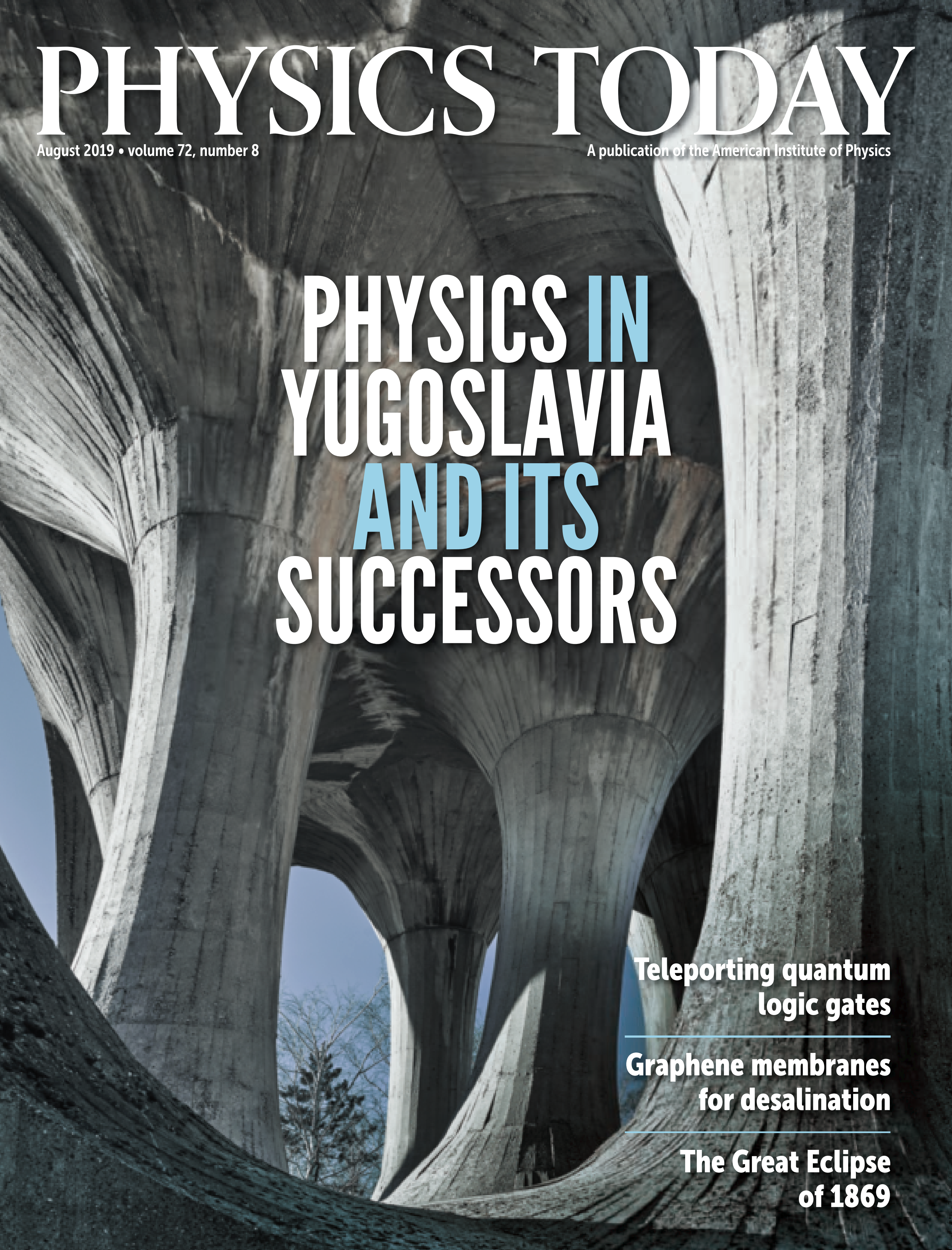

PHYSICS TODAY

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PHYSICS IN YUGOSLAVIA AND ITS SUCCESSORS

Teleporting quantum logic gates

Graphene membranes for desalination

The Great Eclipse of 1869

PHYSICS TODAY

August 2019 | volume 72 number 8

FEATURES

30 Physics in the former Yugoslavia: From socialist dreams to capitalist realities

Mićo Tatalović and Nenad Jarić Dauenhauer

The homeland of Nikola Tesla and Jožef Stefan saw a rise in physics funding after World War II. Now, after the destruction wrought by the Yugoslav Wars of the 1990s, physics in Yugoslavia's successor states is recovering, albeit unevenly.

38 Quantum computing with semiconductor spins

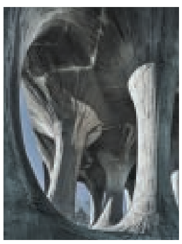
Lieven M. K. Vandersypen and Mark A. Eriksson

Arrays of electrically and magnetically controllable electron-spin qubits can be lithographically fabricated on silicon wafers.

46 The North American eclipse of 1869

Deborah Kent

A coast-to-coast eclipse on 7 August 1869 gave US astronomers a chance to make their mark on 19th-century astronomy.



ON THE COVER: Designed by architect Živa Baraga and sculptor Janez Lenassi, the *Monument to the Fighters Fallen in the People's Liberation Struggle* (1965) stands in a park in Ilirska Bistrica, Slovenia. Physics flourished in Yugoslavia after World War II but foundered during and after the Yugoslav Wars of the 1990s. For an account of the history and current state of physics in the region, read Mićo Tatalović and Nenad Jarić Dauenhauer's article, which begins on **page 30**. (Photo © Valentin Jeck, commissioned by the Museum of Modern Art, 2016.)

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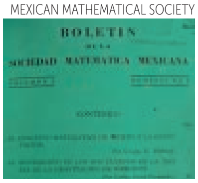
MEXICAN MATHEMATICAL SOCIETY



▶ Graef v. Einstein

In 1944 Albert Einstein invited Mexican physicist Carlos Graef Fernández to discuss a theory of gravity that was an alternative to general relativity. Gustavo Arciniega chronicles the physicists' debate and explains how it signaled the rising prominence of physics in Mexico.

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MICHELLE WANG

▶ Physics Olympiad

Hundreds of high school students from around the world converged on Tel Aviv, Israel, in July for the 50th International Physics Olympiad. PHYSICS TODAY's Toni Feder covers the overall results and the performance of the US team, whose five competitors finished fifth in combined points this year.

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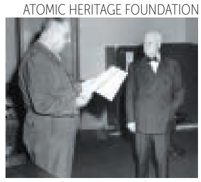
ATOMIC HERITAGE FOUNDATION



▶ Pecher and Sengier

The history of early US radiation science usually focuses on the making of the atomic bomb. Amand Lucas tells the stories of Charles Pecher and of Edgar Sengier (above right), who contributed in other ways—through advances in nuclear medicine and by supplying the Allies with uranium.

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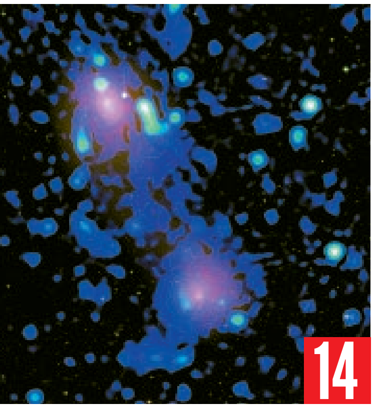
DEPARTMENTS



8 From the editor

10 Readers' forum

Commentary: On the quality and costs of science publication — *Detlef Lohse and Eckart Meiburg* • Letters

14 Search & discovery

Charm-quark decays violate charge–parity symmetry • Radio emission confirms that a magnetic field spans intergalactic space • A big step for nanoporous graphene provides a small step for desalination • Teleportation for device-scale quantum computing

24 Issues & events

Fifth-generation broadband wireless threatens weather forecasting • Germany's most visited museum struggles to complete renovations

54 Books

An engaging look at the physics of fluids — *Michelle Driscoll* • The legacies of the Royal Society of London — *Noah Moxham* • The mathematics and physics of electronic structure theory — *Raffaele Resta* • New books & media

60 New products

Focus on nanotechnology, lasers, and imaging

64 Obituaries

Burton Richter

66 Quick study

Eclipse science today — *Jay M. Pasachoff*

68 Back scatter

Non-Euclidean geometry on a chip

Grimshaw skies

Charles Day

In a recent issue of the British glossy magazine *Country Life*, I spotted an ad for the sale of a landscape by Victorian artist John Atkinson Grimshaw. Titled *Autumn Glow*, the painting evinced one of the most distinct features of Grimshaw's work: an evening or night sky of unusual brightness.

Several of Grimshaw's most characteristic paintings depict lamp-lit streets in Glasgow, Liverpool, and other cities of commerce and industry. Even though Grimshaw was a detailed and realistic artist, his choice to paint at dusk cast an oddly warm, positive light on the same urban worlds that Charles Dickens portrayed as grim and impoverished.

I used to think of Grimshaw whenever I looked up at the night sky on muggy summer nights in Washington, DC, where I've lived since 1990. As in one of his paintings, the leaves and branches of trees overhead would appear black against a luminous sky whose pale apricot color arose from the light of sodium streetlamps scattered by aerosols.

There are fewer Grimshaw nights in Washington now. Despite rising temperatures, the air quality in the DC region has improved, especially during summer. It's still hot and humid, but it's less sickly. In 1997 the region had 18 code-red days. Last year it had one.

I learned of one of the causes of that welcome trend from a poster paper presented at the 2017 annual meeting of the American Meteorological Society. Graduate student Sandra Roberts of the University of Maryland explained to me that more stringent emissions standards had reduced the amount of ozone-creating nitrogen oxides (NOx) in the atmosphere.

BONHAMS

John Atkinson Grimshaw (1836–93) painted this dockside scene in Glasgow, Scotland, around 1889.

The quality of air in London, sadly, has not improved in the past few decades, despite the passage of the Clean Air Acts of 1956, 1968, and 1993. A friend of mine moved from Boston to the British capital three years ago. Within weeks of arrival, he began coughing. A year later he was hospitalized twice and diagnosed with adult-onset refractory eosinophilic asthma. Why is London's air so bad? Energy has been heavily taxed in the UK and other European countries for decades. The good upshot is an energy-efficient economy. According to the World Bank, the US produces 7 units of GDP per unit of energy usage, whereas the UK produces 12. The bad upshot is that high fuel prices and tax incentives have prompted Europeans to buy diesel cars, whose engines are more thermodynamically efficient than their gasoline counterparts. That advantage prevails even though gasoline engines burn almost all of their fuel, whereas diesels do not. The unburnt fraction of diesel fuel is a prime source of pollution—at least in older cars. The European Union's latest emission standards, Euro 6 of 2015, require diesel cars to emit no more than 80 mg/km of NOx. By contrast, Euro 1 of 1992 set no limit; Euro 3 of 2000 set a limit of 500 mg/km.

Earlier this year London mayor Sadiq Khan imposed an Ultra Low Emissions Zone (ULEZ) on Westminster and the City. Diesel cars that don't meet Euro 6 and gasoline cars that don't meet Euro 4 have to pay a daily fee of £12.50 ($15.67) to enter central London or face a fine of £160. Khan has proposed to extend ULEZ to almost all of Greater London by 2021. Londoners who drive older cars are outraged. Some of them bought diesel cars expressly because they are more frugal than gasoline cars. The UK government even incentivized drivers to switch to diesel by lowering the tax on the fuel relative to gasoline.

The lesson from DC is that emissions standards work. The lesson from London is more subtle. Promoting diesel cars lowered carbon dioxide emissions at the expense of increased pollution, which eventually led to emissions standards that are likely more stringent than if the switch to diesel had not occurred. PT


IDEA

Commentary

On the quality and costs of science publication

CYNTHIA B. CUMMINGS

Next to the spoken word, scholarly journals have always been the most immediate and important way for scientists to communicate. Maintaining their quality is therefore crucial to the success and advancement of the scientific enterprise. For centuries, learned societies have taken on the task of reviewing, producing, and monitoring publications for their field. By enabling publishing by scientists for scientists, they have helped the scientific community to self-organize.

Examples of such societies include the Royal Society, the National Academy of Sciences, the French Academy of Sciences, the American Association for the Advancement of Science, and the American Institute of Physics (which publishes PHYSICS TODAY). Also included are the many university presses—Cambridge, Oxford, Harvard, and others.

The society and university presses are nonprofit. Many have evolved over centuries, and each has a great tradition of reporting scientific advances and discoveries. Because scientists see the value in the scholarly publishing enterprise, they are willing to volunteer their time as journal editors, referees, or authors. Their input is invaluable in offering the scientific community a degree of quality control over publications.

In contrast, commercial publishers have discovered that there is money to be made in the growing market for science publications. Commercialization of journals has contributed significantly to an explosion in their price, their numbers, and the quantity of papers they seek to publish. As a consequence, college and university libraries often can no longer afford all the journals.

A way that commercial publishers have maintained their profits is to change the publishing concept from a pay-to-read strategy, which places the financial burden mostly on libraries and thus their universities, to a pay-to-publish scheme in which authors pay a fee to get their papers published. The pay-to-publish approach allows commercial publishers to circumvent quality control both for existing journals and for new journals that often have minimal prepublication review. Thus both the number of publications—and of paying authors—and the publishers' revenue are dramatically increased. The marketing strategy for pay-to-publish is to call it "open access." It plays on the idea that the results of research financed by the public should also be freely accessible to the public.

For more than 25 years, however, the scientific community has benefited from an effective solution to the problem of open, cheap, and easy access to scientific publications: The preprint server arXiv.org and other open internet archives make freely available to everyone the contents of articles in an increasing number of science and engineering fields.

Presently, arXiv.org has operating costs, including salaries for five full-time staff members, that are less than $1 million per year. Expenses are paid by Cornell University with funding from NSF, and the operation is transparent.

In physics, mathematics, astronomy, information science, and statistics, the vast majority of papers worldwide are already freely available on servers like arXiv.org. Other fields are catching up quickly.

Many journals from scientific societies—the Physical Review family from the American Physical Society, for example—accept submissions of papers already posted on arXiv.org. That process leads either to publication of an improved version of the paper in the journal and on the preprint server or to rejection by the journal. Thus journal publication provides the stamp of quality from the scientific community.

The refereeing process and the enhancement of a paper's quality and readability by and for the scientific community are critical for the community's advancement. In principle, that added value is also possible with the pay-to-publish concept, but not together with the for-profit goal of commercial publishers.

A pay-to-publish system will likely lead to two tiers of publications. In some instances, it already has. At the high end, respected for-profit and nonprofit journals will ask authors for exorbitant publication fees to cover costs of refereeing, selection, and marketing; authors will want to publish in them to promote their careers and to secure funding.

At the low end, for-profit journals will publish basically anything, provided the authors pay a publication fee. The net result of the lower tier will be a major problem for the scientific community and a disaster for the public: A flood of publications with minimal quality control will erode the separation between legitimate and junk science and will extract vast additional publishing costs from the scientific community and thus from public coffers.

Plan S, proposed by a group of European funding agencies, would enforce the pay-to-publish model. (See "Concerns remain over European open-access proposal," Physics Today online, 28 June 2019, and "Open access at a crossroads," Physics Today online, 11 October 2018.)

The plan in its present form has several major problems. A glaring example is that it does not allow scientists with funding from Plan S–supporting organizations to publish in the leading scientific journals. In most cases, those journals are published by academic societies. Plan S raises other concerns, too:

- The plan ignores the enormous difference between commercial publishers, with their principal aim of making money, and academic societies, with their principal aim of advancing science.
- Plan S breaks with the centuries-old tradition of quality control in scientific society publishing. Instead, it enforces a top-down approach that effectively promotes publication of all submitted papers. Having a flood of papers that contain flawed or even wrong research but are freely available clearly is not in the interest of the general public, who through taxes still has to pay twice: once for the research itself and again for the pay-to-publish system.
- Plan S implies a redistribution of public research money to commercial publishers and away from support of the research itself. For example, a research group that produces about 20 papers per year would have to pay €100 000 ($114 000) annually for the papers to be freely available in respectable journals. That's the approximate salary equivalent of at least two PhD positions, depending on the country.
- Authors who cannot pay cannot get published.

CONTACT PHYSICS TODAY

Letters and commentary are encouraged and should be sent by email to **ptletters@aip.org** (using your surname as the Subject line), or by standard mail to Letters, Physics Today, American Center for Physics, One Physics Ellipse, College Park, MD 20740-3842. Please include your name, work affiliation, mailing address, email address, and daytime phone number on your letter and attachments. You can also contact us online at **http://contact.physicstoday.org**. We reserve the right to edit submissions.

• Plan S will isolate countries that sign onto it from the rest of the international research community. It will lead to a loss of collaborations because researchers from Plan S–supporting countries will not be able to easily publish with colleagues from nonparticipating nations.
• The plan will inhibit the influx of international talent into countries that are under Plan S.
• Young scientists from countries whose funding agencies have signed onto Plan S will have difficulty finding positions abroad because they have not been able to publish in leading society journals.
• Plan S offers insufficient cost and quality controls. In fact, Plan S in its current form undermines both cost and quality controls.

A practical alternative to rapidly reduce the costs of scientific publishing is for libraries to take coordinated action and simply unsubscribe from high-cost for-profit journals. The incentive for researchers to publish in such journals would then quickly disappear. The Max Planck Society in Germany and many German universities have taken the lead on that approach; as of 1 January 2019, they ceased subscribing to all Elsevier journals. Such a coordinated action will strengthen the position of academic-society journals and will help them preserve the peer-review system and thus maintain quality control. The overall costs of journals then would fall quickly and dramatically.

Good scientific publishing is led by and for the scientific community through its academic societies and university presses. We scientists should be highly skeptical about both commercially driven and ideologically driven movements in scientific publishing. Preprint servers like arXiv.org can make open access easy and inexpensive, and coordinated efforts to avoid for-profit journals can support the tradition of refereed, quality-controlled scientific papers. Ready access and availability have already been achieved in many fields; remaining fields should follow their example.

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LETTERS

Let's expand the vision of a new Bell Labs!

Mark Raizen's commentary "Let's recreate Bell Labs!" appeared in the October 2018 issue of PHYSICS TODAY (page 10). I liked his idea and was quite taken by the scope of his vision. Unfortunately, my enthusiasm was dampened when I read the details of how his idea would work. I understand his desire that fellows "be selected for their track record of exceptional creativity." However, his assumption that they "could utilize the significant resources of their home institutions for fabrication and diagnostics" means that the research foundation and its fellowships would be available only to scientists at major, research-focused universities.

During my career at public regional universities, I have met many physicists who have great ideas. But due to the lack of resources, high teaching loads, few to no graduate students, and difficulties competing for grants, they never could capitalize on them. Since a large number of physicists work at smaller institutions, the structure that Raizen proposes for research at his Pointsman Foundation simply becomes a continuation of the conceit that only scientists at major institutions have anything to contribute.

I challenge Raizen to broaden his vision to truly maximize the impact of his lab. I recommend creating some fellowships—initially one or two but expanding to 10–20% of the total—explicitly for physicists from less affluent institutions. The new fellowships would, of necessity, be more expensive to implement than the other fellowships, since the foundation would have to provide the additional support that Raizen currently expects from home institutions.

Expanding the cadre of fellows and helping to strengthen research capabilities at smaller institutions offsets the added expense and would have an impact beyond the original intent outlined in the commentary. A research institute that includes the broadest possible group of physicists maximizes the potential for discovery and innovation and also significantly benefits students at all levels as faculty return to their home institutions.

Raizen ends his commentary with a rousing call for action. Expanding his proposal to physicists across the profession would make his foundation even more successful.

Daniel J. Suson
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Purdue University Northwest
Hammond, Indiana

▶ **Raizen replies:** I thank Daniel Suson for his comments, and I agree that we must cast the broadest net possible to identify and promote creativity. That will include not only major research universities but smaller institutions where resources are scarcer and teaching loads are higher. We will make resources available at the Pointsman Foundation's laboratory by a combination of internal funding and facilities at nearby institutions. For example, the new Advanced Science Research Center at the Graduate Center, City University of New York, has state-of-the art facilities available to other institutions and companies for a user fee. Having nearby facilities will be important to Pointsman fellows and to the lab's permanent scientific staff and will be a determining factor in the lab's location.

Another activity we will pursue is incubation of patented inventions that are aligned with the foundation's mission. We will license the intellectual property from the institutions, regardless of their size, and pay the inventors as consultants.

I must differ with Suson on one point: We will not apply quotas for any Pointsman fellows but simply look for the best ideas that can lead to breakthroughs and discoveries.

Mark G. Raizen
(raizen@physics.utexas.edu)
University of Texas at Austin
and the Pointsman Foundation

Corrections

June 2019, page 42—In the caption for figure 1, the image should be attributed to Yasunobu Miyoshi.

May 2014, page 20—The length scale in the lower right panel of the figure should be given as 1 mm. PT

Charm-quark decays violate charge–parity symmetry

In the quest to understand how particles behave differently from their antiparticles, the LHCb experiment has a promising new result.

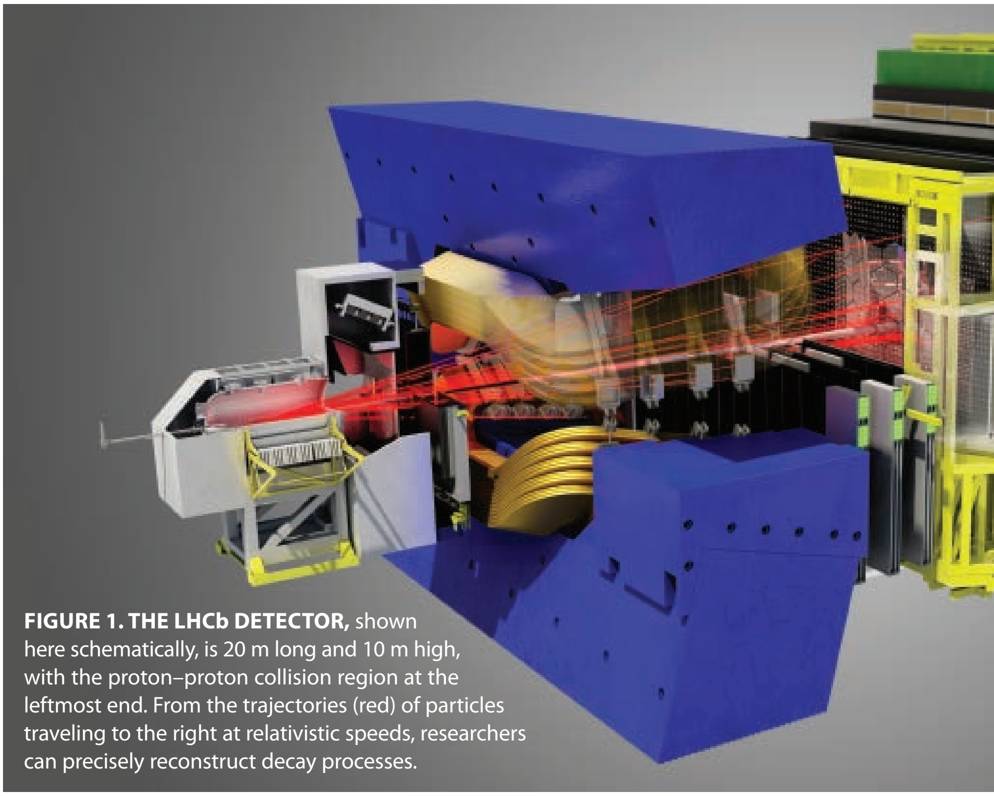


FIGURE 1. THE LHCb DETECTOR, shown here schematically, is 20 m long and 10 m high, with the proton–proton collision region at the leftmost end. From the trajectories (red) of particles traveling to the right at relativistic speeds, researchers can precisely reconstruct decay processes.

Every neutrino ever observed has been left-handed—its spin and linear momentum point in opposite directions—and every antineutrino has been right-handed. That's because the weak interaction, the basis for all neutrino detection, violates the symmetries of both charge conjugation *C* (the replacement of particles by their antiparticles) and parity *P* (spatial inversion). It treats particles and their antiparticles not identically, but as mirror images of one another.

But the combination symmetry, *CP*, isn't quite exact. Weak interactions that transform the flavors of quarks can differ from their antiparticle counterparts not just in their spatial arrangements but in their products and rates of production. *CP* violation is important because of its relevance to a fundamental question: Why is there anything in the universe at all?

The Big Bang should have yielded equal amounts of matter and antimatter, which should promptly have annihilated each other, leaving nothing but photons. Somehow, though, one in a billion matter particles survived, and they went on to form all the stars, planets, and everything else in the observable universe today. For that to have happened, the laws of physics seemingly must treat matter and antimatter differently (see the article by Helen Quinn, PHYSICS TODAY, February 2003, page 30).

Although *CP* violation has been observed in the decays of both strange and bottom quarks and is well described by the standard model of particle physics, the size of that violation is many orders of magnitude too small to explain all the matter that still exists. Particle physicists have thus been on the hunt for new physical effects, beyond those included in the standard model, that could have supplied the additional *CP* violation to the early universe.

The Large Hadron Collider's LHCb experiment, depicted in figure 1, has now taken the hunt to a new sector with the observation of *CP* violation in particles containing charm quarks.[1] Notably, it's the first such violation to be seen in the family of quarks with charge $+\frac{2}{3}$. (The strange and bottom quarks, like the ubiquitous down quark, both have charge $-\frac{1}{3}$.) Of the other positively charged quarks, the top quark is too heavy and too short-lived to even form bound states, and the up quark, the lightest and most stable of all the quarks, doesn't normally decay.

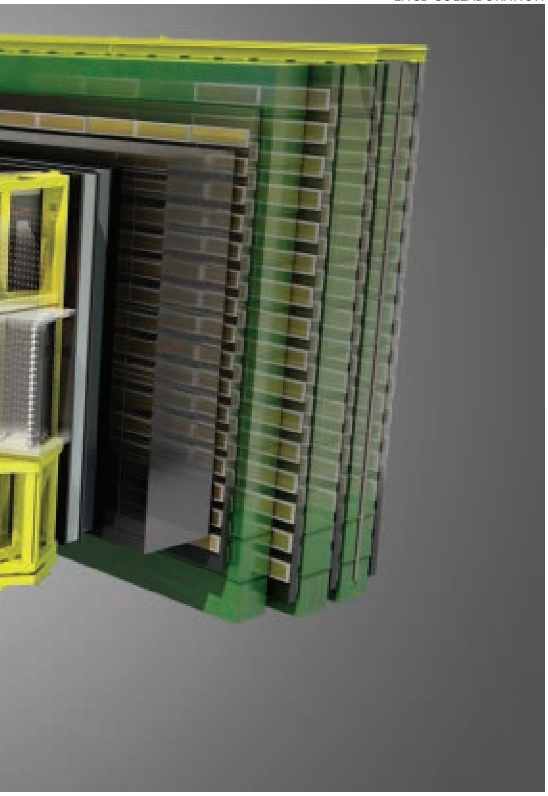
It's not yet known whether the LHCb result represents new physics. The experimenters have pinned down the magnitude of charm *CP* violation rather precisely: Their measurement differs from zero by more than five standard deviations, the accepted threshold for calling the result an "observation." But theoretical predictions have lagged behind, and calculations of the extent of standard-model charm *CP* violation span a factor of 10. The LHCb measurement is at the upper end of that range.

