukzen (Novosibirsk State University, Russia), have devised a work-around. Rather than measuring the states' energies, the optical method measures the singlet and triplet populations through their decay products.[2]

Unlike the existing spin resonance technique for measuring quantum beats, the optical approach isn't limited to certain magnetic field conditions. It also has the potential to extend the study of spin chemistry by boosting temporal resolution by up to two orders of magnitude.

Pump–push pulses

"Years ago, I encouraged David Mims to set up the pump–push experiment to see whether we could shift electrons back and forth in molecular dyads and triads using two laser pulses," says Lambert. But before Mims could do so, he needed the right experimental subject. In 2019, Mims and Herpich designed and synthesized a molecule with electron donor and acceptor moieties that were familiar to the Lambert group.

For the system to form a charge-separated state (CSS) that the researchers could study, the donor and acceptor had to be connected in just the right way. The link they inserted, tetramethyl dihydroanthracene, provides a weak electronic coupling between the two electrons. It holds them about 20 Å apart so they remain in a CSS for at least 100 ns—long enough to observe beats. The connection is also sufficiently rigid that the distance between the two electrons doesn't change much during the lifetime of the CSS.

The researchers then loaded a solution of the test molecules into the experimental setup shown in figure 1. Using two successive laser pulses, they probed the electron-spin dynamics of the molecular ensemble.

In the technique, the first pulse—the "pump"—excites an electron in the donor. From there, about 24% of the electrons fall directly back into the ground state, and the rest travel across the bridge to the acceptor and form a CSS. Those electrons also slowly relax back to the ground state over the course of hundreds of nanoseconds. But while they're in the CSS, the electron pairs oscillate between singlet and triplet states.

A second laser pulse, the "push," hastens the charge-separated electrons' recombination by exciting them into still higher-energy states. Those states have extremely short lifetimes, on the order of a few hundred picoseconds. So rather than taking a leisurely trip back to the ground state, which would leave time for further spin flips, the twice-excited electrons immediately begin their return trip. And the path each electron travels down indicates which state it was in at the time of the push.

The singlets head directly back to the donor to rejoin the ground state, and along the way they produce a fluorescence signal. The triplets linger at the acceptor a bit longer in an intermediate state that is detectable by transient-absorption spectroscopy. Those electrons also eventually make it back to the donor, but only after slowly decaying through an intersystem crossing.

Measurements of the signals from the two spin species as they return to the ground state—fluorescence emission for the singlets and absorption for the triplets—reflect both the total population of charge-separated pairs at the time of the push pulse and the fraction of those pairs that were in each spin state. Applying the push pulse at different delay times, as illustrated in figure 2a, tracks the oscillations in the singlet and triplet populations.

Field control

The oscillation frequencies for quantum beats in radical pairs are determined by the molecule's internal magnetic fields. The researchers therefore designed their test molecule such that a single nucleus—a nitrogen in the triarylamine donor—dominated the effects on the molecule's electronic structure. Otherwise, competing interactions could complicate and blur the signal, thereby making it difficult to identify and interpret.

External magnetic fields can also affect the oscillation. That gives the optical technique an advantage: Spin resonance methods can be applied at only a few discrete magnetic field values, so they can't investigate the system's zero-field behavior or see how its dynamics change as a function of field strength. That field restriction also limits researchers to measuring oscillations involving the triplet state with total spin $m_s = 0$. "In general," says Lambert, "one is interested to know about all situations of spin mixing," including with the $m_s = \pm 1$ triplet states that are accessible only at sufficiently low magnetic fields.

The transient-absorption measurements in figure 2b show oscillations in the triplet-state population at different external magnetic fields. The researchers chose field strengths that give an overall picture of the magnetic field dependence. The 1 mT field is near a resonance that enhances the singlet–triplet spin flip, 500 mT represents the high-field limit, and 7 mT generates about half the high-field response.

How external fields affect quantum beats is an important biological question because cryptochromes are thought to underlie migratory birds' ability to sense Earth's magnetic field and use it for navigation.[3] The proposed mechanism assumes that a cryptochrome's singlet-recombination rate modulates the level of a signaling species and that the rate varies in response to the strength and direction of Earth's magnetic field. A bird would then be able to respond to variations in the field and adjust its flight direction accordingly.

Although cryptochromes are widely suspected to underlie magnetoreception

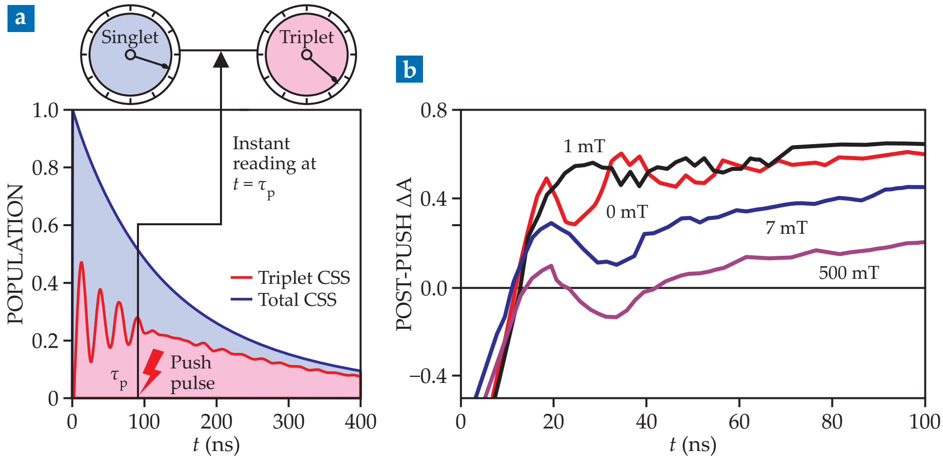

FIGURE 2. (a) A PUMP PULSE at $t = 0$ excites electrons in specially designed test molecules such that each one hosts a charge-separated state (CSS). A push pulse applied after a time delay τ_p measures the fraction of the remaining states that are spin singlets and triplets. As shown schematically here, repeating the measurement with different delay times reveals oscillations that reflect the spins flipping back and forth between singlets and triplets. **(b)** An external magnetic field changes the frequency and amplitude of the singlet–triplet flips. Oscillations in the absorption of a triplet-decay state are plotted here at four magnetic field strengths. (Adapted from ref. 2.)

(see the article by Sönke Johnsen and Ken Lohmann, PHYSICS TODAY, March 2008, page 29), it's unclear which of the avian cryptochromes is behind the phenomenon and how exactly the process works. And Earth's magnetic field strength is quite small, only about 50 μT, which limits the effect it can have. "So far, no direct time-resolved observations of the radical pairs in a bird's retina have been possible," says Lambert. The pump–push method could allow researchers to observe the pairs' dynamics *in vitro* on the relevant time scales.

To take full advantage of the new technique, researchers will have to improve its time resolution, which is currently about 8 ns—similar to the period of the test molecule's oscillations. Biological molecules of interest are unlikely to have the test molecule's simple spin dynamics, and their beats may happen on shorter time scales. Capturing such behavior will require a different photodetection method and shorter laser pulses. For Lambert's lab, that would have meant costly upgrades.

Still, he intends the proof-of-principle experiments to be just the first step: "We hope that this promising novel method will be taken up by many other researchers in the field of spin chemistry and that shorter laser pulses can be applied in our or in other labs to exploit the limits of resolution."

Christine Middleton

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Hong Kong University of Science and Technology: Innovating Today, Imagining Tomorrow

Photo credit: **Guancong Ma**

The Hong Kong University of Science and Technology (HKUST) is a dynamic, young research university with a diverse international student body and faculty who relentlessly pursue excellence in teaching and research. Situated on a hillside overlooking scenic Clear Water Bay at the eastern edge of Hong Kong and the southeastern coast of China, HKUST has rapidly established itself as a leading institution on the academic world map. Since the university's founding in 1991, the physics department has grown from 9 to 37 faculty members and now has 175 research graduate students. The department's research areas have also expanded to include condensed-matter physics; atomic, molecular, and optical systems and quantum optics; particle physics and cosmology; quantum information; scientific computation; soft-matter and biological physics; and metamaterials.

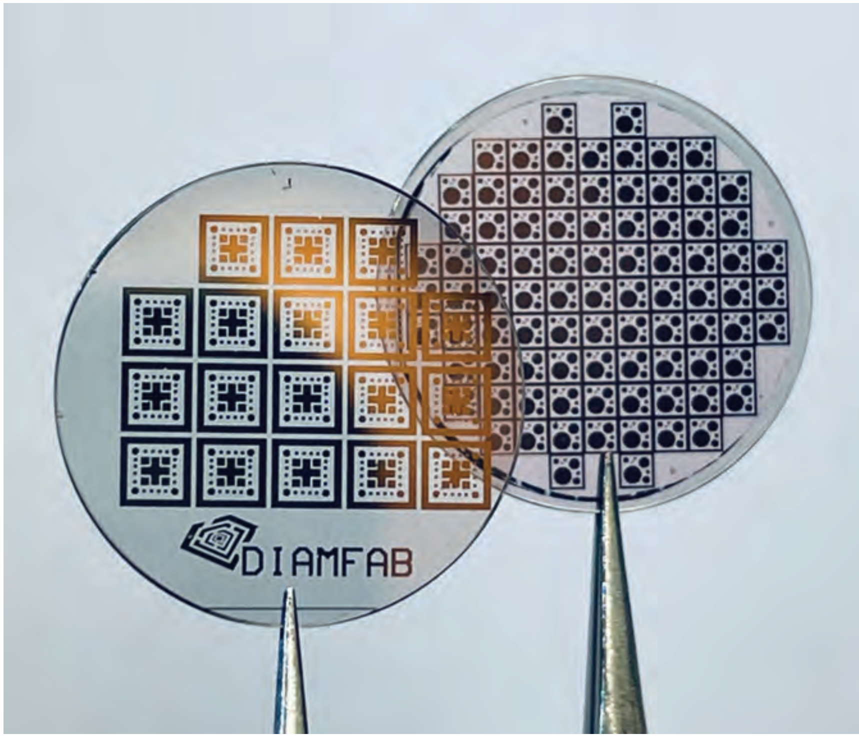
The physics department promotes the pursuit of cutting-edge research by cultivating a collaborative, supportive, and cohesive environment. For example, the Center for Fundamental Physics focuses on theoretical and experimental research about the origin, fate, and fundamental building blocks of the universe, and it has participated in several global endeavors, including the ATLAS collaboration at CERN. The emphasis of the Center for Metamaterials Research is on the design, fabrication, and characterization of different metamaterials to explore novel wave phenomena and to manipulate light and sound in ways not possible before. The newly established Center for Quantum Technologies brings together a team working across several core areas with focuses on quantum materials and devices, quantum control, and software.

The physics department's research efforts are supported by critical infrastructure, specialized equipment, high-performance computer clusters, and services provided by the university's Central Research Facilities. For example, the Materials Characterization and Preparation Facility offers advanced characterization tools, sample and materials preparation apparatus, and a helium liquefier. The Nanosystem Fabrication Facility has state-of-the-art equipment for developing innovative micro/nano devices and systems.

The department's goals for future growth are to enhance existing core strengths and build up world-class capabilities in rapidly developing areas aligned with university initiatives, such as big data and renewable energy and new energy materials. To achieve these goals, the department will strive to continuously attract outstanding new faculty members at all ranks, and it plans to fill 10 new faculty positions in the next few years. To learn about opportunities as soon as they are posted, interested candidates may visit jobs.physicstoday.org and create an alert for "HKUST."

Diamond's sparkle is in more than gemstones

The transparent carbon allotrope is finding new applications, but expanded use for electronics will depend on further advances in crystal growth.



DIAMFAB

SCHOTTKY-DIODE devices are fabricated by DiamFab in Grenoble, France, on 13 mm doped single-crystal diamond wafers.

Dental implants that can last a lifetime. Robots and particle detectors that can withstand brutal radiation environments. Atomic-scale quantum devices. High-voltage converters that can cut energy losses by 75% in electricity transmission.

Those are a few of manmade diamonds' cutting-edge applications, not to mention gemstones that are nearly indistinguishable from the natural, far more expensive ones. Diamond cutting and grinding tools have been ubiquitous since the 1950s. Diamond films are now nearing commercial use as coatings for dental, bone, and other surgical implants.

The use of diamond offers clear performance advantages over silicon for high-temperature, high-power, and radiation-hard semiconductors. Diamond's thermal conductivity is about 20 times that of silicon. For the same surface area, diamond can carry 5000 times the current of silicon. For the same thickness, diamond can withstand 30 times the voltage of silicon, says Khaled Driche, chief technology officer of DiamFab, a startup located in Grenoble, France.

But diamond electronics are held back by the size of crystals that can be manufactured. Diamond will also have to compete against silicon carbide, which has become the go-to replacement material for silicon in high-temperature, high-power environments, according to diamond manufacturers, users, and researchers who work with the material.

Monocrystalline and polycrystalline diamonds differ greatly in their properties and applications, but electronic applications generally require single crystals. Where polycrystalline diamond has been used—in power-electronics applications such as 5G, satellite communications, radar, and fiber-optic data communications—it has been to utilize the material's passive properties, such as unparalleled thermal conductivity and broadband transparency, says Daniel Twitchen, chief technologist at the De Beers Group–owned Element Six.

The two primary techniques of diamond synthesis are high pressure and high temperature (HPHT) and chemical vapor deposition (CVD). First used by the Swedish company Asea in the early 1950s, the HPHT process was kept secret until General Electric claimed the discovery in 1955. Today, metal alloys like iron–nickel, iron–cobalt, and nickel–manganese are used to catalyze diamond growth using graphite in giant anvils at pressures of 5–6 GPa and temperatures of 1300–1600 °C.

A single HPHT system can potentially generate up to a kilogram of diamonds per hour, says Twitchen. The material's high nitrogen content, around 200 ppm, improves its resistance to cracking, providing performance in machining, grinding, and cutting applications.

In contrast, the CVD process grows diamonds typically in a plasma of hydrogen and methane in a high-vacuum chamber. Carbon atoms are deposited layer upon layer onto diamond substrates known as seeds, which can be supplied from HPHT or CVD. The epitaxially grown diamond maintains the single-crystal structure of the seed.

One millimeter of CVD crystal growth requires two days, says Timothy Grotjohn, an electrical- and computer-engineering professor at Michigan State University and former R&D director of the Fraunhofer USA Center for Coatings and Diamond Technologies. In 2019 Grotjohn founded Great Lakes Crystal Technologies, a producer of diamond substrates for semiconductor electronics. The company is funded by multiple Small Business Innovation Research grants, awarded by various federal agencies, but has yet to make a commercial sale.

"There's a whole other side of the industry that is using CVD to grow gemstones," says Grotjohn. "They want to grow 5–6 millimeters, so they can cut a 1–2 carat stone. They will run for hundreds of hours or a couple of weeks." The requirements for semiconductor grade are stiffer than for gems, he adds, since a diamond will look nice even if it includes a large number of impurities that aren't desirable in electronic material.

Heat and radiation

In addition to reducing impurities, CVD provides a way to precisely control other elements that are added to the crystal. Most notably, boron and phosphorus dopants impart diamonds with p-type and n-type semiconductor properties. That process has been studied for over a decade by Robert Nemanich, a physicist at Arizona State University, and has led to the grant of a patent to the institution.

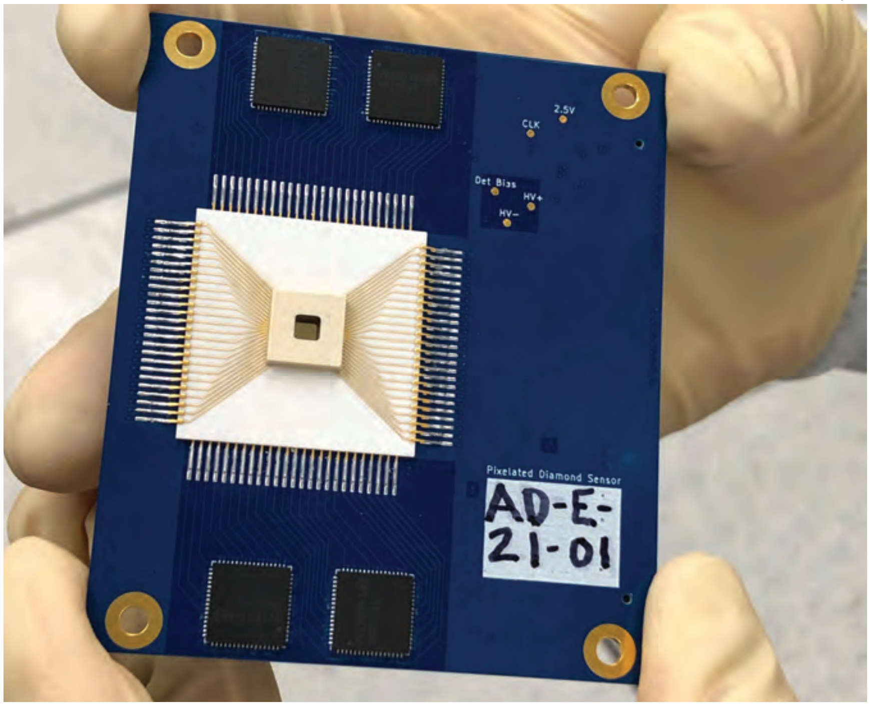
Diamond's capability to work at 500 °C or higher—compared with silicon's limit of about 200 °C—makes doped diamond ideal for high-temperature electronics, says Nemanich. Such conditions occur in, for example, well logging and drilling, aircraft, and electric vehicles.

Nemanich is an adviser to Advent Diamond, an Arizona State spin-off that's developing diamond radiation detectors, power electronics, diodes, and other electronic components. The company has won seven Small Business Innovation Research awards, from government agencies including the Departments of Energy and Defense, but it has yet to have commercial sales, says Manpuneet Benipal, the company's CEO.

Diamond tolerates high-radiation environments. That quality was essential for measuring the neutron flux in the debris from the flooded Fukushima Daiichi nuclear reactors, where a diamond sensor mounted to a small remotely operated submarine probed the submerged sludge. The instrument was able to discriminate neutrons in a high gamma-ray background caused by the presence of radioactive cesium and strontium, says Satoshi Koizumi, who leads the Wide Bandgap Semiconductors Group at Japan's National Institute for Materials Science.

Diamond radiation detectors in the Large Hadron Collider contributed to discovery of the Higgs boson by monitoring the background signal and beam luminosity in the ATLAS and CMS detectors. Diamond could also be a substitute for neutron detectors based on rare helium-3 that are used at border crossings to guard against the smuggling of fissile materials, says Nemanich.

ADVENT DIAMOND



ADVENT DIAMOND, an Arizona State University spin-off, fabricated this detector component for x-ray-beam monitoring. The company has been awarded seven Small Business Innovation Research grants, from several federal agencies.

Nitrogen–vacancy quantum devices are a growing market for single-crystal diamond. Applications include computing, magnetometry sensors, detectors, and cryptography. To make nitrogen–vacancy devices, nitrogen is added to the ingredients during the CVD process. Typically, electron-beam irradiation displaces some carbon atoms, leaving vacancies in the crystal lattice, Grotjohn says. High-temperature annealing then forces the vacancies to locations immediately adjacent to nitrogen atoms.

DiamFab is part of an Airbus-led project to make a hybrid aircraft, in which one engine is fully electric and the other is a conventional turbine. Driche says one component will be a power converter based on diamond transistors.

Replacing all the silicon power electronics used in an airliner with diamond components would cut its weight by 1800 kg, Driche says. Such a reduction is possible because diamond devices wouldn't require the heat dissipators that compose about 80% of the total mass and volume of silicon-based aircraft voltage converters.

Diamond electrodes are used in electrochemical applications such as the destruction of organic wastes that are byproducts of chemical processes found in the oil and gas and pharmaceutical industries. They are also used in point-of-use ozone production systems for chemical-free water purification, which are manufactured by companies including Siemens, Condias, and DiaCCon.

Bigger is better

Currently available synthetic single-crystal sizes, typically up to 10 mm, have been sufficient for applications in spectroscopy, Raman lasers, and particle detectors, says Twitchen. Devices that benefit from diamond's active properties, such as sensing a field or acting as a switch or transistor, remain mostly at the R&D stage.

One thing seems clear: Widespread use of diamond for semiconductors will require larger single-crystal-wafer sizes of at least 50 mm. That's well beyond today's state of the art, which are somewhere shy of 25 mm (1 inch). "We are far from being able to fabricate 1-inch substrates with a homogenous crystalline orientation on a commercial basis," says Philippe Bergonzo, the US representative for Seki Diamond Systems, which makes CVD diamond-synthesis machines.

Twitchen says that there are no fundamental research barriers preventing larger wafer sizes. "The key question here is whether the markets that need this technology will support the engineering costs it will take to scale up."

Driche says wafers a minimum of 200 mm in size will be needed to compete with silicon in nonniche applications. But he says one company told him that if 150 mm wafers were available, they could use them to fabricate RF devices and next-generation 6G cell phones.

Yet if someone were to make even a high-purity 50 mm single-crystal diamond and replicate it for sale, that producer would be giving away their exclusivity to the buyer, who could use it to grow diamonds of the same size. Bergonzo says it's unlikely that the originator could obtain intellectual property rights to the process, because a single crystal of similar size may exist in nature.

Etienne Gheeraert, a professor at the University of Grenoble Alpes and researcher at the Néel Institute, headed a European Union–funded project called GreenDiamond to develop a diamond-based high-voltage converter for carrying electricity produced by offshore wind farms. Such converters are expected to become increasingly important as electricity generated by renewable sources of energy is transported over long distances to consumers. Existing silicon-based electronic devices lose as much as 9% of the energy in the conversion process. Although Gheeraert's project demonstrated that utility-scale diamond voltage converters could reduce those losses to 2%, he says a working device will require 50 mm single-crystal wafers.

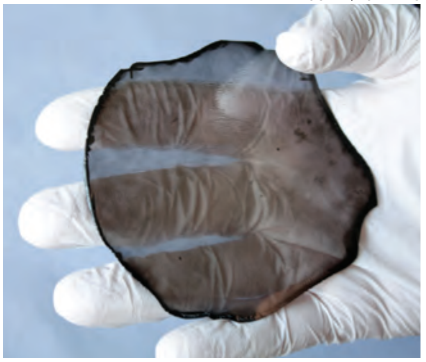
Gheeraert expects CVD, HPHT, or both will be capable of producing 50 mm diamond wafers by 2030, but at a cost of $10 000 apiece. An alternative production method is being developed in a project he's part of that's sponsored by the French Alternative Energies and Atomic Energy Commission in Saclay. Called Mosaic + Smart Cut, the method could reduce that cost to $1000, he says. In that process CVD single-crystal wafers would be sliced horizontally into multiple wafers. Those new seeds would be abutted into a mosaic pattern, and a single wafer would be grown atop the mosaic. Wafers of 75 mm or more should be attainable, he says. Although those wafers won't be single crystal, Gheeraert says semiconductor designers can work around the "dead zones" that correspond to the spaces between the substrate crystals.

The Smart Cut process was developed by Soitec in France for silicon, and a similar process for diamond was commercialized by the company EDP, located in Japan. The duplication method is used to mass-produce diamonds for sale as seeds and substrates, says Bergonzo, whose company distributes EDP seeds globally. If EDP were to be given a 50 mm single crystal with no impurities and with the same crystalline orientation, it would certainly replicate it. "This would be the biggest breakthrough towards diamond becoming a large-market electronic material," he says. "But who would give such a primary substrate to EDP? And even if it would exist, if they sold it, at what price?"

Still, developing diamond device technology will require advances not only in diamond material itself but also in the electrical contacts and manufacturing processes, Twitchen says. And for such applications as voltage converters, diamond will have trouble displacing the widely used silicon carbide, which already offers high efficiencies. "The success that silicon carbide is having across a range of industries shows the importance of new semiconductor materials, and there is growing interest in the role diamond might play over the next 10–20 years," says Twitchen.

DUTCH DIAMOND GROUP

MARTIN FISCHER/AUDIATEC



A SOLID DIAMOND ring (left) was cut by Dutch Diamond Group in Cujik, the Netherlands, from a diamond crystal grown by Audiatec in Augsburg, Germany. That crystal was similar in size to the 92 mm, 155-carat stone (right) that Audiatec produced by ion bombardment of 1-nm-thick carbon on a substrate of iridium.

A different approach

Matthias Schreck, a physicist at the University of Augsburg in Germany, cofounded Audiatec, which sells diamonds produced by a novel process: Ion-bombardment of a 1-nm-thick carbon layer on a heteroepitaxial (nondiamond) iridium substrate. The company sells its diamonds for use in cutting tools, surgical scalpels, IR optics, and optical windows.

Audiatec has grown single crystals as large as 92 mm and 155 carats (see photo above). Other potential uses are in neutron detection, as host materials for nitrogen–vacancy and other quantum color centers, and in Schottky diodes, Schreck says. Still, he adds, the company continues striving to match the crystal uniformity found in diamond-substrate-grown CVD crystals.

Polycrystalline diamonds are generally used for coatings. Doped polycrystalline grains that are small enough (3–5 nm) can be conducting, says Orlando Auciello, a physicist at the University of Texas at Dallas. He codeveloped "ultrananocrystalline diamond," a term he has trademarked. The material's low coefficient of friction, high wear resistance, and biocompatibility have led to applications in seals and bearings for pumps used in drug production and elsewhere.

Auciello's startup company, Original Biomedical Implants, is currently conducting a clinical trial of diamond-coated dental implants in Mexico. Due to diamond's chemical inertness, he says, the implants should far outlast today's widely used but corrosion-prone titanium-aluminum-vanadium alloy. Other potential applications include diamond-coated anodes for lithium-ion batteries that Auciello says will extend cell phone operating time, hydrophilic stents that will prevent blood clotting, and joint implants offering improved wear and biocompatibility.

David Kramer

The US is in dire need of STEM teachers

Faculty attitudes, public perceptions, tuition, and state requirements are barriers to science majors entering the teaching profession.

MARK TWAY

TEACHERS-TO-BE learn research methods in a 2011 UTeach course at the University of Texas at Austin. The woman with the balloon is Gloria Ogboaloh, who for the past decade has taught math at a high school in Round Rock, Texas.

Schoolteachers report career satisfaction. Jobs are plentiful. Pay is better than in many professions. Pensions are good. Yet for decades the US has struggled with acute teacher shortages, especially in physics, math, and chemistry. The shortage of math and science teachers was emphasized as far back as 1983 in the government report *A Nation at Risk: The Imperative for Educational Reform*. These days, COVID-19 is exposing and exacerbating existing strains in education systems. But even as the stresses of the pandemic are pushing some teachers to consider quitting, others are persevering and working for change.

Roughly 27 000 teachers are teaching physics in US high schools, according to the Statistical Research Center of the American Institute of Physics (publisher of PHYSICS TODAY). The shortfall in physics teachers nationwide is 15 000–23 000, says Michael Marder, executive director and cofounder of UTeach, a nearly 25-year-old science and math teacher preparation program at the University of Texas at Austin that is now replicated at 49 universities in 23 states. The range represents the additional numbers of teachers needed for 80% or 100% of high school students to take physics. By contrast, there is no shortage of biology teachers. (Marder explains his calculations in a 25 October 2021 blog post titled "How Bad Is the U.S. STEM Teacher Shortage?")

In science, technology, engineering, and math (STEM) fields more broadly, the shortages in teachers in 2017–18 were about 100 000 in high schools and 150 000 in middle schools, according to Marder. To address the deficits and to make up for retirements and resignations in high schools alone, he says, the US needs to prepare an additional 10 000 STEM teachers annually for a decade.

But the number of certificates awarded for teaching STEM in secondary schools is decreasing. The trend is "alarming" in the case of university-prepared teachers, says Marder. He points to tuition hikes and ever-increasing state requirements as culprits. "The cost to get from an undergraduate degree to teaching is squeezing people out."

Wendy Adams, a researcher at the Colorado School of Mines, is involved in increasing recruitment in STEM fields. According to focus groups and surveys she has conducted, more than half of college physics majors express interest in teaching high school, but the faculty assume students are uninterested. "Students sense that faculty don't consider teaching a good career," she says. It's common, she laments, for the attitude among physics faculty to be, "Why would you waste your talents on teaching?"

Adams is the principal investigator for Get the Facts Out, a five-year, NSF-funded initiative that aims to boost the number of STEM majors who become teachers. It provides resources to counter negative perceptions and repair the profession's reputation. In addition to the School of Mines, the partners are the American Physical Society (APS), the American Chemical Society, the American Association of Physics Teachers (AAPT), and the Association of Mathematics Teacher Educators. On its website, Get the Facts Out highlights attractions of teaching (see the box on page 27).

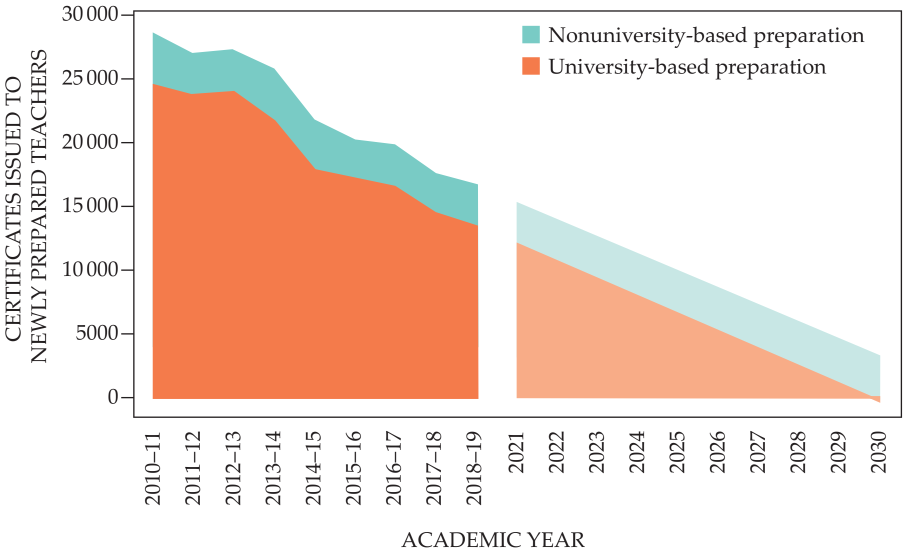
Conditions such as teacher pay, number of colleagues, class size, and autonomy vary widely by district, state, school size, and rural versus urban location. For example, according to the US Bureau of Labor Statistics, the mean annual pay for secondary school teachers is $86 900 in California, $78 900 in New Jersey, $58 040 in Texas, and $46 100 in Mississippi. Salaries also vary within each state.

The teaching profession

Gay Stewart has spearheaded successful teacher recruitment programs through APS's PhysTEC program at West Virginia University (WVU), where she has been for nearly eight years, and at the University of Arkansas, where she previously spent two decades. Arkansas built up to producing five physics teachers a year on average while Stewart was there, and about three WVU physics majors a year go into teaching, she says. But, she notes, the most common number of teachers that college physics departments produce is zero.

One graduate of Stewart's program is John "Charlie" Rea, who has been teaching high school physics since 2005 at a public high school in Fort Smith, Arkansas. Before becoming a teacher, Rea was a glassmaker. "I made more money, and I solved interesting problems," he says, "but it didn't feel like a calling. Teaching does."

Rea and other teachers say they like



DROPPING PRECIPITOUSLY is the number of certificates awarded in the US for secondary school teaching in science, technology, engineering, and math. The right-hand plots show the projected descent if the situation is not reversed. The numbers for certificates from university-based and nonuniversity-based preparation programs are additive. (Courtesy of Michael Marder, based on Title II data from the US Department of Education.)

getting to know the students and seeing them grasp new concepts. They like the experiences and challenges that come with each new batch of students. They like the unpredictability of each day and being kept on their toes. They like talking and thinking about science, and they like the satisfaction of making a difference in people's lives. Many of them like the camaraderie and collaboration with other teachers. They also like that teachers will always be needed and that jobs are relatively easy to come by. They like their pension plans and the flexibility of their summers. Some say the work–life balance is an attraction of the profession.

The difficulty of achieving work–life balance is also among the factors some teachers say they dislike about their jobs; many put in long hours on evenings and weekends. Teachers commonly cite grading as an unappealing part of their responsibilities. And some are frustrated by legislators dictating what and how they should teach.

Many teachers say pay is not a reason to enter—or exit—the field. But to augment their salaries, more than half of teachers take on extra paid work at school, and about 20% of high school and middle school teachers have a second external job, according to the National Center for Education Statistics's 2017–18 survey of teachers and principals. According to the survey, extra duties at school bring a yearly average of $2800 for middle school teachers and $3800 for high school teachers, and outside work yields $6000 and $6400, respectively.

Bree Barnett Dreyfuss is in her 17th year of teaching physics at a large public high school in Pleasanton, California. She's paid to work part-time with AAPT and APS on STEP UP, a program that works to increase the number of women majoring in physics. And although money was not her motivation for chairing her school's science department, the accompanying stipend doesn't hurt. "I know teachers who tutor, garden, run clubs, and coach sports teams," she says. Other teachers report side gigs as educational consultants, technical writers, and Uber or Lyft drivers.

Pandemic pandemonium

In much of the country, in-person school resumed in fall 2021 after more than a year of remote and hybrid teaching. A common observation among teachers is that behavioral problems are up and attention spans are down. "My juniors have the emotional maturity of ninth graders or middle schoolers," says Jessica Watts, who has taught physics for more than a decade at both public and private schools. "Teachers are not trained to catch them up in mental and social well-being, but it's expected of us."

Fostering group projects has become more difficult, teachers report. "Behaviors this year are significantly harder to manage," says Melissa Kovar, who teaches physics at a public high school in San Francisco. "There are more fights at school, more shouting, more standing up." Rea concurs: "A ring of kids was throwing fireworks at each other in the hallways. I never thought I'd see something that brazen."

Schools in higher-income areas tend to see fewer disruptions. "We don't have a lot of behavior issues," says Barnett Dreyfuss. "The main one is cheating." Teachers in wealthier areas also encounter more pressure from students and parents to raise grades.

Coursework is posing problems this year too. In the AP physics class that Rea is teaching, for example, some students have never seen the quadratic formula. "That blew my mind," he says. "I'm dealing with 11th- and 12th-grade motivated kids. If they were all missing the same knowledge, it wouldn't be a big deal. But I can't even discern who is missing what." In required classes where kids may be less motivated, it's worse, he adds. On top of the uneven learning gaps, this year both students and teachers have missed school because of COVID-19.

Nationwide, a shortage of substitute teachers has led to teachers having students from other classes added to their own and to substitutes being in charge of multiple classes at once. Some school districts have raised pay for substitute teachers. And some are pleading with parents to step in. A 14 January email from the Austin Independent School District, for example, promised up to $225 per day, depending on qualifications and local rates of COVID-19.

Marketable skills

The extra demands on teachers during the pandemic has some considering quitting. "I know several," says Hannah Seyb Ensman, who teaches at a large public high school in Indio, California, about 200 km east of Los Angeles. "Some of them left because of the pandemic. They realized it was not good for their mental health."

For her part, Seyb Ensman had planned to earn a PhD in astronomy, but after observing that graduate students "didn't look happy," she became a teacher. She attributes her intentions to stay in the profession partly to being a fellow of the Knowles Teacher Initiative, which provides math and science teachers with extra funding, professional development, and networking.

At first, teaching online "was like being a new teacher all over again," says Cheryl Harper, a 33-year veteran of teaching high school physics in Greensburg, Pennsylvania. "But I've put so much into it, and I've learned so much about technology, there is no way I'm going to give up at this point."

Barnett Dreyfuss notes that a lot of skills that teachers have are marketable. "We can speak and present, we can coalesce information. We can make curriculum that is clean and easy to read. These are resumé-building skills." It can be difficult to hire physics teachers, she adds. "They can earn much more in industry."

Anne Goshorn has taught physics and engineering in public schools in central Texas since 2004. She switched to online teaching when COVID-19 hit. But then, in the fall of 2020, her school insisted she come back in person. Because her own children were still attending elementary school remotely from home in a neighboring district, she quit her job. After a year off, she is now teaching AP physics part-time in her kids' school district.

The pandemic prompted Dean Baird to retire in 2021, two years earlier than he had planned, with a roughly $500 a month cut to his pension. He'd been at the same school in Sacramento, California, for more than three decades. The challenge—and fun—had always been, "How can I use my creativity to coax these kids along?" he says. "If you are not sex or food, they are not interested. I have to reel them in and show them how cool physics is. Seeing kids understand things made me happy." The connection with students disappeared when his classes went online, he says. "I had never worked so hard to be so ineffective. I got beaten down by having to do four physics preps every day remotely. I got crushed by it."

This is Watts's last year teaching. "It's a great job. It doesn't feel like work when you are with students," she says. But the pandemic has revealed "how little value I had" in the eyes of the school administration. For example, her current private Catholic school in Texas called teachers back into the classroom before vaccines against SARS-CoV-2 were available, and she was told her contract would be rescinded unless she showed up in person. "We felt replaceable," she says. Her plan now is to earn a doctorate in education, with a focus on teacher retention in private Catholic schools, and then to "fight the battle to change the system at a higher level."

CHERYL HARPER

HIGH SCHOOL SENIORS test an automatic cornhole bean-bag thrower they designed for Cheryl Harper's engineering class at Greensburg Salem High School in Greensburg, Pennsylvania.

Get the Facts Out wants you to know that*:

- Teachers in the US rate their lives better than do people in other occupations—save physicians.
- Midcareer teacher salaries range between $60 000 and $100 000.
- Most teaching jobs have better retirement benefits than other jobs you can get with the same degree.
- Student loan forgiveness programs and scholarships are available for math and science teachers.
- You can get a job almost anywhere in the US or abroad as a science or math teacher.
- More than 78% of high school science teachers are still in the classroom after five years.
- About half of all science and math majors report an interest in becoming a teacher.
- Grades 7–12 science and math teachers get paid more than most college teaching faculty.
- Research shows that classroom teachers have a greater impact on student learning than all other aspects of schools.

*These statements have been edited for style and clarity.

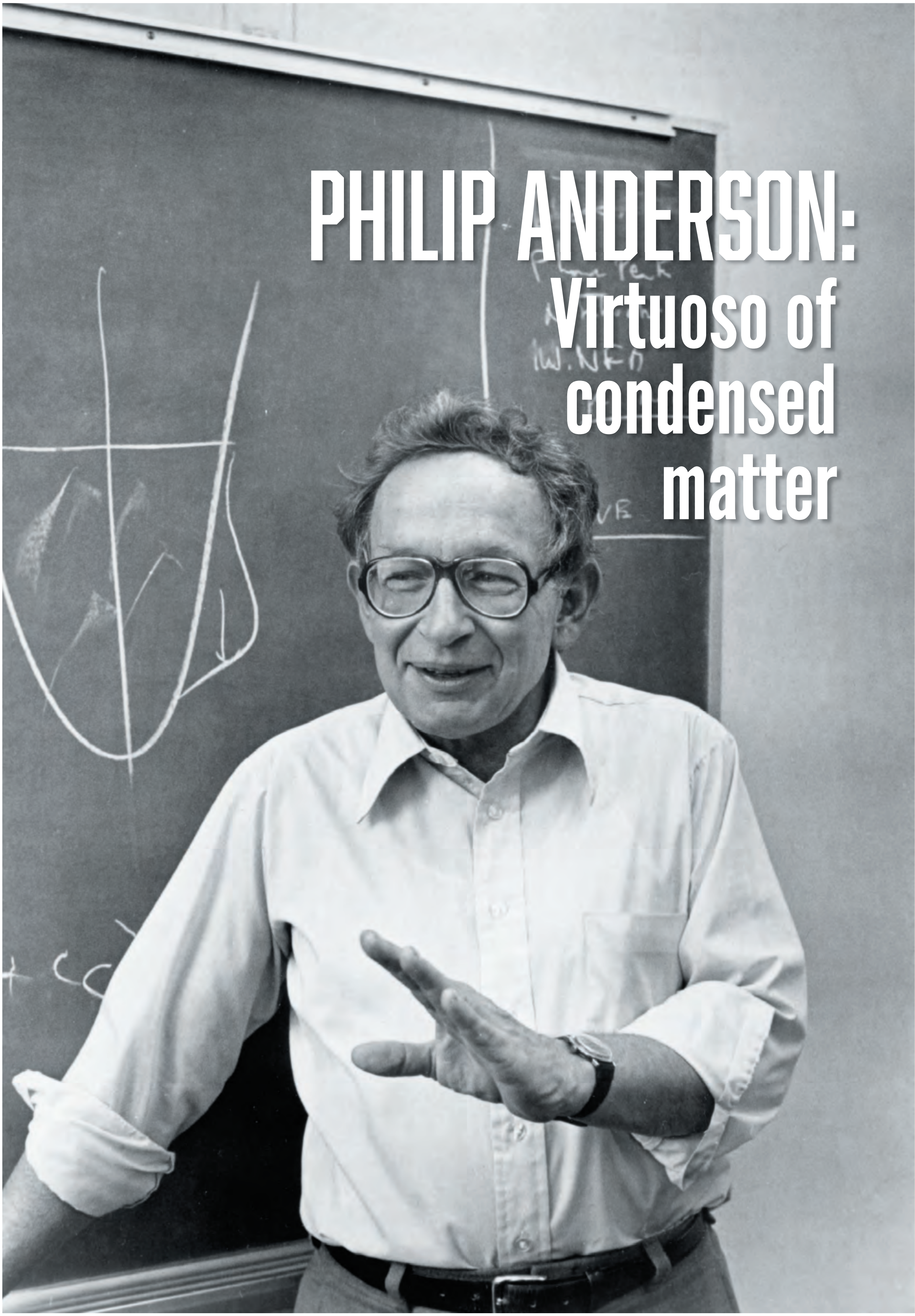
Problems as possibilities

For all the exhaustion that teachers feel this year, some hold out hope that the cracks exposed by the pandemic will lead to improvements. The availability of food, internet, academic help at home, and other inequities in education and beyond are exacerbated by the pandemic. The importance of teachers and the demands placed on them have become more visible. Teachers hope for more respect and higher pay. Some are exploring different methods of teaching and grading.

Seyb Ensman has been experimenting with "standard-based" grading, in which students are evaluated on what they have learned, rather than on the work they've turned in. The students can choose how to demonstrate their knowledge, as long as they follow the given rubric. The approach is fairer to a broader range of students, she says. But switching curriculum and grading procedures is time-consuming, says Barnett Dreyfuss. "I'd love to do more. Students like it. They feel you are investing in them, and they focus more on learning and less on grade grubbing."

Toni Feder PT

PHILIP ANDERSON: Virtuoso of condensed matter



Philip Anderson in October 1977. (Courtesy of the AIP Emilio Segrè Visual Archives, PHYSICS TODAY Collection.)

Andrew Zangwill is a professor of physics at Georgia Tech in Atlanta. This article is based on his book *A Mind Over Matter: Philip Anderson and the Physics of the Very Many*, published by Oxford University Press in 2021.

Andrew Zangwill

The theorist's work on disordered and magnetic solids earned him a Nobel Prize, but it was his profound influence on the condensed-matter community—and well beyond—that set him apart.

Philip Warren Anderson (1923–2020) was one of the most accomplished and important physicists of the second half of the 20th century. Over a 50-year career at Bell Labs, Cambridge University, and Princeton University, he demonstrated superb taste, profound intuition, and remarkable creativity in the effort to understand the way nature works.

More than any other person, Anderson helped combine many-body physics with the patchwork of topics once called solid-state physics into the intellectually coherent field known today as condensed-matter physics. In his 1984 monograph *Basic Notions of Condensed Matter Physics*, he argued that the construction and application of model Hamiltonians was a far better way to understand a system of 10^{23} particles than solving the many-body Schrödinger equation. Textbooks of condensed-matter physics written in the past few decades show that his view has prevailed.

The late Nobel laureate Pierre-Gilles de Gennes greatly admired Anderson and once described him as "the pope of solid-state physics."[1] The nickname is apt because Anderson tried to establish doctrine for his subject. The faithful paid close attention to his every utterance, and many made special efforts to seek his views and approval. By his own reckoning, Anderson was a rebel, a curmudgeon, and a person with an insatiable curiosity about why things in nature behave the way they do. In this article I survey Anderson's life and science with an eye toward understanding his enormous impact.[2]

Son of the heartland

Anderson's ancestors on both sides of his family fought against the British in the American Revolutionary War. Later generations of those Scottish and Irish immigrants established farmsteads in the rich soil of western Indiana. Farming did not appeal to everyone, and Anderson's maternal grandfather and uncle enjoyed long careers teaching Latin, mathematics, and English at Wabash College in Crawfordsville, Indiana. A similar attitude led his father and paternal uncle to become plant pathologists. Anderson grew up in the Urbana–Champaign area because his father was a professor at the University of Illinois. Frequent visits back to Crawfordsville kept him in close touch with his family, shown in figure 1, and with the traditional Hoosier character traits of pugnacity, skepticism, patriotism, and sensitivity.