To B or not to B

Each *CP*-violating quark flavor has a different story. For strange quarks, *CP* violation was first observed by James Cronin and Val Fitch in 1964—before the quark theory of matter was even experimentally confirmed—in the neutral-kaon system (see the article by James Cronin and Margaret Stautberg Greenwood, PHYSICS TODAY, July 1982, page 38). The kaons consist of flavor states K^0, a down quark bound to a strange antiquark, and its antiparticle $\bar{K}^0$, a down antiquark bound to a strange quark. But they're often observed as superpositions of those states that are either *CP*-odd (that is, they pick up a phase of −1 under *CP* transformation) or *CP*-even (that is, they pick up no phase).

Kaons are light—about half the mass of a proton—and they have only a few available decay modes, by far the fastest of which produces two pions. Because the pions are each other's antiparticles,

LHCB COLLABORATION



the product state is *CP*-even, so it can ostensibly arise only from a *CP*-even kaon state. But as Fitch and Cronin found, the longer-lived *CP*-odd kaons, easily isolated by allowing all the *CP*-even ones to decay away, also decay into two pions a few times out of a thousand. For their discovery, they were awarded the 1980 Nobel Prize in Physics (see PHYSICS TODAY, December 1980, page 17).

The theoretical explanation was also the basis for a Nobel (see PHYSICS TODAY, December 2008, page 16). In the early 1970s, Makoto Kobayashi and Toshihide Maskawa formulated a matrix to describe how quarks of different flavors transform into one another. When they included only the two quark generations then known (up and down, charm and strange), the matrix allowed no *CP* violation. In an attempt to explain Fitch and Cronin's kaon result, the theorists postulated a larger matrix, which could accommodate *CP* violation, and thereby predicted a third generation of quarks. The prediction was correct: The top and bottom quarks exist.

In a popular parameterization of the theory, the *CP*-violating terms occupy the matrix elements farthest from the diagonal—those that describe transformations between first- and third-generation quarks. In the decay of second-generation strange quarks, those terms are introduced only via minor contributions from short-lived virtual quarks, so the overall *CP* violation is small. Bottom-quark decays, which incorporate the symmetry-violating terms directly, show much larger *CP* asymmetry.

Bottom-quark physics, however, is complicated. The B mesons come in multiple flavors—a bottom antiquark can bind to an up, down, strange, or charm quark—and each of them is massive enough to have hundreds of available decay modes, only a few of which yield products that are *CP* eigenstates. On the flip side, the system offers a rich variety of experimental observables, such as the phases through which different processes interfere with each other, that can potentially reveal *CP* violation and be tested against the standard model.

Toward that end, several labs around the world have invested in collider experiments specially tailored to the study of bottom quarks. They include LHCb (the "b" stands for beauty, another name for the bottom quark) and the so-called B factories at KEK in Japan and SLAC in the US (see PHYSICS TODAY, January 1999, page 22). Although the details differ, all were designed to study unstable particles created with significant momentum in one direction, so their decay lifetimes are relativistically lengthened. From the momenta of the products, it's possible to precisely reconstruct how far each particle traveled—and thus how long it lived—before decaying. The first observation of bottom-quark *CP* violation came from the B factories in 2001 (see PHYSICS TODAY, September 2001, page 19), and there have been many more since then, all consistent with standard-model predictions.

Charms are all o'erthrown

As a testing ground for studying *CP* violation, the charm quark combines the disadvantages of the strange and bottom quarks. It's a second-generation quark, so the magnitude of symmetry violation is relatively small—on the order of 10^{-3}—and charm-bearing particles have many available decay modes to complicate the analysis. As it happens, LHCb observed *CP* violation through perhaps the most direct measure possible: a census of the numbers of D^0 mesons (charm quarks bound to up antiquarks) and their $\overline{D}^0$ antiparticles (up bound to anticharm) decaying to either $\pi^+ + \pi^-$ or $K^+ + K^-$.

Each of those product modes is its own set of antiparticles, so in a *CP*-invariant world, they'd be equally likely to arise from either D^0 or $\overline{D}^0$; any fractional difference thus reveals *CP* violation. To tell the D^0 and $\overline{D}^0$ mesons apart, the LHCb researchers focused on decay modes that produce the charmed mesons together with so-called tagging particles: a D^0 alongside a π^+ or antimuon, or a $\overline{D}^0$ together with a π^- or muon. The charge of the tagging particle reveals the flavor of the meson.

For a useful measurement of a small fractional difference, tens of millions of decays are needed just to overcome statistical uncertainties. And $\pi^+ + \pi^-$ and $K^+ + K^-$ together make up just 0.5% of all D^0 decays, putting the necessary number of charmed mesons in the billions.

But LHCb was up to the task. The LHC's 2015–18 run at a collision energy of 13 TeV yielded 600 trillion proton–proton collisions. (That's actually a lot less than at some of the other LHC experiments—LHCb deliberately lowers its collision rate due to detector requirements.) About 5% of those collisions produce charm quarks in one way or another. Not all of them yield D^0 mesons in conjunction with tagging particles in the detector angle of acceptance, but enough of them do.

On top of the statistical uncertainties, there are also systematic uncertainties. There's no guarantee, for example, that LHCb produces or detects particles and their antiparticles with equal efficiency. Fortunately, the two D^0 decay modes, $\pi^+ + \pi^-$ and $K^+ + K^-$, are equally influenced by systematic effects, so in the difference ΔA_{CP} of their fractional asymmetries, the systematic errors largely cancel out.

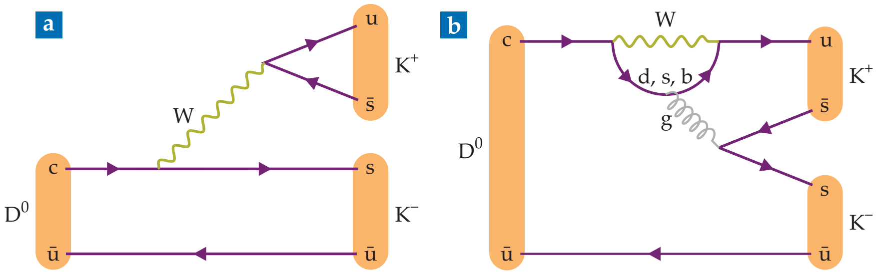


FIGURE 2. A D⁰ MESON DECAY into two charged kaons is the sum of contributions from multiple processes that can be represented as Feynman diagrams. **(a)** The tree-level diagram, mediated by a single W boson carrying the weak force, contains only those quarks present in the initial and final particles: charm, up, and strange. **(b)** A loop-level diagram introduces a gluon and a quark of another flavor. (Adapted from ref. 5.)

Although ΔA_{CP} doesn't have a straightforward physical interpretation, it's similar in magnitude to the asymmetry of each decay mode separately, and importantly, if it's different from zero, then *CP* symmetry must be violated.

Over the years, LHCb, the B factories, and other experiments have tried many times to measure ΔA_{CP}. But until now the results have been consistent with no symmetry violation. The closest thing to a nonzero result came in 2012, when LHCb found a ΔA_{CP} of -8×10^{-3}, 3.5 standard deviations from zero.[2] Such a value, an order of magnitude in excess of nearly all the theoretical predictions, would have been astonishing if it was right, but further data from LHCb and elsewhere showed the result to be a statistical anomaly. The new measurement, -1.54×10^{-3}, differs from zero by a comfortable five standard deviations.

Know this sure uncertainty

The implications of the measurement remain to be seen. Standard-model predictions of the magnitude of charm *CP* violation range from roughly 10^{-4} to 10^{-3}, and in the weeks after the LHCb researchers announced their result, theorists argued both for[3] and against[4] the idea that it represents a new source of *CP* violation unexplained by the standard model.

The discrepancy stems from the complexity of charm-sector calculations. The simplest, so-called tree-level diagram of a D^0 decay, shown in figure 2a, contains no third-generation quarks, so it can't violate *CP* symmetry by itself. More complex loop-level diagrams, such as the one in figure 2b, can introduce *CP* violation, but their relative contributions to the decay rate are extremely challenging to calculate. The calculations are simpler for bottom-quark decays, because the bottom quark's large mass allows for some mathematical approximations. But the charm quark is just light enough that those simplifications don't easily apply. So for now the question of how the LHCb measurement compares with the standard model remains open.

If it's finally established that charm decays do show signs of new physics, the next step will be to figure out what that physics is. Any model to explain the discrepancy will likely introduce new particles, predict similar *CP*-violating effects in other decays, or both, and future generations of experiments can seek to test those predictions.

There's also the question of whether the new physics can supply the many additional orders of magnitude of *CP* violation needed to explain matter's survival in the universe. Although charm *CP* violation can't disagree with the standard model by much more than a factor of 10, it could be the first sign that the standard model is a low-energy approximation, ill-equipped to describe the high-energy processes that were prevalent in the instants after the Big Bang but have rarely been accessed since then.

Johanna Miller

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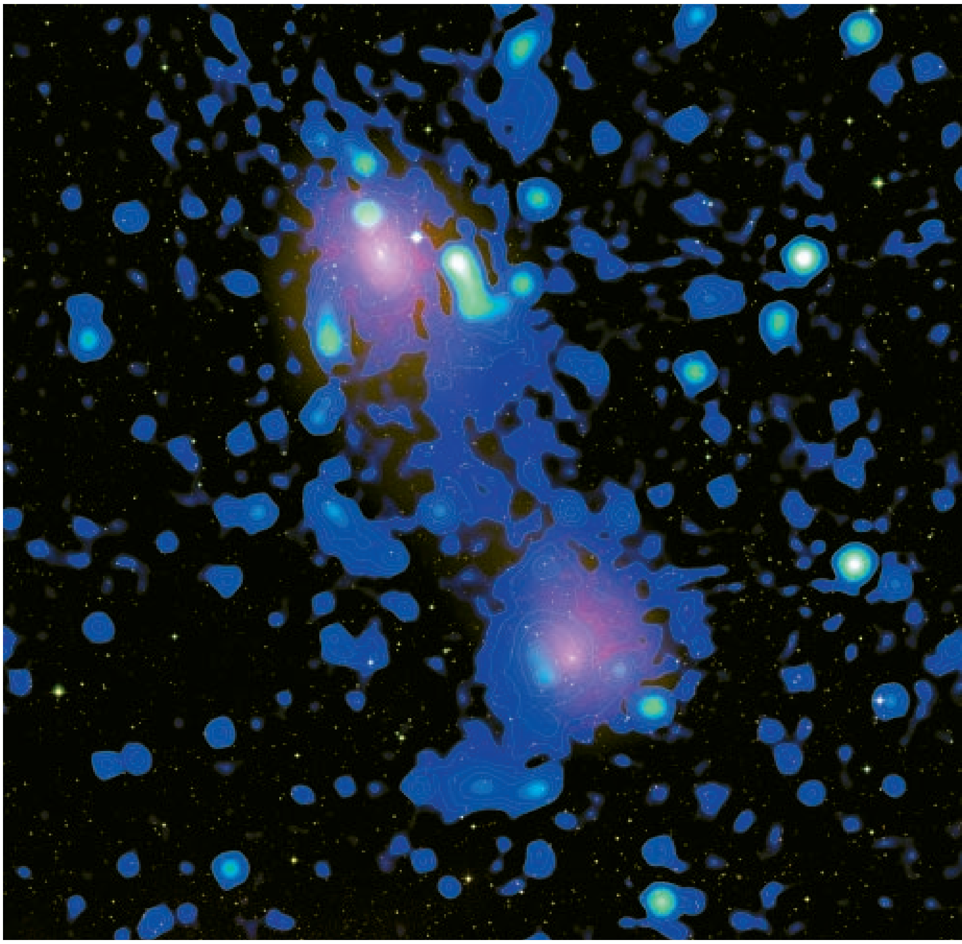
Radio emission confirms that a magnetic field spans intergalactic space



The Low Frequency Array telescope detected previously unobserved synchrotron radiation between two merging galaxy clusters.

Think of the large-scale universe as a web: Filamentary structures—threads of galaxies, gas, and dark matter—crisscross space. Where they intersect, gravitationally collapsing material forms galaxy clusters that can then merge through some still-unknown process. Some of the energy released by cluster mergers helps power relativistic particles that spiral around magnetic field lines.

One way that astronomers observe what happens during a merger is by detecting emissions that come from superheated plasma known as the intracluster medium (ICM). The density of the ICM is so low that the only way for matter to interact is through collisionless dealings between the plasma's electric and magnetic fields. X rays are emitted from the interaction of the plasma's electric field with free electrons; synchrotron radiation is emitted from cosmic-ray particles traveling through magnetic fields. (See the article by Lawrence Rudnick, PHYSICS TODAY, January 2019, page 46.)

Astronomers have long wondered whether the radio emission from magnetic fields in clusters extends to the filamentary structures, which contain about half of the universe's baryons. The detection of emission there would be a first step toward understanding the physical processes that affect those baryons, and it would confirm the cosmic web structure of the universe.

The effort to find emission associated with filamentary structures has come up short so far, although the presence of filaments has been inferred from the detection of UV absorption lines (see PHYSICS TODAY, July 2008, page 12). Radio sources extending beyond the ICM of galaxy clusters haven't been detected by low-frequency radio telescopes because of insufficient sensitivity and calibration difficulties. Searches in the soft-x-ray spectrum await more sensitive satellite observations.

Now radio synchrotron emission has been newly detected between two merging galaxy clusters by the Low Frequency Array (LOFAR) telescope. It was built and designed and is operated by the Netherlands Institute for Radio Astronomy with contributions from international partners. A collaboration led by Federica Govoni of Italy's National Institute for Astrophysics has found that the synchrotron emission arises from a magnetic field that extends over distances greater than previously thought possible.[1]

A European-sized radio dish

Measurements made before the new LOFAR observations led Govoni and her colleagues to suspect that a filamentary structure exists between the merging galaxy clusters Abell 0399 and Abell 0401.

FIGURE 1. A FILAMENTARY STRUCTURE joins the merging galaxy clusters Abell 0399 and Abell 0401. The cluster positions are illuminated by x-ray observations (pink) collected by the European Space Agency's (ESA's) *XMM-Newton* observatory. The faint yellow around and between the clusters shows the filamentary structure inferred from microwave photon-intensity measurements collected by the ESA's *Planck* satellite. The radio synchrotron emission (blue) detected using the Low Frequency Array telescope provides the first evidence for a previously unseen 3-megaparsec-long magnetic field connecting the clusters. (Image by M. Murgia, INAF.)

Figure 1 shows the clusters' x-ray emission collected by the European Space Agency's (ESA's) *XMM-Newton* observatory. Microwave photon-intensity measurements around and between the clusters can help unravel their history and were collected by ESA's *Planck* satellite

FIGURE 2. THE LOW FREQUENCY ARRAY (LOFAR) TELESCOPE is a collection of 25 000 individual dipole antennas distributed among 51 stations across Europe. One of the densely spaced Dutch stations is shown here. Each antenna in the center group—a metal pole with wire mesh underneath—detects low-band frequencies in the range of 10–80 MHz. The other antenna groups are housed in aluminum tile boxes and detect high-band frequencies in the range of 120–240 MHz. (Photo by © Top-Foto, Assen.)

(see PHYSICS TODAY, June 2015, page 20). But without detecting radio emissions, astronomers couldn't conclusively say whether a filamentary structure and magnetic field existed between the two clusters.

LOFAR was designed to detect ultralow-frequency radio emissions in the range of 10–250 MHz (see PHYSICS TODAY, March 2011, page 24). The telescope uses 25 000 electronically linked, digital dipole antennas in stations spread across France, Germany, Ireland, Italy, Latvia, the Netherlands, Poland, Sweden, and the UK. Each antenna is essentially a metal pole in the ground with some mesh wire underneath it. That design "was very cost efficient and that's one of the greatest attributes of LOFAR," says Amanda Wilber, a LOFAR astronomer from the University of Hamburg in Germany not involved with Govoni's research.

Individual antennas far from each other create a long baseline that enables LOFAR to detect the faint radio energy emitted by distant planets, stars, galaxies, and clusters. Such a baseline can be used to produce sharp, highly resolved images. In the Netherlands, the antennas are spaced closely together, which provides an extended picture of the sky. The Dutch stations of the LOFAR array, one of which can be seen in figure 2, provided Govoni and her colleagues with sufficient resolution and sensitivity to detect the broad radio emission coming from the extended magnetic field.

Before the researchers could make the successful detection, they had to synchronize and calibrate all the antennas. "It's one of the most challenging parts for not only LOFAR but [all] low-frequency radio observations," says x-ray astronomer Hiroki Akamatsu of the Netherlands Institute for Space Research. Charged particles in Earth's ionosphere emit energy at frequencies that interfere with radio-astronomy telescopes. But in 2016 a team led by Reinout van Weeren of Leiden University in the Netherlands developed an effective calibration method for the LOFAR telescope that entails modeling the ionosphere and then removing its contribution from the radio-emission observations.[2]

With the new calibration, the LOFAR community "can basically limit the effects of the ionosphere and see what is really happening above the atmosphere of the Earth," says Wilber. "We made a lot of progress, and now we have very reliable results."

The new LOFAR findings, the 140 MHz synchrotron emission shown in figure 1, provide clear evidence for the previously unseen magnetic field. Astronomers have observed radio relic emissions, which originate from individual galaxies and galaxy clusters. But the LOFAR detection is the first to observe the emission connecting two distant clusters. The magnetic field extends 3 megaparsecs (about 10 million light-years) from the clusters, far enough that the emission cannot be mistaken for a radio relic. Using similar magnetic field properties of already identified clusters, Govoni and her team estimate that the field strength is less than 1 μG, or about one-millionth the strength of Earth's magnetic field.

Shocks to the system

Electrons in the magnetic field lose energy to synchrotron radiation and inverse Compton scattering over time. First-order calculations suggest that the electrons in the filament can therefore only travel at relativistic speed for 230 million years. At that rate, the maximum distance they could travel would be 0.1 Mpc, about one order of magnitude less than the length of the observed radio bridge. To get across the filament and its magnetic field, some mechanism acting along the entire cosmic-sized filament must accelerate the relativistic electrons to give them an extra boost.

To identify such a mechanism, one of Govoni's coauthors, Franco Vazza of the University of Bologna in Italy, performed magnetohydrodynamic numerical simulations.[3] In the model, the particles in the filamentary structure are energized by shock waves produced from merging clusters. The first simulation accelerated a population of relatively young electrons to not-quite-relativistic speed for 230 million years. But the associated radio emission was about one-thousandth as intense as the LOFAR observations.

Electrons need a GeV of energy to radiate detectable synchrotron emission at radio frequencies. The shock waves were too small and inefficient to get the job done in the first simulation. The second one reasonably reproduced the LOFAR intensities by including an additional, preexisting population of billion-year-old relativistic electrons that get accelerated by stronger merger-induced shock waves.

Several details about the mechanism still need to be worked out. Govoni and her colleagues do not know yet where the old relativistic electrons come from nor what mechanism fills the filament with them. "It is important to understand whether the emission detected in the filament that connects Abell 0399 and Abell 0401 is a common phenomenon in the cosmic web," says Govoni. "I hope that astronomers will soon find other magnetized filaments."

Alex Lopatka

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A big step for nanoporous graphene provides a small step for desalination

Carbon-nanotube reinforcement and template-based etching help scale up membranes.

Residents of Cape Town, South Africa, planned their daily lives around a quota of 50 liters of water per person per day during the first months of 2018. As the city's freshwater reservoirs dwindled, the municipal government rushed to bring a desalination plant on line. Fortunately, heavy rains in June ended the region's three-year drought. But the city's water crisis illustrated a situation that's becoming increasingly common in the face of growing populations and changing climate. The United Nations predicts that two-thirds of the world's population will face freshwater shortages by 2025.

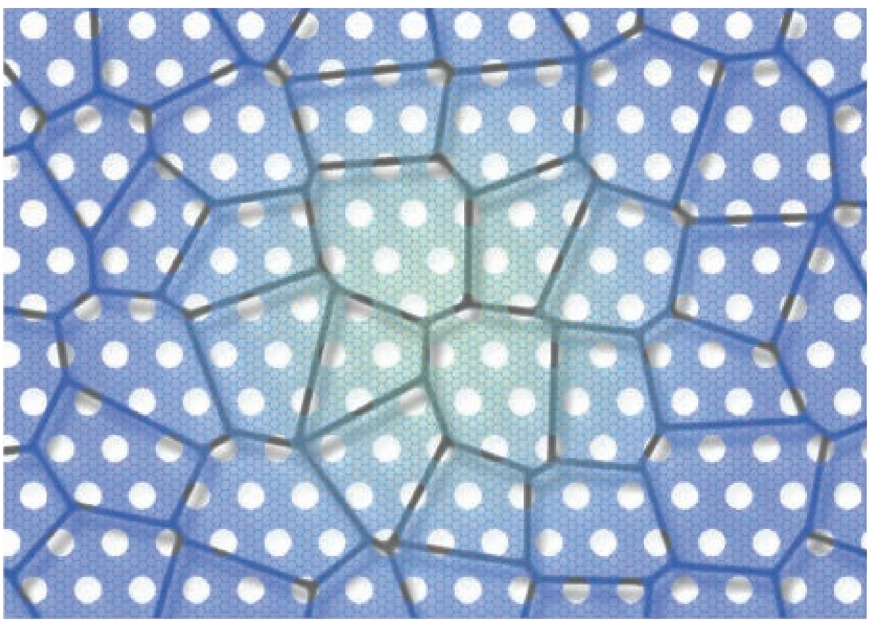

FIGURE 1. NANOPOROUS SINGLE-LAYER GRAPHENE is reinforced by a network of carbon nanotubes. The nanotubes create microscale sections, represented by the outlined polygons, that ensure the membrane's structural integrity. (Adapted from ref. 1.)

The planet's water is 97% seawater, which could in principle provide a steady freshwater supply. The first desalination plants were built in the 1960s, and now 20 000 facilities furnish water to 300 million people globally. Saudi Arabia produces 20% of the world's desalinated water and, along with the United Arab Emirates and Kuwait, relies on desalination for daily life. Israel meets more than half of its domestic needs with Mediterranean seawater, and desalination provides a third of Melbourne, Australia's municipal water supply. (See PHYSICS TODAY, June 2016, page 24.) The US Geological Survey estimates that the average American uses nearly 400 L of water per day. (The average water footprint per capita, which accounts for all goods and services consumed, is nearly 8000 L per day in the US.)

The original desalination plants were based on evaporating and then condensing seawater. Since 2005, however, most new plants have relied on reverse osmosis, and that method now accounts for 50% of the world's desalination capacity. In reverse osmosis, hydrostatic pressure forces saline water through a semipermeable membrane. Dissolved salts are blocked so that fresh water ends up on the other side. Reverse osmosis is the most energy-efficient desalination technology on the market. (See the Quick Study by Greg Thiel, PHYSICS TODAY, June 2015, page 66.)

Reverse osmosis, however, still suffers from poor freshwater recovery rates and high cost due to energy use. Some 40% of seawater and 80% of brackish groundwater can be recovered commercially as freshwater. The by-product is a briny concentrate. The plants require 3–10 kWh of electricity to produce 1000 L of fresh water. That's the energy equivalent of running an electric clothes dryer several times. Most of that energy is used to move saltwater through the membrane.

Research into reducing that energy focuses on improving membrane efficiency and durability. An ideal membrane should be thin to maximize water permeability, selective to isolate particles and solutes, and mechanically robust to avoid breakage and leakage. It also needs to be meters in size for use in commercial desalination. Today's reverse-osmosis

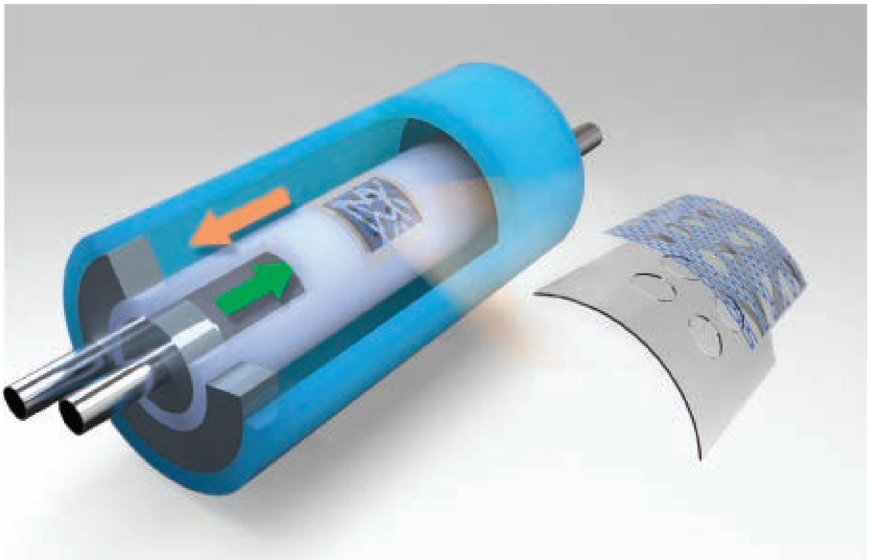

FIGURE 2. IN A TUBULAR DESALINATION MODULE, the nanoporous graphene membrane is fixed to a curved porous polymer substrate that is integrated into the innermost of two silicone tubes. Saline water (orange arrow) feeds into the aperture between the tubes and creates pressure on the membrane. Desalinated water (green arrow) is drawn out from the inner tube. (Adapted from ref. 1.)

plants mostly use polyamide composite membranes based on ones developed two decades ago. The membranes are easily clogged and require constant maintenance.

One alternative membrane being pursued by several groups around the world is a single layer of graphene perforated with an array of subnanometer-sized pores. The tiny pores trap salt but allow water molecules to pass freely. But nanoporous graphene tends to tear easily when its area is more than a few square microns. Now Xiangfeng Duan (UCLA), Quan Yuan (Wuhan University and Hunan University in China), and colleagues have designed a centimeter-scale freestanding, mechanically robust nanoporous graphene membrane, shown in figure 1, that filters salt and larger ions from saline solution and avoids fouling.[1]

Big, strong, and freestanding

Graphene's chemical and mechanical stability, its flexibility, and its single-atom thickness make the material attractive for membrane technologies. Based on molecular dynamics simulations, David Cohen-Tanugi and Jeffrey Grossman at MIT predicted that nanoporous graphene could have a water permeability orders of magnitude greater than conventional reverse-osmosis membranes.[2] For a single sheet of graphene etched with 0.45-nm-diameter pores, the simulations predicted 100% salt rejection.

Translating complete salt rejection from theory to practice meant finding a way to create pores without damaging the graphene's mechanical strength. Ivan Vlassiouk and colleagues at Oak Ridge National Laboratory did so by exposing a 50 μm × 50 μm square of defect-free graphene to short bursts of oxygen plasma.[3] To test the sample's desalination performance, the researchers transferred it to a silicon substrate that had a hole in the middle 5 μm in diameter. The section of exposed membrane over the hole rejected 100% of salt in a pressure-driven flow.

Commercial desalination, though, requires membranes with areas of square meters, not square microns. Scaling to larger sheets is difficult because grain boundaries weaken graphene's mechanical strength, and pores further compromise the structural integrity. In one recent development, Rohit Karnik and colleagues at MIT carefully sealed rips and leaks before creating pores in a sheet of graphene.[4] In another development by MIT researchers including Karnik, Piran Kidambi, and A. John Hart, a polymer support strengthened the membrane.[5]

Inspired by those advances, Yuan and her colleagues combined a series of steps to develop a strong, freestanding, and flexible membrane. The researchers started with a single layer of graphene, which they grew by chemical vapor deposition to avoid grain boundaries. Then they reinforced it with a layer of carbon nanotubes. Finally, with a mesoporous silicon dioxide film as a mask, the researchers punched a grid of 0.3- to 1.2-nm-diameter holes using short bursts of oxygen plasma. The SiO_2 film had a uniform grid of pores several nanometers wide; removing the film left a precise network of pores in a strong, freestanding, 50-nm-thick membrane. As illustrated in figure 1, the nanotubes partitioned the membrane into micron-sized islands and acted as a supportive framework.

The researchers constructed a benchtop filtration system that pumped saline water across a flat section of membrane. The membrane blocked 85% of sodium chloride and up to 98% of larger-molecule solutes. It also withstood pressures up to 10 MPa, characteristic of commercial filtration systems, and achieved permeability two orders of magnitude higher than that of commercial membranes.

The carbon nanotube network had the mechanical strength and flexibility to endure large deformations without compromising structural integrity. A 0.36 cm^2 sheet of the membrane suspended on a frame supported 0.16 g without rupturing. Yuan also synthesized a graphene-only sample without the nanotube reinforcements. When she applied pressure to the center of the graphene-only version with a 0.5-μm-diameter pin, the sample quickly cracked into small pieces.

To improve desalination output, commercial membranes are usually rolled into a tubular structure to maximize their contact area with the water. Unlike previous graphene membranes, Yuan's is mechanically sound enough to bend into that configuration. She tested its performance in the module shown in figure 2. Despite some small cracks that formed during the bending process, the tubular membrane still removed 95% of the salt after 24 hours of operation.

Scrubbing salt from the wound

Commercial-scale nanoporous graphene may still be years away. Although Yuan's technique for drilling pores achieved an impressively narrow size distribution, with 95% of the pore diameters between 0.5 nm and 0.75 nm, simulations indicate that pores greater than 0.55 nm in diameter may allow salt through. Additionally, larger sheets are more prone to larger-than-desired pores and defects. And growing graphene sheets by chemical vapor deposition makes the cost of a nanoporous graphene membrane much higher than that of a polymer membrane.

Even with improved membrane technology, desalination will still be plagued by environmental problems. Disposing of the concentrated brine left behind after desalination is no simple matter. Pumping it back into the ocean changes the region's salinity and harms ocean life. Also of concern are the copper and chlorine that get added to seawater at various stages in the desalination process. They help to control bacterial growth and reduce corrosion but remain in the discharged brine.[6]

Rachel Berkowitz

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Teleportation for device-scale quantum computing

Trapped ions interact with help from an entangled pair of messengers.

A quantum computer will need a method to perform logic operations on qubits that are physically distant. Gate teleportation, proposed 20 years ago,[1] does just that. It takes an approach similar to teleporting a qubit (see the article by Charles Bennett, PHYSICS TODAY, October 1995, page 24) and uses entangled particles, or messengers, to teleport a logic gate that executes the operation. The messengers are entangled beforehand, and each one travels to a qubit and ropes it into the entangled state. Gate teleportation may also help deal with error propagation (see the article by John Preskill, PHYSICS TODAY, June 1999, page 24).

In a modern classical computer, a switch uses many electrons, $N \sim 10^5$ or more. Provided the number of electrons doesn't deviate by more than $\sqrt{N}$, the gate works flawlessly—typical failure rates are less than 10^{-18}. In a quantum logic gate, any error in the input carries over to the output, and the gate can't correct itself. The best isolated two-qubit quantum gate operations in trapped ions have an error rate of 10^{-3}. A quantum computation that enlisted more than a modest 1000 gates would always fail—without quantum error correction, that is.

To correct errors, a quantum computer needs redundancy: The more qubits encoding the same information, the less likely all, or even a majority, of them will err. A practical device would use many physical qubits to encode every logical qubit in the computation and require millions of physical qubits total. But a device that large can't have all its qubits in close proximity. Gate teleportation is one way for qubits to interact without the inherently slow process of migrating distant qubits together.

Now the Ion Storage Group at NIST in Boulder, Colorado, has demonstrated gate teleportation in trapped ions.[2] The experiment was led by Dietrich Leibfried, Andrew Wilson, and David Wineland. Gate teleportation serves as a test case for many necessary features of a trapped-ion quantum computing architecture that can be scaled to thousands or even millions of qubits (see the article by Ignacio Cirac and Peter Zoller, PHYSICS TODAY, March 2004, page 38).

Making it happen

Fifteen years ago, Guang-Can Guo of the University of Science and Technology of China and his collaborators demonstrated

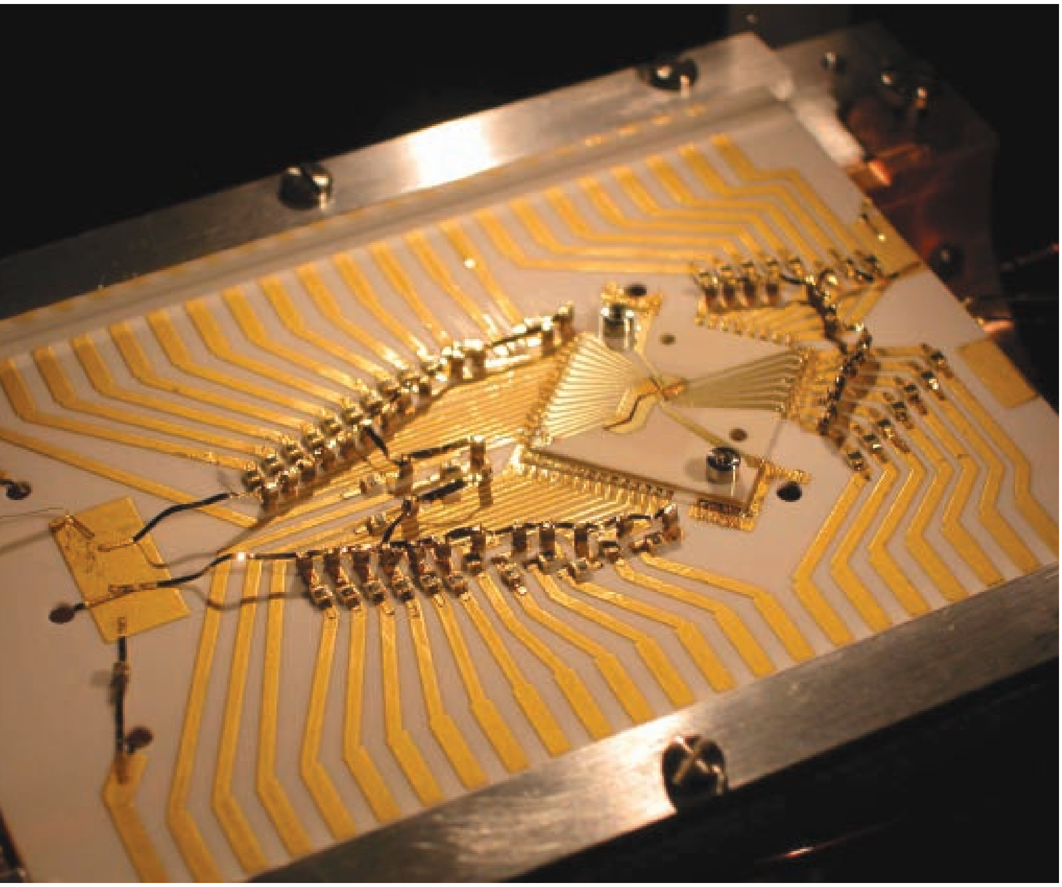

FIGURE 1. NIST'S TRAPPED-ION DEVICE uses electrodes to shuttle around ions trapped in potential wells. The interaction zone, where ions are exposed to a laser, is near the center of the about 15 mm × 15 mm square region on the right. (Courtesy of Brad Blakestad.)

that they could teleport gates in a photonic system probabilistically.[3] To move from probabilistic to deterministic gate teleportation requires real-time measurement and the communication of that classical information from one qubit to the other. That's because only a specific state of the messengers teleports the correct gate. For deterministic gate teleportation, therefore, the messenger state must be measured and adjusted if it is not the one desired. Deterministic gate teleportation was demonstrated a year ago in superconducting qubits[4] by Yale University's Robert Schoelkopf and colleagues. In that work, the researchers used superconducting microwave cavities as the logic qubits and a type of superconducting qubit, called a transmon, as the messengers.

The NIST researchers built a device that implements qubits using ions stored in potential wells that can be brought together, separated, and moved around the device, including to an interaction zone where qubits are exposed to laser fields. Using the device, the team deterministically teleported a controlled-NOT (CNOT) logic gate, similar to the classical exclusive-OR (XOR) gate, in which a target qubit's spin flips only if a control qubit's spin has a specific orientation. A CNOT operation paired with single-qubit rotations can perform any possible operation in quantum computing. Wineland and his colleagues demonstrated a CNOT gate in 1995 on a single beryllium ion in a harmonic trap, with the ion's electronic state as one qubit and its vibrational state as the other.[5]

The new device, shown in figure 1, requires two specific capabilities. First, physical manipulations such as shuttling, separation, and recombination of the ions must be accurate and reliable. Second, ions of different types must be capable of entanglement so that they can take on specialized roles, such as memory storage or helping in error correction. The second capability is crucial, and the NIST team accomplished it only a few years ago through a laser-driven direct CNOT operation on Be^+ and Mg^+ ions.[6] The biggest technical achievement in the new study is implementing all of those things in a single device.

Gate performance

In the gate-teleportation experiment, NIST postdocs Yong Wan and Daniel Kienzler, now at ETH Zürich, perform a CNOT operation on two Be ions (B1 and B2 in figure 2) kept over 300 μm apart. First, they prepare B1 and B2 in a superposition of spin states and entangle two magnesium ions (M1 and M2) to use as messengers. M1 is shuttled off to B1, where a local CNOT operation entangles B1, M1, and M2. A measurement of M1's spin removes it from the entangled state and leaves B1 and M2 entangled. If M1's spin is up, B1 and M2 are in the desired state. If M1's spin is down, M2's spin is flipped to achieve the desired state. Afterward, M2, which has been shuttled to B2, is entangled with B2 through another local CNOT, and a measurement of M2's spin leaves B1 and B2 entangled. After a conditional phase flip on B1 if M2 is spin down, the teleported CNOT gate between B1 and B2 is complete.

The sequence performs as expected for an ideal CNOT 85–87% of the time—Schoelkopf and colleagues obtained a similar fidelity, 79%, in their study on superconducting qubits.[4] In NIST's trapped-ion platform, the error rate for each of the steps when performed together in the same device was higher than the best rate for any one operation in isolation. The largest error contribution, about 4%, came from entangling M1 and M2. Notably, the error was about the same, or less, for entanglement between different types of ions: It is only about 3% for the CNOT between B1 and M1. The current error rate is too high to put the gate to work in practically useful quantum computers. However, researchers now know which steps in trapped-ion devices need the most improvement.

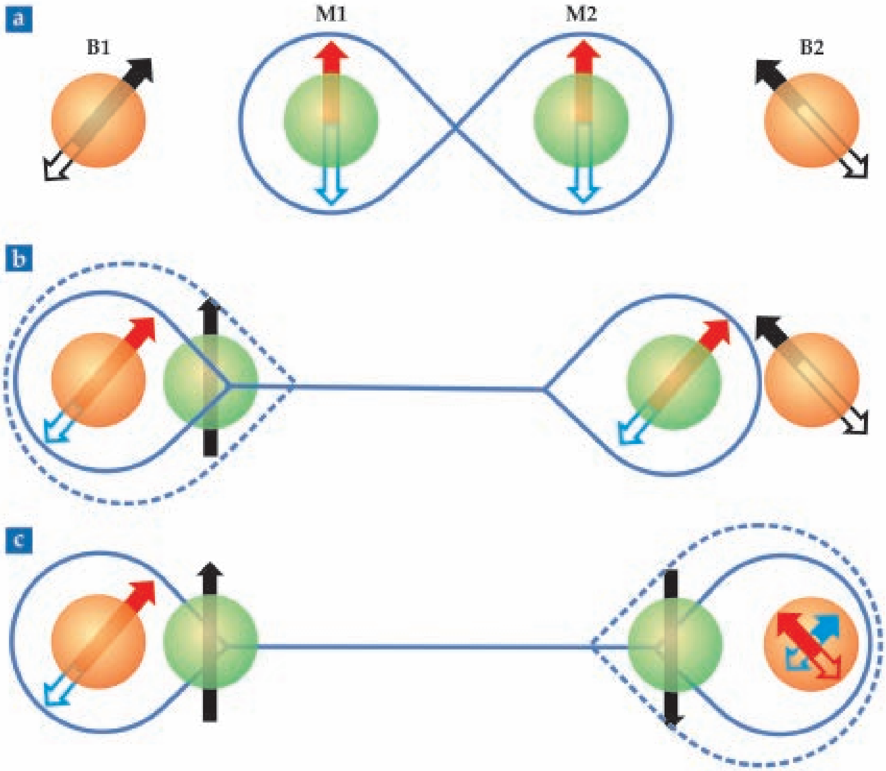

FIGURE 2. GATE TELEPORTATION BETWEEN TWO QUBITS, beryllium ions B1 and B2 (orange), requires messengers, magnesium ions M1 and M2 (green). **(a)** The messengers are prepared in an entangled state of spin-up and spin-down. B1 and B2 are each in a superposition of spin-up and spin-down and are too far apart to interact directly. **(b)** A local CNOT operation brings B1 into the entangled state, and a measurement on M1 removes it from the entangled state. **(c)** A similar process on B2 and M2 yields the desired CNOT gate operation between B1 and B2. (Courtesy of Dietrich Leibfried.)

Quantum computing platforms

Gate teleportation can be a test for the pros and cons of different quantum computing platforms—for example, architectures based on superconducting qubits or trapped-ion qubits. "Development of large-scale quantum computing is such a massive undertaking that devices will likely be a hybrid of different technologies," says Leibfried. "There probably won't be a single winner, and therefore, in this field it's crucial to advance multiple platforms."

The group's device needs improvement before the number of qubits can be increased significantly, but it is a major step toward the quantum charge-coupled device (QCCD), a proposed architecture for quantum computing using trapped ions. Presented in 1998, the QCCD houses many interconnected ion traps. Changing the voltages on its electrodes shuttles ions from trap to trap, and regions are set aside for memory storage or interaction with other ions. Overall, it is similar to the device used for gate teleportation but accommodates more qubits.

In the proposed QCCD, entangled pairs of ions for gate teleportation can be churned out in a dedicated part of the device, stockpiled in advance, split up, and shipped throughout the device. With messengers ready to go, gate operations would not need to wait for ion qubits to be moved together. The same entangled messenger states can teleport many different kinds of gates, and used messengers can be entangled again and redeployed.

Heather M. Hill

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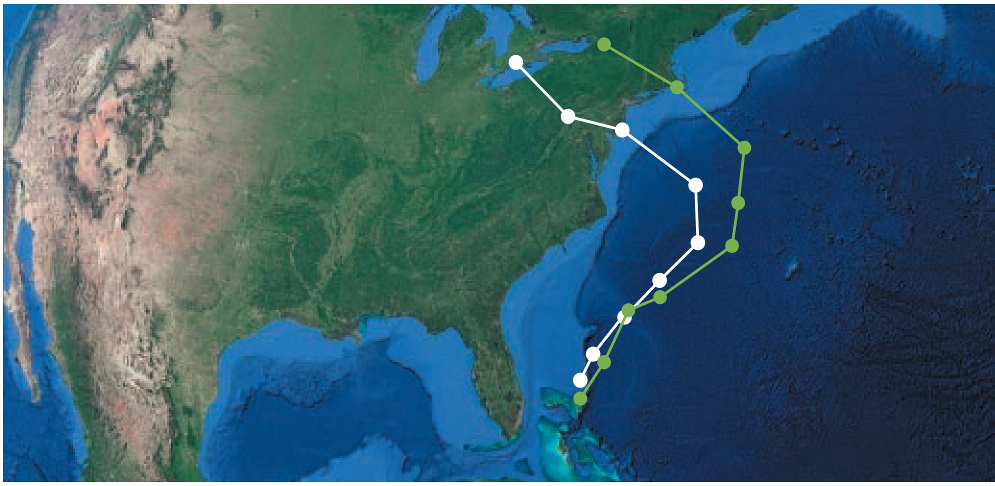
Fifth-generation broadband wireless threatens weather forecasting

Radio-frequency interference from upcoming 5G networks may make it more difficult to collect critical water-vapor data.



THE SUCCESSFUL HURRICANE SANDY FORECAST (white) is compared with one (green) that removed the contribution of water-vapor data from the model of the European Centre for Medium-Range Weather Forecasts in Reading, UK. Rather than predicting the hit along the New Jersey and New York coasts, the forecast without water-vapor data put landfall in Maine. Many meteorologists worry that passive microwave instruments that collect critical water-vapor data from satellites may be disrupted by upcoming 5G technology. (Adapted from T. McNally, M. Bonavita, J.-N. Thépaut, *Mon. Weather Rev.* **142**, 634, 2014. © American Meteorological Society. Used with permission.)

The fight is on over 5G. Telecommunication companies and the US government promote the latest mobile broadband because it will provide faster data-transfer rates than the current broadband communication standard. Faster, more reliable digital communication is needed for the newest technologies—autonomous vehicles, internet-of-things devices, and smart energy grids, among others. But meteorologists, US science agencies, and other countries worry that strong 5G signals, if not properly regulated, may interfere with satellites that are crucial to weather forecasting.

Today's 4G network, nearly a decade old, moves data by bouncing radio waves between cell towers and devices such as smartphones. A 5G network would operate similarly but use a wider frequency range and more bandwidth, which would increase data-transfer rates by an order of magnitude. The higher-frequency signals proposed for 5G can't travel through buildings like their lower-frequency 4G counterparts, but specialized antenna arrays would transmit the 5G signal across long distances. Earlier this year, two telecom companies in South Korea launched small 5G networks using busy lower-frequency bands, and Verizon deployed a 5G test in Chicago at the higher-frequency 28 GHz band.

Widespread 5G deployment will depend on building a new infrastructure of antennas that operate in high-frequency radio bands. Telecom companies and US regulators support 24 GHz for 5G networks because of its greater bandwidth and because the 1–6 GHz radio spectrum is already crowded with 4G, digital TV, radar, and other applications. (The 24 GHz band spans 24.25–24.45 GHz and 24.75–25.25 GHz.)

Spectrum is a finite resource, and the Federal Communications Commission (FCC), which coordinates the commercial use of spectrum in the US, is racing to allocate as much higher-frequency spectrum as possible for 5G technology. The FCC "5G FAST" plan, unveiled in September 2018, is bringing more spectrum to market, updating infrastructure policy, and modernizing regulations. Other bands are being considered, including 28, 37, 39, and 47 GHz.

In October at the United Nations International Telecommunication Union Radiocommunication Sector (ITU-R) conference, member countries will discuss and vote on how to regulate the 5G signal in the 24 GHz band. The US is poised to push for a higher maximum 5G signal power than what European countries favor. Lower signal power would decrease the range of the 5G signal.

Radio chatter

"The precipitating issue here is the potential for what's called out-of-band interference," says Jordan Gerth of the University of Wisconsin–Madison. Water-vapor molecules emit electromagnetic radiation at 23.8 GHz, and instruments such as the Advanced Technology Microwave Sounder aboard NOAA's Joint Polar Satellite System infer atmospheric air-temperature and moisture data from the 23.6–24.0 GHz emission band. The measurements are used to calibrate numerical weather-prediction models, such as NOAA's Global Forecast System (see PHYSICS TODAY, May 2019, page 32).

Radio signals transmit at their highest power at a central frequency, and the signal progressively loses power at more distant frequencies. A 5G signal, therefore, could leak across the 250 MHz gap between the water-vapor emission band and the 24 GHz 5G band, which could make it nearly impossible for microwave instruments to differentiate between water vapor and emissions from multitudes of 5G smartphones. Microwave instruments have no other frequencies they can use to sense water vapor. Filtering for noise from a 5G network would be difficult, especially for broadband transmitters, says Joel Johnson of the Ohio State University. "If there's thousands of these little transmitters all over the place, then it's very hard to correct for them." Documents provided by two other passive microwave experts—who, like many sources for this story, spoke on condition of anonymity—indicate that 16 operational weather satellites worldwide use passive microwave sounders or imagers to gather water-vapor data. Another 18 future satellites worldwide scheduled for deployment from 2021 through 2036 could be affected by 24 GHz 5G interference.

The FCC, NASA, the US Navy, and NOAA have been analyzing the potential for 5G interference since 2017. During a hearing of the House Science, Space and Technology Subcommittee on Environment on 16 May 2019, Neil Jacobs, a NOAA assistant secretary of commerce, explained that using the 24 GHz band for 5G with the signal strength proposed by the FCC, −20 decibel watts per 200 MHz, would decrease the data collected from microwave instruments by 77%.

Jacobs said that such data loss "would degrade the forecast skill by up to 30%" and return the US weather prediction capability to "somewhere around 1980." Citing an unpublished NOAA study, he further testified that a lower signal strength of −40 or −50 dBW per 200 MHz "would result in roughly zero data loss." That range, one-hundredth to one-thousandth of the FCC's proposed limit, was determined with guidance from the ITU-R and industry.

However, on 12 June, FCC chairman Ajit Pai told the Senate Commerce, Science, and Transportation Committee, "We [at the FCC] believe that our protection limits are appropriate. . . . In our view, the assumptions that undergird that [NOAA] study are fundamentally flawed." Pai noted that the NOAA study did not consider beamforming technology, which employs adaptive antenna arrays to focus radio waves to specific receivers and is already used in 4G networks and other applications.

Beamforming, though, would not solve the interference problem, according to two experts in passive microwave sensors and the regulatory process. The technology wouldn't mitigate out-of-band interference. Furthermore, beamforming wouldn't protect satellite instruments against interference from upward-scattered signals in urban environments, according to the experts.

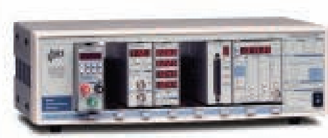
Political noise

Despite concerns from NASA, NOAA, and several countries, the FCC auctioned 24 GHz spectrum this past spring. The two highest bidders, T-Mobile and AT&T, respectively paid about $1 billion and $800 million for licenses. T-Mobile didn't return a request for comment, and an AT&T spokesperson said the details were still under a company "quiet period." An FCC source confirmed that the license contracts do not specify signal strength. In a different auction earlier this year, the FCC sold 28 GHz spectrum for 5G: Verizon paid $500 million for licenses, and T-Mobile spent $40 million.

The FCC has a pre-auction commenting period to help determine how to regulate the use of spectrum. "As a matter of practice, the FCC does not conduct its own studies," says a source at the FCC. But according to a lobbyist for the meteorological community, the commenting process is so convoluted that "it's become the realm of regulatory attorneys" rather than concerned citizens and scientists. "You really need to have a full-time law firm to be able to track this stuff," the lobbyist said, and added that the FCC has "experts in wireless technology, but it does not mean that they have any expertise in meteorology or meteorological technologies."

The 5G conflict escalated when Commerce secretary Wilbur Ross and NASA administrator Jim Bridenstine sent Pai a cease-and-desist letter a week before the 24 GHz auction. Pai refused to delay the process. In the immediate aftermath, David Redl resigned from his post as assistant secretary of the National Telecommunications and Information Administration, which manages federal spectrum use and identifies other spectrum bands for commercial use. Several sources say that Redl's resignation is a direct result of the interagency dispute.

The meteorology lobbyist and a telecom lobbyist both said that the White House has pressured the FCC to quickly bring spectrum to market. They said President Trump hopes that touting auction revenue and bringing broadband to rural voters will help his 2020 campaign. The FCC source denied any pressure, saying that "spectrum policy is driven by the FCC."



NEW 5G ANTENNAS (LEFT) ARE SMALLER THAN 4G ONES (RIGHT). Upcoming 5G networks will use higher-frequency radio spectrum, which will provide more bandwidth and enable the faster data-transfer rates that new technologies, such as autonomous vehicles, smart energy grids, and internet-of-things devices, will demand. (Photos by KPhrom/Shutterstock.com.)

According to a May 2019 report by the White House Office of Science and Technology Policy (OSTP), the Trump administration believes that 5G is "one of four industries of the future that will ensure American prosperity and national security." In a separate interview, the OSTP director, atmospheric scientist Kelvin Droegemeier, said he is "absolutely convinced we'll address [5G] in a way that will bring maximum benefit to taxpayers and minimum disruption to the services we need to provide." (See "Q&A: Kelvin Droegemeier, President Trump's science adviser," PHYSICS TODAY online, 30 May 2019.)

A trade association of telecommunication companies, CTIA, supports the White House in wanting 5G implemented quickly across many currently unused bands. In a May 2019 blog post, CTIA executive vice president Brad Gillen argued that the Commerce Department's caution regarding interference from 5G is "undermining our global leadership efforts." Establishing a national position on 24 GHz for 5G, Gillen claimed, is critical before October, when the monthlong ITU-R World Radiocommunication Conference (WRC-19) takes place in Egypt.

International negotiations

At WRC-19, expert study groups organized by the ITU-R will discuss the results of their 24 GHz interference analyses before UN member countries vote on 5G signal strength. Paolo de Matthaeis, a remote-sensing researcher at NASA's Goddard Space Flight Center and technical chair of the IEEE Geoscience and Remote Sensing Society's committee on frequency allocations in remote sensing, says a majority of member nations must agree in order to issue a new regulation or alter an existing one. By arguing that the FCC has already set a 5G signal level through various auctions, he says, the US could negotiate for a looser regulation of the 24 GHz band.

Member countries are not obligated to follow an ITU-R regulation if their activities don't affect others. But if the US adopts a stronger signal for the 24 GHz band, global weather models may suffer. Other member countries could argue for the US to adhere to the proposed ITU-R regulation, says de Matthaeis.

ITU-R member countries at WRC-19 will consider about a dozen other bands above 24 GHz for 5G use. A report by the UK-based trade group GSMA recommends using the 26, 28, 40, and 66 to 71 GHz bands. The report says that the 26 and 28 GHz bands have the most international support because they are adjacent and easily harmonized, so they can be allocated for use across country borders.

The US ITU-R delegation is finalizing its official position on allowable signal levels for 5G networks. The Inter-American Telecommunication Commission (CITEL), a coalition of North, Central, and South American countries, will discuss the limits for the 24 GHz band this month in Ottawa, Canada. "The US will try to convince the other CITEL countries to adopt its position," says de Matthaeis. "If that happens, it will carry considerable weight into WRC-19."

Alex Lopatka

Germany's most visited museum struggles to complete renovations

A preeminent museum of inventions reinvents itself to explore the social relevance of scientific and technological progress.