In high school, Anderson excelled in both academics and athletics—track, tennis, and speed skating. He acted in the school play every year, wrote and read the senior class history at commencement, and participated in the biology and chess clubs. His senior yearbook photograph was labeled *The Importance of Being Earnest*, after the title of an Oscar Wilde play.

During those years, Anderson often accompanied his father and a group of University of Illinois faculty members, known as the Saturday Hikers, on outings that featured hiking, swimming, softball, and left-wing political talk. The latter instilled in the boy what became a lifelong commitment to social justice. One Saturday Hiker, F. Wheeler Loomis, chaired the university's physics department, and his recommendation helped Anderson win a scholarship to attend college at Harvard University.

The US entered World War II when Anderson was a sophomore. Eager to contribute to the national effort, he switched from physics to an accelerated degree program in electronics physics created by Harvard specifically to prepare students for war work. After graduation he served for two years as a microwave engineer at the US Naval Research Laboratory in Washington, DC. That experience convinced him that his talents lay in theoretical physics. When the war ended, Anderson returned to his alma mater to pursue a PhD. He felt that Harvard still owed him a proper physics education because his electronics-physics courses never mentioned quantum theory.

Like Anderson, many wartime college graduates had gone into war work or military service. Peacetime thus brought a pent-up supply of applicants to graduate programs. As a result, a large group of theoretically minded graduate students arrived at Harvard at the same time that Anderson did. Eleven of them chose to work in nuclear physics with the university's newly hired superstar Julian Schwinger. For his part, Anderson exhibited a contrarianism that would become familiar to later observers when he found a reason to dislike nuclear physics. Instead, he worked with department chair John Van Vleck and did the first fully quantum mechanical calculations of the microwave absorption spectrum of small molecules.

Anderson graduated in January 1949 with a PhD thesis that is still widely cited today. Job hunting was difficult because interviewers showed little interest in a person trained in molecular physics; they were looking for experts in nuclear physics. He had already accepted his only offer—at an academic institution with no graduate program—when Van Vleck arranged an interview at Bell Labs. A few weeks later, Anderson began working at Bell as a theoretical physicist in William Shockley's solid-state-physics group. At the time it was the only group in the US devoted to the subject.

FIGURE 1. A FAMILY PORTRAIT. Philip Anderson stands front and center in 1934 at age 10, with his immediate family and some of his Crawfordsville, Indiana, relatives. Directly behind Anderson is his mother, Elsie. His sister, Eleanor Grace, stands at the far left. His father, Harry, stands third from the left. (Courtesy of Susan Anderson.)

Bell Labs

For 50 years in the middle of the 20th century, Bell Labs was arguably the greatest R&D organization in the world. Anderson benefited greatly by being there, and the labs benefited greatly from his presence. In his first few months, he consumed Frederick Seitz's 1940 monograph *The Modern Theory of Solids*, confirmed a speculation of Shockley's about the origin of ferroelectricity in the ceramic oxide barium titanate, and conducted a journal club discussion of a paper in which Linus Pauling proposed what he called a resonating valence bond approach to metallic cohesion.

Like many before him, Anderson soon grew frustrated with Shockley's imperious manner. He turned for guidance to three other outstanding Bell Labs theorists: Gregory Wannier, Conyers Herring, and Charles Kittel, all shown in figure 2. Wannier taught him to love statistical mechanics. Herring taught him solid-state physics and shared his encyclopedic knowledge of the literature. Kittel taught him magnetism and specifically proposed that Anderson work on antiferromagnetism, a topic that was newly accessible experimentally by using magnetic neutron scattering.

In January 1952 Anderson submitted to the *Physical Review* an approximate quantum theory of antiferromagnetism.[3] The paper is significant historically because it includes the first discussion of spontaneous symmetry breaking, the phenomenon whereby a system adopts one particular configuration from among a set of degenerate and symmetry-connected configurations, despite the invariance of the system's Hamiltonian to that symmetry. Among other things, Anderson discussed what is today called a Goldstone mode in connection with the collective rotation of the direction of the spins of an antiferromagnet. It took a decade before any other physicist took special note of Anderson's ideas about symmetry breaking.

An encounter with the Japanese theorist Ryogo Kubo led to an invitation for Anderson to attend what was the first International Conference of Theoretical Physics in Tokyo and then to spend six months visiting Kubo's research group. Bell Labs gave Anderson an unpaid leave of absence—the Fulbright Foundation paid his salary—and he, his wife Joyce, and his daughter Susan arrived in Japan in September 1953 (see figure 3).

At the conference, Anderson spoke up in a half-dozen sessions and discovered that he could talk comfortably with such senior, first-rank theorists as Felix Bloch, Lars Onsager, and Nevill Mott. Afterward, the positive reaction Anderson got from Kubo and other young Japanese theorists to a lecture series he presented on contemporary magnetism boosted his confidence even more. He realized on the trip home that he was no longer a neophyte solid-state physicist. He felt secure in his abilities, confident in his scientific taste, and certain that he could strike out independently as a theoretical physicist.

Most of Anderson's single-authored papers from his first 15 years at Bell Labs combined intuitive arguments with detailed analytic calculations. Examples include his incorporation of Coulomb effects into a self-consistent treatment of the Bardeen-Cooper-Schrieffer model of superconductivity and two papers cited by the Nobel Committee for Physics of the Royal Swedish Academy of Sciences when it awarded Anderson a share of the 1977 Nobel Prize in Physics.

The Nobel committee drew attention to Anderson's discovery that a propagating wave can be trapped and localized by a disordered medium.[4] Perplexing spin resonance data obtained from doped silicon crystals by his Bell Labs colleague George Feher led Anderson to construct and analyze a simple model for the motion of electrons in a spatially disordered lattice. He guessed and then proved that such disorder could suppress quantum mechanical tunneling enough to localize otherwise freely propagating electron wavefunctions. Like spontaneous symmetry breaking, disorder-induced wave trapping—now called Anderson localization—was not appreciated (or even believed) by many of his colleagues until well after the paper appeared.

The Nobel committee also cited Anderson's analysis of the persistence (or not) of a magnetic moment when an atom with unpaired spins is immersed in a nonmagnetic host metal.[5] He tackled that problem after spending weeks studying pertinent data obtained by another of his Bell Labs colleagues, Bernd Matthias. The paper Anderson wrote on magnetic moments is one of the best written of all his scientific publications. He summarizes the experimental situation, discusses previous theory on the subject, develops a model Hamiltonian, gives a qualitative discussion of special cases, performs a Hartree–Fock analysis, extracts the important conclusions, and points out the limitations of his approximations.

Anderson enjoyed talking to experimenters, and he was eager to learn the technical details of their work. He took the time to understand their motivations and laboratory strategies, and he relished grappling with the raw data himself. In a 1999 oral history interview with the American Institute of Physics (publisher of PHYSICS TODAY), he went so far as to characterize himself as "six tenths theorist and four tenths experimentalist," despite never having performed an experiment himself.

Cambridge

Anderson spent a sabbatical year (1961–62) at the University of Cambridge. He published only one minor paper there, but his influence led directly to Nobel prizes for two other physicists. The first went to Brian Josephson, who learned about symmetry breaking from a graduate class Anderson taught. Outside of class, Josephson and Anderson spent hours discussing the meaning of the phase of the macroscopic superconducting wavefunction. Less than a year later, Josephson published the short paper in which he predicted the DC and AC effects that today bear his name (see the article by Anderson, PHYSICS TODAY, November 1970, page 23). For that work, he earned a share of the 1973 Nobel Prize in Physics.

Anderson played a similarly important role when the Nobel committee awarded a share of its 2013 physics prize to Peter Higgs (see PHYSICS TODAY, December 2013, page 10). Anderson had learned at daily tea with Cambridge particle physicists that existing gauge field theories failed to produce a mass for the carriers of the weak nuclear force. In a flash of insight, he realized that with a suitable change of variables, his earlier analysis of Coulomb effects in the Bardeen-Cooper-Schrieffer model for superconductivity was relevant to the elementary particle's mass. In 1963 Anderson wrote a *Physical Review* article aimed at particle physicists outlining his idea,[6] and Higgs realized that a relativistic version of Anderson's discussion was all that was needed.

The sabbatical year confirmed a long-standing Anglophilia in Anderson and Joyce. Anderson thus was happy to accept a job offer from Mott, chair of physics at Cambridge and a longtime champion of Anderson localization, for a half-time professorship in the department's solid-state theory group. Bell Labs reduced Anderson's commitment to half time as well. From 1967 to 1975, that schedule allowed him to teach and supervise research students at Cambridge from October to March.

FIGURE 2. ANDERSON'S MENTORS at Bell Labs (from left): Gregory Wannier, Conyers Herring, and Charles Kittel. (Wannier portrait courtesy of the AIP Emilio Segrè Visual Archives, PHYSICS TODAY Collection; Herring and Kittel portraits courtesy of the AIP Emilio Segrè Visual Archives.)

Some of the issues he addressed during that period are listed in figure 4.

A particular triumph of Anderson's involved what's known as the Kondo effect. To explain that phenomenon, the task of theory was to characterize the ground-state spin configuration for a class of magnetic alloys in which the electrical resistance showed a minimum as the temperature decreased toward zero. That task turned out to be the most challenging many-electron problem of the 1960s. Anderson presented his final solution in 1970—first, in a difficult and equation-rich paper written with two junior collaborators and then in a masterful and elegant single-author paper.[7] In both, one finds the invention of the renormalization group method a full year before Kenneth Wilson's magisterial formulation of that technique in its full generality.

A few years later, Anderson and the distinguished Welsh physicist Sam Edwards invented a model to describe the magnetic behavior of an exotic class of metal alloys called spin glasses.[8] Their solution for the ground-state configuration of spins was approximate, but attempts to do better soon revealed a huge problem. The simultaneous presence of disorder and conflicting constraints implied that the number of computations required to obtain a solution increased exponentially with the number of spins in the system.

The same computational problem occurs when one tries to solve the celebrated traveling-salesperson problem. Notwithstanding the difficulty, the Edwards–Anderson model has enjoyed steady popularity over many years. That happened because, with a change of variables, the model applies to a host of nonphysics problems, such as airplane scheduling, mail delivery, pattern recognition, integrated circuit wiring, and message encoding.

More is different

In 1972 Anderson published an article called "More is different: Broken symmetry and the nature of the hierarchical structure of science."[9] Its purpose was to rebut an often-stated claim by some high-energy physicists that their research into the physics of the very small was somehow more fundamental than the research conducted by solid-state physicists into the physics of the very many. That fundamentality argument had been used for decades to enhance high-energy physicists' prestige and to justify the large claim they made on government funds to plan, build, and maintain the large particle accelerators needed for their work.

Anderson accepted the reductionist view that all things seen in nature must be consistent with the known properties of elementary particles. What he denied was the claim that the behavior of complex many-particle systems could somehow be derived from the rules of particle physics. To the contrary, considerations no less fundamental than those used by particle physicists are required to discover laws and properties present at, say, the micron scale. That's because, like symmetry breaking, those laws and properties emerge for reasons that are not at all apparent if one's analysis begins at the nanometer scale.

Wetness is an example. That property of a liquid would be quite unfathomable and would never be predicted by someone familiar with only the properties of individual molecules and their interactions. One must experience wetness to be able to formulate a language to understand it.

Anderson's emergence arguments in "More is different" resonated not only with condensed-matter physicists and chemists but also with physiologists, ecologists, and other

FIGURE 3. CHATTING OVER TEA in Japan in January 1954 are, from left, Susan Anderson, Masao Kotani, Philip Anderson, Ryogo Kubo, Takahiko Yamanouchi, and Joyce Anderson. (Courtesy of Hiroto Kono and the Kubo family.)

"macroscopic" biologists who felt marginalized by molecular biologists who claimed a unique fundamentality for their own work. Other people responded to Anderson's statement in the article suggesting that when the size of a system becomes large enough, one should stop thinking about decreasing symmetry and start thinking about increasing complexity.

A decade later Anderson and a small group of scientists launched the Sante Fe Institute, a think tank dedicated to the study of complex systems. There, ideas about complexity dovetailed with developments in nonlinear dynamics and found fertile ground among experts in fields as diverse as economics, neuroscience, computer science, and operations research.

Princeton

In 1975 Anderson swapped his half-professorship at Cambridge for a half-professorship at Princeton. As was the case at Cambridge, Anderson was often disorganized as a lecturer, but the classes he taught to advanced students permitted him to hone the ideas that, nearly a decade later, formed the basis for his book *Basic Notions of Condensed Matter Physics.* The publication of that grand synthesis coincided with his retirement from Bell Labs and the expansion of his professorship from half-time to full-time.

Anderson's research style at Princeton remained what it had always been: Engage deeply with experimental data; look for "anomalies," cases where experiment and current theory do not agree; and construct a model Hamiltonian—90% of the task, Anderson said—to explicate the physics. His remarkable intuition often told him the answer he was seeking. But he relied increasingly on others to supply the supporting mathematics. That was the case when he recruited three colleagues and prodded them to construct a scaling theory of disorder-induced wave localization.[10]

The final results of the so-called Gang of Four collaboration elegantly reproduced Anderson's previous wave-localization results in three dimensions and extended them to one and two dimensions. An avalanche of work on localization by others ensued (see the articles by Ad Lagendijk, Bart van Tiggelen, and Diederik Wiersma and by Alain Aspect and Massimo Inguscio, Physics Today, August 2009, pages 24 and 30, respectively).

It was not easy to be an Anderson research student because he rarely provided guidance about how to proceed with calculations. More than a few students have characterized his supervision of their PhD theses as "oracular." They left meetings with him having no idea what he was trying to communicate, only to realize weeks or months later what he had meant. Many senior physicists had the same problem, a situation summarized by the Russian theorist Anatoly Larkin when he said, "God speaks to us through Phil Anderson. The only mystery is why He chose a vessel that is so difficult to understand."[11]

Superconducting Super Collider

In 1970 Anderson learned from a panel at an American Physical Society meeting that financial commitments needed to build the National Accelerator Laboratory (later Fermilab) might disrupt funding for "small science" projects across the country. He responded with an article in *New Scientist* magazine that was critical of Big Science as practiced by the high-energy physics community.[12] Years later he reiterated those views when he assumed the role of the most outstanding public opponent of the Superconducting Super Collider (SSC), a giant machine being built by the US to test the standard model of particle physics.

On 4 August 1993, Anderson and the theoretical physicist Steven Weinberg, a principal architect of the standard model, testified back-to-back at a congressional hearing about the project. Weinberg defended the SSC on the grounds of fundamentality. Anderson argued that the truth or falsity of the standard model did not justify the cost of the SSC if the funds needed to maintain its operation diverted funds from projects in other scientific fields, where equally important questions—many with more practical import—remained to be answered. Although a great deal of money had already been spent, Congress pulled the plug on the SSC two months later.

Historians of science have concluded that testimony by scientists played almost no role in the decision to discontinue the SSC. Ever-increasing cost estimates, poor project management, and political expediency were the main reasons for its demise (see the article by Michael Riordan, Physics Today, October 2016, page 48). Nevertheless, to this day, some people blame Anderson for the debacle.

High-temperature superconductivity

In 1986 the world of condensed-matter physics was turned upside down by the discovery of superconductivity at unprecedentedly high temperatures in a class of ceramic copper oxides. Anderson had long been fascinated by superconductivity, and he was the first theoretical physicist to discuss the new superconductors in print.[13] The paper was groundbreaking because it dismissed the relevance of the electron–phonon interaction—the well-understood mechanism for superconductivity in conventional metals and alloys—in the new materials and instead emphasized the short-range Coulomb repulsion between electrons.

Anderson's paper suggested that the oxide superconductors were best studied using a Hamiltonian introduced years earlier by John Hubbard as a model for ferromagnetism. An aside: Anderson often claimed invention of the Hubbard model for himself, which is almost true. An exact solution of the Hubbard model was (and remains) unknown, so he outlined a guess for the ground-state many-body wavefunction that was related to the resonating valence bond state that Linus Pauling had studied 40 years earlier (see the Reference Frame by Anderson, Physics Today, April 2008, page 8).

At the 1987 March Meeting of the American Physical Society, Anderson was the first theorist to speak at the famous all-night "Woodstock of physics" session devoted to high-temperature superconductivity. He was also the only theorist to sit on the dais at a news conference the next morning to discuss the issue. Other theorists had different ideas about the new superconductors, and a 20-year period began during which Anderson was unable to convince the majority of his colleagues to accept his views. The fact that his ideas kept changing—mostly in response to new experimental results—did not help.

Anderson was fiercely competitive as a physicist. He had a good relationship with almost all experimenters, but he could be quite abrasive in the heat of debate with other theorists. Unfortunately, he became possessive about the theory of high-temperature superconductivity (even as his ideas changed), and he dismissed the work of other theorists as wrongheaded or worse.

A handful of people responded in kind, and the field began to resemble a combat sport. For that reason, more than a few young people declined to enter the field. Today, with the rancor of the early years long past, no single theory can account for all the behavior seen in the oxide superconductors. Probably the only universally accepted idea is one that Anderson fully embraced: Subtle many-body physics lays at the heart of the matter.

A man in full

Later in life, Anderson became interested in reaching audiences beyond the physics community. He did so by publishing essays and book reviews in journals, magazines, and newspapers. Topics he discussed include arms control, complexity, religion, science politics, futurology, the culture wars, and the meaning of science.[14] He engaged philosophers of science by reckoning that the structure of science was more like a highly interconnected web than an evolutionary tree or a pyramid.[15] A provocative 1994 essay he wrote for the British newspaper *Daily Telegraph* offered "four facts everyone ought to know about science." Anderson identified those as: science is not democratic, computers will not replace scientists, statistics are sometimes misused and often misunderstood, and good science has aesthetic qualities.[16]

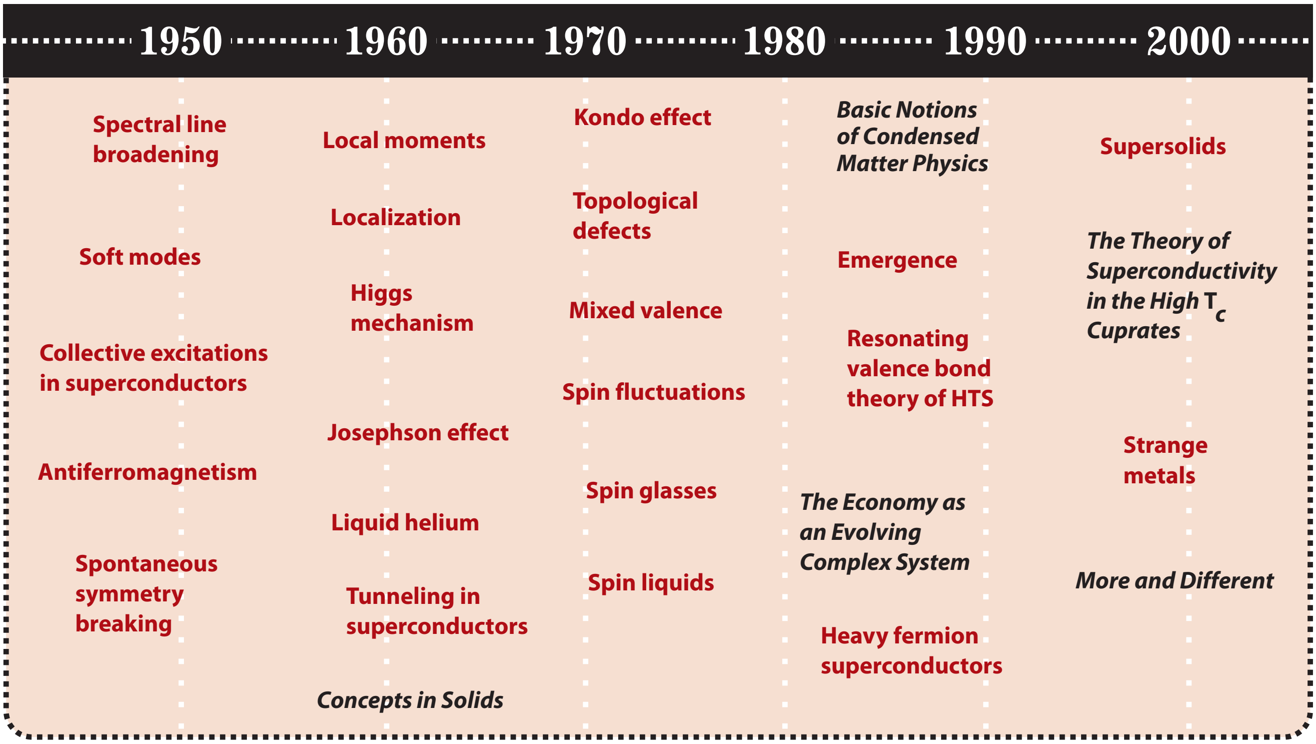


FIGURE 4. TIMELINE of some of Philip Anderson's research activities. The list is not comprehensive. Book titles are in italics. The acronym HTS stands for high-temperature superconductivity.

The second "fact" reflects Anderson's peculiar attitude about the use of computers in theoretical physics. On the one hand, he admired the computational work of personal friends, such as William McMillan and Volker Heine. On the other hand, much more than most scientists of his generation, he quite unfairly identified the least creative practitioners as typical of the field. That tendency led him, for example, to disparage numerical calculations of the electronic structure of matter without bothering to familiarize himself with the state of the subject. It is ironic, then, that some of the greatest progress in understanding the origins of high-temperature superconductivity in recent years has come from extensive computer simulations of the Hubbard model and its variants.

Anderson was a lover of knowledge, rationality, culture, and nature. Outside of physics, his main passions were hiking, politics, gardening, the game of Go, and Romanesque architecture. His close friends knew him to be warm, generous, and loyal—particularly to those in need. On more than one occasion, he made it possible for a struggling former student or postdoc to spend time at Princeton so he could help as they got their lives in order. He was witty and a charming storyteller, but not a joke teller. Several years after receiving the Nobel Prize, he used an assumed name and wore big black glasses and a fake moustache to present a poster at a conference where 10% of the presented talks included the words "Anderson model" in their titles.