THE DEUTSCHES MUSEUM in Munich is in the midst of a major makeover.

TONI FEDER

At the Deutsches Museum in Munich, visitors can see a Wright Brothers' Model A biplane from 1909, the Magdeburg hemispheres with which Otto von Guericke performed his pioneering vacuum experiments in the 17th century, and some 28 000 other emblems of progress. Since it opened in 1906, the museum has showcased and explained science and technology with an emphasis on advances that impact society. "We don't show every Apple computer," says museum director Wolfgang Heckl. "We show the first one, and the first iPhone, because they are iconographic of revolutions."

Now the museum is in the midst of a head-to-toe overhaul. The renovations were officially launched in 2006, after local authorities said the buildings had to be updated to meet modern safety codes—or be shuttered. Among the upgrades are improved emergency egress and a €10 million ($11.4 million) skirt that extends 12 meters deep to bedrock to prevent water seeping into the basements.

As the museum implements those and other measures, it is taking the opportunity to modernize its exhibits, many of which are decades old. Most transformational is the museum's overarching aim to present social context and engage the public in topics, some controversial, that have global implications. "Our museum wants to show the future of science and technology as well as the past," says Heckl. "The whole idea of the new exhibitions is to provide information so visitors can discuss issues and form opinions. In a sense, we are becoming much more political."

Financial morass

Renovations started on the roof and facade in 2011, and ramped up in 2015. They are scheduled for completion in 2025, the centenary of the museum's move to its island site in the Isar River. The museum has raised €445 million for the renovation project, with 10% in donations from industry and the rest from the state of Bavaria and the German federal government. The funds were initially intended to cover the main construction work and new exhibitions, but it was clear from the get-go that it would be tight. At least another €150 million will be needed, Heckl says.

Unforeseen problems that stem from the building's original construction, the financial collapse of the architectural firm hired to design the renovations, a worker shortage, and other sources of delay are pushing costs up even more. A perception of ineptness and obfuscation surrounding the cost estimates has created disgruntlement among the region's policymakers, according to local news reports. On 25 June the museum's board of directors gave Heckl and the management team until fall 2020 to come up with a detailed plan and budget for the full renovation.

The exhibit renovations are planned in two stages. Roughly half the museum's 50 galleries are currently closed and scheduled to reopen in 2021, when the others are to close for makeovers. Unless more money is found soon, however, some of the renovations, and the reimagining and reopening of some galleries, will be delayed.

"Arguments for answers"

From its start, the museum featured not only a collection of historical objects but also hands-on experiments, which for the time was revolutionary. "Touching things in a museum!" says Heckl. "That was outrageous." Dioramas ranging from less than a meter on a side to several meters make up a third pillar of displays at the Deutsches Museum. "They are much more fascinating than a video screen or multimedia," says Andreas Gundelwein, who oversees the museum's galleries. The dioramas are researched and crafted at the museum; each represents several thousand hours of work.

The museum became a model for similar institutions, such as the Museum of Science and Industry in Chicago, founded in 1933, and the San Francisco Exploratorium, established in 1969. The full collection of the Deutsches Museum comprises more than 100 000 objects. To view every exhibit would require walking about 18 kilometers. Some 1.5 million visitors a year tour the museum.

The Deutsches Museum has a research division on site and close ties with academia, and it also houses extensive science and technology archives and libraries.

A POPULAR DEMONSTRATION highlighting the characteristics and properties of liquid nitrogen will survive the Deutsches Museum's renewal.

In recent decades the museum opened outposts in Munich on aviation and land transportation and a branch in Bonn that focuses on German research and technology.

One hall of the museum features an exhibition on nano- and biotechnology, where since 2009, scientists have conducted research in public view and answered visitors' questions. It includes historical objects, such as a cardboard model of an early scanning tunneling image made by Gerd Binnig, who shared the 1986 Nobel Prize in Physics for inventing the scanning tunneling microscope. The exhibition is related to federally funded joint work with several local universities and other research partners and represents one way the museum supplements its income.

A nearby exhibit exemplifies the museum's new head-on approach to controversial topics: Six images of faces protrude from a wall; they introduce themselves and launch into their views on genetic testing. A woman who works for a health insurance company says the results of genetic testing should be provided to insurers. A man with a rare genetic disease opposes testing because it could lead to abortions of fetuses with a condition such as his. Another man contemplates testing to plan a baby that could help provide an existing child with bone marrow transplants, and so on. The statements are read by actors and attributed to fictional people. The exhibit includes legal, ethical, and other information; surveys visitors about their opinions; and tallies the results.

In the same vein, many of the museum's historical exhibits will be refreshed to include more social and historical context. The original signage next to a Messerschmitt Me 163, for example, touted the rocket-powered interceptor from World War II as a "masterpiece" of German engineering and praised it for its swept wings and tailless design, says aviation curator Andreas Hempfer. Not previously included were the facts that the plane was built by forced laborers, was dangerous to fly, and performed poorly in combat. Presenting the full story, says Hempfer, "is part of our greater focus to be more critical about technology and put it in its social context."

Expanding context and scope goes beyond individual exhibits. The agricultural gallery, for example, has always featured farm machines and an idyllic *Almhütte*—an Alpine hut for small-scale farming. Those exhibits will remain, but they will focus on food production for the world's growing population and feature information on satellite imagery and on social implications such as the distribution of wealth. Among the topics to be addressed are raising animals for slaughter, using chemical fertilizers and pesticides, and genetic engineering and other plant breeding methods.

"What does high meat consumption mean for the world? For the environment? For the visitor?" asks Helmuth Trischler, the museum's head of research. The museum looks at how to present controversial topics, he says. "How do visitors respond to conflicting evidence? How do they tolerate scientific ambiguity?"

From the genetic testing exhibit, and from recent special exhibitions on renewable energy and on the Anthropocene, specifically human impact on Earth's geology and ecosystems, museum researchers know that visitors like to engage. "We want to give arguments for answers," says Johannes-Geert Hagmann, head of the museum's curatorial department for technology. "What would you do if you were a policymaker?" (See also the interview with Hagmann about his career path, PHYSICS TODAY online, at http://physicstoday.org/hagmann.)

The physics portfolio

The physics galleries are scheduled for updating in the second phase of the museum's renovations and will happen only if more money comes through. But they are ripe for renewal, says physics curator Daniela Schneevoigt. Demonstration experiments date back to the 1960s, and "people walk through pushing buttons instead of learning from them."

Schneevoigt plans to cull those experiments and to make the ones that remain more hands-on. She also plans to bring out from storage the resonators, mirrors, and other instruments that Heinrich Hertz used to study electromagnetic waves in the 1880s and original tubes, photographs, and other equipment used by Wilhelm Röntgen, who discovered x rays in 1895. And subject to approval from internal and external advisory boards, she'd like to replace the re-creation of Galileo's workroom with a set of compact dioramas. She says she wants to "show how the lab environment has changed over time, and not just stress one single scientist but rather show how science is becoming more diverse, interdisciplinary, and international."

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A PROTOTYPE VEHICLE, which on voice or eye-tracking command rises out of traffic, expands accessible travel space to a third dimension. Controlled by artificial intelligence, the removable capsule would detach from its chassis and land on a different one. It will be on display when the Museum of the Future, a branch of the Deutsches Museum, opens in Nuremberg in December 2020.

The physics exhibition will also absorb the measurements gallery, which has been separate. Many of the historic instruments will be moved to storage, but a recent addition to the collection is already on display: a smooth silicon sphere that was used to measure Avogadro's and Planck's constants. The measurements informed new definitions of the mole and kilogram, which were adopted this past May.

"There are some hard choices," says Trischler. The reopened museum will include only about 60% of its previous exhibits, he says. Still, the museum will remain true to its goal of telling stories about science and technology and connecting the interactive exhibits with the artifacts. Among the icons that will remain are a giant Foucault pendulum and a hanging Faraday cage in which a member of the museum staff sits safely during a seemingly alarming transformer discharge of up to 270 kilovolts.

The fate of a model mine depends on independently raising between €10 million and €20 million to bring it up to code. The zigzagging walk through the 400-meter-long mine is one of the most liked exhibits at the museum. Even so, several visitors commented that it could go in favor of exhibits that represent modern science and technology.

Hagmann is overseeing the revamping of the optics exhibitions, which will be divided into two parts. The first exhibition, slated to open in 2021, will cover from antiquity through 1930. The second will focus on quantum optics and will open in 2025. Funded externally by a joint grant to museum and university researchers, the quantum optics exhibition is part of the collaboration's public outreach.

One highlight of the first optics exhibition will be a trio of dioramas, each roughly a cubic meter in size, that links scientists across history on the themes of light and sight; all three scenes are built around the topic of the camera obscura. The first scene shows philosophers in ancient Athens examining speckles produced by sunlight filtering through leaves. The second shows Cairo-based scientist Ibn al-Haytham and his experiments, in which light from a candle flame appears upside down after going through a slit in curtains. The third depicts Johannes Kepler in Dresden in the early 17th century, when the floating images produced by a large lens led him to his theory of visual perception.

As part of the renewal, the museum will digitize its collection. That includes putting images, videos, and documentation online. As an example, Trischler points to Konrad Zuse, who built the first fully operable programmable digital computer, the electromechanical Z3, in Berlin in 1941. In digitally bringing together his artifacts, laboratory notes, correspondence, papers from his company, and his library, says Trischler, "we get a view of the process that resulted in the computer."

Museum of the Future

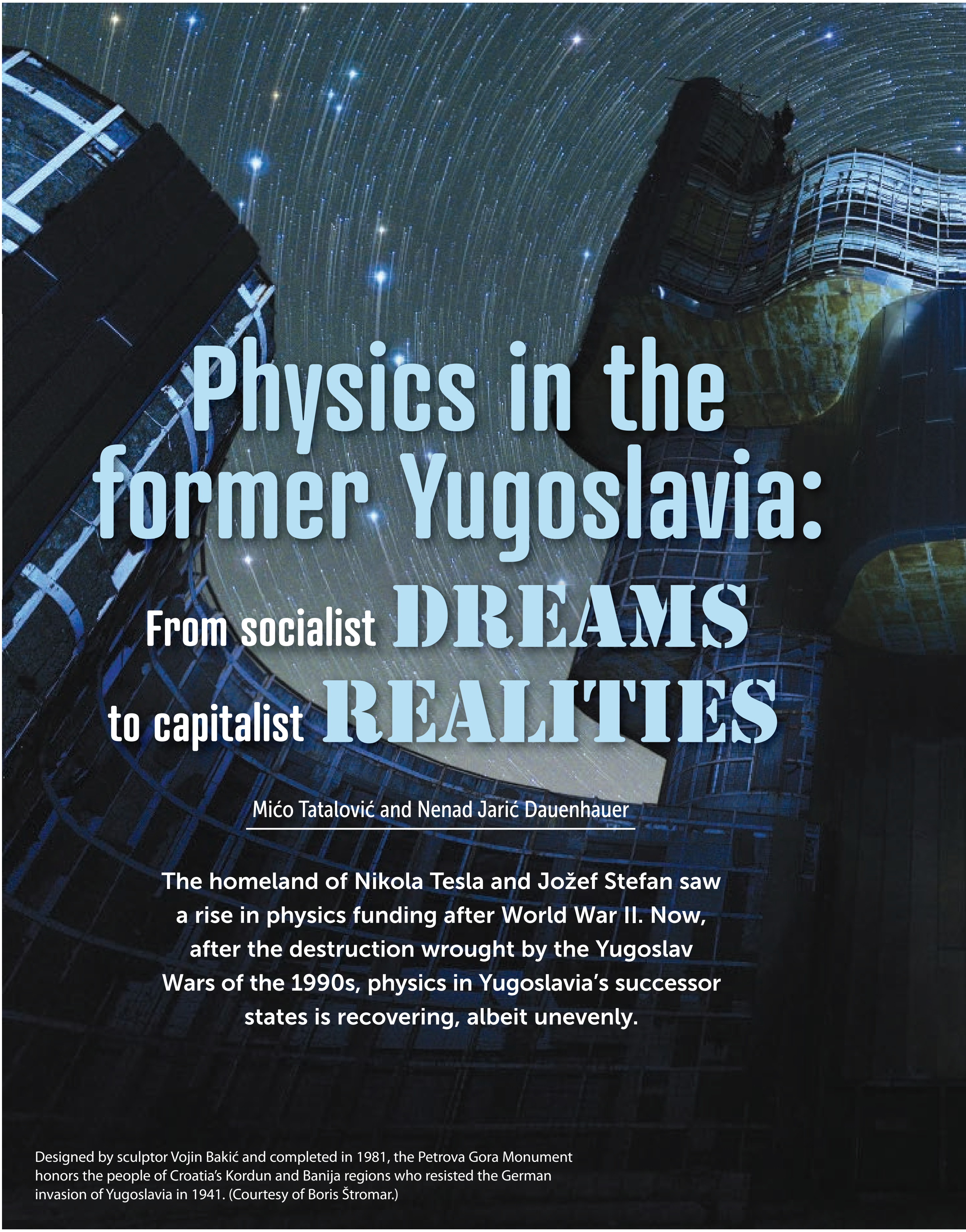
Concurrent with the renovations, the Deutsches Museum is preparing its new Museum of the Future, set to open in Nuremberg in December 2020. It is separately funded with €27.6 million, plus €7 million a year, as part of a mostly state-funded initiative to stimulate the economy and promote northern Bavaria.

The Nuremberg museum will focus on science and science fiction across five themes: body and mind, work and daily life, urban life, system Earth, and space and time. The exhibits, which will be changed at least every other year, will include prototypes of futuristic technologies and questions for discussion. The intended audience is people from ages 12 to 20. "For them, the future is most important," says Gundelwein, who spearheads work on the new museum. An example is a 3D printer that uses human cells; the eventual goal is to print a human heart. The museum will update the printer, and the heart, as advances are made. The scientist who is developing the technology envisions such an instrument in every operating room, says chief curator Melanie Saverimuthu. "It is for the visitor to decide, Would you like this technology? Would you want to live forever?"

Visitors to the Museum of the Future may be surprised when personal messages and photos from their own smartphones appear on the museum walls. That will be an experiment, and it is in the final stages of obtaining legal clearance, says Gundelwein. "We hope the young people will use [our free wireless] until they detect their personal use on display. And we hope that will be the moment when they think about privacy issues."

Both in the Museum of the Future and in the rethinking of the mother ship, "we want to introduce the interactions between technology and society and promote critical discussions," says Gundelwein. "We are changing from a pure technology museum to a museum of technology and society."

Toni Feder PT



Physics in the former Yugoslavia:

From socialist DREAMS to capitalist REALITIES

Mićo Tatalović and Nenad Jarić Dauenhauer

The homeland of Nikola Tesla and Jožef Stefan saw a rise in physics funding after World War II. Now, after the destruction wrought by the Yugoslav Wars of the 1990s, physics in Yugoslavia's successor states is recovering, albeit unevenly.

Designed by sculptor Vojin Bakić and completed in 1981, the Petrova Gora Monument honors the people of Croatia's Kordun and Banija regions who resisted the German invasion of Yugoslavia in 1941. (Courtesy of Boris Štromar.)

Mićo Tatalović is a science journalist from Rijeka, Croatia. He is based in London. **Nenad Jarić Dauenhauer** is a science journalist from Zagreb, Croatia.

Houston, we have a problem! A fictional Slovenian documentary by that name shook the Western Balkans three years ago by positing that Yugoslav leader Josip Broz Tito had sold his country's secret space program to the US for $3 billion in aid money a few years before the Apollo Moon landings. A secret underground hangar, faked deaths of scientists working on the Yugoslav program to cover their actual transfer to the US, and a visit to Washington, DC, where Tito narrowly escaped an assassination attempt months before President John F. Kennedy was killed made for some tense viewing. Could any of it be true?

Yugoslavia did have an active rocket program. Some of its citizens worked for NASA. Slovenian astronautics pioneer Herman Potočnik Noordung had published ideas in 1928 that were ahead of his time. And Tito once reportedly asked Mike Vucelić, a Yugoslav NASA engineer who worked on the Apollo program, to bring space travel "back home." The media and scientists have since debunked most of *Houston, We Have a Problem!*, but what stood out is that it needed debunking in the first place.

The movie's reception testifies to the murkiness and lack of consensus regarding the region's own recent events and to the legendary status that Tito and his regime still hold in many Yugoslavs' minds. After all, it was under socialism that Yugoslavia rose during the Cold War from poverty and insignificance to become a potent political, diplomatic, and military force. The period also saw the rise in the status of science, which Tito considered a tool for realizing his dream of worldwide socialism.

A major part of the push for science was the establishment of several elite physics institutes with the goal, at least partly, of developing a nuclear weapon. Tito's socialist dream collapsed in the early 1990s with the fall of the Communist regimes in Eastern Europe and the bloody wars that tore Yugoslavia apart.

One consequence of the wars was the dissolution of collaborations among physicists from Yugoslavia's six republics—Slovenia, Croatia, Bosnia and Herzegovina (BiH for short), Serbia, Montenegro, and North Macedonia. They have yet to fully recover. International collaboration also suffered, and the region entered a dark period of isolation as the wars dragged on and the economy slumped. Some republics got off lightly. Slovenia's struggle for independence lasted 10 days. Others, notably Serbia, entered a prolonged period of military conflict and economic sanctions. Brain drain surged.

The six republics continue to share similarities that stem from their common, socialist-era history. But differences are emerging in how physics is faring. Slovenia and Croatia belong to the European Union (EU) and enjoy the benefits of membership. Montenegro and North Macedonia await full integration into the West. Brain drain barely affected Slovenia, but it has devastated research in BiH, where scientists' salaries are half those in Slovenia. In Serbia, past brain drain is having a positive effect as Serbian physicists who left are now returning, and collaborations with Serbian physicists abroad burgeon.

EU funding based on merit has helped the region's best physicists improve further, but lack of domestic merit-based grants means that with a handful of exceptions overall research is underfunded and mediocre.

R&D investment as percentage of GDP is generally still well below what it was in Yugoslavia. Once-strong links with industry are gone.

Much remains to be done to make the region attractive to researchers and relevant globally. But despite the challenges, the region has several strong institutes and many groups doing excellent work in physics, including a few recipients of large grants from the EU's European Research Council (ERC). Pockets of excellence were a feature of science in the former Yugoslavia. In its successor nations, they are likely to continue.

A proud tradition

For much of its history, the region that became Yugoslavia has been near, next to, or part of large, advanced civilizations, among them the Roman Empire, the Venetian Republic, and the Austro-Hungarian and Ottoman Empires. A long and proud tradition of scholarship was the result.

The tradition goes back to at least the 12th century, when philosopher and astronomer Herman the Dalmatian (Dalmatia is the southern part of modern Croatia) translated Ptolemy's *Planisphaerium* from the only language it had survived in—Arabic—to Latin and helped to transmit the work to the rest of medieval Europe. Ruđer Bošković (1711–87) introduced the idea of a force that is repulsive at short distances but attractive at long ones. Croatia's largest research institute bears his name. Stefan–Boltzmann's law is named in part after Jožef Stefan (1835–93), who conducted experiments on the radiation of dark bodies. Andrija Mohorovičić (1857–1936) discovered the Mohorovičić discontinuity, the physical boundary between Earth's crust and the upper mantle. Milutin Milanković (1879–1958) discovered Milankovitch cycles, changes in climate driven by changes in Earth's orbit around the Sun.

Nikola Tesla (1856–1943) is the most famous scientist from the region. His innovations with alternating current paved the way for modern electricity. He remains celebrated in Croatia and Serbia, where museums and airports bear his name. An ethnic Serb, he was born in what is now Croatia. He is held as an exemplar of ethnic tolerance, having said that he was proud of his Serbian ethnicity and his Croatian homeland.

Mihajlo Idvorski Pupin (1858–1935) was one of the developers of the loading coil, a device that boosts the range of telegraph transmission. He became rich when AT&T bought the US rights to his patent. His book, *From Immigrant to Inventor*, was awarded the 1924 Pulitzer Prize for biography.

Although the region gave the world these eminent physicists, all of them worked abroad. Physics began to blossom in Yugoslavia itself only after World War II. Before then, when Yugoslavia was a constitutional monarchy, it was typically taught in university philosophy departments in big cities, such as Belgrade, Ljubljana, and Zagreb.

FORMER YUGLOSLAVIA is divided into six states, whose capitals are indicated by stars. The status of Kosovo is disputed. Vojvodina is an autonomous province within Serbia.

The Federal People's Republic of Yugoslavia was proclaimed on 29 November 1945. Two aspects of the regime's vision helped fuel the postwar development of physics. One was the establishment of nuclear programs for military and civilian purposes. The other aspect was a belief that science and technology are important for industrialization, for the improvement of the well-being of the working class, and for the general prosperity of the newly born confederation.

Tito's Communist partisans liberated Yugoslavia from its German occupiers without an invasion by Western or Soviet forces. His regime was not beholden to either postwar superpower. Though avowedly Communist, Tito broke with Joseph Stalin in 1948. With Indian prime minister Jawaharlal Nehru, he led the "third way" diplomacy of the Non-Aligned Movement. Tito knew that physics could help the country develop economically and militarily and remain independent. He also took a personal interest in promoting science and technology. In 1962, for example, he attended the launch of the cyclotron built at the Ruđer Bošković Institute (IRB) in Zagreb. At the time, the device was the fourth most powerful particle accelerator in Europe.

From today's perspective, the resources that were being invested in the development of physics were astonishing. Serbian physicist and journalist Slobodan Bubnjević of the Institute of Physics Belgrade recounts the period: "New institutes were being set up, and even the educational system was being changed to respond to the need to create new physicists. These physicists were being sent overseas in large numbers for further education to both the USSR and the US." Physics became one of the country's most developed sciences.

Despite being one of the poorest countries in postwar Europe, Yugoslavia twice attempted to develop a nuclear weapon. The first attempt occurred in 1947. Tito spent $35 million between 1948 and 1953 to build and equip three nuclear institutes: the Boris Kidrič Institute in Vinča near Belgrade, the Jožef Stefan Institute (IJS) in Ljubljana, and the IRB. The Vinča institute was headed by Pavle Savić, whose work on the action of neutrons on heavy elements done at the Radium Institute in Paris in the 1930s helped pave the way for the discovery of nuclear fission. Anton Peterlin, who trained at Humboldt University in Berlin, led the IJS. Ivan Supek led the IRB until 1958, when his open, forthright pacifism triggered his dismissal.

The country's first nuclear research program included the development of manufacturing capabilities. The Boris Kidrič Institute housed a department for recycling nuclear waste and a 6.5 MW reactor. In 1958 six young scientists were irradiated because of sloppy procedure. One died; the five others were saved by bone marrow transplants in Paris. The accident may have been one of the reasons Tito abruptly ended the program in the early 1960s. Another factor may have been his leading role in the Non-Aligned Movement, which declared its opposition to nuclear weapons in 1961.

In 1974 Tito revived Yugoslavia's nuclear program. A nuclear test carried out by India, another prominent member of the Non-Aligned Movement, was a likely impetus. One part of the new nuclear program, led by the Military Technical Institute in Belgrade, pursued a plutonium implosion bomb like the one dropped on Nagasaki. The other part, led by Energoinvest and based in Sarajevo, pursued civilian uses. As a company that produced power lines, transformers, and other energy infrastructure, Energoinvest was an excellent cover for a clandestine nuclear program. At its peak, the company employed 44 000 people and was Yugoslavia's largest exporter.

The second nuclear program was suspended mysteriously in 1987, possibly because of an economic crisis, which had begun four years earlier. Besides strong research and industrial capacities, the program left Yugoslavia with 50 kg of enriched uranium—enough for two atomic bombs. Stored at Vinča, the material was eventually removed in 2002 by Russia and the US under the auspices of the International Atomic Energy Agency.

The breakup of Yugoslavia

By the 1980s Yugoslavia was in such poor fiscal condition that it struggled to pay even the interest on the foreign loans that had propped up its economy. Ethnic, religious, and ideological issues seething amid state-imposed austerity eventually led to the breakdown of Yugoslavia, already weakened by the death of Tito in 1980. Some academics also contributed: In 1986 a leaked memorandum prepared by 16 members of the Serbian Academy of Sciences and Arts laid out a case that Serbia and Serbians were victims of a Yugoslavian state that had been purposely set up to discriminate against them.

Slovenia and Croatia seceded from Yugoslavia on 25 June 1991; BiH on 3 March 1992. How violent and protracted the ensuing wars for independence were depended on the extent and complexity of ethnic mixing. Slovenia's war lasted 10 days and cost 63 lives. BiH's, the bloodiest, lasted 3 years and 8 months and cost more than 100 000 lives.

By 1999 Yugoslavia had broken into five states: Slovenia, Croatia, BiH, Serbia and Montenegro, and Macedonia. Later, in 2006 and 2008, respectively, Montenegro and Kosovo proclaimed independence from Serbia. This year, under pressure from Greece, Macedonia renamed itself North Macedonia.

What happened to physics during the upheaval? Besides ending collaboration among the five states, the conflict and its aftermath saw declines in science funding and industrial activity. Yugoslavia invested around 1.5% of its GDP in R&D. Today none of the individual states except Slovenia invests more than 1% of its GDP in R&D.

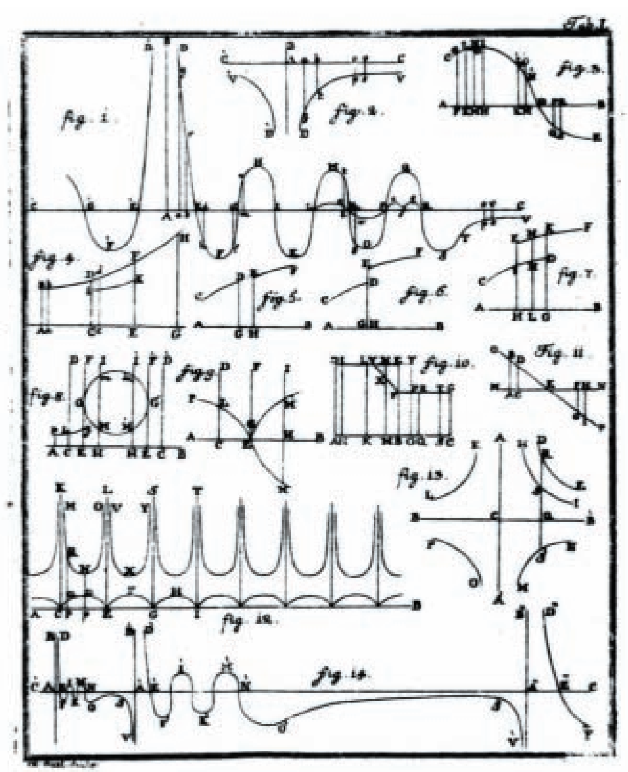
Cronyism, low levels of investment, and brain drain beset science to some degree in all the newly independent states. Yet the condition of physics in the individual states has turned out to be different. Some, like Croatia, Slovenia, and Serbia, had strong research centers during the Yugoslavian period; they continue to harbor centers of excellence. Others, such as BiH and North Macedonia, never had the same quantity or quality of physics research; they remain at the periphery of the global scientific community. Let's look at each state in turn.

Slovenia

Slovenia, with a population of about 2 million, was the most developed of the Yugoslav republics. It suffered lightly in the breakup, and in 2004 it was the first to join the EU.

Physics is mainly done at the IJS and at the University of Ljubljana. Smaller centers of physics exist at the University of Maribor and the University of Nova Gorica, which was established in 1995. The Society of Mathematicians, Physicists and Astronomers of Slovenia focuses on pedagogical activities.

Slovenia is home to the Krško Nuclear Power Plant, the only one in the former Yugoslavia. Operational since 1981, the 700 MW plant supplies 25% of Slovenia's electricity and 15% of



FIGURES FROM *THEORIA PHILOSOPHIÆ NATURALIS* by Ruđer Bošković. First published in 1758, the treatise expounded Bošković's theory of atoms and forces.

Croatia's. Physicists from the IJS work at the plant, but in supporting and educational roles rather than in research.

After gaining independence in 1991, Slovenia opened up to the world. It joined CERN, ITER, and the European Space Agency. Pre-war cooperation with physicists in other Yugoslav republics was good, especially with condensed-matter physicists at the IRB and the Institute of Physics in Zagreb. Collaborations continued after independence, though at a lower level, mainly because many excellent researchers left Zagreb in the 1990s.

Slovenia continued to develop all the areas of physics that were strong in Yugoslavia, particularly condensed matter, statistical physics, biophysics, and elementary particles. New areas have also emerged, such as quantum optics, laser spectroscopy, and soft matter.

Slovenia's R&D allocations, at about 2.39% of GDP, are significantly higher than in other former Yugoslav republics. Yet, says Dragan Mihailović of the IJS, the figures are misleading. Of R&D funding, 77% comes from the private sector, mainly from just two pharmaceutical companies: Krka and Lek. What's more, the actual spending on private-sector R&D is likely lower, given the tax breaks that, Mihailović says, "incentivize companies to class all sorts of activities as research."

Slovenia was comparatively free of brain drain until recently. In 2011 the government cut spending in science and other areas in response to the global financial crisis of 2007–8. "This is a new problem for Slovenia, and it is becoming a serious one, because the best researchers are leaving," says Mihailović.

Physics is the leading scientific discipline in Slovenia, according to criteria such as the number of ERC projects and papers published in leading journals. The highest-ranking scientists and professors at universities and institutes earn around €2500 ($2804) per month.

Croatia

With approximately 4 million inhabitants, Croatia was one of the most developed republics in Yugoslavia. When Europe's socialist regimes collapsed in the late 1980s and early 1990s, the country seemed poised for success. Many Croatians expected their small country to become rich, a "new Switzerland."

Croatia suffered some of the greatest devastation in the Yugoslav Wars. Lower salaries, fewer jobs, and a lack of resources prompted many physicists to emigrate. A 2007 World Bank study found that at 29.4%, Croatia's emigration rate of highly skilled people was the highest in Europe. Investment in R&D has fallen to around 0.9% today. Croatia is last in the EU for registered patents and other indicators of economic development. Around 80% of science funding is spent on salaries. Nationally funded research projects typically get the equivalent of only a few thousand US dollars a year. Because funds are not allocated on a competitive basis, mediocrity is sustained at the expense of supporting the country's best researchers.

Poorly executed—and often corrupt and illegal—privatization of state-owned companies in the late 1990s and early 2000s led to a drop in private-sector investment in science. Today it accounts for only about 40% of the total. For example, Končar, a manufacturer of turbines for hydroelectric plants, electrical appliances, and other equipment, has drastically cut its investment in science. The company still manufactures cutting-edge devices, such as magnets for CERN's Large Hadron Collider, but its involvement with physics has significantly diminished.

Physicists can readily get jobs in Croatia, but because funding for fundamental research is too low to support serious career development, many move abroad. Salaries for physicists at public institutions range from €1200 to €2000 a month.

Foreign scientists rarely visit Croatia; when they do, they generally don't stay for long. Still, Croatia is gradually attracting more and more physicists from abroad, especially to the best institutions. The IRB's permanent staff includes two from Italy, one from China, and one from Greece. David Smith, an Australian chemist, became the IRB's head in 2018.

For Croatia, joining the EU in 2013 has led to increased brain drain but also to closer cooperation with international institutions and access to EU grants. Physicist Tome Antičić directed the IRB until his recent appointment as state secretary for science. He cites CMS, ALICE, and NA61 experiments at CERN as examples of collaborations. Croatia also participates in MAGIC, a pair of imaging atmospheric Cherenkov telescopes on La Palma, one of the Canary Islands. Another fruitful source of collaboration is ITER, in which Croatian companies are participating. Croatia has also signed up to help build an ITER precursor, the DEMO Oriented Neutron Source, in Granada, Spain.

Yugoslavia was among the 12 countries that founded CERN in 1954, but it left the organization in 1961 as it struggled to pay membership fees. In 1962 it was given the status of an observer, which made it easier for physicists from Yugoslavia to work at CERN. IRB physicists have worked there since 1977; they were joined by physicists from the University of Split in 1993. Physicists from Zagreb and Split participated in the search for the Higgs boson. After years of negotiations, Croatia became an associate member of CERN this past February.

The EU is the source of the country's largest grants, many of which are linked to the IRB's accelerator center. The biggest project, PaRaDeSEC, is worth €2.5 million and is headed by IRB's Neven Soić. He and his team are developing semiconductor-based particle detectors. Astronomer Vernesa Smolčić of the University of Zagreb holds a €1.5 million ERC early-career grant.

Bosnia and Herzegovina

BiH, with its 3.8 million inhabitants, suffered the longest and bloodiest destruction during the Yugoslav Wars. The US-brokered Dayton Agreement of 1995 divided the republic into two entities, the largely Serb-populated Republika Srpska and the largely Bosniak- and Croat-populated Federation of Bosnia and Herzegovina. The two entities are further divided into 10

JOSIP BROZ TITO (seated) visited the Ruđer Bošković Institute in Zagreb, Croatia, in October 1965 to inspect the institute's new cyclotron, then the fourth most powerful in Europe. (Courtesy of IRB.)

autonomous cantons. No well-functioning state-level science institutions exist in BiH, as each entity and each canton sets its own science policies. Universities in BiH are now administered locally. Before Dayton there were four—in Sarajevo, Banja Luka, Tuzla, and Mostar. Now there are 8 state and 35 private ones.

Nenad Tanović, a physicist at the University of Sarajevo, notes that physics in BiH was never as strong as in Croatia, Slovenia, and Serbia. Even the country's premier physics center, University of Sarajevo's department of physics, has struggled because, says Tanović, "there were no capital investments in instruments such as reactors, accelerators, or other types of equipment." Despite the dearth of funding, the university has established a metal-physics laboratory. Physicists educated there work today as professors and researchers in the UK, the US, and other countries.

On average, BiH invests less than 0.1% of GDP in R&D; some of the cantons invest nothing. Physicists are mostly employed in educational institutions. At universities, their monthly salaries range between €800 and €1200. Brain drain is persistent and severe.

Cooperation between academic physicists and the private sector is practically nonexistent. Zrak, a precision optics company based in Sarajevo, made gunsights and binoculars for the Yugoslav People's Army. The company remains in business, but it has cut back its R&D and, with it, the need to employ physicists. In Zenica, BiH's steel town, physicists used to work in the metallurgy industry.

Because BiH lacks a national strategy to develop its physics programs, cooperation with foreign institutions barely exists. "For almost two decades," Tanović says, "CERN has been organizing a yearly seminar for young physicists from the region at the Natural Science Faculty in Sarajevo, but the state has not supported it."

Fewer than 15 physics majors graduate in BiH a year. They end up teaching, they work for state organizations such as the Federal Hydrometeorological Institute in Sarajevo, or they go abroad.

Serbia

Serbia is the largest of the former Yugoslav republics with a population of around 7.5 million. According to Bubnjević, there were almost no physicists in Serbia immediately after World War II. He credits Yugoslav policy for building up significant research capacity. Nuclear physics was the first priority. Then, starting in the early 1960s, investment in physics broadened. In 1961 the Institute of Physics was established in Belgrade and explored other fields of physics, such as atomic, condensed matter, complex systems, photonics, and ionized gases. Those areas remain the institute's focus of research.

In 1996 armed clashes broke out in Kosovo between Serbian authorities, who wanted the territory to remain part of Serbia, and the Kosovo Liberation Army, which wanted independence. The conflict that ensued, the Kosovo War, lasted from February 1998 to June 1999. Serbia, already weakened by earlier wars, saw the development of physics halted by economic sanctions and NATO airstrikes. A large number of researchers emigrated to the West, though some of them continued to help the young scientists left behind. Conditions have since improved. In the past 10 years, about 40 researchers have returned to the Institute of Physics.

Although Serbia is not an EU member, its scientists are eligible for some EU grants, which have attracted returnees. Milan Ćirković of the Astronomical Observatory of Belgrade is encouraged: "In the last five years, the observatory has employed six researchers with PhDs obtained from US and European universities, which is a huge relative improvement given that the total number of researchers in astronomy and astrophysics in Serbia is about 50."

The largest physics centers in Serbia are the Institute of Physics (around 200 researchers), the faculty of physics of the University of Belgrade (around 100 researchers), and the Institute of Nuclear Sciences in Vinča. Universities in Novi Sad and Niš also have significant physics departments.

Despite the positive role Yugoslavia played in physics, many negative aspects of the socialist regime have survived, especially in Serbia. "The first and most obvious is hypercentralization of everything, including science, and civil servants' obsession with controlling everything," says Ćirković. He cites strict controls over the governing boards of scientific institutes and infringements of universities' autonomy. "It is impossible for any noteworthy science to be done outside the two main centers of Belgrade and Novi Sad."

Serbia's economy is dominated by services and agriculture. Private-sector R&D is almost nonexistent. Bubnjević sums up the situation: "The long-term cooperation of physicists with a dedicated industry that provided heavy financing was drastically weakened after the breakup of Yugoslavia, and there was no new branch of the economy with a clear need for physicists." Serbia's growing IT sector is an exception. IT companies work with researchers who study complex systems and supercomputing. BioSense in Novi Sad, for example, combines data analytics and remote sensing to improve agriculture.

Serbia now invests around 0.87% of GDP in R&D, and physics gets an above-average portion compared with other sciences. Most labs in Serbia also have international grants for their research at an average of one grant per two researchers. EU grants that support centers of excellence helped equip several research centers in Serbia. In 2016 Magdalena Djordjevic of the Institute of Physics received an ERC grant worth €1.4 million for the study of quark–gluon plasma.

Serbia has been an associate member of CERN since 2012, and in 2019 it became a full member. Several Serbian groups have been collaborating on CERN experiments such as ATLAS and CMS since 2001, when economic sanctions were lifted.

Montenegro

Montenegro has just 0.6 million inhabitants. While Yugoslavia remained intact, Montenegro's physicists typically studied at the University of Belgrade and then went on to do postdocs in the Soviet Union. Most research focused on high-energy particle physics, nuclear physics, isotopes, and radiation.

VERNESA SMOLČIĆ of the University of Zagreb uses surveys and multiwavelength observations to study the formation and evolution of galaxies. (Courtesy of Petar Krajačić Vilović.)

After the dissolution of the Socialist Federal Republic of Yugoslavia in 1992, Montenegro remained part of the smaller Federal Republic of Yugoslavia with Serbia. Although it was largely spared in the wars of independence, its association with Serbia exposed it to the sanctions that the United Nations Security Council had imposed on Slobodan Milošević's Serbian regime. Montenegro was a target of NATO's 1999 bombing campaign.

Physicist Gordana Jovanović from the University of Montenegro in Podgorica recalls the sanctions' impact on science: "Studying was very difficult because there was no money for laboratory equipment, for computers, for literature. We had to use textbooks that our teachers brought with them from Russia when they studied." Russia did not strictly obey the sanctions, and cooperation continued with Russian universities and institutes.

In 1996 Jovanović enrolled at the University of Belgrade. When NATO aircraft bombed Belgrade three years later, she took a train back to Podgorica, where, half an hour before her arrival, the city's airport had been struck. "At that moment," she said, "it was hard to think of anything but survival."

Things are looking up. The University of Montenegro has signed a cooperation agreement with 118 universities in 34 countries. Montenegro is a member of the Europlanet network. Since 2017 it has been a full member of the CMS experiment at CERN. The current science minister, Sanja Damjanović, is a theoretical physicist, who has held positions at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany, and at CERN.

Physicists mainly find work in state institutes such as the meteorology and seismological institutes, but they are valued and often appointed to ministerial and diplomatic posts. A former deputy prime minister, Dragiša Burzan, is a theoretical physicist.

The main lines of research in Montenegro are particle and nuclear physics, condensed-matter physics, and ionized gases.

Modest conditions, primarily with regard to laboratory equipment, limit research opportunities for students and scientists. For now, students try to leave the country and stay abroad.

North Macedonia

North Macedonia has a population of just over 2 million. It was not involved in the wars of the 1990s. The small, poor, landlocked country took a step toward greater Western integration this year when it agreed to drop its claim, disputed by its neighbor Greece, to the name Macedonia, which is shared by a northern Greek region.

The situation for science is dire. During the past 20 years, North Macedonia has been spending about 0.2% of GDP on R&D, mainly on salaries in institutes dedicated to soft sciences. National grants barely exist. Physicist Viktor Urumov of Saints Cyril and Methodius University in Skopje recalls that the decline began after Tito's death, when subscriptions to international scientific journals were no longer renewed. "Luckily there is the internet and access to whatever is freely available," he says.

Few physicists work in North Macedonia, and their numbers are decreasing. The staff of Urumov's department, the Institute of Physics, includes 21 physicists with PhDs. That's down from around 30 when, 15 years ago, the government decided to save money by not backfilling the positions of people who retired. Urumov estimates that fewer than 50 physicists are employed outside elementary and secondary schools. Very few work in industry. Urumov says the average monthly salary in his department is €600.

North Macedonia now has six public universities and more than a dozen private ones. Physics degrees can be earned from universities in Skopje and Tetovo. "For more than a decade, the number of students studying physics has been very small, fewer than 10 new students annually," says Urumov. "But this has increased in recent years because the government began offering larger scholarships."

Optics and metals used to be the main research areas, but metals research has been abandoned. The country's modest number of physicists work in several areas, including thin films, the interaction of electromagnetic waves with matter, nonlinear phenomena, complex systems and networks, natural radiation, and radiation for medical purposes and environmental studies. The number of North Macedonians who study physics abroad has been growing, and the lack of jobs back home means few ever return.

The country's largest grants (up to €250 000) were obtained by the Institute of Physics through the EU's Trans-European Mobility Programme for University Studies. The projects are for establishing new curricula and modernizing higher education. North Macedonia does not yet participate officially in large European collaborations.

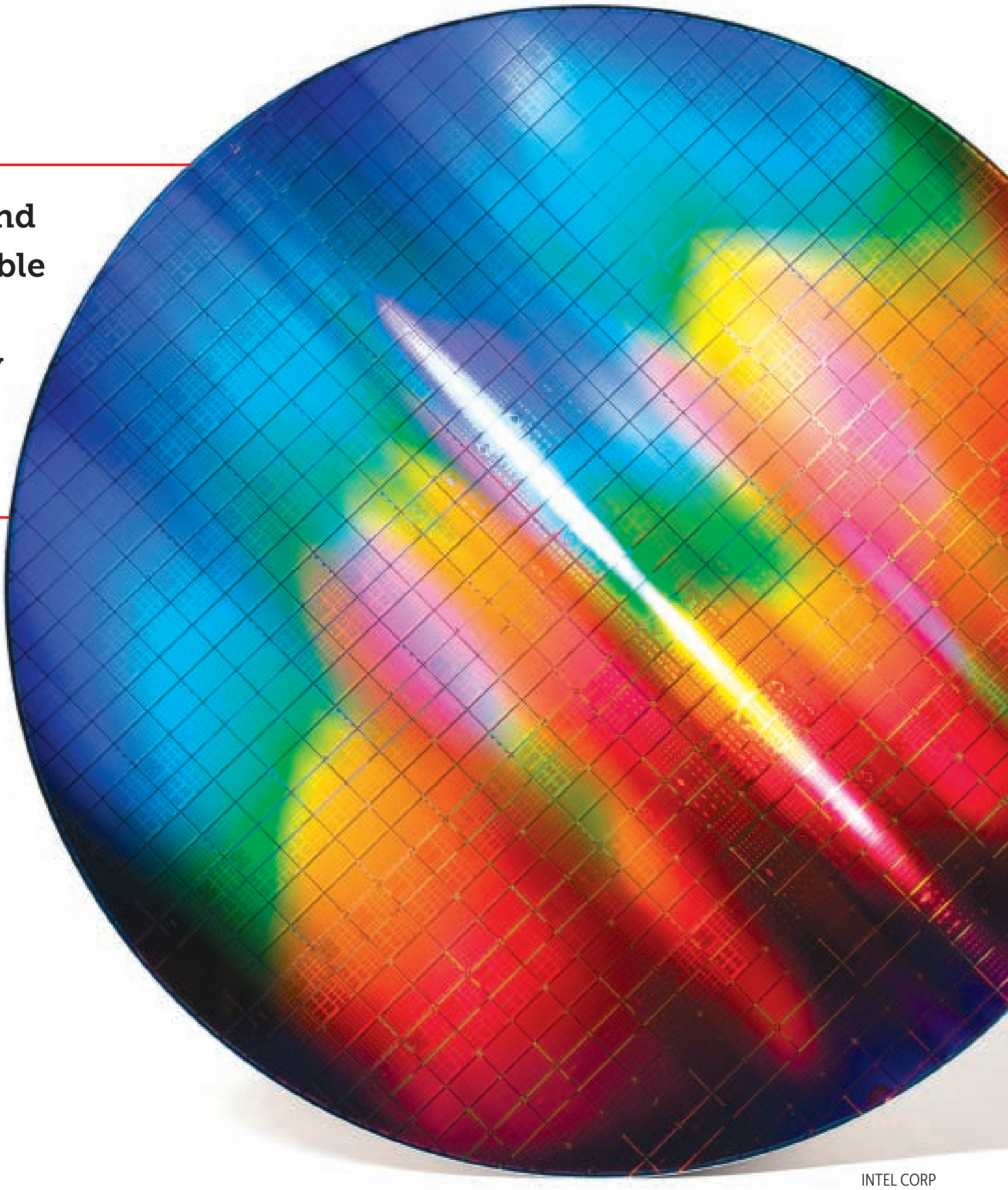
"In early 2000 UNESCO made a survey of equipment worth more than €100 000," Urumov recalls. "It was very easy to provide an answer for Macedonia, since there were no such instruments and the situation is unchanged." Nevertheless, the publication record of physicists from North Macedonia registered in international journals is steadily rising and the field of physics is among the best represented. PT


PEM-200

QUANTUM COMPUTING with semiconductor spins

Lieven M. K. Vandersypen
and Mark A. Eriksson

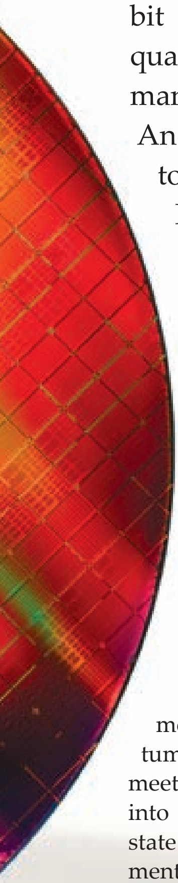
Arrays of electrically and magnetically controllable electron-spin qubits can be lithographically fabricated on silicon wafers.



INTEL CORP

Lieven Vandersypen is an Antoni van Leeuwenhoek Professor in the Kavli Institute of Nanoscience Delft and QuTech, a research center of Delft University of Technology in the Netherlands. **Mark Eriksson** is a Vilas Distinguished Achievement Professor in the department of physics at the University of Wisconsin–Madison.

Open any textbook on quantum mechanics, and the two-state system of choice is likely to be a spin-½ particle, such as an electron. The corresponding states, spin up and spin down, form the prototypical quantum bit (qubit), and rotations of the spin state constitute the simplest quantum logic gates. Because of their negative charge, electrons can be manipulated with voltages applied to nanoscale electrodes, or gates. And the application of appropriate voltages can confine the electrons to small islands called quantum dots (see the article by Marc Kastner, PHYSICS TODAY, January 1993, page 24).



Twenty years ago Daniel Loss and David DiVincenzo proposed that the spin of a single electron in a semiconductor quantum dot could form not just a model but also a real, physical qubit.[1] Their theoretical work predated by four years the first experiments to successfully trap a single electron in a gate-defined quantum dot, and it predated by several more years the first coherent manipulation of a single spin in a semiconductor. Semiconductor spin qubits now come in four distinct flavors, each of which was proposed by theory that set a target for experiments to pursue. Those experiments always brought surprises, and the interplay between theory and experiment makes semiconductor spin qubits a particularly vibrant field of study.

In this article we describe the experimental development and the current state of the art of semiconductor quantum-dot spin qubits. Functional and scalable qubits must meet well-defined criteria.[2] First, reliably initializing each qubit into one of its two levels must be possible. Second, the final state of each qubit must be knowable by a projective measurement that gives the correct answer with high probability. Third, qubit manipulation must be implementable using high-quality single- and two-qubit gates.

Imagine the spin state as a vector pointing on a sphere, commonly known as the Bloch sphere. Single-qubit gates correspond to rotations of the state vector that are independent of the state of any other qubit in the system. In the case of two-qubit gates, rotation of one qubit depends on the state of the other. And when the second qubit itself starts off in a superposition of states, the two qubits become entangled with each other. The recent satisfaction of all those requirements with quantum dots led to the demonstration of the first—and at two qubits the smallest possible—quantum semiconductor processor.

That single-electron spins in a semiconductor chip can act as qubits is remarkable. Unlike atoms or photons in a vacuum, an electron in a semiconductor resides in a noisy, solid-state environment. Engineering that environment so that it doesn't rapidly degrade or decohere the spin-qubit states has been a key challenge for our field.

Errors are unavoidable and necessitate quantum error-correction techniques (see PHYSICS TODAY, February 2005, page 19). To be effective, the techniques require that initialization, readout, and single- and two-qubit operations have error rates below 1%. Furthermore, quantum error correction involves an overhead in the number of qubits that can easily reach 1000 physical error-prone qubits to encode one protected error-free qubit. Therefore, a future quantum computer capable of solving relevant problems beyond the reach of a supercomputer will likely contain millions of physical qubits. (See the article by David Weiss and Mark Saffman, PHYSICS TODAY, July 2017, page 44.)

Semiconductor quantum dots have a tiny footprint that offers the prospect of integrating millions of qubits, akin to classical integrated circuits. The corresponding electron density in quantum-dot devices, however, is far smaller than in classical transistors, with each single electron in a qubit typically spread over a region roughly 20 nm × 20 nm in size. For such a device to work as intended, the materials and nanofabricated structures must have very little disorder, to ensure that electrons are easy to position and control. Pulling off that achievement entails uniform patterning of the gate electrodes but also having low densities of trapped charges in the substrate, in the dielectrics, and at the interfaces.

Because of the need for ultrahigh quality, the path to a large-scale quantum computer of any type is a marathon, not a

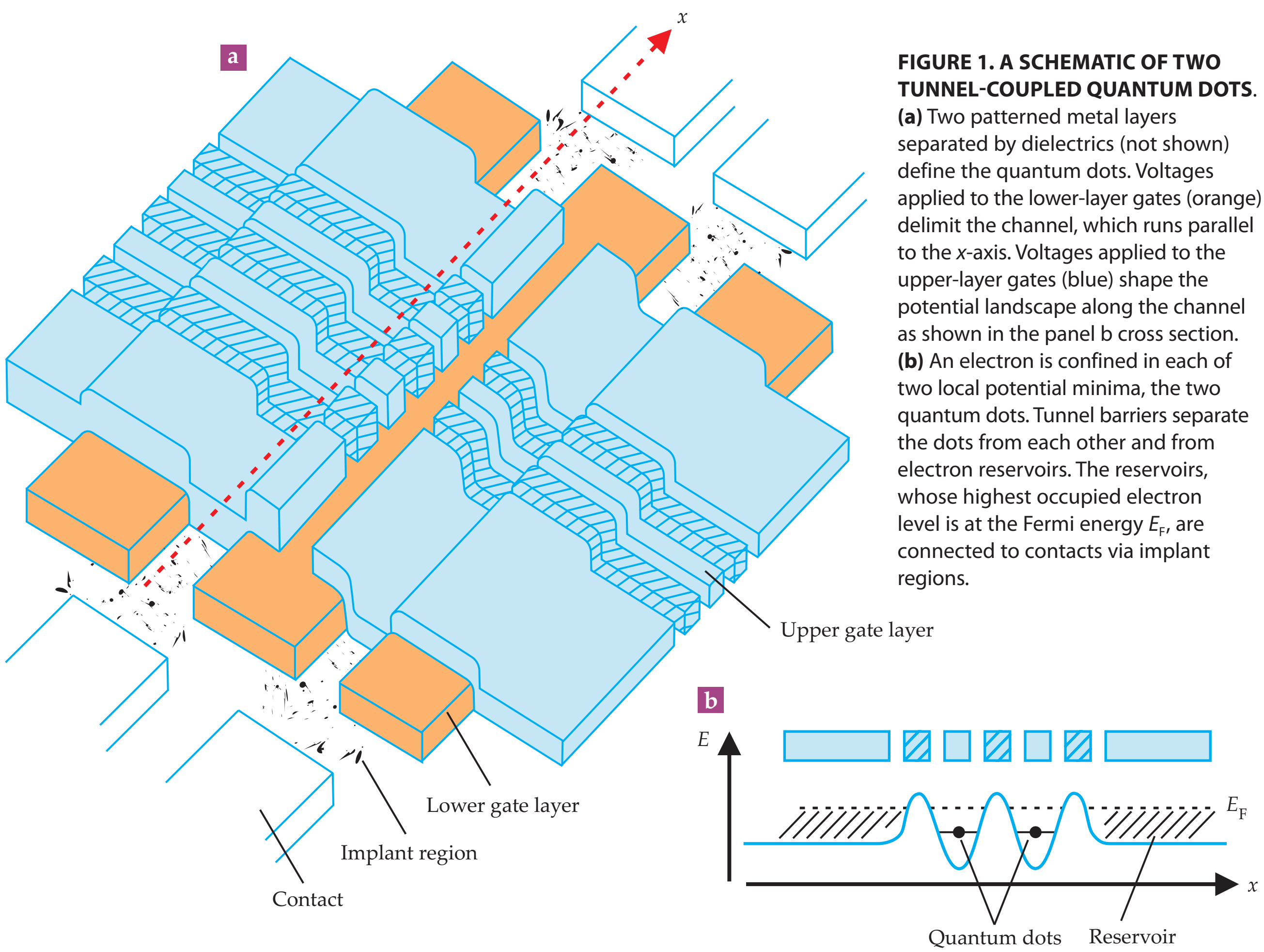


FIGURE 1. A SCHEMATIC OF TWO TUNNEL-COUPLED QUANTUM DOTS. **(a)** Two patterned metal layers separated by dielectrics (not shown) define the quantum dots. Voltages applied to the lower-layer gates (orange) delimit the channel, which runs parallel to the *x*-axis. Voltages applied to the upper-layer gates (blue) shape the potential landscape along the channel as shown in the panel b cross section. **(b)** An electron is confined in each of two local potential minima, the two quantum dots. Tunnel barriers separate the dots from each other and from electron reservoirs. The reservoirs, whose highest occupied electron level is at the Fermi energy E_F, are connected to contacts via implant regions.

sprint. And research today is motivated by a vision that will take years to bring to fruition. In the case of semiconductor spin qubits, that vision relies on long coherence times and on recent advances in gate fidelity—a common metric to express the quality of quantum gates—fueled by a move to silicon-based devices.