Anderson's wife and life partner, Joyce, played an essential role in his professional success. Particularly during the full-time Bell Labs years, she provided discipline and structure and worked hard to ensure that he behaved in the manner expected of a rising star in the organization. As a former English major, she later made a point of editing all his nontechnical writing for clarity and precision. Over more than 70 years of marriage, Anderson rarely remained in the office after 5:00pm because he knew his wife was waiting for him at home.

Philip Anderson was one of the brightest stars in the firmament of theoretical physics for half a century. Bell Labs launched and sustained him for many years, but he only rarely involved himself with applied problems. Nevertheless, his conceptual formulations profoundly influenced a broad swath of the physics world. Future historians will count him as one of the world's greatest scientists.

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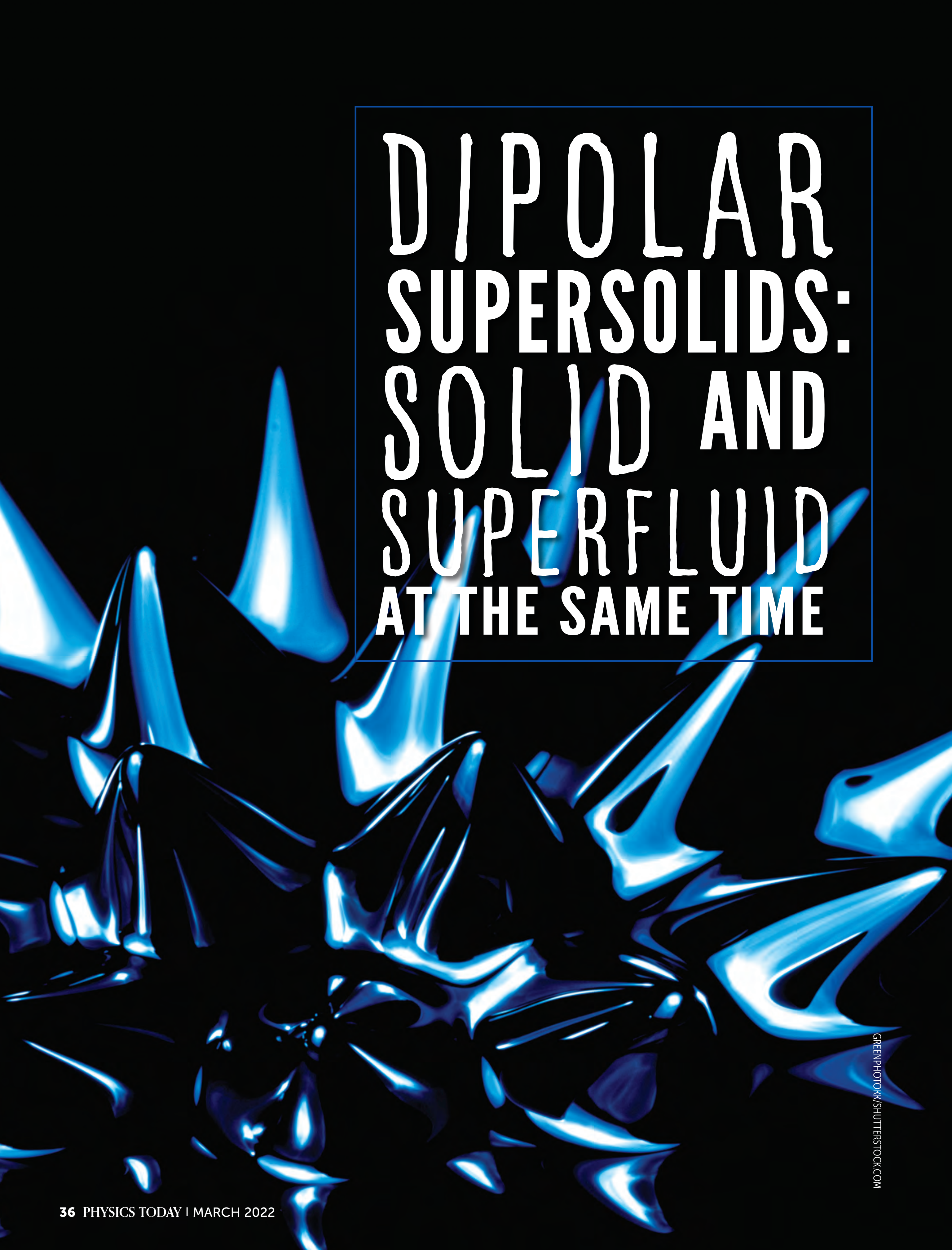

DIPOLAR SUPERSOLIDS: SOLID AND SUPERFLUID AT THE SAME TIME

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Ultracold atomic gases with the right balance of interactions enter a phase that demonstrates a superposition of seemingly opposing properties.

The microscopic laws of quantum mechanics can influence behavior at the macroscopic scale. In superconductors, for example, the coupling of electrons into Cooper pairs leads to current flow without resistance. In superfluids, the collective motion of atoms as a coherent matter wave suppresses dissipation and produces frictionless mass flow. Both phenomena starkly contrast with our everyday experience. Recent experiments with ultracold gases of magnetic atoms have demonstrated that a long sought after and, perhaps, even more counterintuitive "super" state exists: the supersolid, a state that combines the properties of a solid and a superfluid.

One of the fundamental principles of quantum mechanics is the superposition principle. A single atom can be not only in a particular quantum state, such as spin up or down, but also in a coherent superposition of two such states.

Since the 1950s theoretical physicists have pondered whether quantum mechanics allows for a phase of matter—that is, a collective state of many atoms—that shows behavior similar to superposition.[1] That so-called supersolid phase would simultaneously feature the contradictory properties of a superfluid's perfect flow and of a solid's rigid, crystalline structure. Think of a jar of honey, whose contents can be in a liquid or in a crystalline phase. A hypothetical supersolid honey would, counterintuitively, exhibit a quantum mechanical superposition of both phases.

The idea of supersolids triggered an ongoing decade-long search for that exotic state in helium, which was for a long time considered the most "quantum" material available. Liquid ^{4}He famously becomes a superfluid at temperatures below about 2.17 K at atmospheric pressure. Its superfluid behavior is closely related to Bose–Einstein condensation, a phenomenon in which atoms accumulate in the lowest quantum mechanical energy state of a system and form a collective matter wave. Unlike the energy-dissipating random motion of particles in a classical liquid, a superfluid's coherent flow is frictionless.

Not only can helium be a liquid or a superfluid, but at sufficiently high pressures of several megapascals and temperatures around a few kelvin, it also can form a solid. In that solid, the helium atoms arrange in the rigid periodic structure of a crystal lattice. Intuitively, solid helium thus shouldn't have superfluid properties. But theoretical studies have long suggested that solid helium may turn into a supersolid if the lattice contains empty sites, so-called vacancies, in the crystal structure that can easily hop around and become delocalized over the entire crystal. At sufficiently low temperatures, those vacancies can undergo Bose–Einstein condensation just like atoms, and superfluid properties emerge. While most of the helium remains a solid, a small part of the solid's mass becomes free to flow without friction.

Supersolid formation should be clear from measurements of transport properties or of the moment of inertia of a bulk helium sample. Such measurements turned out to be very challenging, and the results often difficult to interpret. (See PHYSICS TODAY, February 2008, page 14, and the article by Robert Hallock, PHYSICS TODAY, May 2015, page 30.) For example, theory predicts that some defects are necessary for supersolidity, but in experiments, too many or the wrong sorts of impurities can change the properties beyond what's modeled. Moreover, changes in the moment of inertia that seemingly indicate the presence of a supersolid can instead result from unexpected changes in the sheer modulus of a helium crystal at low temperatures. So far, the consensus is that no conclusive evidence exists for supersolidity in bulk ^{4}He. It seems to be either a solid or a superfluid, but just like honey, it can't be in a superposition of both.

Can a superfluid be solid?

Over the past two decades, ultracold atomic gases have emerged as a new kind of quantum material for exploring unusual phases of matter. (See PHYSICS TODAY, August 2017, page 17, and the article by Keith Burnett, Mark Edwards, and Charles Clark, PHYSICS TODAY, December 1999, page 37.) Those gases are collections of atoms cooled to near absolute zero in two stages. First, through laser cooling, the atoms are slowed down by the recoil from thousands of precisely tuned photon absorption and emission cycles. Then evaporation provides further cooling, reminiscent of a cooling cup of hot coffee, where the most energetic coffee particles evaporate away as steam. Similarly, in ultracold gases, the most energetic atoms can continuously be removed, and the remaining atoms rethermalize at lower and lower temperatures.

In contrast to familiar materials, ultracold gases contain only between a few thousand and a few million atoms. They must also be isolated from their environment in traps formed by focused laser beams or magnetic fields in ultrahigh-vacuum chambers. As their preparation is specific to a certain atomic species, however, they are inherently clean and controllable. Crucially, they can be manipulated and minutely probed with the precise tools of atomic physics to create textbook realizations of open quantum mechanical questions.

Once cooled to sufficiently low temperatures—typically a few tens of nanokelvin—atomic gases will undergo Bose–Einstein condensation. The resulting quantum material is about a million times as dilute as helium but still shows similar superfluid properties. That low density means individual atoms are fairly isolated from one another and, as a result, typically much easier to model and understand than helium. Atomic gases' superfluidity allows supersolidity to be considered from a new direction: Instead of a solid turning into a supersolid, can a gaseous superfluid turn into a supersolid?

For a supersolid to form, the atoms in the Bose–Einstein condensate (BEC) must spontaneously arrange into a periodic crystal structure while maintaining their collective superfluid properties. That spatial periodicity has an associated characteristic length scale, which must arise in some way during the transition to a supersolid. The most straightforward way to introduce that length scale is to manipulate the BEC with laser beams, whose wavelengths naturally offer a length scale.

The specific implementations vary. For example, some researchers place the atoms in a standing wave of an optical cavity, and others use lasers to induce a spin–orbit coupling.[2] The result in both cases is the spontaneous emergence of a periodic crystal structure and properties of a supersolid, such as characteristic excitations and coherence. But the corresponding crystals have an infinitely stiff structure fixed by the external laser field. The atoms are thus always localized at the same distance from one another and only behave in that way because of an external influence. Both properties are fundamentally distinct from those of natural materials, whose atoms are free to oscillate around the individual lattice sites and spontaneously arrange into crystal patterns because of their intrinsic interactions.

Ultracold dipolar atoms

Properties more akin to those of real materials are possible with a BEC made from highly magnetic atoms. In most BECs, ultracold atoms interact only through contact interactions—they repel each other isotropically like billiard balls when a pair of them get close. The atoms in magnetic BECs also feature long-range dipolar interactions, similar to those of bar magnets. Depending on the relative orientation of the atoms, the interactions can be attractive or repulsive. Suitable atomic species that exhibit sizable dipolar interactions include transition metals, such as chromium, and lanthanides, such as dysprosium and erbium. Because of their complex electronic structure, those elements feature large angular momenta, which produce large magnetic dipole moments.

The competition between contact and dipolar interactions produces behavior that can be understood best from their excitation spectrum, shown in figure 1. The excitations in a normal BEC, with only contact interactions, are simple sound waves

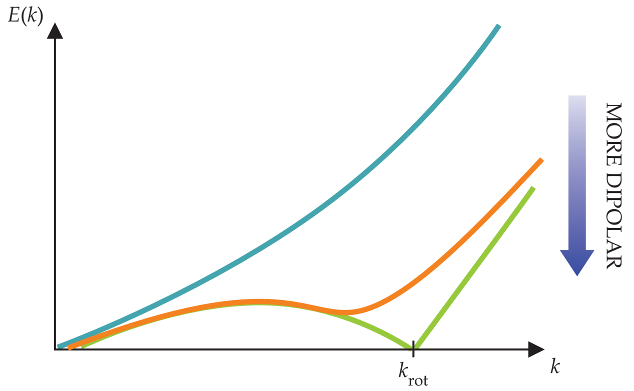

FIGURE 1. IN BOSE–EINSTEIN CONDENSATES (BECs), the magnitude of the dipolar interactions between atoms changes the excitation spectrum. Creating an excitation at a momentum k requires an energy $E(k)$. For BECs with weak or no dipolar interactions, $E(k)$ monotonically increases (blue), but those with stronger interactions (orange and green) develop a distinct energy minimum at momentum k_{rot}. The lower the energy minimum is, the easier it is to excite atoms and form a periodic structure with a length scale given by $1/k_{rot}$. (Image by Donna Padian.)

(the energy spectrum shown in blue), but a magnetic BEC can additionally support so-called rotons.[3]

Rotons are excitations with a finite momentum (k_{rot} in figure 1) that cost less energy to excite as dipolar interactions strengthen, as shown by the green curve's lower local energy minimum than the orange curve's in figure 1. They are most intuitively pictured in a BEC confined to a tubelike potential, in which a roton is a small sinusoidal modulation on top of the smooth BEC wavefunction. The length scale of that modulation is related to the inverse of the roton's momentum. The less energy needed to excite the modulation, the higher the number of participating atoms, until at some point, the modulation is no longer small but a significant crystal structure. Given the right conditions, magnetic BECs thus favor crystal structures, which form solely because of the interactions among the atoms.

Classical ferrofluids—nanoscale ferromagnetic particles suspended in an oily solution—show analogous restructuring behavior. When those ferrofluids are on a hydrophobic surface and polarized by a sufficiently large external magnetic field, they can undergo a so-called Rosensweig instability to form a crystal of little droplets, shown in figure 2. The mechanism of that instability is similar to the one responsible for crystallization in dipolar BECs; both systems feature a dispersion relation with a minimum at finite momentum. The key difference, however, is that dipolar BECs are quantum systems with the possibility of coherent, superfluid behavior.

But there's a catch: For ultracold atomic gases to be stable, the sum of all interactions between the atoms must be repulsive. (See PHYSICS TODAY, August 2000, page 17.) Without that repulsion, the atoms move closer and closer together and eventually form molecules or react in other ways. For example, if three atoms come close enough to one another to collide inelastically, two of them can form a molecule, with the third carrying away excess energy. Typically, neither the molecule nor the remaining atom can be trapped, so the process leads to strong losses and eventually the destruction of the sample.

The conditions for stability appear to be in conflict with the dominant dipolar interactions necessary for crystallization. As in a classical ferrofluid, the sites of the BEC crystal are droplets made up of many atoms, rather than individual atoms, as is the case in helium and other solids. The structure is sometimes referred to as a droplet crystal. Inside the elongated droplets, the atoms predominantly arrange themselves in a head-to-tail configuration, in which dipolar interactions are strongly attractive. Stability would then require strong repulsive contact interactions to compensate for the dipolar interactions, but stronger contact interactions would preclude crystallization of the BEC in the first place. Either the atoms form a stable BEC or an unstable crystal. The result is that dipolar BECs collapse when they approach the expected crystallization transition,[4] as was observed for weakly dipolar chromium atoms in 2008.

Dysprosium BECs

The unexpected solution to the apparent conflict between stability and crystallization turned out to be BECs made of more magnetic atoms. In 2016, experiments similar to the earlier studies on chromium found that BECs of dysprosium atoms, which feature a magnetic dipole moment that is almost twice as large as chromium's, did spontaneously self-assemble into droplet crystals.[5] That observation was a big surprise, and making sense of it required an extension of the established theoretical models of dipolar BECs.

The key to understanding that stability against collapse is a phenomenon known as quantum fluctuations. The wavefunction of a BEC can be modulated by not only rotons but also many other excitations with different energies and momenta given by the dispersion relation shown in figure 1. As quantum objects, those excitations will always fluctuate with some amplitude even at their lowest energies. So small but persistent noise—the quantum fluctuations—will always be present on top of the smooth BEC wavefunction. Counterintuitively, that tiny effect can stabilize gases such that they can form stable droplets.[6] (See the article by Igor Ferrier-Barbut, Physics Today, April 2019, page 46.)

The quantum fluctuations of a BEC, described by Lee-Huang-Yang (LHY) corrections, have been known for decades, but they are typically negligible. Their effect, however, can become important in systems with more than one type of interaction, such as magnetic BECs, which have a combination of contact and dipolar interactions, and mixtures of different atomic species. At the point when droplet crystals would be expected to collapse, the attractive dipolar and the repulsive contact interactions almost perfectly cancel each other. What's left is weak attractive dipolar interactions, which would normally trigger collapse but can instead be compensated for by the small repulsive LHY corrections.

The magnitude of the LHY correction scales with the number of atoms in the BEC and the magnitudes of their magnetic moments. For relatively weakly dipolar systems, such as chromium, stability requires far more atoms than the few tens of thousands that are produced experimentally—hence the system collapses. For strongly dipolar dysprosium, on the other hand, the LHY correction perfectly balances the other interactions, and stable droplet crystals can form with an experimentally accessible number of atoms, as shown in figure 2.

A supersolid, however, is more than just a crystal. The atoms forming it must also maintain the superfluid properties of the original BEC. The crystals shown in figure 2 aren't superfluid because the individual droplets are too far apart to have overlapping wavefunctions. The BEC's coherence, which is crucial to the superfluid nature, is thus quickly lost.

Recent experiments in the labs of Giovanni Modugno at the University of Florence in Italy, Tilman Pfau and I at the University of Stuttgart in Germany, and Francesca Ferlaino at the University of Innsbruck in Austria indicate that, in addition to crystals of isolated droplets, a small range of interaction strengths and atom numbers produces coherent crystals.[7–9] In those crystals, the individual droplets stay mutually coherent because of their strong wavefunction overlap, which can be interpreted as a superfluid background keeping the droplets linked. The observations suggest the simultaneous presence of superfluid and crystal properties.

The researchers use a microscope to image the spontaneously forming crystal structure, shown in figure 3, with single-site resolution. To probe the coherence of the droplets, they turn off all trapping potentials and let the gas expand. A freed coherent matter wave produces a reproducible, high-contrast interference pattern similar to diffraction from a grating, as shown in figure 4. (A gas without coherence would instead create random or no interference patterns.) As expected, the length scale of the observed crystal structure exactly matches the roton length scale. It turns out that BECs can smoothly transform into a coherent droplet crystal simply by becoming more dipolar.

The magnetic moment of an atomic species is fixed, so in practice, instead of the dipolar interactions being enhanced, the gas's contact interactions are made weaker. Such tuning of the

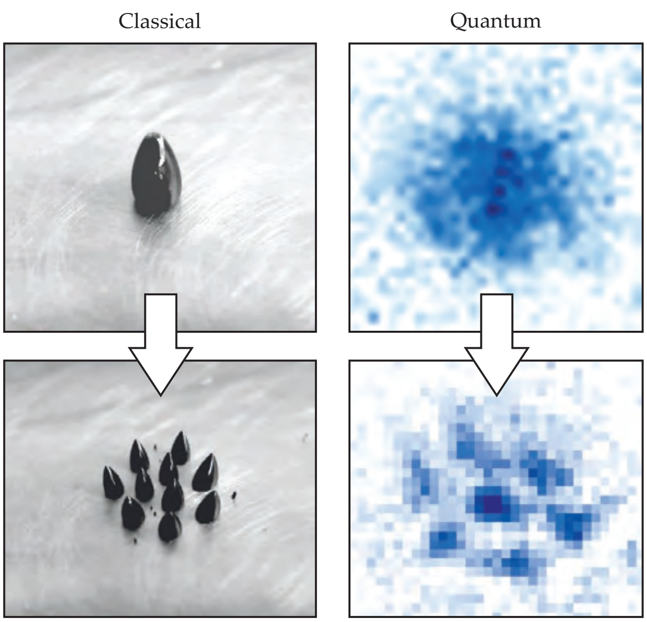

FIGURE 2. CRYSTALLIZATION of a classical ferrofluid on a hydrophobic surface (left) resembles that of a Bose–Einstein condensate of magnetic dysprosium atoms (right), imaged through their absorption. In both cases, periodic patterns spontaneously emerge as magnetic interactions start to dominate the system. Neither of the cases is a supersolid (yet) because the individual droplets don't overlap to form the single coherent matter wave required for superfluid flow. (Adapted from refs. 5 and 16.)

contact interactions is possible with scattering resonances. Those resonances arise when the quantum state of two colliding atoms in a gas is energetically degenerate with a molecular bound state of the pair. Those free and bound states exhibit different Zeeman shifts, so their resonance can be controlled using an external magnetic field. In that way, the contact-interaction strength of the atoms is tunable, and the desired states—BEC, supersolid, or isolated droplet crystal—can be created at will. Although the balance of contact and dipolar interactions and their LHY corrections is subtle, the behavior is not limited to dysprosium atoms but has also been observed in gases of magnetic erbium atoms.

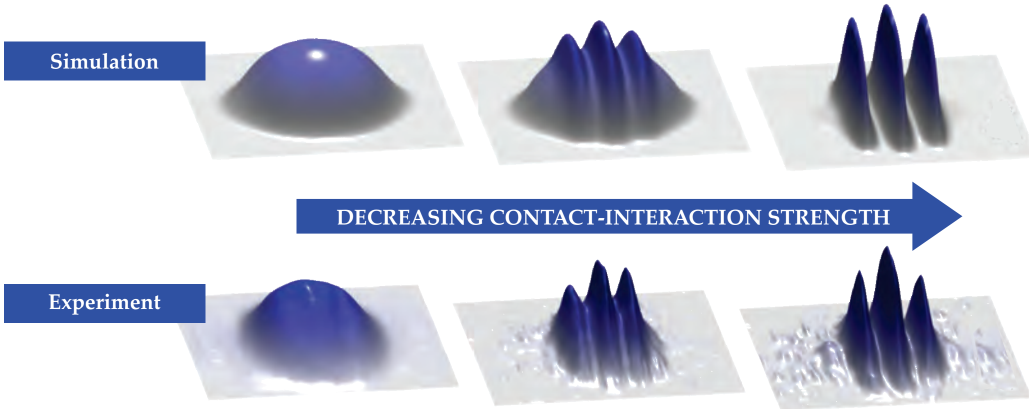

FIGURE 3. DENSITY DISTRIBUTIONS show the transition from a Bose–Einstein condensate (BEC, on the left) to a one-dimensional crystal of three isolated droplets (on the right) as a function of contact-interaction strength. Between the BEC and isolated droplet crystal, a supersolid emerges that features both the periodic structure of the crystal and the superfluid properties of the BEC. The typical distance between density peaks is about 1.5 μm. (Adapted from ref. 6.)