Intriguingly, spin qubits in semiconductors could also be integrated with classical integrated-circuit technology, including processing, memory, and the distribution of signals. Integration on chip is natural, because quantum-dot qubits use gate electrodes just as field-effect transistors do. Integration could also occur at the system level, with clusters of chips communicating with one another.

From transistor to qubit

The field-effect transistor is a good starting point for understanding a quantum dot. In a transistor, the flow of electrons between two contacts (source and drain) is switched on or off via the voltage on a metal gate electrode placed above the space between the contacts (the channel). A positive gate voltage attracts electrons to the channel and produces a conducting path from source to drain. A negative gate voltage, by contrast, empties the channel such that no source–drain current can flow. If one were to replace the gate electrode with three independently biased electrodes, the electronic potential landscape between the contacts could be shaped to create a potential-energy minimum separated from the contact regions by potential barriers.

At low temperature, typically below 4 K, the thermal energy is lower than the energy needed to add or remove electrons from the potential well. Thus the well is occupied by a discrete number of electrons. When the electrons are confined tightly enough that orbital motion is frozen out quantum mechanically, the device is known as a quantum dot.

Arrays of tunnel-coupled quantum dots can be formed with additional gate electrodes, as shown in figure 1. The voltages on the blue gate electrodes control the depth of the potential minima and thereby the number of electrons on each quantum dot. The voltages on the hatched blue gates control the tunnel barriers between adjacent dots and between the dots and the reservoirs. Nowadays, quantum dots are routinely tuned to the limit in which just a single electron resides on each dot. Researchers can verify the tuning by monitoring the current through an auxiliary nearby quantum dot that acts as an electrometer.

Spin qubits

When one electron resides in each quantum dot in the presence of a magnetic field, each electron spin becomes an appealing qubit. Indeed, that simple configuration, with one electron in one dot, was proposed by Loss and DiVincenzo in 1998. In subsequent years, alternative spin qubits have made their debut.

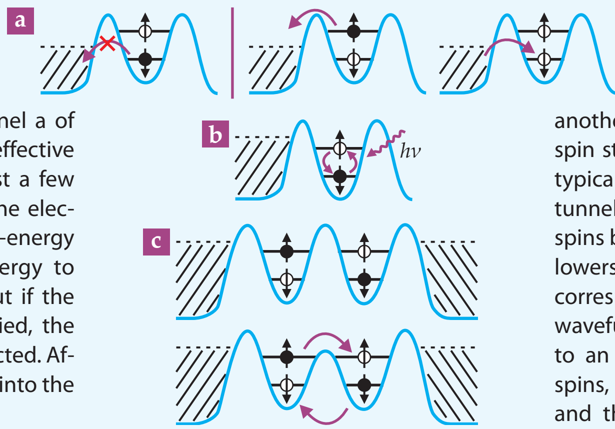
HOW TO INITIALIZE, MANIPULATE, AND READ OUT A SPIN QUBIT

Reading out the spin state of an electron on a quantum dot involves making a so-called spin-to-charge conversion,[16] whereby the electron is allowed to tunnel from one location to another in a way that depends on its spin state—or more specifically, on whether the qubit is up or down. A nearby charge sensor is sensitive to the dots' electron occupation; the current through the sensor thus indirectly reveals the spin state.

In one scenario, the Pauli exclusion principle provides the spin dependence: Two electrons can reside on the same dot only when they are in a spin-singlet state. For a spin-triplet state, each electron is forced to reside on its own dot. In another scenario, a qubit's two spin states are aligned above and below the reservoir's Fermi level—the highest occupied energy level (see panel a of the figure). That protocol is usually effective for any qubit separated by at least a few times the thermal energy. When the electron in the dot occupies the lower-energy spin, it doesn't have enough energy to leave and no tunneling occurs. But if the higher-energy spin state is occupied, the electron can tunnel out and is detected. Afterwards, another electron tunnels into the dot from the reservoir.

Initialization is commonly the result of readout, after which an electron with a known spin resides in the dot. Alternatively, initialization can be achieved by allowing the electron spin qubit to thermalize to its ground state.

Resonant control of spin qubits uses magnetic or electric excitation at radio or microwave frequencies. Magnetic excitation can coherently drive spin transitions directly when the excitation is resonant with the energy difference between spin-up and spin-down states (see panel b in the figure).[17] The excitation's amplitude controls the rotation frequency of the spin vector around the Bloch sphere, its phase controls the rotation axis, and its duration controls the rotation angle.



Resonant electrical excitation, by contrast, can drive single-spin transitions because of spin–orbit coupling.[18] The excitation causes the electron to oscillate back and forth in a quantum dot, and the electron experiences an oscillating effective magnetic field that rotates the electron's spin. Alternatively, in the presence of a suitably engineered magnetic field gradient at the dot location, an electrically driven electron experiences a real, oscillating magnetic field, again allowing for coherent spin rotations. In the case of the quantum-dot hybrid qubit (three electrons in two dots), resonant electric fields alone drive transitions between the qubit states.[5]

Gate-voltage pulses provide another method to controllably manipulate spin states. The basic idea is to abruptly—typically within nanoseconds—turn on the tunnel coupling between two neighboring spins by applying a gate-voltage pulse that lowers the tunneling barrier between their corresponding dots, so that the electron wavefunctions overlap. The overlap leads to an exchange interaction between the spins, as suggested in the figure's panel c, and the two spin states are periodically exchanged.

For instance, a qubit can comprise two collective states of two or three spins that reside in either two or three quantum dots. Those flavors are known as singlet–triplet qubits[3] (two electrons, one each in two dots), exchange-only qubits[4] (three electrons in three dots), and quantum-dot hybrid qubits (three electrons in two dots).[5] The trade-offs between them are many and still under investigation. Ultimately, the various qubit types are initialized, manipulated, and read out using the same physical principles, but their robustness to specific noise sources varies, as does their ease of operation.

The first wave of successful spin-qubit experiments started in the early 2000s and used quantum dots defined by gate electrodes over a gallium arsenide/aluminum gallium arsenide two-dimensional electron gas. That heterostructure technology had been the workhorse of mesoscopic physics for more than a decade and provided a platform in which spin qubits were easy to control. Initial work largely met the important requirements for individual qubits—namely, that they could be initialized, manipulated, and read out.

As outlined in the box above, qubits can be implemented using nanosecond gate-voltage pulses and resonant microwave excitation of gate electrodes or current-carrying wires. Single-shot readout is performed indirectly, by inducing spin-dependent tunneling of an electron while detecting the position of the electron in real time. The groups of Leo Kouwenhoven and one of us (Vandersypen) at Delft University of Technology (TU Delft), Charles Marcus at Harvard University, and Seigo Tarucha at the University of Tokyo were the main players to carry out those early experimental demonstrations. The GaAs work culminated in the creation of entangled states of singlet–triplet qubits by Amir Yacoby and coworkers at Harvard. They reached a fidelity—the extent to which the actual state resembles a two-qubit entangled state—of 72% and later improved it[6] to greater than 90%.

Relaxation and decoherence

Spin qubits in GaAs benefit from remarkably long energy relaxation times T_1, the time it takes a qubit to change from a high-energy state to the ground state. For single-spin qubits, T_1 can exceed 1 second at low temperature (100 mK or lower) in a 1 T field. That's three orders of magnitude longer than the longest T_1 in superconducting qubits.

By comparison, T_2^*, the time it takes the qubit phase to randomize, is just tens of nanoseconds in GaAs dots.[3] The phase of the electron's spin is randomized through hyperfine coupling to the roughly 1 million nuclear spins of atoms in the

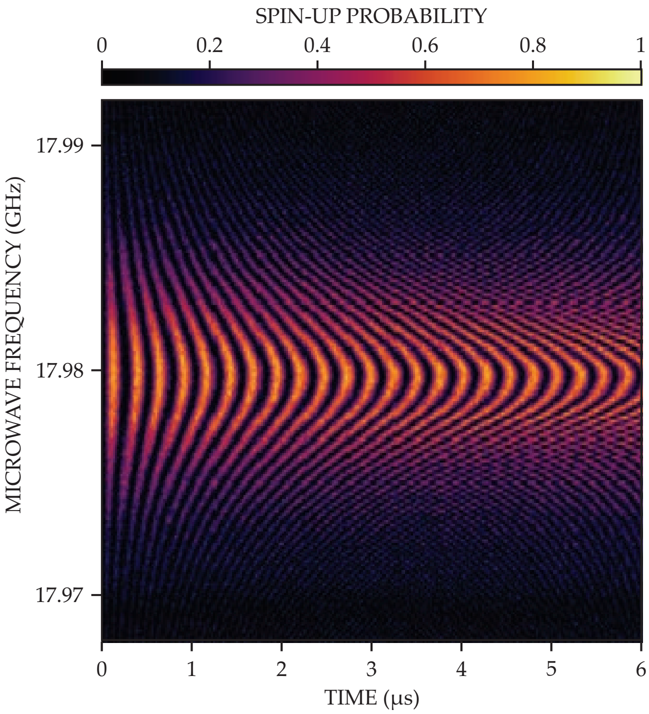


FIGURE 2. DRIVEN EVOLUTION OF A SINGLE QUBIT. When an applied microwave pulse is close to resonance with the spin qubit—that is, with the energy difference between its up and down states (17.98 GHz here)—the qubit undergoes driven rotations, or Rabi oscillation, and the probability of finding it spin-up oscillates as a function of the pulse duration. (Adapted from ref. 10.)

quantum dot, with which the electron wavefunction overlaps. The interaction is impossible to avoid because every Ga and As isotope carries a nuclear spin of $3/2$.

Moreover, despite the low temperatures and strong magnetic fields used with typical spin-qubit measurements, the nuclear spins point in nearly random orientations. The result is a statistically fluctuating and slowly varying collective effect on the electron spin known as the random nuclear or Overhauser field. Although the randomness of the nuclear field can be significantly reduced for singlet–triplet qubits by using sophisticated pulse schemes,[6] the random nuclear field has significantly slowed the progress of GaAs-based spin qubits.

Enter silicon

As early as 1998, it was clear that silicon would be preferable to GaAs as a host material for spin qubits. Fewer than 5% of naturally occurring Si atoms carry a nuclear spin, and those nuclear spins can be largely eliminated by using isotopically enriched ^{28}Si. Although Si is the cornerstone of today's semiconductor technology, it has taken many years of materials development and nanofabrication advances to make Si quantum dots suitable for spin-qubit experiments.

Two main quantum-dot platforms have emerged. In the first, pioneered by one of us (Eriksson) and colleagues at the University of Wisconsin–Madison, electrons are confined in Si quantum wells by silicon germanium barriers above and below the well.[7] In the second, developed by Andrew Dzurak and colleagues at the University of New South Wales (UNSW) in Sydney, electrons are confined against a Si-SiO_2 interface—as in n-doped metal oxide semiconductor technology.[8] In both cases, gate electrodes on the surface are used to accumulate electrons in quantum dots and to form tunnel barriers between the dots.

The randomization time T_2^* is significantly longer in Si than in GaAs, with T_2^* reaching 1 μs in natural Si and up to 100 μs in purified ^{28}Si. That's an improvement over GaAs by four orders of magnitude,[9] and it translates directly to single-spin gate

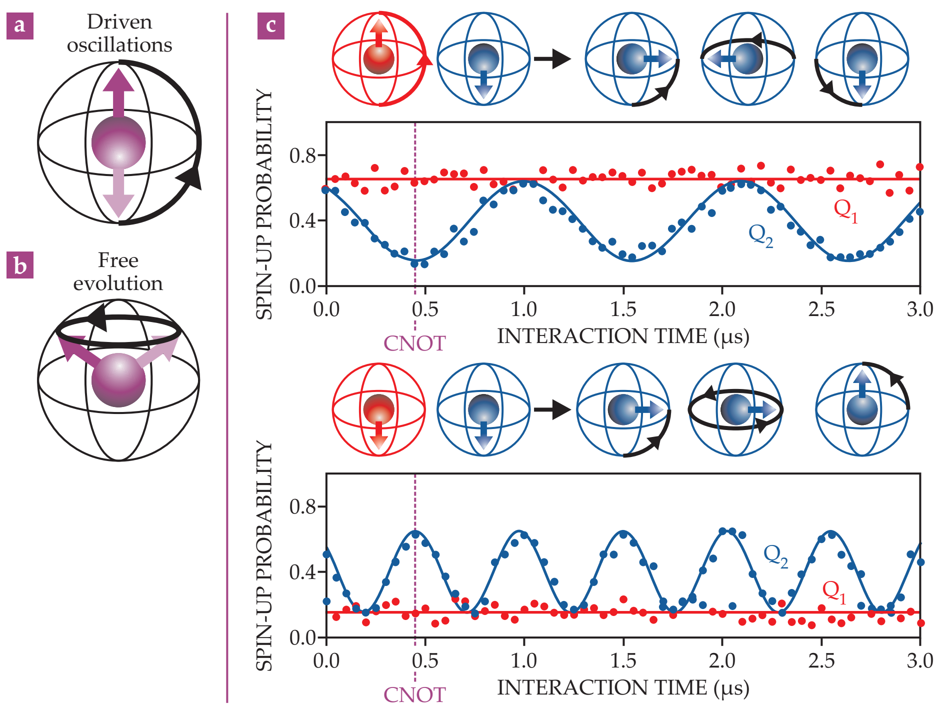


FIGURE 3. A TWO-QUBIT LOGIC GATE. (a) In a Bloch sphere diagram, a qubit rotates along a line of longitude during a resonant microwave pulse (see figure 2). **(b)** In the absence of a microwave pulse, a state precesses along a latitude line around the vertical axis of the Bloch sphere. **(c)** A controlled NOT (CNOT) gate is an operation that flips a target qubit (Q2, blue) based on the state of the control qubit (Q1, red). With Q2 initialized spin down, the plots show the time evolution of the spin-up probability of both qubits when Q1 is spin up (top) or spin down (bottom). In each case, two single-qubit $\pi/2$ rotations are applied, separated by free evolution, during which the two qubits interact. For an interaction of 0.5 μs, the sequence flips Q2 if Q1 is down but not if Q1 is up. (Adapted from ref. 11, M. Veldhorst et al.)

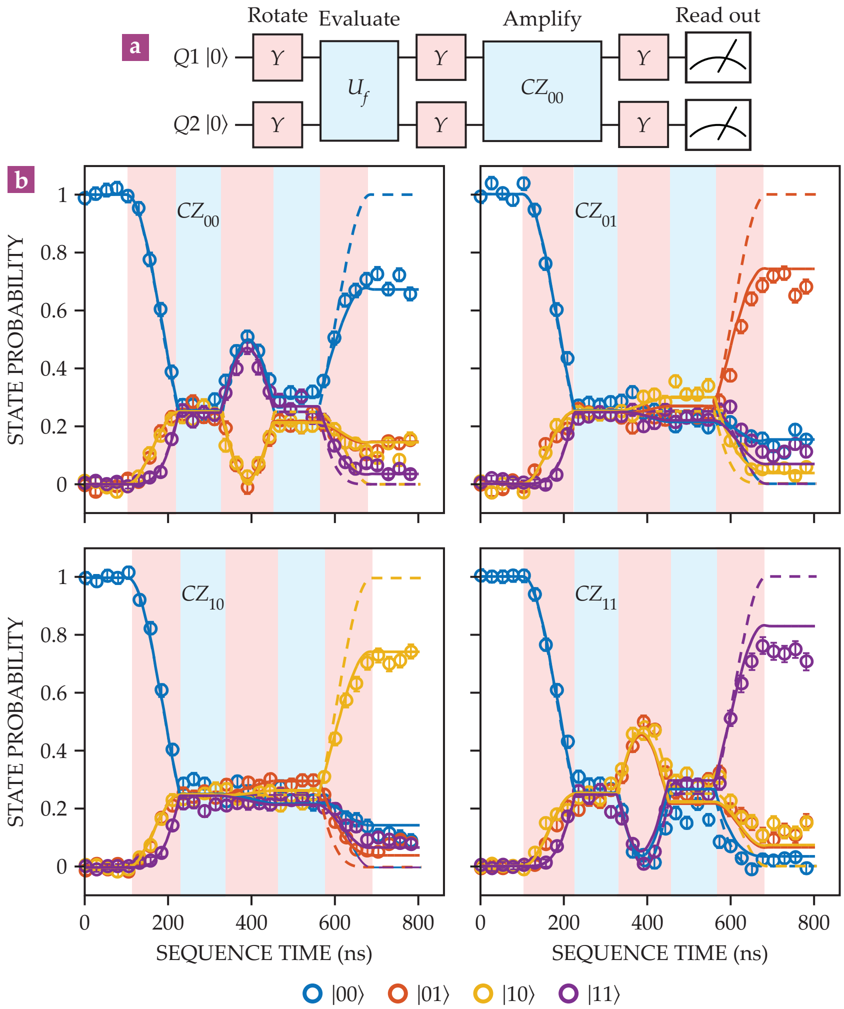


FIGURE 4. A TWO-QUBIT CIRCUIT THAT IMPLEMENTS A QUANTUM SEARCH ALGORITHM. (a) A sequence of operations acts on qubits Q1 and Q2: rotation (*Y*), interaction (U_f), and amplification (*CZ*). A detector reads out the final state probabilities of each qubit. **(b)** The two-spin probabilities of the qubit states' populations are plotted as a function of time; the background colors (white, pink, and blue) correspond to the colors of operations in the circuit. After the first rotation around the *y*-axis, the qubits are in a superposition (|00⟩ + |01⟩ + |10⟩ + |11⟩)/2, with each term having equal weight. In each panel, U_f is a different interaction (CZ_{ij}) that picks out one particular two-qubit state; that state then gets amplified in subsequent steps due to quantum interference. Dashed and solid lines show, respectively, the ideal populations and the results of a model that includes decoherence. (Adapted from ref. 11, T. F. Watson et al.)

fidelities[10] of greater than 99.9% (see figure 2). Furthermore, given that the nuclear-spin bath evolves slowly on the time scale of the electron-spin dynamics, it is possible to extend the coherence times to tens of milliseconds[9] using dynamic decoupling techniques, extensions of the Hahn spin-echo concept.

Even longer electron-spin coherence times are obtained for electrons bound to phosphorus-31 dopants in ^{28}Si-enriched material. The positively charged ^{31}P donor provides the confining potential for the electron. The system is convenient because it avoids the need for bandgap engineering, though actual devices do contain gate electrodes to manipulate the confining potential in time. The group of Andrea Morello at UNSW has shown that individual ^{31}P nuclear spins can provide a nuclear-spin qubit with an exceedingly long T_2^* of 0.6 s.

Quantum-dot and donor qubits in ^{28}Si behave in many respects like isolated electrons trapped in a vacuum, and they allow for extremely high single-qubit control fidelity. In contrast to quantum-dot lithography, ion implantation produces an uncertainty that makes it challenging to position multiple donors with respect to each other. The group of Michelle Simmons, also at UNSW, has shown that scanning tunneling microscope lithography can position atoms with much higher precision than is possible through implantation.

With isotopically enriched ^{28}Si now available on wafer scales and at moderate costs, and with several methods available to confine electron spins in electronic devices, the prospects for practical Si spin qubits have risen sharply.

Putting it all together

Building on the long-lived coherence in Si quantum-dot spin qubits, several groups have now demonstrated high-fidelity control of two single-spin qubits.[11] In 2015 the Dzurak group got a two-qubit gate working with single-qubit control and independent readout of the two spins. The two-qubit gate relied on the interaction between neighboring spins, as outlined in the box. That interaction, in combination with single-qubit rotations, enables a controlled-NOT (CNOT) gate, as illustrated in figure 3. Two years later two teams—a collaboration of our own groups at TU Delft and at the University of Wisconsin–Madison and, independently, the group of Jason Petta at Princeton University—demonstrated entanglement of two single-spin qubits in a Si/SiGe double quantum dot.

To further illustrate the recent progress of Si spin qubits, figure 4 shows the implementation of a simple quantum algorithm on two Si spin qubits. We and our colleagues at TU Delft and the University of Wisconsin–Madison successfully programmed all four instances of Grover's search algorithm for two qubits.[11] The algorithm is designed to invert a function $f(x)$ and identify the unique *n*-bit input value x_0 for which $f(x_0) = 1$. For all other input values, $f(x) = 0$. Without further knowledge of *f*, there is no more efficient method using a classical computer than exhaustively searching through the space of input values, evaluating $f(x)$ using one input value after another until hitting the input value x_0.

The quantum case behaves very differently. Figure 4 illustrates how the occupation probabilities of the four basis states |00⟩, |01⟩, |10⟩, and |11⟩ evolve throughout the steps of the quantum algorithm for each of the four possible functions *f*. Starting off with qubits Q1 and Q2 both in the |00⟩ ground state, the first step is to prepare an equal superposition of the four basis states via simultaneous 90-degree rotations of each qubit from about 100 ns to 200 ns in the circuit. Next, a unitary transformation U_f is executed that corresponds to calling the function f from about 200 ns to 350 ns.

Because the qubits are in superposition, the function is evaluated for all four of its input values (00, 01, 10, and 11) in a quantum superposition as well. The function call is implemented with a two-qubit gate, which flips the phase of the $|x_0\rangle$ component in the superposition. At that point in the circuit, all probabilities remain ¼, as shown in figure 4. Subsequent single-qubit and two-qubit operations, identical for the four cases, boost the amplitude of the term $|x_0\rangle$ using quantum interference at the expense of the other terms.

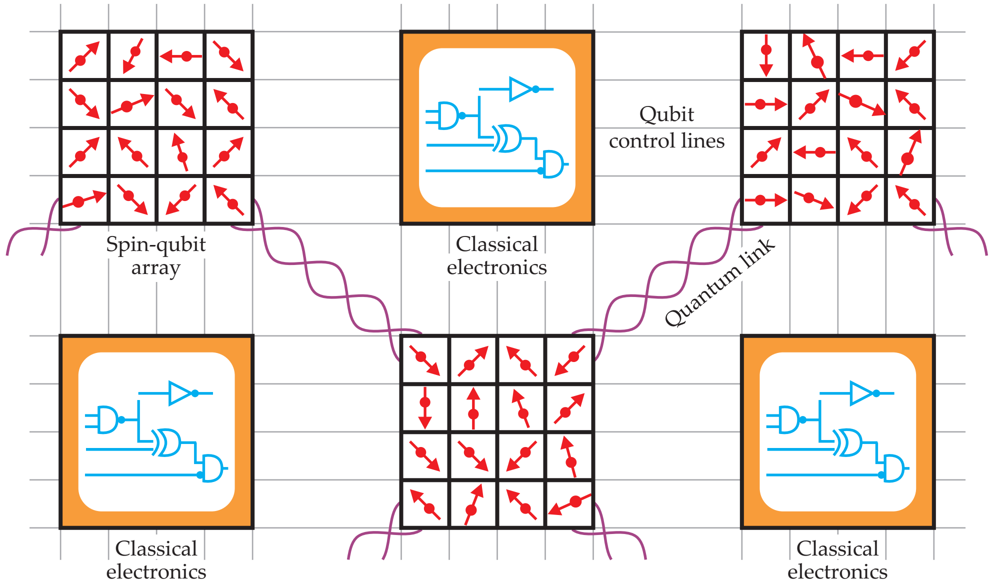


FIGURE 5. A VISION OF FUTURE SILICON QUANTUM ELECTRONICS, containing dense local registers of quantum dots interconnected with quantum links. Classical electronics between the spin-qubit arrays distribute signals on the chip.

Networked qubit registers

The two-qubit experiment can be scaled up to a few dozen qubits in linear arrays of quantum dots. Researchers, most notably at CNRS Grenoble, have already gone beyond 1D arrays and reported the first demonstrations of small 2D arrays of quantum dots. But limits exist to the number of tunnel-coupled quantum dots that can be realistically integrated monolithically. To scale up further, it is likely that on-chip quantum links will be required to connect distant quantum registers with each other, forming networks of interconnected multiqubit registers.

Many proposals exist for making such links, and their realization is an active area of research. One heavily pursued approach uses microwave photons stored in on-chip superconducting resonators to indirectly mediate the coupling between distant spins on the chip. Adopting that tack, three groups made a major breakthrough in their recent observation of so-called strong coupling of a single microwave photon and an electron spin qubit (see reference 12 and PHYSICS TODAY, April 2018, page 17). A second promising approach is to apply periodic gate voltages to induce a traveling-wave potential that shuttles electrons through channels across the chip. Initial results on quantum-dot arrays indicate that spin coherence can be preserved during such shuttling.[13]

Challenges in scaling up

Low fabrication yield still slows progress in many labs, and working devices are not all identical. Researchers must compensate for disorder in the form of charged defects and impurities in the semiconductor by tweaking the gate voltages. That's time-consuming, and low-frequency charge noise makes frequent retuning necessary. Furthermore, high-frequency charge noise limits the two-qubit gate fidelity. Nevertheless, the first experiments achieved two-qubit gate fidelities of 92–98% under suboptimal conditions, and 99% fidelity seems within reach.[14]

Recent experiments have shown encouraging improvements in charge noise. And yield, qubit uniformity, and charge noise are expected to benefit from industrial efforts to fabricate quantum-dot arrays using commercial methods. The work is ongoing at the CEA's Leti Institute, an electronics information technology laboratory in Grenoble, France; at Imec, headquartered in Belgium, using electron-beam lithography; and at Intel Corp using all-optical lithography (see page 38).

Another challenge comes from the nature of Si, whose conduction band has six degenerate minima, or valleys, in the bulk. The degeneracy is problematic for spin-qubit operation because the Pauli exclusion principle, which normally forbids two electrons with the same spin to occupy the orbital ground state, gets circumvented and the two-qubit gate fails.

Confined structures such as quantum dots lift that sixfold degeneracy. But the so-called valley splitting—the energy gap to the first excited valley state—depends strongly on atomic-scale details that are locked in during growth and that can vary across a sample. In some of the Si/SiGe quantum dots measured to date, the valley splitting is too small to be useful. In contrast, a metal-oxide semiconductor quantum dot can have large valley splitting because of the hard confinement from the silicon oxide layer. The flip side is that this same oxide interface is a source of disorder that is larger than the disorder at the epitaxial interface of Si/SiGe quantum wells.

Scaling challenges can also arise at higher levels in the system—from the control electronics to the quantum-computer architecture and software layers. For example, every quantum dot (and superconducting qubit) made today requires that at least one wire be connected off-chip, which presents a wiring bottleneck for going beyond a few thousand qubits. To overcome the bottleneck, we envision two solutions that work in tandem: crossbar addressing schemes, like those used in displays and memory chips, and on-chip classical multiplexing circuits to distribute signals.[15]

A vision of qubit registers

Imagine a large-scale Si chip consisting of local 2D quantum-dot arrays addressed using crossbars and classical multiplexing electronics that are connected by quantum links.[15] Figure 5 depicts what such a network of quantum and classical electronics might look like.