Coherent crystal or supersolid?

Although the observed coherence is a strong indication of superfluidity and, hence, the supersolidity of the crystal state, it's not definitive proof. Superfluidity, Bose–Einstein condensation, and coherence are closely related but not the same thing. For example, in some low-dimensional systems, Bose–Einstein condensation is absent, but superfluidity and coherence still emerge. The superfluid properties of the system thus need to be investigated directly.

Studying how a superfluid reacts to a perturbation is a common way to assess its properties. For example, the rotation of a superfluid reveals its characteristic irrotational flow. Another perturbation well suited for the observed crystals is a sudden change of the atoms' trapping potential or a change in the interactions in the system. In both cases the system is no longer in equilibrium and reacts by creating characteristic excitations, such as sound waves. The supersolid, which simultaneously has superfluid and solid properties, should feature two kinds of sound waves: the usual sound waves of a superfluid BEC and the sound waves from the lattice oscillations of a crystal.

Those two kinds of sound waves are closely connected to the two symmetries that are broken by the supersolid. First, similarly to a BEC, the supersolid breaks phase symmetry—upon its creation, it spontaneously acquires a certain quantum mechanical phase. Second, the emerging crystal structure breaks continuous translation symmetry. Whenever such symmetry breaking occurs, characteristic excitations, called Nambu–Goldstone modes, arise. In the case of supersolids, those modes correspond to the previously discussed sound waves. Another example from condensed-matter physics is magnons, which are excitations that emerge in ferromagnets below the Curie point when a spontaneous magnetization breaks rotational symmetry. In high-energy physics, the breaking of chiral symmetry in quantum chromodynamics is connected to the emergence of pions.

In experiments, an ultracold gas's evolution after a sudden change of the system's parameters indicates the presence of sound waves.[10] High-resolution images of the atomic distribution, such as those in figure 3, facilitate precise measurements of the periodic changes in the crystal spacing, the size and position of the atomic cloud, and other parameters. It is even possible to extract the characteristic mode patterns of the sound waves, in a process similar to observing the waves forming on a water surface. The observations unambiguously reveal the characteristic sound waves of both the crystal and the BEC. The coherent droplet crystals are indeed supersolids.

Not only can atomic gases transition from a superfluid to a supersolid state with the addition of a crystal structure—that is, start as a BEC with one broken symmetry and then break the second one—but they can also be cooled directly into the supersolid state and thus break two symmetries at once. That process is identical to the evaporative cooling used for BECs, except that the interaction parameters in the gas must be fine-tuned to the appropriate values for the emergence of a super-

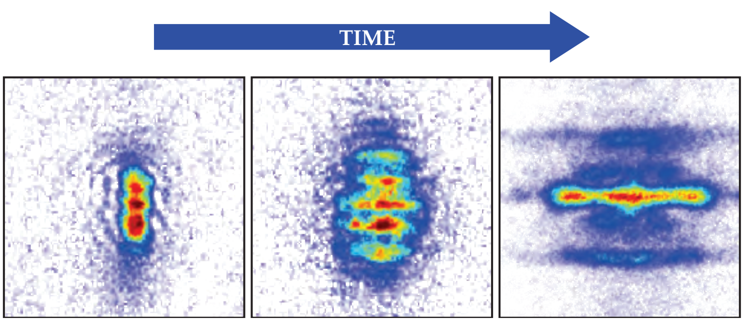

FIGURE 4. INTERFERENCE patterns form if a supersolid is released from its confining potential. The supersolid atoms start out trapped (left). High densities are shown in red and low densities in blue. Once the atoms are released, they expand out and produce distinct and reproducible minima and maxima (right), similar to diffraction from a grating. The emergence of interference demonstrates the coherence of the supersolid. (Adapted from ref. 8.)

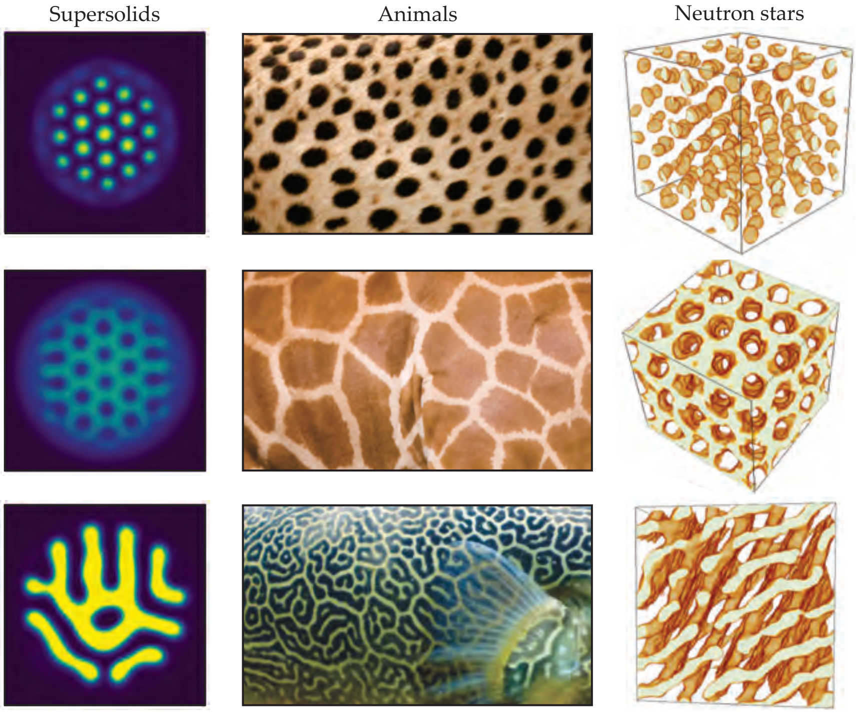

FIGURE 5. PATTERNS take a similar form in a wide range of systems, including dipolar quantum gases, the animal kingdom, and neutron stars. Supersolids are predicted to produce shapes beyond the one-dimensional and simple two-dimensional ones produced thus far. Some of those predictions, shown in the left-hand column with high density in yellow and low density in purple, may offer a new approach to study pattern formation in quantum systems. (Figure design by Jens Hertkorn, adapted from refs. 15 and 17. Animal photos, from top, by Christoph Strässler/CC BY-SA 2.0, John/Wikimedia Commons/CC BY-SA 2.0, and Chiswick Chap/Wikimedia Commons/CC BY-SA 3.0.)

solid state prior to cooling. Moreover, dynamically changing the interactions flips the gas back and forth between the BEC and supersolid phases.

What's next?

The experiments with dipolar gases provide clear evidence that supersolids indeed exist in nature and offer a powerful platform to explore supersolids' properties.

Much is still unknown about the nature of that exotic state of matter. For example, several groups are currently investigating supersolid properties under rotation, in research analogous to that performed previously on helium. The fate of the transition at higher temperatures also is widely unexplored. Moreover, the crystals realized from magnetic atoms so far contain only a handful of crystal sites and are thus minuscule by the standards of a materials scientist. Making them larger is simply a matter of cooling more atoms. Boosting the laser power or cooling and manipulating the atoms more efficiently are among the many strategies—some of which are already being tested—that could increase the number of ultracold atoms. A first step in that direction is the recent extension of the one-dimensional chains of droplet crystals to a 2D triangular lattice.[11]

Another lingering question is the generality of the observations. Do stable droplet supersolids exist only in magnetic atoms? A change of the dipole moment by a factor of less than two from the first chromium BECs to the recent strongly dipolar dysprosium and erbium BECs turned unstable collapsing systems into supersolids. Current efforts to produce BECs of diatomic molecules could provide a new supersolid system. Those molecules can feature dipole interactions that are orders of magnitude stronger than those in magnetic atoms because of their electric dipole moments. What's more, those interactions are tunable by external electric fields.

Other cold-atom systems in optical cavities and with spin–orbit coupling may also transition to compressible supersolids.[12] And what about helium supersolids? Experiments are currently exploring confined superfluid ^{3}He and ^{4}He films, where transitions to structured states similar to the ones in dipolar atomic gases have been observed.[13]

Finally, the observed droplet crystals seem to be, by no means, the only supersolid states possible. Recent theoretical work has established a variety of potential supersolid patterns in dipolar quantum gases.[14,15] As shown in figure 5, those predicted patterns are reminiscent of those in a range of systems, including the animal kingdom and neutron stars, that cover vastly different energy and length scales. Beyond the fundamental interest in new states of matter and their properties, the observation of supersolid states in dipolar atomic gases could thus provide an unexpected and versatile approach to study pattern formation in the quantum world.

I thank Francesca Ferlaino, Giovanni Modugno, Tilman Pfau, and the Stuttgart Dipolar Quantum Gases team for fruitful discussions and suggestions.

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Samantha Pedek, graduate student, University of Iowa; co-chair, Physics Congress 2022 Planning Committee

Find Your People and Grad Program at the 2022 Physics Congress

Join hundreds of physics undergrads, grad school reps, and physics luminaries

Samantha Pedek, 2022 Program Co-chair

Samantha Pedek

Networking is one of the most important aspects of being a young professional. We've all heard the spiel about how networking can have positive impacts on future educational and career-related opportunities, but many of us struggle with making the initial contact that can lead to lasting connections.

In 2016 I attended the Physics Congress (PhysCon), the largest gathering of undergraduate physics students in the United States. Every few years, PhysCon brings together students, alumni, and faculty members for three days of frontier physics, interactive professional development workshops, and networking. It is hosted by Sigma Pi Sigma, the physics honor society, and anyone interested in physics can attend.

Networking at PhysCon was unlike any other professional development experience I had as an undergraduate physics student. The sheer number of like-minded people was daunting—hundreds of physics and astronomy undergraduates, representatives from graduate schools and summer research programs, employers from all over the country, and well-established professionals at the height of their careers were all under one roof for three days.

The Physics Congress is a high-energy, hands-on weekend designed explicitly for undergraduate physics students. Photo courtesy of SPS National.

PhysCon has continued growing in attendance, scope, and opportunities, and you won't want to miss the next one! In celebration of the 100th anniversary of Sigma Pi Sigma, an extra-special PhysCon is planned for October 6–8, 2022 in Washington, DC. With a little preparation, you'll have the chance to narrow down your graduate school search, meet potential employers, and make lasting connections with people heading down similar career paths.

The most direct opportunity to meet with representatives from physics and astronomy grad programs and potential employers occurs during the Expo, which encompasses both a grad school fair and a career fair. During the Expo, attendees can visit booths to learn more about a program, company, or undergraduate research experience as well as get tips and advice on applying. When I attended, seeing the wide variety of vendors enabled me to start thinking about my life after col-

NETWORKING TIPS

Before you attend a networking event, craft and practice your **elevator pitch**—a 30-second narration of who you are professionally, what you've accomplished, and where you hope to go in the future.

If you're attending an in-person event as a prospective student or employee, **business cards** (or contact cards) show that you're serious about your future and make it easy for new contacts to connect with you.

BE AN SPS INTERN

The Society of Physics Students summer internship program offers 10-week, paid positions for undergraduate physics students in science research, education, communication, and policy with various organizations in the Washington, DC, area.

www.spsnational.org/programs/internships.

lege, and I was blown away by the versatility that a degree in physics can provide.

A more subtle opportunity to build your network as a young professional is to engage with attendees you don't already know, between events or at meals. Shuffling between workshops, plenaries, and banquets will be hundreds of people with lived experiences similar to yours. Be adventurous and sit at a meal or workshop table with strangers! You might find yourself next to a professor from a graduate school you're interested in, or even from a school you didn't realize you should be interested in. A quick conversation can leave a lasting impression.

A straightforward way to meet students and professionals is to go to the poster sessions, as a presenter or an attendee. These are excellent opportunities to have one-on-one interactions with others and to learn about new topics. Seeking out posters in subfields you're doing research in or interested in studying in grad school is a great way to form connections and learn about current research in the field. My favorite question to ask a presenter is "Can you tell me more about your research?" They likely have an answer prepared, which can be a bridge to more natural conversation.

2019 Physics Congress attendees visit one of the many graduate school booths in the exhibit hall to learn about the program and check out physics demonstrations. Photo courtesy of SPS National.

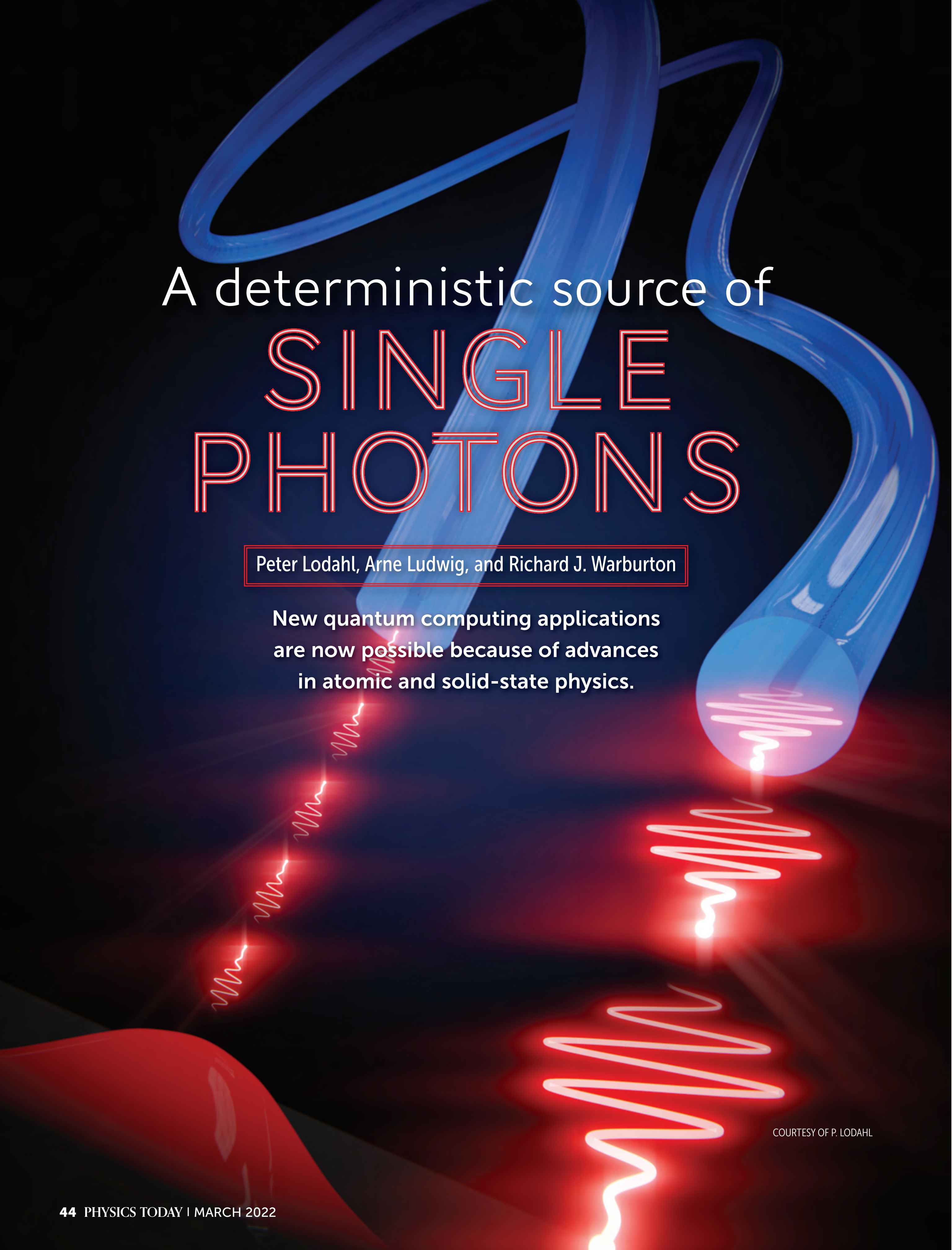
The physics and astronomy community is quite small, so if you meet people at PhysCon, you're likely to run into them again. Almost a year after I attended PhysCon 2016, I was a Society of Physics Students intern. Of the 14 of us, over half had met previously, largely at PhysCon. Having that shared experience helped me connect with the other interns right from the start. We even looked back at old PhysCon photos and tried to spot one another in the background, which was wildly entertaining.

Attending PhysCon is the networking gift that keeps giving. I have met others who attended in different years and we're still able to bond over our shared experiences. You are bound to find someone with similar interests and goals in a sea of over a thousand physics students, mentors, and advisers. Preparation is the key to successful networking, so practice your elevator pitch, make business cards, and I'll see you in 2022! GSS

A deterministic source of SINGLE PHOTONS

Peter Lodahl, Arne Ludwig, and Richard J. Warburton

New quantum computing applications are now possible because of advances in atomic and solid-state physics.



COURTESY OF P. LODAHL

Peter Lodahl is a professor in quantum physics and technology with the Niels Bohr Institute at the University of Copenhagen in Denmark. **Arne Ludwig** is a researcher at Ruhr University Bochum in Germany. **Richard Warburton** is a professor in the department of physics at the University of Basel in Switzerland.

Photons are the quantum constituents of light and are fundamental to the quantum theory of light and to the light–matter interaction. The quantum information stored in photonic qubits can be sent over large distances using photons at optical frequencies. But photons are elusive: They travel at the speed of light, are often created by spontaneous emission, are susceptible to propagation loss, and do not interact with each other. Although creating and controlling single photons is challenging, the benefits to quantum information applications are significant.

The merger of atomic and solid-state physics has led to new opportunities in quantum photonics, specifically in developing a deterministic source of single photons. Advances rely on state-of-the-art growth of semiconductor heterostructures, nanofabrication, and optical techniques. One fundamental improvement that offers a scalable route to advanced quantum applications is a coherent photon-emitter interface. The technology enables multiphoton entanglement generation and deterministic photon–photon quantum gates.

The granularity of light and matter, proposed more than a century ago by Max Planck, Albert Einstein, and Niels Bohr, lies at the core of quantum mechanics. The quantized nature of the electromagnetic field extends James Clerk Maxwell's classical description. The quantum particle of light is referred to as the photon and constitutes the fundamental entity by which light and matter exchange energy. Bohr's 1913 atom model describes the birth of a photon: A single atom may hop from an excited electronic state to a lower one. That process of spontaneous emission creates a photon.

Much later, Edward Purcell realized that spontaneous emission is not an immutable property of the atom. Rather, one can control it by engineering the atom's environment. Purcell's profound idea underpins many opportunities in photonics, including the operation of single-photon sources. When an atom is embedded in a tailored waveguide or cavity, the generated photons are funneled rapidly and with near-unity efficiency into a single optical mode. At birth, the photon is sent in a predefined direction. Implementing photons in that way requires control of the atom's environment at optical frequencies that correspond to nanometer-scale wavelengths. Today, deterministic single-photon sources, which are available in a number of research labs, generate photonic qubits on demand for photonic quantum information processing.

Artificial 1D atom

An ideal single-photon source creates a photon deterministically when triggered by a laser or electrical pulse. The workhorse in quantum optics has been the spontaneous parametric down-conversion source in which the energy of a photon from a laser is used to create two separate photons. The source is simple to operate. It requires only a pulsed laser and readily available nonlinear crystals, and the detection of one photon heralds the creation of the other. The source, however, has a key drawback: It is inherently probabilistic, meaning that the photons cannot be produced on demand.

An alternative approach creates single photons with an atom. In the simplest case of an atom with two energy levels, a photon is produced each time the atom decays from the upper energy state to the lower state. In free space, photons are emitted in all directions or into a continuum of optical modes. A useful source, however, creates photons in just one optical mode. To develop such a source, two approaches can be pursued, based on either cavities or waveguides. For tightly confined modes, the atom decays preferentially into a single mode in the cavity or waveguide. The collected photon can be subsequently coupled into a single-mode optical fiber.

One implementation of those approaches uses an artificial atom, which takes the form of a semiconductor quantum dot.[1,2] The quantum dot is grown by self-assembly using the III–V semiconductors indium arsenide and gallium arsenide. When the low bandgap, high lattice-constant InAs is grown on top of the high bandgap, low lattice-constant GaAs, the lattice mismatch induces strain. The strain leads to the self-assembly of an InAs island, the quantum dot shown in figure 1. Quantum dots are typically 20 nm in diameter at the base and 5–10 nm high with a potentially complex topology.

In a semiconductor, the bandgap separates occupied continuum valence states from unoccupied continuum conduction states. A quantum dot confines valence and conduction electrons to a narrow spatial region, shown in figure 2. As a result, discrete energy levels develop. The wavefunctions of the energy levels have a spatial extent that's determined by the size

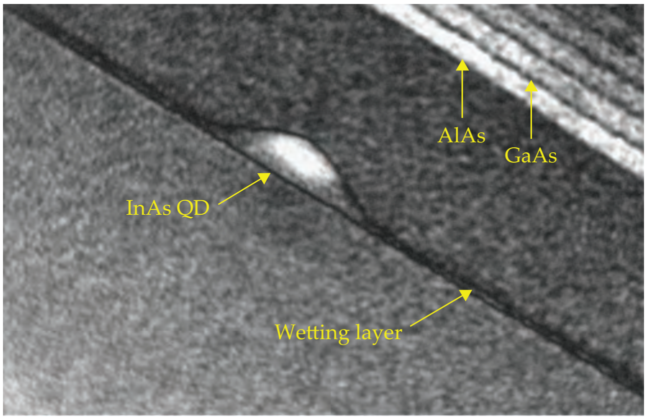


FIGURE 1. THIS IMAGE, taken with a transmission electron microscope, shows an indium arsenide quantum dot (QD) in gallium arsenide. (Courtesy of Jean-Michel Chauveau and Arne Ludwig.)

of the quantum dot. A photon can promote a valence electron to the conduction level, which leaves a vacancy, or hole, in the valence level, and the resulting electron–hole pair is termed an exciton. The ground state and the exciton constitute a two-level system. Because the exciton's optical dipole moment is related to the quantum-dot size, it is much larger than the size of a single atom. That is advantageous because the radiative lifetime of a quantum-dot exciton is rather short, typically a nanosecond.

A self-assembled quantum dot is trapped inside its host semiconductor, GaAs, which is a huge benefit. Because the quantum dot is locked at one particular location, a laser trap is not required, as is the case for single atoms or ions in a vacuum. The semiconductor environment, however, is a potentially complex source of noise, as figure 2 illustrates. The evolution of an exciton is disrupted by the thermal wobbling of the atoms, known as phonon scattering, in the quantum dot and by charge and spin noise in the host semiconductor. Charge and spin noise typically have correlation times much longer than the radiative lifetime, which leads to variability of the exciton's frequency. In contrast, phonon scattering randomly dephases the exciton before recombination.

A crucial feature of the GaAs system is that the complex and deleterious noise processes can be ameliorated. Specially designed heterostructures[3] reduce charge noise to extremely small levels at low temperature, and the GaAs system's performance is retained even in nanostructures.[4] Likewise, phonon scattering is suppressed at low temperature, but it is not completely eliminated. The creation of an exciton locally distorts the semiconductor lattice, which means that some phonon scattering remains even at absolute zero, although it tends to be slow relative to the radiative decay time. The net result is that the exciton mimics a two-level system. When resonantly driven with a laser, single quantum dots exhibit all the features known from atomic physics, such as photon antibunching, Rabi oscillations, and the Mollow triplet.

Single InAs quantum dots in GaAs are the semiconductor workhorses of two-level systems. Decades of work on the quantum Hall effect in two-dimensional electron gases has led to the creation of extremely clean GaAs-based heterostructures. The same technology has been applied to low-noise quantum-dot devices for quantum photonics. Typically, the quantum dots emit radiation at wavelengths between 900 nm and 1200 nm. Unlike single atoms, each quantum dot emits at a slightly different wavelength. Nevertheless, tuning techniques exist, and the ultimate goal is to tune most of the quantum dots in a chip to a common wavelength. Research is ongoing to solve the long-standing problem of quantum dots nucleating at random locations. Rapid progress has been made in creating low-noise quantum dots at other wavelengths, notably at red wavelengths (780 nm) and at those relevant for telecommunications (1300 nm and 1550 nm). Whereas the latter targets low-loss propagation in optical fibers, the former can be coupled to atomic rubidium memory cells.

The creation of cavities and waveguides exploits a special feature of GaAs: A partner material, aluminum arsenide, has almost the same lattice constant but different electronic and chemical properties. The significantly lower refractive index of AlAs enables a Bragg mirror to be created via a stack of layers, each of which is one-quarter of a wavelength thick. Then a quantum dot can be embedded between two such mirrors to confine the light field along the growth direction. Lateral confinement can be realized by etching a miniature pillar, a so-called micropillar.[5,6] Alternatively, figure 3 shows how a miniaturized dielectric mirror is used as the top mirror.[7,8]

A waveguide can be created by growing an AlAs layer below the active part of the GaAs heterostructure. The subsequent chemical removal of the AlAs yields a free-standing GaAs membrane, shown in figure 4. The high refractive index of GaAs results in laterally propagating modes confined to the membrane. A photonic crystal lattice can contain photonic bandgaps where no optical modes are allowed, and a thin unstructured

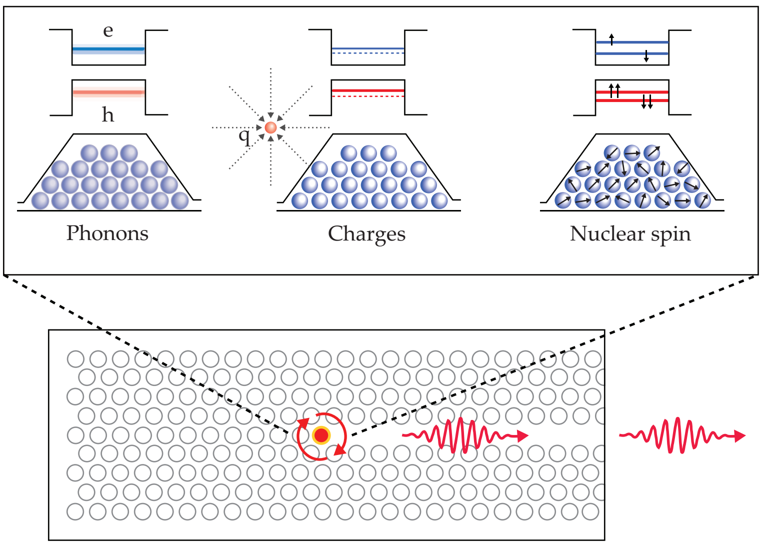


FIGURE. 2. THIS SCHEMATIC shows the bound electron e and hole h states in a quantum-dot exciton and their responses to noise processes. Phonons induce thermal fluctuations of the atomic lattice, residual charges cause electrostatic fluctuations, and nuclear-spin noise arises from spin–spin coupling between the exciton and the randomly polarized nuclear-spin ensemble of the quantum dot. The quantum dot (red circle in the bottom figure) is embedded in a photonic crystal waveguide membrane and emits single photons (red wavepackets). (Adapted from ref. 18.)

region can constitute a waveguide,[9] in which the dispersion of light is engineered by the photonic-crystal structure.

Figures of merit

Advanced single-photon applications require high-performance sources. Ideally, all of a source's figures of merit should have high values simultaneously, which is realizable with quantum-dot single-photon sources.[2,10]

Single-photon purity quantifies to what extent an emitted pulse contains only one photon. The absence of any two-photon coincidence event signifies an ideal single-photon source. Greater than 99% purity is typically obtained with quantum-dot sources that are limited by a small probability of two-photon emission. Single-photon purity may be further improved with optimized excitation schemes.

Photon indistinguishability quantifies to what extent the individual photons in a photon stream are identical. Two identical photons can interfere perfectly on a beamsplitter, leading to vanishing coincidence events. Residual coincidences quantify the indistinguishability through the interference visibility V. A single quantum emitter can produce a massive photonic resource: Near-unity indistinguishability[11] has been achieved with quantum-dot sources that extend over long strings of more than 100 photons.[8,12] Additionally, $V = 93\%$ has been achieved on interfering photons from two separate quantum dots.[13] The results demonstrate how quantum-dot sources generate low noise over a wide-frequency bandwidth.

Single-photon generation rate specifies the number of photons that can be created per second. The operation speed of the sources is ultimately limited by the radiative lifetime of the emitter, which reaches the 20–100 picosecond range in Purcell-enhanced cavities and waveguides.[2,7] Quantum-dot sources, therefore, can operate at a repetition rate exceeding 1 GHz.

Photon-emitter coupling is quantified via the β factor. It expresses the probability that an excited quantum dot emits a photon into the designated mode. The β factor depends on the success with which one can tailor the quantum-dot environment. Values of 96–99% have been realized with quantum dots in nanophotonic waveguides[2,12] and cavities.[7,10]

Out-coupling efficiency assesses the effectiveness of extracting photons from the device. The relevant parameter depends on the application, but one key quantity is the coupling efficiency from the device into an optical fiber. An efficiency of 57% has been realized by combining a high β value and good mode matching to the fiber.[8]

Growing high-quality quantum dots

Figure 5 shows modern semiconductor devices created with layer-by-layer epitaxy of thin films on ultraclean, single-crystal substrates. The manufacturing process allows for the creation of heterostructures in which layers of dissimilar materials are stacked on top of each other. The combination of materials with different bandgaps and electrical doping forms devices with new functionalities.

One high-precision and ultraclean method to produce such semiconductor heterostructures is molecular-beam epitaxy (MBE). In that method, evaporation sources filled with ultrapure elemental charges—purified up to 99.999999% in the case of gallium—are used to create atomic beams. The atoms adsorb to a crystal substrate, and the resulting adatoms form layers of near-perfect crystalline arrangement. To avoid contamination, the process takes place in an ultrahigh vacuum with a pressure 10^{-14} that of ambient air. Fewer molecules are found in such extreme conditions than, for example, in the vacuum of space around the International Space Station. The cleanest crystals made by MBE have impurity concentrations of about 0.1 ppb. The relevant dimensions for a quantum dot and its immediate environment are on a 100 nm length scale, so the active parts of the devices are essentially free of impurities.

The substrates are heated to enable the adatoms to move freely over the crystal surface such that the growth of one monolayer is completed before the growth of the next begins. Several techniques improve the crystal quality, including short growth interruptions and temperature regimes that prevent the growth of specific species. With the tremendously high material purity and the control of layer thicknesses and arrangements down to the atomic level, MBE is a critical enabler of modern nanotechnology.[14] Although the method allows for the creation of ultrahigh reflectivity Bragg mirrors and thin GaAs membranes, another operating principle is required to form quantum dots—self-assembly of 3D nanostructures.

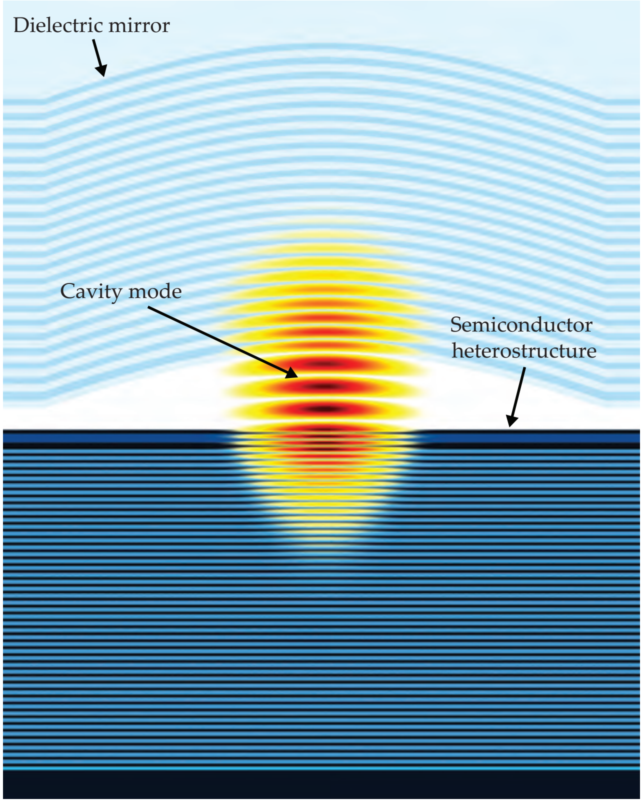


FIGURE 3. THIS VERTICAL-CAVITY DEVICE is an illustration of a semiconductor heterostructure that consists of a gallium arsenide and aluminum arsenide Bragg mirror (bottom) and a p-i-n diode. The InAs quantum dots are located in the intrinsic i region in tunnel contact with the Fermi sea in the n-layer. The concave dielectric mirror (top) is micro-machined in a silica substrate. A single quantum dot is located at the exact center of the cavity mode. The position of the heterostructure can be adjusted with respect to the top mirror by using an x-y-z nanopositioner. It ensures that the quantum dot is centered and that the frequency of the quantum-dot exciton matches that of the cavity's fundamental mode. (Adapted from ref. 7.)

To stack layers of dissimilar materials on top of each other, several parameters must conform with one another. One is the lattice constant, the size of the crystal's unit cell. If InAs, a material with a relatively large lattice constant, is stacked on top of GaAs, a material with a smaller lattice constant, elastic strain builds up. After a certain amount of accumulated strain, instead of continued layer-by-layer growth, the surface breaks up. Dome-shaped indium-rich islands form that each contain about 100 000 atoms. The islands, or quantum dots, nucleate at random positions on the GaAs substrate following the deposition of 1.5 monolayers of InAs.[15]

Another method to form quantum dots via self-assembly is to create nanometer-sized metallic droplets on an alloy such as AlGaAs. The droplets can be recrystallized or used alternatively to drill tiny holes in the surface. The holes are subsequently filled with GaAs, resulting in inverted domes. The quantum dots consist of GaAs in an AlGaAs matrix and emit photons with a higher energy than InAs quantum dots.

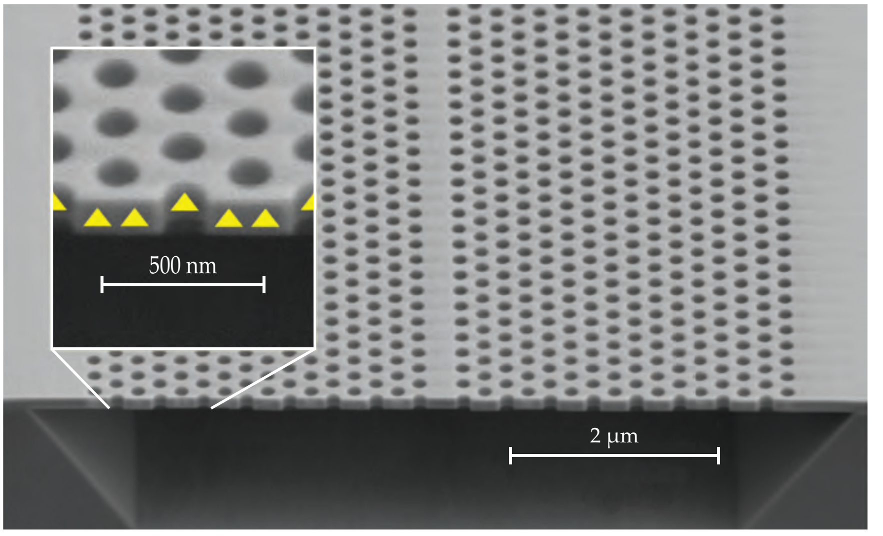


FIGURE 4. THIS ON-CHIP WAVEGUIDE, taken with a scanning electron microscope, consists of a hexagonal arrangement of holes etched in a gallium arsenide membrane. The row of missing holes constitutes the waveguide. The yellow triangles (inset) indicate the position of the quantum dots in the center of the membrane. (Adapted from ref. 2.)

Fluctuating charges in the vicinity of the quantum dot lead to noise. They vary the electric field around the quantum dot, which in turn results in variations in photon energy. Even worse are fluctuations in the charge of the quantum dot itself. If one captures a single electron, the photon energy is strongly redshifted such that a resonantly driven quantum dot is no longer excited, and the single-photon source shuts off. The source turns back on only when the extra electron is released. Under that scenario, the photon stream contains telegraph noise, or blinking.

To minimize charge noise, the host material must be as clean as possible. One elegant way to stabilize the quantum dot's charge exploits the Coulomb blockade.[1] A quantum dot in close proximity to a Fermi sea can be controlled by a bias field. At low temperature, the singly charged quantum-dot state lies above the Fermi energy and is therefore unoccupied. To realize such a structure requires a layer made of doped GaAs or AlGaAs. Provided that the doping level is high enough, a Fermi sea forms at low temperature when every 10 000th crystal-matrix atom is replaced by an impurity atom. That amount is so low that the crystal remains in a perfect arrangement and stays highly transparent to single photons. Silicon is an excellent choice for electron doping (n-type); and carbon, for hole doping (p-type). Both are used in n-i-p devices in which the grounded n-layer hosts the Fermi sea, the quantum dots are located in the intrinsic i-type layer, and a bias is applied to the p-layer.[1]

Vertical-cavity structures

Once quantum dots are grown, the next step is to make an efficient source of single photons. A high β factor can be achieved in a resonant cavity. The requirements are a small cavity-mode volume of order λ^3, where λ is the photon's free-space wavelength, and a reasonably long photon lifetime.

The model system is described with the Jaynes–Cummings Hamiltonian. It consists of a two-level system, a single cavity mode, a coherent coupling rate g, and two decay processes: unwanted emission of the atom into noncavity modes (rate γ) and leakage out of the cavity (rate κ). A quantum-dot cavity system can be brought into the strong-coupling regime where $g \gg \gamma$ and $g \gg \kappa$. The cooperativity, $C = 2g^2/(\kappa\gamma)$, is a measure of coherent coupling efficiency. An ultrahigh C of 150 has been achieved,[7,8] which is one of the highest cooperativities reached with a single emitter at optical frequencies. That regime is potentially useful for photon–photon gates. A single-photon source, however, works better in the weak-coupling regime ($\kappa > g \gg \gamma$) that exploits the large β factor of $\beta = 2C/(1 + 2C)$. If κ is dominated by leakage through the top mirror, the conversion efficiency of a quantum-dot exciton to a photon exiting the cavity is maximized by choosing $\kappa = 2g$.

The weak-coupling regime has been implemented with semiconductor micropillars.[5,6,10] End-to-end efficiency, however, is currently highest (> 50%) with an open microcavity,[8] shown in figure 3. That device has a photon indistinguishability of 97.5% and a purity of 98%. The strong Purcell effect results in a radiative lifetime of just 50 ps, which allows a photon to be created each nanosecond.

The open-microcavity design has enabled researchers to optimize many parameters simultaneously. First, the design's tunability allows a quantum dot to be brought into exact spectral and spatial resonances with the cavity mode. That capability addresses the weakness of the self-assembly process's lack of control in the exact emission frequency and spatial position. Second, the cavity losses are dominated by those through the top mirror. Third, the design is compatible with an n-i-p structure. The charge noise is extremely low during operation, and the quantum-dot charge is locked by Coulomb blockade. Lastly, the output mode is a simple Gaussian and is therefore naturally matched to the propagating mode in the output fiber. The open-microcavity device showcases what quantum dots can achieve: fast and bright creation of high-quality single photons at the output of a standard single-mode fiber.

Planar nanophotonic waveguides

Vertical-cavity structures are necessarily narrowband. Only quantum dots at the cavity resonance of a few gigahertz linewidth emit photons deterministically into the cavity mode. The others emit into noncavity "leaky" modes. Planar nanophotonic devices work in an orthogonal way: Emission in the vertical direction is suppressed, and emission in a single propagating lateral mode is encouraged.[9] The lateral mode is part of a 1D continuum of broadband operation. That approach creates single photons in a specific mode in the chip and offers a pathway to single-photon sources integrated on a chip. Ultimately, fully integrated quantum processors may be possible in which the sources are combined on the chip with advanced processing circuits and high-efficiency detectors.

The planar platform is based on photonic membranes with a thickness of less than half the targeted optical wavelength, as shown in figure 2. Light is confined to the lateral plane, and the refractive index contrast between the membrane material and the surrounding vacuum strongly suppresses out-of-plane light leakage and emission by the process of total internal reflection. A 2D photonic-crystal lattice controls the in-plane light emission by photonic bandgap effects. The coupling into the waveguide mode is Purcell-enhanced by the dispersion-engineered waveguide mode that features slow light. Values of β greater than 98% are possible because of the suppression of leaky modes and Purcell enhancement of the waveguide.[2]

Fabricating thin-membrane structures and photonic crystals for ultralow-noise devices is challenging. Figure 4 shows representative physical dimensions: A 150-nm-thin GaAs membrane contains quantum dots in the center, and a photonic-crystal lattice of etched holes has a lattice parameter of 260 nm. With those dimensions, the embedded quantum dots are positioned unavoidably close to free surfaces, which could potentially cause fluctuations via uncontrolled electronic surface states.

Those challenges have been overcome in nanophotonic membranes made from an electrically contacted n-i-p device. Despite the extreme miniaturization, the exquisite control of the doping and postgrowth fabrication reduces the quantity of current leaking from the devices to the level of nanoamps. A highly sensitive measure of the total noise is the optical linewidth of the quantum dots. It is responsive to broadening processes over a wide range of time scales covering subnanosecond (phonon scattering), microsecond (spin noise), and millisecond (charge noise). Emission lines with less than 15% residual broadening beyond intrinsic spontaneous-emission broadening have been reported on quantum dots in photonic-crystal waveguides.[4] Other accomplishments include long strings of more than 100 indistinguishable photons with no signature of coherence degradation, V greater than 96%, and highly efficient chip-to-fiber outcoupling techniques.[12]

Advanced photonic applications

Photonic hardware with more advanced functionality than on-demand, single-photon generation benefits from the elaborate device engineering implemented for single-photon sources. Coherently controlling a single spin in the quantum dot[1] has led to new opportunities. Spin-photon entanglement, for example, can be realized by performing spin operations between excitation and emission. If the process is repeated multiple times, a multiphoton entangled state is created. Different entanglement structures can be realized, including Greenberger-Horne-Zeilinger states and 1D photonic cluster states.[16,17]

The approach may be extended to generate higher-dimensional photonic cluster states for measurement-based quantum computing. Multiphoton entanglement sources require a coherent spin that can be manipulated with high fidelity. Whereas single spins in self-assembled quantum dots have relatively short coherence times, typically of a few microseconds, rapid spin control with short optical pulses means that high-fidelity multiphoton entanglement is within reach.[18]

Another opportunity exploits a single spin in a quantum dot as a photonic quantum gate. The spin represents a quantum memory whereby two successively emitted photons can become entangled. Such a photon–photon quantum gate has been a missing component in quantum photonics, and the nonlinearity of the photon-emitter coupling enables it. Ultimately, a fully deterministic photon–photon quantum gate requires researchers to pursue the challenging task of eliminating all unwanted losses. A heralding approach may relax such requirements. In that method, the gate operation is conditioned on the detection of a photon.

High-quality single-photon qubits are critical in the burgeoning area of quantum technology.[18] For quantum communication, single photons are the natural carriers of quantum information over long distances. For other

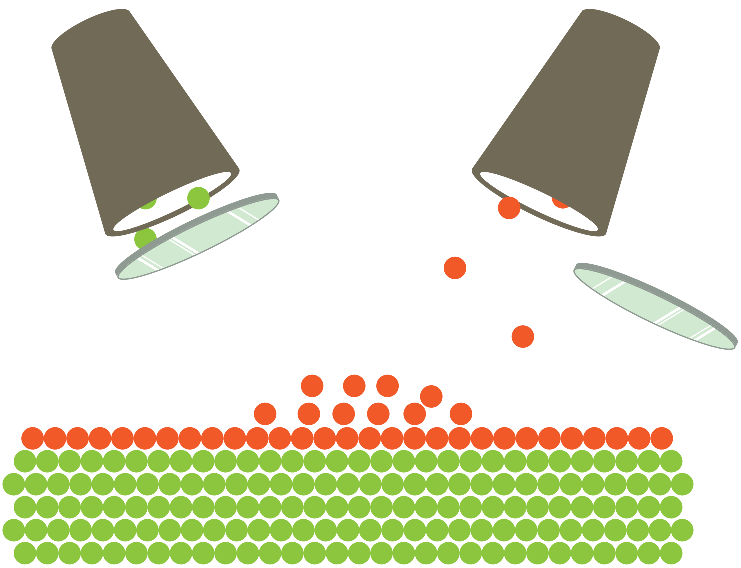


FIGURE 5. QUANTUM DOTS can be self-assembled using molecular-beam epitaxy. A stream of gallium atoms (green dots) and indium atoms (red dots) is created in two heated cells (brown cones). The ultrahigh vacuum environment is arsenic rich. By opening and closing the cell shutters, the growth is switched from GaAs to InAs. GaAs grows layer by layer. In contrast, the deposition of InAs on GaAs results in the formation of nanoscale islands, or quantum dots, each of which are connected by a thin InAs wetting layer. (Courtesy of Arne Ludwig.)

applications, such as trusted-node quantum-key distribution, coherent single photons are not strictly required. But they do offer a route to ultimately secure quantum cryptography, where security against any hacking attacks is confirmed by the violation of a Bell inequality. (See the article by Marcos Curty, Koji Azuma, and Hoi-Kwong Lo, PHYSICS TODAY, March 2021, page 36.)