Si spin qubits are particularly well suited to realize that vision. First, the quantum dots, quantum links, and classical on-chip electronics can all be integrated using the same process steps. Those parts, moreover, can leverage today's transistor technology. Second, with a typical spacing of 100 nm, quantum dots are extremely compact: 1000 dots can fit inside an area of 10 μm^2. Third, Si spin-qubit coherence times are extremely long and can accommodate sequential operations on the qubits, which may be needed using crossbar addressing schemes. Fourth, Si spin qubits are resilient to temperature and suffer only modest degradation of charge noise and spin-relaxation times between 20 mK and 1 K.

Those are significant assets for scaling up Si spin qubits into a truly integrated circuit of quantum and classical components on a single chip. Scientific and technological challenges remain, but the prospect is very real that Si spin qubits may be scaled up to the many millions of qubits that will likely be needed to solve real-world problems beyond the reach of any classical machine. For example, a large-scale quantum computer will be capable of efficiently computing the properties of materials and molecules, with possible applications ranging from energy harvesting and storage to the design of drugs and catalysts.

We thank our many colleagues at TU Delft, the University of Wisconsin–Madison, and around the world for numerous collaborations and productive discussions.

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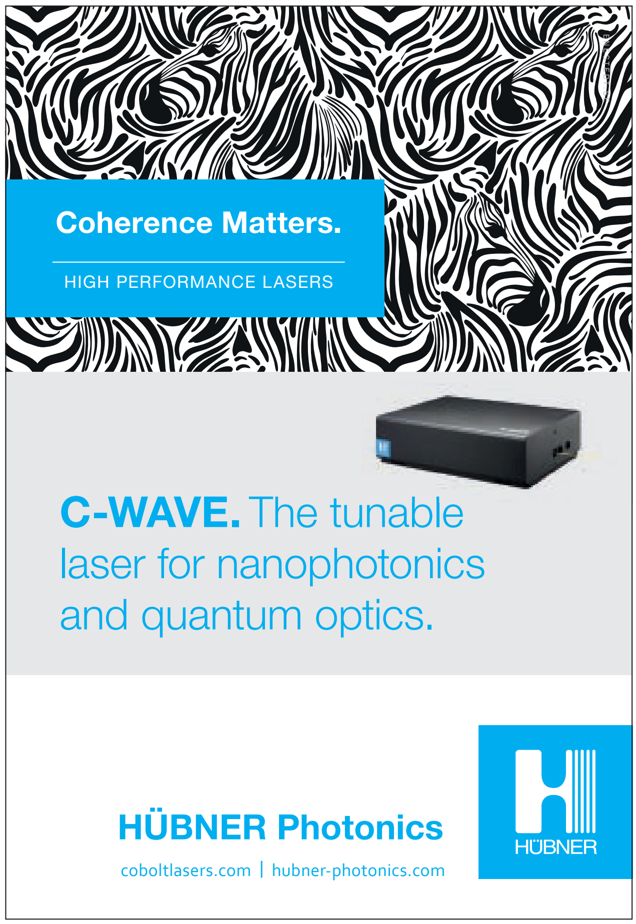

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The North American ECLIPSE of 1869

Deborah Kent

A coast-to-coast eclipse on 7 August 1869 gave US astronomers a chance to make their mark on 19th-century astronomy.

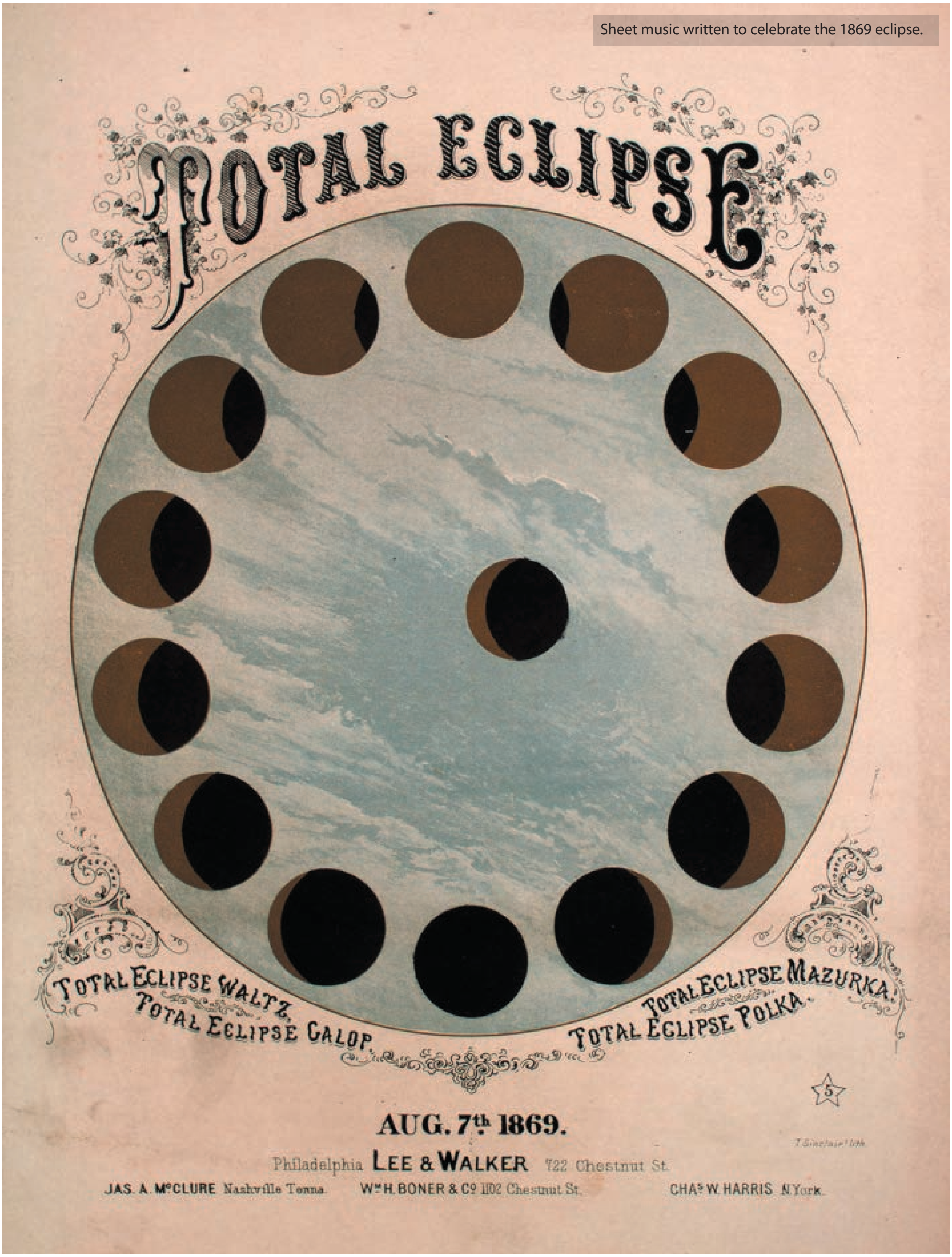
On 7 August 1869, hundreds of scientists awaited mere minutes of solar darkness along an eclipse path that stretched from Alaska to North Carolina. With a good chance of clear summer skies in the central US came a prime opportunity for North American scientists to combine eclipse science with new technology to answer some of astronomy's most pressing questions.

Work in the 1820s gave astronomers mathematical tools to compute eclipse paths in ample time to mount viewing expeditions. Throughout the mid 19th century, such eclipse expeditions enabled astronomers to refine theories of solar and lunar motion to generate tables that would improve navigational accuracy. They also raised new questions about undiscovered celestial bodies, the nature of the solar corona, and the precision of observational techniques.

US astronomers saw the 1869 eclipse as a chance for scientific redemption. They had been sorely disappointed when clouds obscured the eclipse over North America in 1860, and they hoped to use the lessons from that experience for better outcomes the second time around.

Astronomers would also benefit from the expansion of communication with and transportation to the western states. By 1869 messages sent on speedy new telegraph networks

GADO IMAGES/ALAMY STOCK PHOTO.



Sheet music written to celebrate the 1869 eclipse.

facilitated preparations, and freshly built railroads meant bulky instruments and teams of observers could easily reach the zone of totality. There, they aimed to refine tables of lunar motion, explore photography as a measurement tool, and investigate the composition of the chromosphere. US scientists' efforts to prepare for and observe the 1869 eclipse highlight the ambitions of a scientific community just beginning to take its place on the world stage.

Astronomical mysteries to solve

A total solar eclipse observed over Europe on 8 July 1842 generated some enticing questions for astronomers. Reports described brilliant red flames protruding from the lunar disk. What were those rosy prominences? Did they belong to the Sun or the Moon?

The brevity of totality complicated the analysis, but technology brought hope. In 1840 New York University chemistry professor John Draper had made a one-inch-diameter daguerreotype image of the Moon and displayed it in New York City to great acclaim. By 1845 French physicists Armand Fizeau and Jean Foucault had built a camera shutter capable of just 1/60th of a second exposure and used it to photograph the Sun. The race was on to photograph the solar corona.

Meanwhile, astronomers using Newtonian mechanics had predicted the existence of a celestial body large enough to explain the orbital perturbations of Uranus. After the 1846 observation of Neptune confirmed those predictions, new speculation arose about an as yet undiscovered planet that might explain the unaccounted-for drift in Mercury's perihelion. Hopes ran high that the hypothetical body, often called Vulcan, could be spotted near the Sun during an eclipse.

The pride of superior-precision lunar tables was also on the line. Solar eclipse observations on 28 July 1851 verified the US Nautical Almanac Office's claim that its tables for the Moon's position were significantly more accurate than those of its British counterpart. In Washington, DC, predictions in the British almanac were observed to be off by 78 seconds at the start of the eclipse and 62 seconds at the end. The US almanac only missed by 13 seconds and 1.5 seconds.[1] Could the US do even better?

Midcentury astronomers also used eclipse expeditions as practice for observing an even rarer predictable phenomenon: the transit of Venus, when Venus's path crosses between the Sun and Earth. Transits of Venus occur in pairs eight years apart, with pairs separated by more than a century. It has only been observed seven times, first in 1639 and most recently in 2004 and 2012. The transit of Venus won't happen again until 2117. One of the rarest recurring predictable astronomical events, it requires that observers be in a specific location on the globe.

For 19th-century scientists, observing and timing the transit phases would provide data essential for determining the distance between the Sun and Earth. Ultimately, the scientists hoped to tackle one of the great open questions of the time: How big was the solar system? US astronomers were already planning major expeditions to observe upcoming transits of Venus in 1874 and 1882. The two total solar eclipses of the 1860s were a chance for Americans to test observational techniques for even higher-stakes astronomy.

The disappointment of 1860

The total solar eclipse of 18 July 1860, which would arc across the Washington Territory, over the tip of Labrador, and to the Red Sea, seemed like an ideal opportunity to explore those key astronomical questions. The remoteness of totality did not discourage US Navy lieutenant James Gilliss, who boarded a steamer in New York with a few boxes of second-rate equipment and arrived three weeks later in San Francisco. There he joined his son, who was stationed with the US Coast Survey, for a two-week trek to camp just west of the Cascade mountains.

FIGURE 1. THE KEW PHOTOHELIOGRAPH, an instrument that combined a telescope with a camera for eclipse observation and photography, designed by Warren De la Rue. (Courtesy of the Science Museum Group Collection, CC BY 4.0.)

A young navy computer, Simon Newcomb, undertook a far more arduous 47-day journey to the Saskatchewan River. Despite difficult travel through clouds of mosquitoes on a mud-stuck stagecoach and the occasional night in a canoe, he and three colleagues somehow had fireworks to celebrate the Fourth of July.[2] A Coast Survey steamer took 11 other men on a "somewhat dangerous" trip through ice fields, mountain snow, and coastal mist to the northern extremity of Aulezavik Island.[3]

In the end, not much came from those extraordinary efforts. Gilliss got a clear view of the corona, but he didn't have a camera. He reported rosy prominences that "greatly resembled" those he'd seen during an 1858 eclipse in Peru, and he was now certain they were part of the Sun. But the sunrise eclipse was so spectacular that he "was irresistibly drawn to its contemplation" and neglected scientific observations.[4] Newcomb's colleague, entymologist Samuel Scudder, described their party's experience as "three thousand miles of constant travel . . . to reach by heroic endeavor the outer edge of the belt of totality; to sit in a marsh, and view the eclipse through the clouds!"[5] The group in Labrador fared little better. At totality, "nine-tenths of the sky was covered with clouds" and only one astronomer saw a glimpse of the corona.[6] Equally disappointing, clouds thwarted the search for the intra-Mercurial planet.

An ocean away, European scientists accomplished much more with the same eclipse. Aided by the British Admiralty and a newly built railroad in Northern Spain, Royal Society fellow Warren De la Rue transported observational equipment and an entire darkroom to the zone of totality. De la Rue made the controversial choice to use collodion photography (see figure 1), which was more sensitive to light, capable of capturing finer detail, and far less reliable than daguerreotype. His gamble paid off. On 12 September 1860, the *New York Times* gushed that "the rosy flames" shooting out from the eclipsed Sun had been "not only observed, but measured and photographed!" De la Rue's photo of the corona combined with observations like Gilliss's showed that the flames were features of the Sun and not the Moon.

Again in 1868 European astronomers made eclipse news. The Royal Astronomical Society sent John Herschel to Jamkhandi, India, to observe an eclipse on 18 August 1868; he used a telescope outfitted with a prism to study the chemical composition of the solar corona. French astronomer Pierre Janssen undertook a similar spectrographic project. For both, the spectrum of the chromosphere showed an unfamiliar yellow line near the sodium-D lines. It turned out to be helium, an element not isolated on Earth until 1895.[7]

That discovery raised new questions about the chemistry of the corona. US astronomers hoped to find answers during the upcoming solar eclipse of 7 August 1869. The empty experience of the 1860 eclipse informed preparations for the 1869 expeditions. With so much potential for scientific glory, the good fortune of an accessible eclipse path in the US was an opportunity not to be missed for US science.

Preparations for 1869

Late in 1868 Congress appropriated $5000 for a special expedition directed by James Coffin, a professor of mathematics at the US Naval Academy and the superintendent of the US Nautical Almanac Office. Coffin selected Burlington, Iowa, as his point of observation because both spectators and scientists could easily reach it by train from Chicago (see the map in figure 2). In anticipation, the Burlington City Council formed a committee for the support of eclipse visitors; police were provided to guard the observatory at night and control crowds on eclipse day.

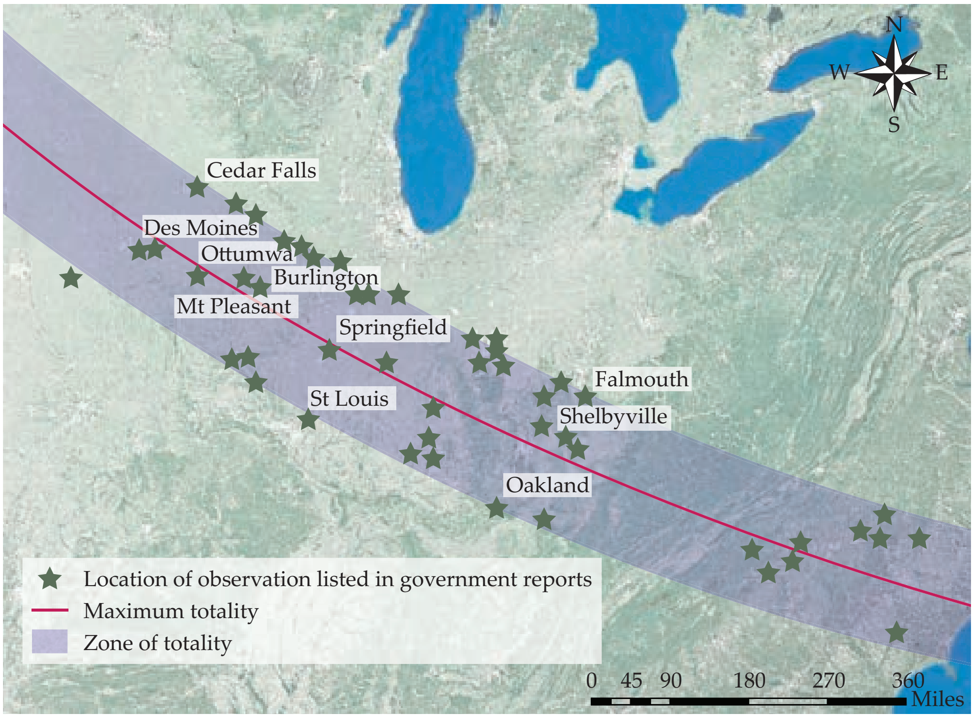


FIGURE 2. A MAP OF 1869 ECLIPSE OBSERVATION SITES and the zone of totality.

In May, Coffin asked Henry Morton, University of Pennsylvania chemistry professor and secretary of the Franklin Institute, to organize a party of photographers to join the expedition. Shipments to Iowa left Washington, DC, in late June so temporary observatories could be built. Preparations proceeded for official scientific tasks: observe the corona, conduct spectral analysis, search for intra-Mercurial planetoids, and photograph phases of the eclipse, especially totality.

Meanwhile, the Burlington Collegiate Institute offered its telescope to astronomer Maria Mitchell and a cohort of 11 current and former Vassar College students who had made eclipse calculations in Mitchell's classes. Among them was Coffin's daughter Martha.

The Coast Survey planned to station personnel and equipment all along the path of totality. Coast Survey explorer George Davidson had surveyed Alaska before its final purchase in 1868 and specifically mapped the Chilkat River in anticipation of observing the eclipse there. Asaph Hall, a US Naval Observatory professor of mathematics, was sent to the Bering Strait. Cincinnati Observatory director Cleveland Abbe led a wagon train to the northwestern end of the eclipse path in the Dakota Territory.

Farther east, Coast Survey staff began finding the geographical positions of their observing locations in April. Violent thunderstorms slowed survey work and made camping in the prairies miserable. The president of Western Union Telegraph Company helped by arranging an extensive telegraph relay and donating free use of the wires for the determination of longitude.[8]

From the US Naval Corps, Newcomb, William Harkness, and J. R. Eastman, along with assistant surgeon general Edward

FIGURE 3. A PHOTOGRAPH OF TOTALITY obtained at Burlington, Iowa. (From ref. 8.)

Curtis, would observe in Des Moines, Iowa, the westernmost site of totality that was accessible by railroad. Not knowing what to expect so far west, Curtis, Eastman, and Harkness arrived in Des Moines a month before the eclipse. Harkness found a builder to construct an observatory with a darkroom at the chosen hilltop site overlooking the river at the outskirts of town. Starting 10 July, Eastman and his wife meticulously recorded hourly meteorological observations.

In the weeks leading up to the eclipse, Curtis and his assistants rehearsed an elaborate choreography of exposing and developing a range of photographic plates in various weather conditions. They would have only about three minutes to attempt to capture a coronal image with a multistep photographic process. To practice, they self-imposed narrow time constraints for taking a photograph to replicate the immediacy of the anticipated eclipse event.

Academic astronomers also planned to take advantage of the eclipse. Joseph Winlock, director of the Harvard Observatory, made arrangements for several stations in his home state of Kentucky. Harvard University mathematics professor and Coast Survey superintendent Benjamin Peirce would oversee observations in Springfield, Illinois. Scientific parties were also assembled for Tennessee, Kentucky, and Virginia to distribute observers and reduce the risk of being completely clouded out.

Photography for research

Despite successes like De la Rue's, the status of photography as a research tool remained uncertain in the mid 19th century.[9] US scientists saw the 1869 eclipse as an opportunity to explore its utility during a high-stakes astronomical event. In particular, they hoped photography could produce images that would be measured after the event to determine precise times of the principal eclipse phases. They hoped similar photographs of the transit of Venus in 1874 could be used to determine the exact time at which Venus crossed in front of the Sun, information that could enable them to calculate a precise value for solar parallax.

Morton recruited 20 Philadelphia-area volunteer photographers to join Coffin's party. For months, they practiced astrophotography in a purpose-built temporary structure on private grounds in West Philadelphia. They used two equatorially mounted telescopes, one with a 6-inch aperture and 9-foot focal length borrowed from Philadelphia High School and the other with a 6.42-inch aperture and 8.5-foot focal length lent by Pennsylvania College at Gettysburg. Both instruments were outfitted with chronographs to record the time each photo was taken. From the University of Pennsylvania, Coffin's group had a third equatorial telescope, with 4-inch aperture and no clockwork. The volunteers experimented with developer fluids, photographed the Moon to set time exposures, made mechanical adjustments, and refined techniques in hopes of precise work during the eclipse event.

Exactly a week before eclipse day, the photographers loaded more than five furniture cartloads of equipment into a custom car furnished by the Pennsylvania Central Railroad Company. Railroad companies also donated free transportation for the entire Philadelphia photographers' expedition, a generosity that stretched Coffin's government appropriation by $1500.

Picturing totality

Alfred Mayer, an astronomy professor at Lehigh University, joined Coffin in Burlington around noon on Wednesday, 4 August. Torrential rains on Friday night meant a sleepless night of nerves and instrument adjustments for Mayer, but the clouds cleared by 10:00am. Everything was ready by 3:00pm, about one hour before first contact, when the Moon starts to pass in front of the solar disk. By taking a rapid sequence of exposures around the calculated time of first contact, they got a photo of first contact and, as a pleased Morton put it in a Naval Observatory report, "a very good result."[10] The Burlington team also took six pictures of totality (see figure 3).

In Mount Pleasant, Iowa, 28 miles farther west in the zone of totality, a second party set up the University of Pennsylvania telescope under the guidance of Morton and MIT professor Edward Pickering. That group used a globe lens with a 12-inch

FIGURE 4. AN ECLIPSE OBSERVATION SITE AT OTTUMWA, IOWA. This building was constructed to enable eclipse observation and photography. (Digital positive from the original collodion silver negative in the George Eastman Museum collection. © George Eastman House.)

focal length to capture the most extensive photo of the 1869 corona. Their 41 total photos also included one with an improbably slight indentation between the shadow of the Moon and the bright edge of the Sun—given contemporary predictions and technology, it would be nearly impossible to photograph first contact exactly. From that valuable image, said Morton, calculations would produce the time of actual first contact "more precisely than would be possible with any eye observation."[10]

Dickinson College professor Charles Himes and his party took the Pennsylvania College telescope 75 miles west of Burlington to the Ottumwa, Iowa, observation site (see figure 4). The group did not fare as well as the Burlington and Mount Pleasant teams. Severe thunderstorms ruined the observatory roof. They had also forgotten their chronometer in Burlington, and, worse, the telescope clockwork suffered serious damage in transit. Instrument maker Joseph Zentmayer avoided catastrophe by rebuilding the chronograph in record time. In the end, with clear skies Saturday afternoon, they obtained 34 negatives—including four pictures of totality.

The Philadelphia photographers were not the only ones who successfully photographed the 1869 eclipse. In Shelbyville, Kentucky, Winlock's alma mater and prior employer Shelby College provided accommodations for more than a dozen observers. The college lent its state-of-the-art telescope to Winlock. His main goals were to capture a good photograph of the corona and to establish a systematic approach to determining via photograph the relative positions of celestial bodies. To achieve the latter, he kept the camera in the same position throughout the eclipse, with the aim of comparing partial and total views to determine accurate position angles between the Sun, Moon, and Earth. Those hopes were largely dashed, but his goal of photographing the corona was better realized. Winlock was pleased with his seven photos of totality.

Peirce's party in Springfield included a trio of photographers and their assistant along with an entourage of Coast Survey assistants, Harvard faculty, and students. With them, Boston photographer James Wallace Black took 178 photos at nine-second intervals. On their plates, the Sun's image was about two-thirds of an inch in diameter. In Des Moines, navy observers' elaborate practice routine paid off. Curtis made a total of 115 photographs, including two remarkable images of totality.

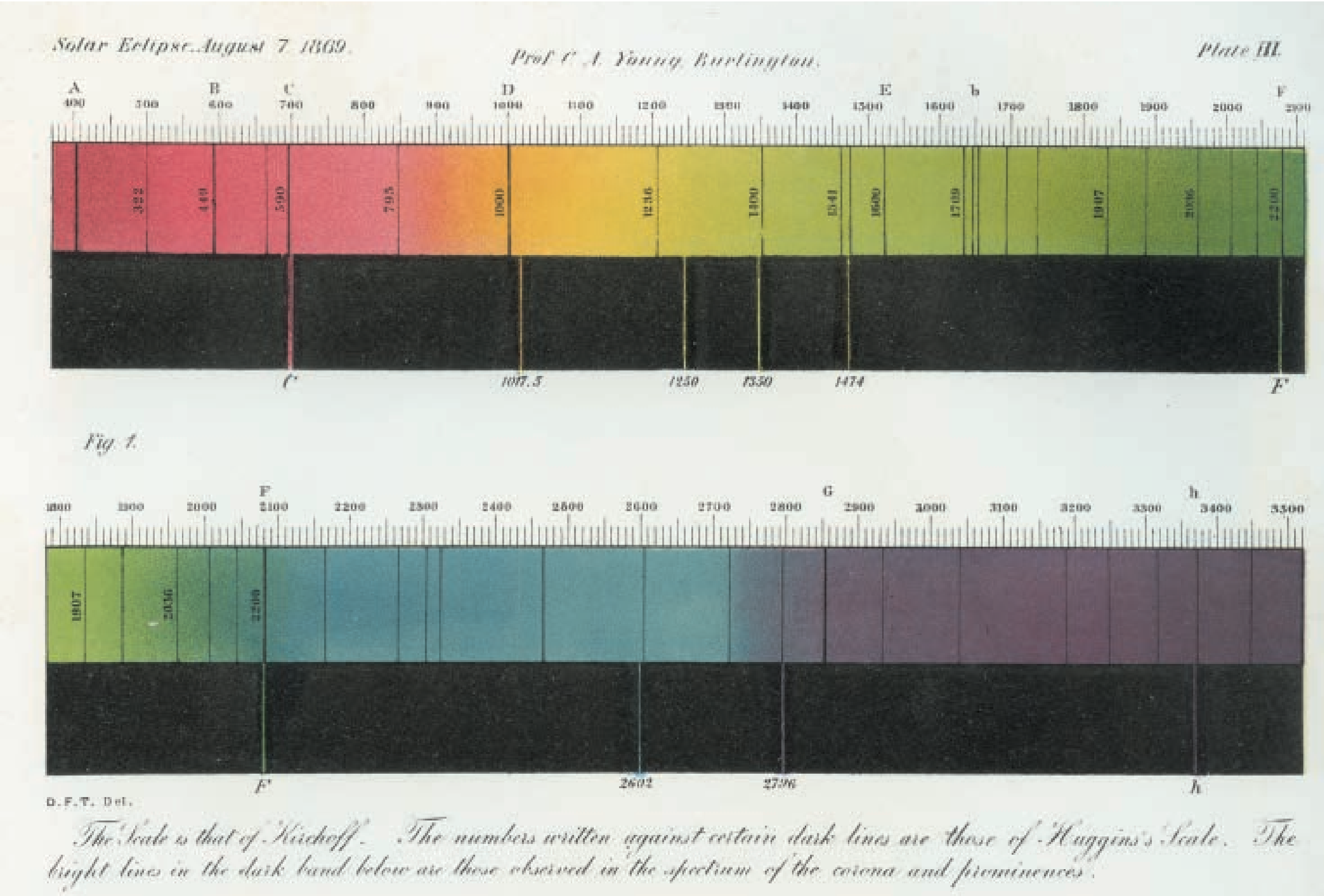


FIGURE 5. CHARLES AUGUSTUS YOUNG'S SPECTRUM of the corona. (From ref. 8.)