Another line of research concerns loss-robust encoding of photonic qubits for quantum communication. The idea is that a single qubit can be encoded nonlocally in a multiphoton cluster state. The encoding redundancy means that a qubit is more resilient to photon loss and can therefore be sent over extended distances. Such encoding is a precursor of a one-way quantum repeater, which allows quantum information to be transmitted faithfully over any distance. Such a device would form the backbone technology of a quantum internet.

Measurement-based quantum computing architectures appear well suited for photonics. The overall challenge is to create large-scale multiphoton entanglement that is subsequently consumed during computation. Importantly, only single-qubit operations on the entangled state are required, which circumvents the need for direct photon–photon interactions. Quantum-dot deterministic sources may be exploited as a highly resource-efficient way of producing multiphoton entanglement, an attractive alternative to probabilistic spontaneous parametric down-conversion sources that require massive multiplexing capabilities.

An optimal strategy may be to use a single quantum-dot source to create small-scale entangled cluster states that are demultiplexed from the overall string of photons produced by the source. The clusters could subsequently be fused together in linear-optics photonic circuits to grow a universal resource state for photonic quantum computing. In the fusion-based quantum computing paradigm, computation proceeds by measuring the photons constituting the entangled states. Photons are consequently consumed during computation. Then the highly loss-tolerant encoding schemes, which are an essential trait of a photonic quantum computing architecture, can be implemented.

We acknowledge the work of all our group members past and present who have contributed to the work described in this article.

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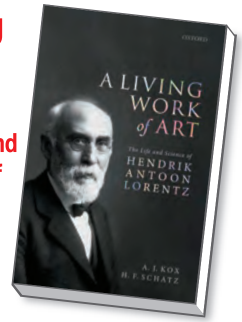
A forgotten trailblazer



"A Living Work of Art" The Life and Science of Hendrik Antoon Lorentz

A. J. Kox and H. F. Schatz

Oxford U. Press, 2021. $45.95

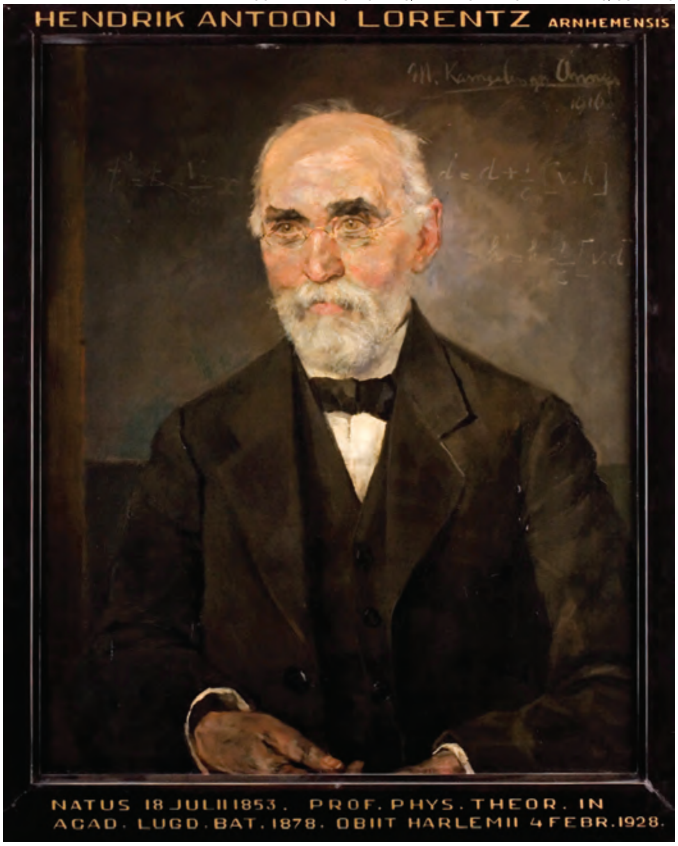
Although 21st-century physicists have heard the terms Lorentz force, Lorentz transformation, and Lorentz group, they probably know little about the man after whom those concepts are named. At the turn of the 20th century, it would have been quite different: No physicist would have asked, "Who is Hendrik Lorentz?" In those days, he embodied the nascent discipline of theoretical physics.

The first theorist to be awarded the Nobel Prize in Physics, Lorentz made discoveries that paved the way for Albert Einstein's theory of relativity. Yet little is known about Lorentz's life. In other words: *"A Living Work of Art": The Life and Science of Hendrik Antoon Lorentz* fills a blatant deficiency in the historiography of modern physics.

Historians of electromagnetism and relativity know A. J. Kox as the editor of Lorentz's scientific correspondence. His expert knowledge makes him the ideal biographer of Lorentz. Kox initially published a biography of Lorentz in the author's native Dutch in 2019. Together with H. F. Schatz, a sociolinguist and translator, Kox has now transformed the original into the present biography for an international readership.

"A Living Work of Art" is not just a translation: Kox and Schatz also added a chapter on Lorentz's wife, Aletta. In addition to caring for her husband and children, Aletta was an active member of the women's movement in the Netherlands. The authors argue she deserves attention as a "woman in her own right." Aletta's letters add a personal element to the story of "Pa," as Lorentz's family called him.

The authors take great pains to portray Lorentz in his social context, but they do not include a technical account of Lorentz's scientific achievements. Electrodynamics, electron theory, the Zeeman effect, and the special theory of relativity are all confined to one of the 12 chapters, and general relativity and quantum theory to another. Not a single formula appears in the book. Physicists with a closer interest in Lorentz's scientific achievements should consult Kox's many relevant articles, which have been published in the *Archive for History of Exact Sciences* and elsewhere.



A 1916 PORTRAIT of Hendrik Lorentz by Menso Kamerlingh Onnes, the younger brother of Lorentz's close friend and colleague Heike Kamerlingh Onnes.

The virtue of *"A Living Work of Art"* is its portrayal of Lorentz as a central figure in the Dutch and international scientific communities. Lorentz's gift with languages, calm demeanor, and administrative skills made him a linchpin in the world of early 20th-century physics. It was no coincidence that he chaired the first five Solvay Conferences: His compatriot Heike Kamerlingh Onnes recalled that Lorentz easily found the "right tone" to create the "desired atmosphere of confidentiality" for the meetings.

Coupled with his scientific authority, that administrative ability made Lorentz a sought-after head of panels outside his own field. From 1918 to 1926, Lorentz acted as chairman of the Zuiderzee Commission, which advocated reclaiming land in the North Sea by means of a large-scale hydraulic engineering project. As chairman of the League of Nations' International Committee on Intellectual Co-operation, he also attempted to promote international scientific reconciliation. Sadly, that effort saw little lasting success. As a result of post–World War I tensions between former enemies and the persistent unwillingness of national governments to support a supranational organization, the committee "did not manage to achieve much in the way of concrete results," according to the authors.

The final chapter portrays Lorentz as an internationally revered scientist. Still, the authors retain the human side of the story. "Pa is holding a triumphal march through the country," Aletta remarked during a journey through England and Scotland. To sum up: *"A Living Work of Art"* is a commendable and highly readable biography of a great scientist.

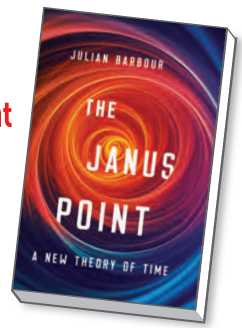
Michael Eckert
Deutsches Museum
Munich, Germany

ALBUM/ALAMY STOCK PHOTO

THE TWO-FACED ROMAN god Janus, as depicted in a miniature from a 15th-century illuminated manuscript.

Romantic cosmology

The Janus Point
A New Theory of Time
Julian Barbour
Basic Books, 2020. $32.00



In Roman mythology, Janus is the two-faced god of transition and change. One of his faces looks toward the past; the other looks toward the future. In *The Janus Point: A New Theory of Time*, Julian Barbour offers not a new theory of time, as the subtitle suggests, but a new perspective on the arrow of time, one that builds on the theory he expounded in *The End of Time: The Next Revolution in Physics* (1999).

Barbour challenges the conventional wisdom that the one-way nature of physical processes—such as ripples emanating from a stone thrown into a pond—is best accounted for by postulating that the universe began in a special initial condition. According to that standard worldview, the ever-increasing entropy predicted by the second law of thermodynamics eventually leads to a featureless, cold universe with no meaningful structure.

In *The Janus Point*, Barbour aims to present an alternative to that picture, one in which the universe's starting point is not so atypical and the unidirectionality of physical processes is a consequence of either the universe's expansion or its increasing complexity. He associates that increasing complexity with what one might call the finer things: life, humanity, art, and science. That vision of inexorable progress echoes Gottfried Leibniz's view that we live in the best of all possible worlds. Barbour contrasts that vision with what he sees as the bleak pessimism of the traditional explanation.

After a long introductory critique of the history of thermodynamics, Barbour turns to N-body theory. Drawing on the results of Joseph Louis de Lagrange and Carl Jacobi, he shows that isolated systems of gravitating point masses with a nonnegative total energy have a finite minimum size at some point in time. He calls that minimum the Janus point because at that point one can face toward the past or toward the future and "see" an expanding universe.

Because Barbour wants to defeat what he sees as the pessimism of the second law, and because he needs a quantity more plausibly associated with time asymmetry than just the expansion of the universe, he introduces the term "shape complexity," which he defines as $-\sqrt{I}\,V/M^2$, in which I is the moment of inertia about the center of mass, V is its potential energy, and M is its total mass.

Away from the Janus point, I increases monotonically, which means it is plausible that the shape complexity will too—just like entropy does in the traditional worldview. That increase reflects the tendency of gravitating systems both to expand (given sufficient kinetic energy) and to form what Barbour calls "Kepler pairs" (the result of gravitational attraction).

Barbour presents the example of three bodies that nearly collide. As a result of their interaction, two of the particles wind up orbiting each other and the other heads off to infinity, thus increasing the shape complexity. It is nontrivial to show that the complexity increases monotonically as the system moves away from the Janus point, but Barbour and collaborators have managed to put bounds on the amount it deviates from monotonic increase. Those bounds get narrower as the number of particles increases. That is certainly an interesting result.

The next part of the book involves a technical demonstration of another intriguingly suggestive result: If one assumes that both the energy and the total angular momentum of the universe are equal to zero, one can show that the Janus point is a point of total collision or total explosion akin to our Big Bang singularity. It thus follows that particle configurations become highly symmetric as the Janus point approaches, which suggests that the "special" initial conditions that seem to dominate in the early universe might actually be generic features of the early stages of a gravity-dominated universe.

To show that increasing complexity is a good proxy for time's arrow, Barbour must demonstrate that it not only strongly tends to increase monotonically but also that the increase manifests in the myriad temporally asymmetric processes that provide the observational basis for our arrow of time. At times he fully embraces that idea and argues that the growth of complexity, not the growth of disorder, "puts the direction into time—and us into the universe to witness its forward march." Elsewhere he is content to concede that purely dissipative processes in which complexity decreases are also part of the arrow of time.

Be that as it may, making a precise connection between complexity or cosmological expansion and the observed arrow of time is of secondary interest to Barbour. More important for him is to overcome what he and others, including Bertrand Russell and Steven Weinberg, regard as the bleak prospect of heat death. Although he acknowledges that energy is continually dissipated in an expanding universe in accordance with the second law, Barbour wants to explain why structure, complexity, life, and art nevertheless continue to emerge. As he says on the penultimate page, *The Janus Point* is "in part, a song of thanks to the cosmos and the fact that I, like you, am a participant in whatever it does."

One could hardly find a more romantic view of the cosmos.

Steven Weinstein
University of Waterloo
Waterloo, Ontario, Canada

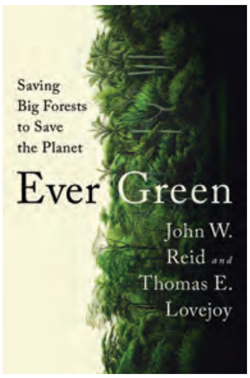
NEW BOOKS & MEDIA

How to Take Over the World

Practical Schemes and Scientific Solutions for the Aspiring Supervillain

Ryan North
Riverhead Books, 2022. $28.00

Have you ever watched a James Bond movie and thought, "Wow, I'd love to have a secret base like the ones those supervillains romp around in!" If so, *How to Take Over the World* by Ryan North, a comic-book writer, is the book for you. By outlining how one could theoretically carry out various schemes like cloning dinosaurs, controlling weather, destroying the internet, and becoming immortal (Spoiler alert: It's not possible!), North cleverly presents readers with an introduction to subjects as varied as the chemical makeup of Earth's core and the international treaties governing the use of Antarctica (the ideal location for a secret base). Fun, snarky illustrations by Carly Monardo round out the compelling package. —RD

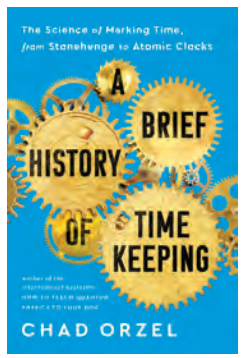


Ever Green

Saving Big Forests to Save the Planet

John W. Reid and Thomas E. Lovejoy
W. W. Norton, 2022. $30.00

Just five megaforests—"stunningly large, wooded territories"—remain on Earth, write John W. Reid and Thomas E. Lovejoy, a conservationist and a biologist, respectively. Yet those vast expanses continue to be threatened by human deforestation. In *Ever Green*, Reid and Lovejoy describe their extensive expeditions to all five megaforests, the forests' vast biodiversity and geography, and the many researchers and Indigenous people who work and live in them. They focus on megaforests' importance not just as Earth's wildest, most biologically diverse lands but also as vital carbon sinks. Thus, *Ever Green* serves as a call to arms to modern society to better appreciate this natural resource, which is key to curtailing climate change and averting the social crises and ecological disasters that it will cause. —CC



A Brief History of Timekeeping

The Science of Marking Time, from Stonehenge to Atomic Clocks

Chad Orzel
BenBella Books, 2022. $16.95 (paper)

How do we keep track of time? Why have societies invested so much effort into doing so? Those questions are the subject of *A Brief History of Timekeeping* by Chad Orzel, a professor of physics at Union College. Much of the focus is on the science of keeping time—from solar and lunar calendars to modern-day atomic clocks—but Orzel also considers the social context of keeping time. As he points out, politics, philosophy, and theology have been part of timekeeping since its beginnings. One cannot help but be amazed by some of the historical anecdotes Orzel relates, such as the remarkable reliability of the Gregorian calendar system, used by most of the world today. Developed in the late 1500s, the Gregorian year differs from the tropical year by only 26 seconds. Ultimately, Orzel notes, measuring time is a "signature preoccupation" of human society. —RD PT

Focus on photonics, spectroscopy, and spectrometry

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

Multiple-color, pulsed diode laser

PicoQuant's new picosecond laser, Prima, gives researchers access to three excitation wavelengths in one compact laser module. Prima generates laser light at 635, 510, and 450 nm, with each color emitted individually, one at a time. The three wavelengths cover most of the excitation needs for daily laboratory tasks, such as lifetime or quantum-yield measurements, photoluminescence, and fluorescence. Prima supports pulsed operation with repetition rates of up to 200 MHz, CW mode with fast switching capability, and rise and fall times of less than 3 ns. When the laser is in pulsed mode, an average optical output power of typically 5 mW can be achieved for each wavelength, and up to 50 mW in CW mode. Because of its standalone design, no additional laser driver is necessary. According to the company, Prima's flexibility and ease of use make it a versatile yet affordable tool for many research applications in the life and materials sciences. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

Laser for quantum measurements

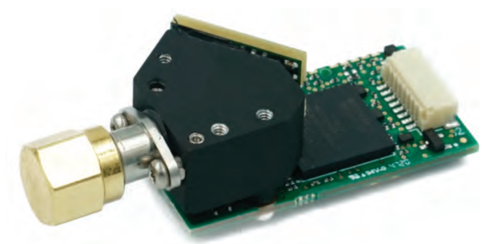
Toptica has expanded its CTL product line, which comprises lasers for exciting microcavities or quantum dots, pumping microcombs, and testing components. The newest member of the family, the CTL 900, is tunable between 880 nm and 950 nm. That wavelength range is especially useful for nanophotonics and spectroscopy, for resonantly exciting quantum dots, and for addressing, for example, rare-earth ions or the cesium D_1 line. The CTL lasers provide wide, continuous tunability without mode hops. They offer high power, a narrow linewidth of less than 10 kHz, and low drift, and they can perform scans with high resolution. That unique combination of features enables researchers to perform measurements at the quantum limit. A test-system mode is included and can characterize components or record spectra. ***Toptica Photonics Inc***, *5847 County Rd 41, Farmington, NY 14425, www.toptica.com*

Ultrafast quantum cascade photodetector

Hamamatsu Photonics has announced its creation of the world's first quantum cascade photodetector (QCD), the P16309-01. The new QCD's sensitivity to mid-IR light was achieved by leveraging a quantum-structure design technology and circuit-design expertise the company accrued through developing quantum cascade lasers. The P16309-01 QCD delivers a cutoff frequency of 20 GHz with no cooling, the highest response bandwidth of any currently available mid-IR photodetector operating at room temperature, according to Hamamatsu. Using the ultrafast QCD as a photodetector for analytical instruments allows the measurement of chemical reactions such as combustion and explosion on a scale of picoseconds. The company says that it has previously been impossible to perform analysis at extremely short time intervals. Other promising applications include high-speed, large-capacity spatial communications and long-range lidar. The new QCD is suitable for use by research institutes, analytical instrument manufacturers, telecommunications carriers, and more. ***Hamamatsu Corporation***, *360 Foothill Rd, Bridgewater, NJ 08807, www.hamamatsu.com*

Ultrastable laser

Menlo Systems designed its ORS-Mini, an ultrastable laser with less than 2 Hz linewidth, as a 19-inch compact, rack-mountable module for field applications. It offers a laser frequency stability (also known as the modified Allan deviation) of less than 5×10^{-15} in 1 s and phase noise of −94 dBc/Hz at 10 kHz offset. The system's centerpiece is a 5 cm high-finesse ultralow-expansion cavity licensed from the UK's National Physical Laboratory. According to the company, the cubic cavity design provides the lowest vibration sensitivity reported to date. It enables a rigid cavity mounting and allows for mobile use of the apparatus. The laser system is available at 1542 nm and 1064 nm wavelengths. It operates fully autonomously, can be intuitively controlled via touch screen, and is remotely accessible via a network connection. The ORS-Mini was conceived as an ultrastable optical reference intended for terrestrial use. It is suitable for applications in quantum computation, as a source of ultralow-noise microwaves for radar systems, as a flywheel in optical clocks, for frequency dissemination via optical fibers, and in various spectroscopic experiments. ***Menlo Systems Inc****, 56 Sparta Ave, Newton, NJ 07860, www.menlosystems.com*



Ultracompact spectrometer module

The latest addition to Ibsen Photonics' platform of ultracompact spectrometers is the Pebble NIR OEM model, which measures only 23 mm × 21 mm × 8 mm. At its core is Ibsen's highly effective transmission grating, a key benefit of which is a high resolution of 12 nm across the full 950–1700 nm wavelength range. Because Pebble uses a compact indium gallium arsenide detector array with short integration time and a large numerical aperture of 0.22 (low f-number of *f*/2.2), it is very sensitive and fast for such a small spectrometer. Its pure transmission-based optics ensure good thermal stability and facilitate real-time fluorescence or absorbance measurements in the field. The cost-effective, rugged Pebble is a handheld and portable multispectral instrument suitable for use in biophotonics, medical, food, and precision-agriculture applications. ***Ibsen Photonics A/S****, Ryttermarken 17, DK-3520 Farum, Denmark, https://ibsen.com*

Eye-safe lasers

Frankfurt Laser has brought to market its FERT-1535-XXXμJ-Q series of 1535 nm erbium glass lasers, which are designated as "eye-safe" because of the wavelength range in which they operate. The diode-pumped passively Q-switched lasers have pulse energies of 40–2000 μJ and peak powers of 10–133 kW. The output beam has a diameter of 0.2 mm with a divergence of ≤12 mrad. The operating temperature ranges from −40 °C to 65 °C. Just 34 mm in length, 18 mm in width, and 7.7 mm in height, the lasers are very compact. Those features and their high reliability make the eye-safe lasers suitable sources for applications such as laser range-finding, laser imaging, and surveying equipment. ***Frankfurt Laser Company****, An den 30 Morgen 13, D-61381 Friedrichsdorf, Germany, https://frlaserco.com*

Trace VOC analyzer

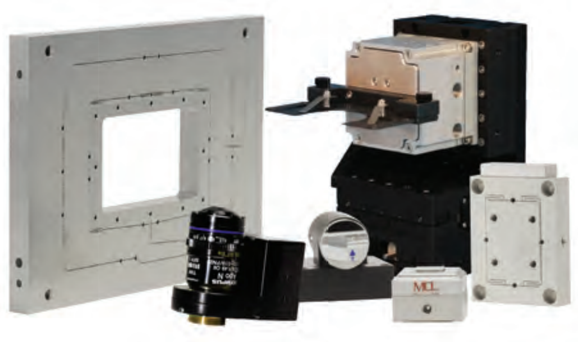
Ionicon developed its high-resolution PTR-TOF-MS trace VOC analyzer, the PTR-TOF 10k, for challenging samples and complex mass spectra, where the additional insight provided by high mass-resolving power is a major asset for the analysis. (PTR-TOF-MS denotes "proton transfer reaction time-of-flight mass spectrometer" and VOC denotes "volatile organic compound.") Powered by the company's novel ioniTOF 10k, the PTR-TOF 10k features an exceptional mass resolution of 10 000–15 000 $m/\Delta m$. It allows peak separation and substance identification that would not have been possible with lower-resolving instruments, according to Ionicon. The PTR-TOF 10k offers a detection limit of less than 1 pptv, a response time of less than 100 ms, and sensitivity greater than 1000 cps/ppbv. It uses TRU-E/N, a patented Ionicon ion-chemistry quality standard that ensures precise electric field strength (E/N) conditions, well-reproducible measurement results, and the highest possible level of quantification accuracy. ***Ionicon Analytick GES mbH****, Eduard-Bodem-Gasse 3, 6020 Innsbruck, Austria, www.ionicon.com*

X-ray fluorescence spectrometer

Applied Rigaku Technologies, a division of Rigaku Corporation, has unveiled its NEX CG II, an indirect-excitation analyzer for energy-dispersive x-ray fluorescence (EDXRF). The multielement, multipurpose NEX CG II delivers rapid qualitative and quantitative elemental analyses of solids, liquids, powders, coatings, and thin films. According to the company, the second-generation spectrometer advances EDXRF with its unique close-coupled Cartesian-geometry (CG) optical kernel and hardware upgrades. Its high-power 50 kV and 50 W x-ray tube, a high-performance large-area silicon drift detector, and Rigaku's advanced Fundamental Parameters software enhance analytical sensitivity and ease of use. The NEX CG II provides nondestructive analysis of sodium to uranium in almost any matrix and measures ultralow and trace-element concentrations up to percent levels. Users can achieve the lowest limits of detection for elements in highly scattering matrices such as water, hydrocarbons, and biological materials. ***Rigaku Americas Corporation***, *9009 New Trails Dr, The Woodlands, TX 77381-5209, www.rigaku.com*

Spectroradiometer series

Admesy's versatile new spectroradiometer platform, its Neo Series, is suitable for a wide array of spectral measurement needs in development and production applications. The series can perform analytical, transmission, and absorbance testing and can be used for solid-state lighting applications such as LED testing, thin-film coating, and other demanding areas. Neo is robust and easy to integrate and, according to the company, ensures high optical performance, accuracy, and repeatability even in tough conditions. The cost-effective Neo VIS spectroradiometer is offered for measurements in the visible wavelength range (380–780 nm). The Neo UV-NIR's extended wavelength range (250–1100 nm), with measurement power in the visible, UV, and near-IR ranges, makes it suitable for analytical applications. ***Admesy***, *Sleestraat 3, 6014 CA Ittervoort, the Netherlands, www.admesy.com* PT



Francis Patton Bretherton

Francis Patton Bretherton had two overlapping careers: He made brilliant theoretical advances in the dynamics of the rotating and density-stratified atmosphere and ocean and later became a pioneering, passionate, and influential leader in atmospheric and global change research programs. He died from dementia-related health problems on 27 June 2021 in Saint Louis, Missouri.

Born in Oxford, UK, on 6 July 1935, Francis attended Clifton College on a scholarship from 1948 to 1952. He played the flute, acted in school plays, and joined a meteorology club, which entailed rising early to study the latest weather maps. In December 1952 he won a scholarship to Trinity College, Cambridge, to study mathematics. He spent part of 1953 as an exchange student in Munich, Germany, where he met his future wife, Inge Kornrumpf. After two years of compulsory military service, he entered Cambridge University in October 1955 and graduated in 1958.

Francis stayed at Cambridge for graduate studies, supervised by G. I. Taylor and Philip Saffman. His study of the motion of bubbles in tubes is highly relevant to practical problems in microfluidics. In 1961 he joined MIT as a postdoc, loving the scientific environment and a camping trip across the country. He returned to Cambridge in 1962 to start a program in theoretical meteorology, conceived by George Batchelor, in the department of applied mathematics and theoretical physics.

During the next five years, Francis centered much of his research on the conservation of potential vorticity, the principle that generalizes angular-momentum conservation for wildly deforming fluid elements on a rotating planet and underlies dynamical oceanography and meteorology. Francis recognized that a relation between the fluxes of momentum and potential vorticity provides far-reaching insights into how flow instabilities lead to nonlinear eddies, which contribute to weather and shape global-scale mean circulations. He also showed how flows can be sharpened into intense singularities, such as the fronts associated with the passage of storms in the atmosphere.

Francis made key contributions to theories of wave motion. Using a Hamiltonian formulation, he proved that wave groups propagating in a moving fluid do not conserve energy but rather conserve energy divided by the wave frequency that would be observed moving with the mean flow. The "wave action" is an adiabatic invariant, analogous to that of a pendulum with a string of changing length. Francis also showed that for steady internal waves generated by wind blowing over mountains, a persistent force is felt at the ground. Unlike for simple friction, however, the reaction on the atmosphere is distributed aloft where the waves are dissipated, including via wave breaking near critical heights where the wind speed vanishes. The results are now incorporated into all weather-forecasting and climate models.

The US continued to beckon. Francis was the principal lecturer at the Woods Hole Oceanographic Institution's Summer Study Program in Geophysical Fluid Dynamics in 1965 and spent a sabbatical in Miami, Florida, and San Diego, California, in 1967. In 1969 he joined the faculty of the Johns Hopkins University, where Inge obtained her doctorate as a step on the way to a distinguished career in developmental psychology.

At Johns Hopkins, Francis built on his 1964 paper exploring nonlinear wave–wave interactions—using an idealized "Bretherton equation"—and clarified the classes of wave–wave interaction that redistribute internal wave energy in the ocean across wavenumber–frequency space. The redistribution has significant implications for the turbulent mixing that controls many aspects of the overturning ocean circulation, oceanic carbon storage, and climate.

Francis also played a leading role in the 1973 Mid-Ocean Dynamics Experiment. It was the first multicomponent investigation of large-scale turbulence—the 100-km-wide eddies that dominate the kinetic energy of the entire world ocean—using a vast array of new moored and drifting instruments. Francis's exposure to large programs led to his appointment as director of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, from 1974 to 1980. There he helped pioneer a broader concept of climate research.

UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

Francis Patton Bretherton

From 1983 to 1988, Francis chaired NASA's hugely influential interdisciplinary Earth System Sciences Committee, with recommendations that led to the establishment of the US Global Change Research Program and NASA's Earth Observing System. The committee's approach to understanding climate in terms of interacting Earth processes is graphically depicted in what became known as the Bretherton diagram.

In 1988 Francis and Inge accepted faculty positions at the University of Wisconsin–Madison; Francis also took over as director of the Space Science and Engineering Center. He continued research on remote sensing that he had started while at NCAR. He retired in 2001, and in 2017 he and Inge moved to Saint Louis to be near family.

With a memorably loud voice and commanding presence, Francis could dominate meetings, but in an inspiring rather than intimidating way. In the words of Bill Hooke, "The authority he carried . . . was always the power of his ideas, not his position on any organization chart." His influence lives on.

Chris Garrett
Victoria, British Columbia, Canada
Michael Edgeworth McIntyre
Cambridge, UK
Peter Rhines
Port Townsend, Washington

QUICK STUDY

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How does light behave in a material whose refractive index vanishes?

Iñigo Liberal and Nader Engheta

The light's wavelength becomes effectively infinite, and the spatial and temporal variations of its electric and magnetic fields decouple.

The refractive index of a material describes how fast light travels through it. The index is the dimensionless ratio of light's speed in a vacuum to its speed, or phase velocity, in the material. For a light wave whose temporal variation is given by a frequency ω, the refractive index $n(\omega)$ defines the wavelength λ inside the material as $2\pi c/\omega n(\omega)$, and the phase velocity $v_p = c/n(\omega)$, where c is the speed of light in vacuum.

Both of those quantities dictate how light changes shape in space. Following Snell's law, $n(\omega)$ determines the angle θ at which an incident wave is refracted at an optical interface between two materials: $n_1 \sin\theta_1 = n_2 \sin\theta_2$. And in nonmagnetic dielectrics, it dictates how much light is reflected at that interface: $(n_1 - n_2)/(n_1 + n_2)$.

Because the refractive index is so prevalent in light–matter interactions, one might wonder how an electromagnetic wave behaves in materials for which $n(\omega)$ approaches zero—known as near-zero-index (NZI) materials. In such cases, λ becomes effectively infinite and the wave appears completely delocalized. Likewise, v_p approaches infinity and the phase advance is essentially frozen.

Snell's law collapses into highly selective angular filtering because only normally incident radiation can penetrate an NZI material. And unusual reflection rules produce mirrors with a reversed phase. Such optically unusual materials open a fundamentally new regime for light–matter interactions, where even the most basic intuition of classical electrodynamics can become distorted. This Quick Study explores a few physical consequences.

Origins

How is it even possible for $n(\omega)$ to approach zero? Derived from Maxwell's equations, $n(\omega) = \sqrt{\varepsilon\mu}$, where ε and μ refer to the medium's relative permittivity and relative permeability, respectively. That equation makes $n(\omega)$ a measure of the density of electric and magnetic polarization in a medium. In a vacuum, both μ and ε equal 1, and thus so does $n(\omega)$. But most materials present a larger density of polarization, with μ, ε, and n exceeding 1.

Some materials are complex, as we suggested in the introduction, with a refractive index that changes with frequency. Metals are a good example. Their response at optical frequencies can be approximated by $\mu(\omega) = 1$ and $\varepsilon(\omega) = 1 - \omega_p^2/\omega(\omega + i\omega_c)$, where ω_p is the plasma frequency (which relates to the number density of electrons) and ω_c is the collision frequency in the metal. If ω_c is not too high (less than a few percent of ω_p), ε of the metal approaches zero near its plasma frequency, and hence so does $n(\omega_p)$.

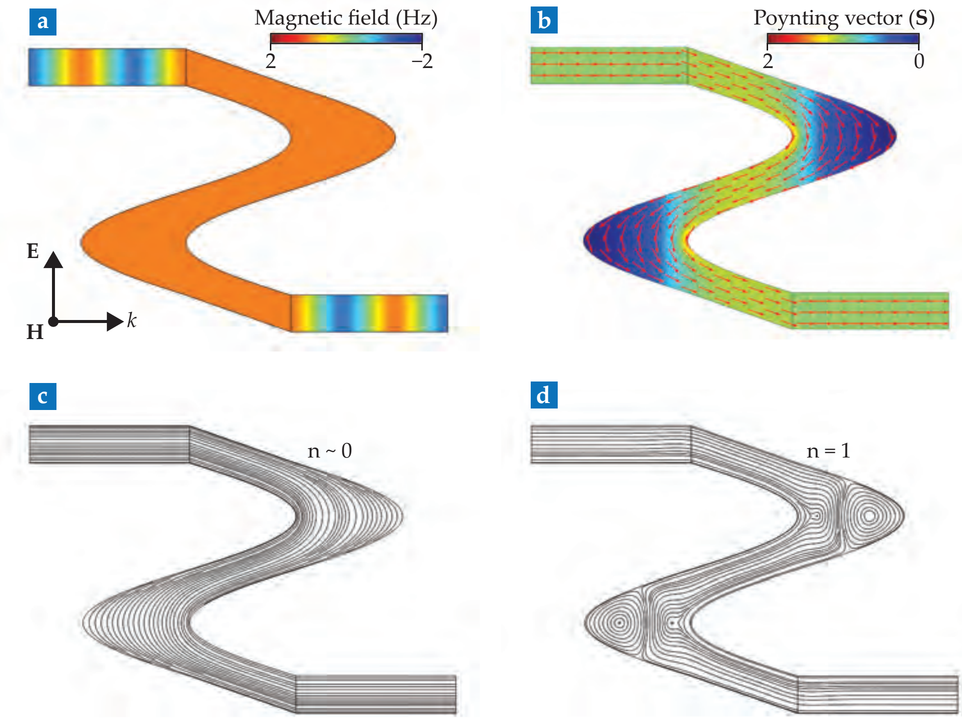
Beyond that simple model, various materials with complex dispersion profiles exhibit a near-zero refractive index in a limited frequency range. Examples include doped semiconductors, polar dielectrics, and transition-metal nitrides. What's more, metamaterials—electromagnetic constructs whose effective refractive indices emerge from their geometrical structure—can be built with a negative refractive index (see the article by John Pendry and David Smith, Physics Today, June 2004, page 37). Researchers can also artificially engineer NZI materials, including dispersive waveguides and all-dielectric structures.

Static–dynamic optics

It took the genius of James Clerk Maxwell to unify electricity, magnetism, and light into a single entity—the electromagnetic field. In his dynamical theory, he showed that the spatial and temporal variations of electric and magnetic fields are fundamentally intertwined and give rise to waves that travel at the speed of light in a vacuum. Maxwell's curl equations $\nabla \times \mathbf{E} = i\omega\mu_0\mu\mathbf{H}$ and $\nabla \times \mathbf{H} = -i\omega\varepsilon_0\varepsilon\mathbf{E}$ best exemplify that notion of oscillating electric and magnetic fields.

From those equations, it's clear that as ε and μ approach zero at the operating frequency ω, the spatial and temporal variations of the electromagnetic fields decouple, so that $\nabla \times \mathbf{E} = 0$ and $\nabla \times \mathbf{H} = 0$. But the decoupling induced by NZI media does not invalidate Maxwell's work. On the contrary, it expands electrodynamics into new directions. In the NZI regime, the time-harmonic solutions to Maxwell's equations are neither completely static nor fully dynamic. They consist of spatially static field distributions that oscillate in time.

One consequence of that decoupling between spatial and temporal field variations is that the resonance frequency of an optical cavity can be independent of the geometry of its external boundary. That's not how resonators are supposed to behave. Waves in an optical cavity typically exist only at specific frequencies where the phase variations satisfy the boundary conditions imposed by the walls of the cavity. But that restric-



IDEAL FLUIDS OF LIGHT. In a material whose refractive index is near zero **(a)**, the wavelength of light becomes enormous. As a result, the electromagnetic wave becomes completely delocalized and its transmission through a deformed waveguide (orange) perfect—that is, turbulence-free—an effect known as supercoupling. **(b)** The flow of power and **(c)** transmission streamlines in the waveguide are equivalent to those of an ideal fluid and inhibit optical turbulence. A light wave entering the deformed waveguide (from left) smoothly adapts to the deformation and suffers no backflow or vortex formation. **(d)** In a material whose refractive index $n = 1$, by contrast, vortices typically form in the corners of the waveguide and in the presence of obstacles to the flow.

tion disappears when the phase is frozen and resonant modes in NZI cavities obey completely different rules. In this newly created class of optical resonators, the geometry of an external boundary confining the optical mode has no effect on the resonance frequency.

In another example, arbitrarily sized dielectric particles immersed in NZI media do not scatter light in the way that conventional materials do. Instead, they act as photonic dopants that modify the effective permeability (see PHYSICS TODAY, May 2017, page 20). In doing so, the particles suppress the geometrical restrictions of standard effective medium theories.

Ideal fluids of light

One surprising aspect of electrodynamics is that power can be transmitted through an NZI body from one region to another. Despite its spatially static character, the electromagnetic field's time evolution is not halted. Power can be transmitted through NZI media, but it does so in an unexpected way. We recently demonstrated, analytically and numerically, that the Poynting vector field $\mathbf{S}(\mathbf{r},\omega) = \frac{1}{2}\mathrm{Re}[\mathbf{E}(\mathbf{r},\omega) \times \mathbf{H}(\mathbf{r},\omega)^*]$, which describes the local properties of the power flow in two-dimensional NZI media, is a divergenceless and irrotational field. That is, it satisfies $\nabla \cdot \mathbf{S} = 0$ and $\nabla \times \mathbf{S} = 0$, equations that also describe the velocity field in an ideal fluid.

So far as power flow is concerned, NZI media can therefore be regarded as a perfect electromagnetic fluid—incompressible, inviscid, and irrotational, characterized by a total inhibition of turbulence. For that reason, light in NZI media flows smoothly and circumvents any obstacles in the way. As shown in the figure, the flow doesn't generate any vortices or reflection.

The concept of an ideal fluid provides a fresh perspective on one of the most iconic NZI phenomena—supercoupling. Typically, when a field propagating in a waveguide encounters a deformed section, part of the incident power is reflected backward. But if the deformed section is filled with NZI material, the power can be efficiently transmitted through it without experiencing any scattering.

The effect takes place independently of the geometry of the deformed section and can be understood as a consequence of wavelength enlargement. Indeed, the wavelength becomes so large that the entire deformed, NZI-filled section becomes effectively compressed in space, much like an electromagnetic point. Input and output ports of the deformed waveguide become connected; waves in one section can tunnel, unimpeded, into another.

Electromagnetic fluids in NZI materials can be considered a bridge between fluid dynamics and electrodynamics. They offer multiple crossbreeding opportunities. The application of airfoil theory to scattering systems, for example, might reveal new forms of optical manipulation. In addition, optical systems in which turbulence is intrinsically inhibited might also enable high-precision metrology systems to operate under harsh mechanical conditions.

Additional resources

▶ I. Liberal, N. Engheta, "Near-zero refractive index photonics," *Nat. Photonics* **11**, 149 (2017).

▶ O. Reshef et al., "Nonlinear optical effects in epsilon-near-zero media," *Nat. Rev. Mater.* **4**, 535 (2019).

▶ N. Kinsey et al., "Near-zero-index materials for photonics," *Nat. Rev. Mater.* **4**, 742 (2019).

▶ I. Liberal et al., "Near-zero-index media as electromagnetic ideal fluids," *Proc. Natl. Acad. Sci. USA* **117**, 24050 (2020).

▶ I. Liberal et al., "Photonic doping of epsilon-near-zero media," *Science* **355**, 1058 (2017).

▶ I. Liberal, A. M. Mahmoud, N. Engheta, "Geometry-invariant resonant cavities," *Nat. Commun.* **7**, 10989 (2016). PT

Morphing of particle rafts

Materials incorporated into soft actuators for robotics, medical devices, and other technologies and architectures must deform deftly and reversibly in response to external stimuli. To address that challenge, Kyungmin Son, Jeong-Yun Sun, and Ho-Young Kim at Seoul National University in South Korea used so-called particle rafts composed of a liquid-oil interface coated with dielectric hollow glass particles. The rafts morph in response to spatiotemporally varying electric fields and are further modulated by electric discharge in the air.

This image shows the shape morphing of particle rafts guided by human fingers. Because living tissues have a high capacity for charge storage, bare fingers can morph the soft-composite interface when the electrode at the bottom of the liquid is turned on. The particle rafts change from flat floors to upheaved mounds in seconds as the fingertips approach. Because the raft system can be driven by bioelectricity, it could serve as a human–machine interface. (K. Son, J.-Y. Sun, H.-Y. Kim, *Soft Matter* **17**, 7554, 2021; photo courtesy of Kyungmin Son and Ho-Young Kim.)

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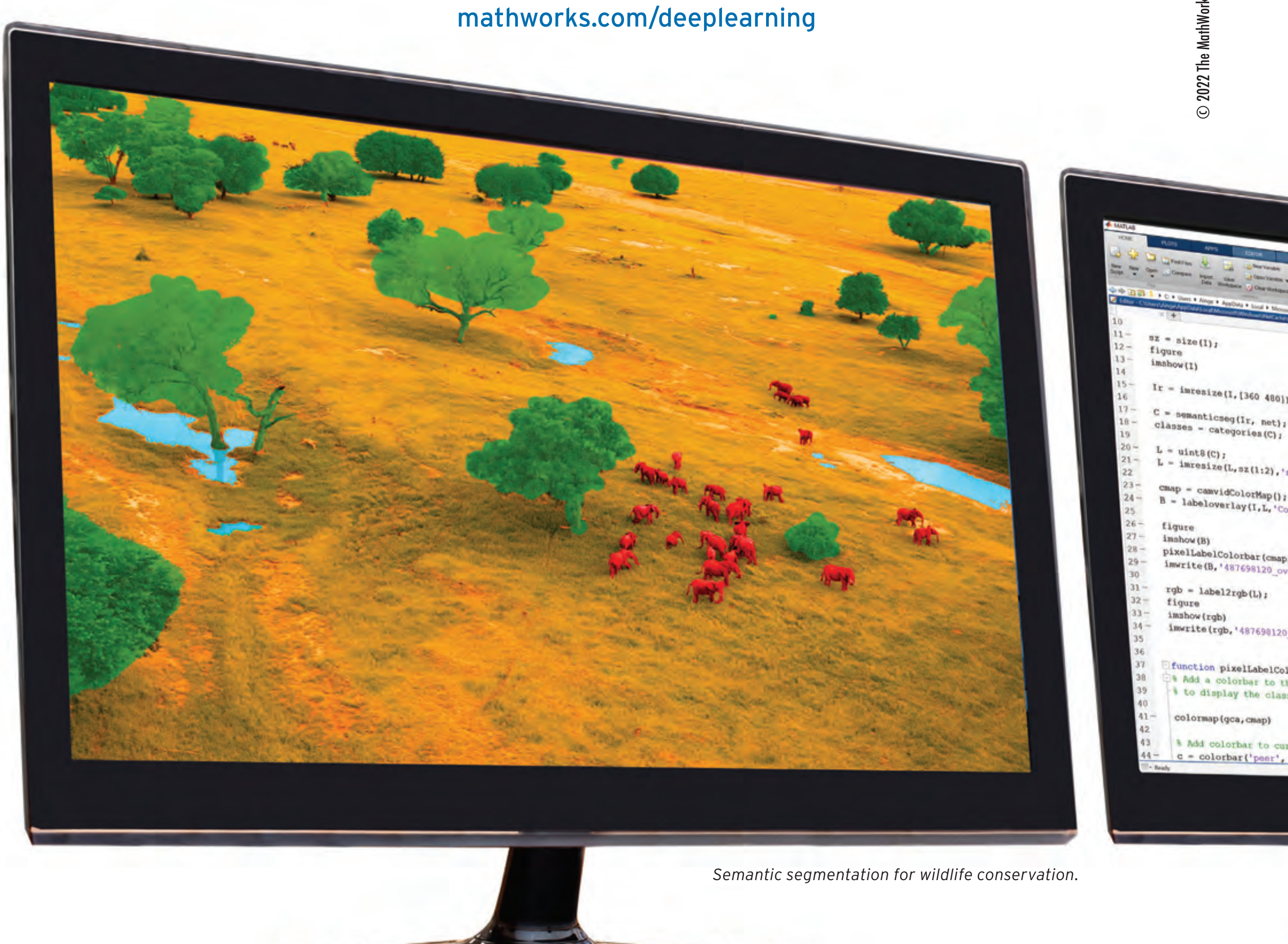

Semantic segmentation for wildlife conservation.