Spectroscopy and the 1869 eclipse

Since spectroscopic results from the 1868 eclipse had yielded insight into the content of the corona, US scientists hoped the 1869 eclipse observations would produce more information about the chemical composition of the Sun. Spectroscopes were less common instruments than telescopes and chronometers, however, and not every observing party had one. Davidson, for example, had initially hoped for spectroscopic readings in Alaska, but he was told in May that no one had volunteered for the daunting journey to deliver an instrument there.

The most productive spectroscopic results came from Charles Augustus Young, an astronomy professor at Dartmouth College who was with Coffin's party in Burlington. Young used various Dartmouth instruments to rig up a spectroscope with five prisms. The instrument, Young wrote, had been arranged "in a manner somewhat different from anything heretofore used, but which proved efficient."[11] Young observed initial contact through his spectroscope and concluded that the approach would be ideal for timing the transit of Venus. During totality, he observed a green line, K1474, that appeared from the coronal light beyond the prominences; he concluded it belonged to the spectrum of the corona (see figure 5).

Harkness obtained similar results in Des Moines. He used a single-prism spectroscope originally designed for use in laboratory chemistry, but significantly altered and attached to his personal 3-inch telescope for eclipse observations. Like Young, Harkness also observed a coronal spectrum containing a bright green line.

Collecting better eclipse data

In November 1868, Peirce wrote to Davidson that the highest Coast Survey priority during the eclipse was to "secure the greatest precision in observing the phases, times, &c. with reference to data for the longitude."[12] To that end, Davidson took 17 chronometers north from San Francisco. He left 9 of them in Sitka, Alaska, and traveled the last 250 miles over dangerous rivers in an open canoe. His use of multiple timepieces illustrates his interest in minimizing error.

Similar concerns about error led the Coast Survey to distribute observers across the zone of totality. Observations from multiple stations at different sites could be averaged to yield a more accurate value for the Moon's distance from Earth. Coast Survey observers in Des Moines were sent out to determine the north and south limits of totality. A group of at least eight headed toward St Louis, Missouri. They stationed themselves at one-mile intervals near the calculated limit, and each observer timed totality. Five other observers headed toward Cedar Falls, Iowa, and spread out to three different points in an effort to locate the northern boundary of the eclipse path.

Observers were likewise dispatched at intervals near the limits of totality in Kentucky. Arthur Searle, from the Harvard Observatory, had marked stations to measure the breadth of the Moon's shadow. Searle himself was stationed at Falmouth, Kentucky, just inside the line of totality. A mechanical malfunction voided his timing, but others in his party noted that the duration of totality was 45 seconds. On a hill just north of Falmouth, two observers recorded 41.5 seconds. Another pair nearer the northern limit timed 12 seconds of totality, and two farther out missed it entirely. Near the southern boundary of totality in Oakland, Kentucky, Samuel Langley, director of the Allegheny Observatory outside Pittsburgh, Pennsylvania, clocked just two seconds of totality.

Newcomb's 1869 eclipse work also focused on precision. He observed from Des Moines in conditions that must have seemed luxurious compared with his backwoods ordeal of 1860. He arrived in Iowa at the end of July and staged his search for intra-Mercurial planetoids from the statehouse yard. Not seeing any new planets during totality, he switched focus to comparing observed times of contact with those predicted by existing tables to check theories of solar and lunar motion. He found discrepancies of several tenths of a second.

The afterglow

Newspapers from San Francisco to New Hampshire and even overseas carried news of the total solar eclipse across North America. Millions witnessed a partial eclipse as far east as Boston and as far west as California. Thousands traveled to experience totality, which Newcomb described as "glorious beyond description."[13] Newspapers also circulated glowing descriptions of both the flaming corona and the eerie features preceding totality.

And what of the scientific venture? The search for an intra-Mercurial planet came up empty, and reams of painstakingly recorded meteorological data did not prove illuminating. Still, the parties exceeded contemporary expectations in the number and precision of eclipse observations collected. Spectroscopic work by Harkness and Young resulted in the discovery of a new coronal line, K1474. For a time, observers believed it was from a new element that they named coronium; it would be another 70 years before the K1474 line was correctly attributed to highly ionized iron at over 1 million kelvins.

Remarkable photographs of the eclipse also established hope for photography as a useful astronomical tool. Micrometric analysis of the glass-plate negatives generated improvements to photographic measurement before the transit of Venus.

After his 1869 experience, Mayer saw potential for photography to produce "solar parallax comporting with the most exact astronomical measures of this century."[14] The efforts and output of the 1869 expeditions gave the 19th-century American audience something to celebrate. It also gave scientific practitioners valuable experience with equipment and techniques for major event science.

In 1874 patriotic arguments swayed Congress to grant a staggering $177 000 for the Transit of Venus Commission. This funded eight expeditions to locations that included the Kerguelen Islands in the Southern Indian Ocean; Hobart, Tasmania; Peking, China; and Vladivostok, Russia.[15] Alas, eight sets of new equipment and many observers with eclipse experience were no match for a day of bad weather and the black-drop effect—when a dark linkage between the end of Venus's silhouette and the sky develops for a few seconds before Venus is clearly inside the Sun's disk. The black drop made it impossible to time the contacts precisely.[16]

By 1882 Newcomb had abandoned hope that photography could help calculate the distance from Earth to the Sun, but Harkness persisted. He obtained more appropriations—$10 000 to improve instruments and $75 000 for the expeditions—for the 1882 Transit of Venus. In the end, he produced a landmark result. By early 1889 Harkness had measured and analyzed 1475 photographs to arrive at a final result of 92 455 000 ± 123 400 miles. In 1894 he refined that result to 92 797 000 ± 59 000 miles.[17] In 2012, the International Astronomical Union adopted a value of 149 597 870 700 meters (92 955 807 miles) for the astronomical unit, a measure of the average distance to the Sun.

The second half of the 19th century was arguably the golden age of eclipse expeditions. Then, as now, observational astronomers made herculean efforts to organize and implement major projects to gain insight on the biggest scientific questions of the day. The success of extensive planning and major expenditures depended on accurate theories and well-posed questions and also on the vagaries of weather and technology. And observers had to deliver despite the thrall of mesmerizing events. For the US, the 1869 eclipse expeditions merged new transportation technologies with the marvel of celestial observation. They capitalized on the technologies of astrophotography and deployed legions of government and civilian scientific practitioners who would build on that experience in future high-stakes astronomical events. The great success and attendant publicity boosted US astronomy and laid a foundation for the ventures to come.

The author thanks David Baron, David J. Muraki, Jay Pasachoff, Shari Stelling, and Bradford Wirt for their assistance. The US Coast Survey reports cited in this article were made available by the NOAA Central Library Data Imaging Project.

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PT

VECTORIG/ISTOCK

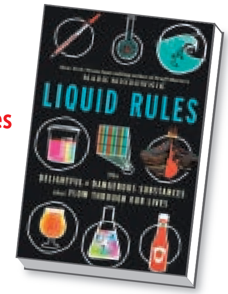
An engaging look at the physics of fluids

A wide range of readers will appreciate the snappy, appealing *Liquid Rules: The Delightful and Dangerous Substances That Flow Through Our Lives*. Author and materials scientist Mark Miodownik introduces numerous topics related to liquids, from fluid dynamics and rheology to chemistry and engineering—all presented in a clear, entertaining, and easy-to-read manner. Miodownik is well known for introducing materials science topics to the general public, and *Liquid Rules* reflects his talent for communicating science. I would happily recommend this book to my family and friends to give them a window into the delightful ways in which liquids behave.

Although liquids constantly touch our everyday lives, the wider public often doesn't appreciate their large variety of peculiar behaviors. I am elated that Miodownik has created a witty book that collects some of the more intriguing and beguiling fluid phenomena in one place. Most importantly, the science presented throughout is accurately, clearly, and thoroughly elucidated. Popular science writers often err on the side of explaining too little in order to simplify their message, but that is not at all the case with Miodownik. He describes the science precisely, but in a straightforward way using everyday language. I think that anyone who picks up the book will both gain a new appreciation for the everyday marvels of fluid behavior and learn something about the science behind it all. Although *Liquid Rules* is intended for a general audience, everyone can learn from it—for example, I picked up a new understanding of the chemistry behind coffee roasting.

The story in *Liquid Rules* is constructed around a transatlantic airplane journey from London to San Francisco. The author discusses the various liquids that he or the plane uses along the way, from the kerosene in the aviation fuel to the soap in the lavatory. Although I appreciate the effort to tie the book together, the thread of the airplane journey feels a bit forced. Furthermore, I don't think the overarching story is necessary. What I enjoyed most was that each chapter stood well on its own—the book feels almost like a short story collection. Each chapter highlights a way in which liquids touch our lives and teaches readers about the science behind it; the explanations often are complemented by beautiful, hand-drawn illustrations. It is quite possible to read a chapter out of order. Although the book as a whole can feel a bit

Liquid Rules
The Delightful and Dangerous Substances That Flow Through Our Lives
Mark Miodownik
Houghton Mifflin Harcourt, 2019. $26.00



scattershot—Miodownik jumps quickly from topic to topic, even within chapters—I believe the self-contained chapters are a plus for a popular science text.

One of the book's real strengths is that many of the topics are discussed in a well-presented historical context. For example, the first chapter, "Explosive," focuses on the kerosene in airplane engines. Miodownik discusses how fuel sources have evolved throughout the centuries, starting with oil lamps and ending with jet fuel. Along the way, he introduces surface tension by examining the wick inside an oil lamp. In the fourth chapter, "Sticky," he covers topics from glue to rubber to plywood and treats readers to an overview of how those materials have shaped engineering and manufacturing throughout history. I quite enjoyed all the book's detours into history, and I imagine most readers will as well. The historical material skillfully places the science in a larger context and answers the eternal question, "What is that knowledge good for?"

Miodownik's background in materials science is apparent throughout the book. For example, not only does he discuss how jet engines are cooled, as a typical fluids scientist might, but he also explains the chemistry behind epoxy. His presentation of science, touching on chemistry, engineering, and physics, is a wonderful and accurate representation of how science is evolving. I hope that readers will be able to take away the message that science is highly cross-disciplinary. More and more of us work on problems that do not neatly fall into traditional categories but instead require understanding from many perspectives. A well-written and entertaining popular science book highlighting all the ways fluids touch our lives seems like an excellent champion for interdisciplinary science.

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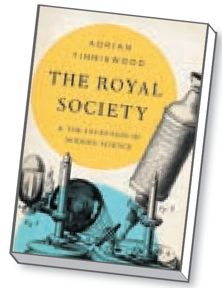
An engraving depicting an early meeting of the Royal Society.

The legacies of the Royal Society of London



The Royal Society and the Invention of Modern Science

Adrian Tinniswood

Basic Books, 2019.
$26.00

Writing a balanced, accurate, and broadly positive history of the Royal Society of London is a difficult task. The society figures in virtually all accounts of early modern experimental science, but the true extent of its influence is notoriously hard to assess. Early members of the society include some of the most renowned names in 17th-century science—Robert Boyle, Christopher Wren, Robert Hooke, Isaac Newton, Giovanni Domenico Cassini, Christiaan Huygens—but the Royal Society itself is not the primary reason for their fame. Furthermore, popular writing about the society unhelpfully tends to seize upon methods and practices from the 17th century that vaguely resemble modern science, and to treat those methods and practices as if the Royal Society immediately established them as permanent features of science. Historically nuanced accounts often try to clear away misguided overclaiming before they set to work, but they can seem grudging or disparaging as a result.

With *The Royal Society and the Invention of Modern Science*, author Adrian Tinniswood has made a respectable compromise between the constraints of academic history, the power of the origin myths of modern science, and the need to keep readers entertained. The book's most contentious claim is implied in its title—that the Royal Society was principally responsible for inventing modern science. That is a huge stretch, one made barely deniable by the slightly evasive "and." In practice, however, the book makes no real attempt to defend it.

Instead, Tinniswood offers a brisk institutional history slanted heavily toward the Royal Society's foundation in 1660 and its early years. A series of thematic chapters highlights key phases in the society's development and the most important areas of its activity—notably its early commitment to experiments and the emergence of *Philosophical Transactions*, the world's first scientific periodical, which contributed significantly to the society's wider reputation and to its burgeoning role as a hub of scientific communication.

The significance of *Philosophical Transactions* is emblematic of a more general historical insight about the society—that it mattered more as a constructor and promoter of scientific communities than as a primary producer of experimental knowledge about nature. *The Royal Society and the Invention of Modern Science* is careful to keep that distinction in view. Tinniswood's previous books, including *The Polite Tourist: Four Centuries of Country House Visiting* (1999) and *Behind the Throne: A Domestic History of the British Royal Household* (2018), reflect his abiding preoccupation with English social elites. That preoccupation serves him well when he writes about the society's first members. He recognizes the society's tendency to consider rank as a qualification for membership and is able to view titled members with interest without making undue claims about their actual scientific achievements.

In fact, many members of the Royal Society were ambivalent about the virtues of a self-selecting association sustained entirely by voluntary labor and about the preponderance of gentlemen amateurs in the membership. Tinniswood devotes a chapter to the important reformist critiques of the 1830s, which were articulated by mathematician Charles Babbage, among others. Babbage and his allies argued passionately in favor of making scientific expertise a formal criterion for both the election of fellows and the evaluation of research.

And the critiques didn't just come from within. An organization that dedicated its time to transfusing the blood of a sheep into a young man, or to investigating the luminescence produced by putrid meat, or to discussing the possibility of a civilization on the Moon, always ran the risk of being lampooned as a gang of crackpots and fantasists. Jonathan Swift and Henry Fielding were merely the most prominent of those taking satirical aim at the society during the first 80-odd years of its existence.

Mockery might have upset the fellows of the Royal Society but, as Tinniswood observes, it did little to deter them. The society's prestige and its involvement with scientific projects at a state level increased as the 18th century wore on. The society oversaw major expeditions such as Charles Mason and Jeremiah Dixon's surveying work in North America and James Cook's voyage to the South Pacific in 1769. Joseph Banks, a gentleman botanist from Lincolnshire who took part in Cook's voyage as a naturalist, became an instant celebrity on his return and was elected president of the Royal Society in 1778; he served until 1820. It was Banks, more than anyone, who helped to develop the society's role in public life and the advisory functions it still exercises today.

Tinniswood's account of the society's history from about 1800 to the present, including Banks's transformative presidency, is rather perfunctory, focusing on a couple of episodes only. He offers a useful retelling of the society's drawn-out efforts to exclude women until the election of Kathleen Lonsdale and Marjory Stephenson as the first women fellows in 1945, but his account of the debates in the 1930s about the social responsibilities of science and scientists could have been extended. Within the constraints imposed by brevity, however, Tinniswood's book is an entertaining and remarkably balanced account of a fascinating institution.

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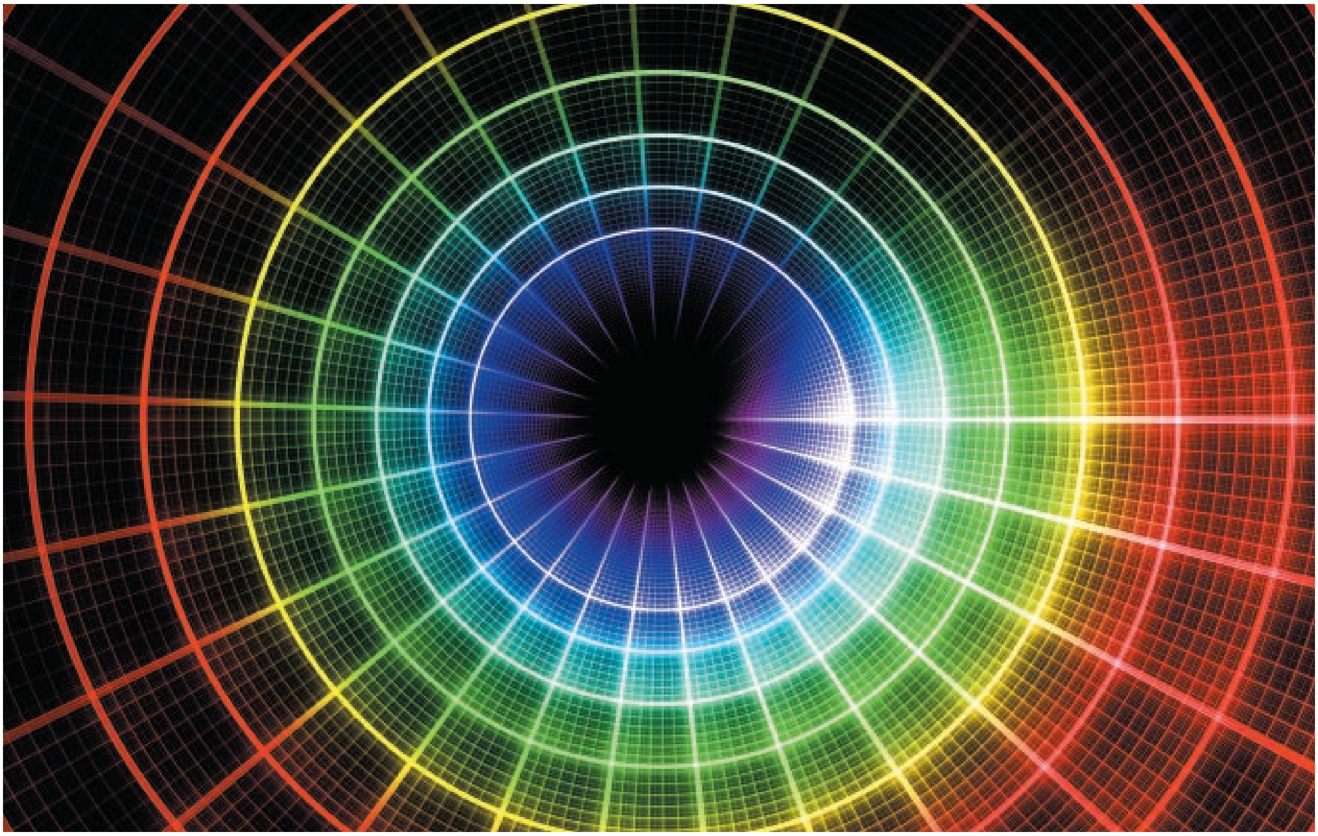

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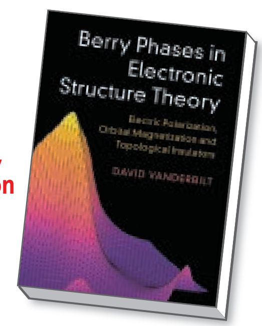
The mathematics and physics of electronic structure theory



Berry Phases in Electronic Structure Theory
Electric Polarization, Orbital Magnetization and Topological Insulators

David Vanderbilt
Cambridge U. Press, 2018. $79.99

The theory of electric polarization underwent a genuine revolution in the early 1990s. In the wake of that revolution, some long-established views about other observables have been superseded, the most notable being orbital magnetization. The geometry of the electronic ground state provides the formal mathematical expression for those observables, and the archetype for all of them is the geometric phase in quantum mechanics, discovered by Michael Berry in 1984.

Berry Phases in Electronic Structure Theory: Electric Polarization, Orbital Magnetization and Topological Insulators provides a comprehensive pedagogical account of several breakthrough developments in electronic structure theory associated with geometric phases. Its author, Rutgers University physicist David Vanderbilt, is eminently qualified for the task: He is the senior author of a large part of the research at the book's core. That literature is now fundamental knowledge for any scientist working on modern electronic structure. Some of the methods presented in Vanderbilt's book have such wide-ranging impact and use that they are now standard options in many open-source computer codes for electronic structure in solids.

The book's presentation combines mathematical rigor with illuminating discussions and examples. It clearly connects the underlying mathematics with the physics of the phenomena addressed. Although several review papers over the years have covered some of the same topics, Vanderbilt's book is the first to present them systematically and comprehensively at the textbook level.

Berry Phases in Electronic Structure Theory is primarily aimed at graduate students, and it looks like the ideal textbook for any special-topics course that broadly covers geometry and topology in electronic structure. It comes at a time when such courses are becoming more and more popular worldwide. The book is also aimed at both theorists and experimentalists who want to become familiar with geometric or topologic observables and, more generally, with the most basic concepts in electronic structure that have been unveiled in the past three decades.

Electric polarization and orbital magnetization, two of the observables Vanderbilt mentions, are basic undergraduate-level concepts that unfortunately often receive severely flawed accounts in other textbooks. General literacy about those topics beyond the community of electronic-structure specialists is poor. Vanderbilt's comprehensive treatment of electric polarization and orbital magnetization will hopefully improve the situation. The book also addresses other, less popular, observables and concepts, all based on the geometry and topology of the electronic ground state in solids.

The book's first three chapters are devoted to introductory or formal topics. After a semiquantitative overview of phenomena that have a geometrical or topological character, the book starts at an elementary level and provides the fundamentals of electronic structure theory. I have noticed that a large part of the geometrical–topological literature often overemphasizes tight binding. Vanderbilt, however, begins with first principles and then progresses to the tight-binding level, an approach that I prefer and that is more appropriate to a textbook.

After that review, the book addresses "Berryology,"—Vanderbilt's neologism for geometry in electronic structure—first in a very general way and then in terms of crystal momentum and in relationship with band-structure theory. The Wannier functions in their modern formulation, pioneered by the author in the late 1990s, are a key part of that section. The last three chapters of the book are devoted to the geometrical or topological observables, namely electric polarization, quantum anomalous Hall conductivity, the nature of the topological insulating state, orbital magnetization, and the so-called axion term in magnetoelectric coupling.

Every chapter includes traditional paper-and-pencil examples and exercises along with computational ones based on an open-source package developed by the author in Python. Thus the book encourages students and researchers alike to take a hands-on approach to the many fundamental properties of electrons in solids.

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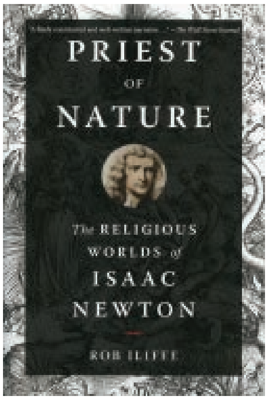
NEW BOOKS & MEDIA



Priest of Nature

The Religious Worlds of Isaac Newton

Rob Iliffe

Oxford U. Press, 2019. $24.95 (paper)

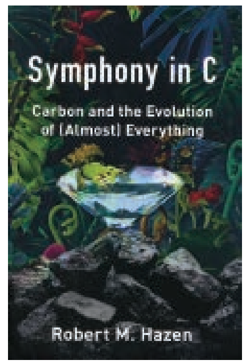
Rob Iliffe is a professor of history of science at Oxford University and a general editor of the Newton Project, an ambitious effort to put all of Isaac Newton's published and unpublished writings online. He brings a lifetime of Newton scholarship to *Priest of Nature: The Religious Worlds of Isaac Newton*. The book explores Newton's largely unpublished research into Christian theology, Biblical prophecy, and church history—projects that Newton himself considered at least as important as his mathematical work—and untangles the complicated picture that emerges from them of Newton's religious beliefs. Newton came to some conclusions that were outright heretical for his day, including his firm rejection of the doctrine of the Holy Trinity. First published to wide acclaim in 2017, *Priest of Nature* is now available in paperback. Anyone interested in Newton's life and thought will want a copy for their bookshelves. —MB

Symphony in C

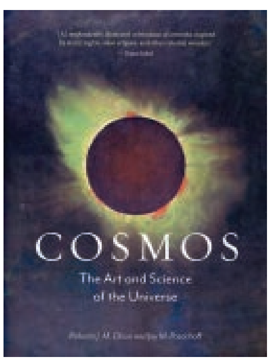
Carbon and the Evolution of (Almost) Everything

Robert M. Hazen

W. W. Norton, 2019. $26.95



"We live on a carbon planet and we are carbon life," Robert Hazen tells us in the prologue of his new book *Symphony in C*. Carbon makes our DNA possible, forms the chemical backbone of thousands of synthetic materials, and is the heart of the fossil fuels that made the Industrial Revolution possible and that are now causing a climate crisis. Given all that it does, carbon might seem like too vast a subject for a single book, but geophysicist and accomplished science writer Hazen manages to bring together physics, chemistry, geology, and history to tell carbon's story in less than 300 pages. Told in four "movements"—Earth, Air, Fire, and Water—*Symphony in C* explores carbon's role in everything from the Big Bang to volcanic eruptions to the evolution of life on Earth. —MB



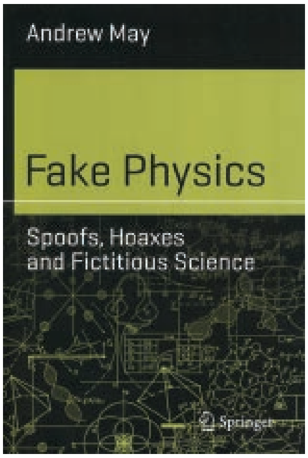
Cosmos

The Art and Science of the Universe

Roberta J. M. Olson and Jay M. Pasachoff

Reaktion Books, 2019. $49.95

Featuring hundreds of beautiful illustrations, paintings, prints, and photographs, *Cosmos: The Art and Science of the Universe* explores astronomical phenomena and humans' fascination with them throughout history, as evidenced by depictions in works of art. The book is the result of a collaboration between astronomer Jay Pasachoff and art historian Roberta Olson, who spent the past three decades collecting the images that would feature in this interdisciplinary study. Complementing the imagery is a narrative that chronicles developments in both astronomy and art over the past several millennia. —CC



Fake Physics

Spoofs, Hoaxes and Fictitious Science

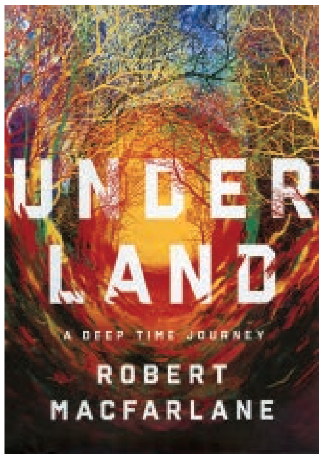
Andrew May
Springer, 2019. $27.99 (paper)

Astrophysicist Andrew May's third volume in Springer's Science and Fiction series, *Fake Physics: Spoofs, Hoaxes and Fictitious Science*, is a playful exploration of the boundary between science fiction and science fact. Meant to entertain rather than to expose fraud, the book covers such topics as the art of technobabble, spoof papers in science journals, April Fool's Day joke articles, several amusing "sting operations" aimed at predatory journals, and thought experiments that apply scientific methods to subjects more associated with sci-fi, like Fermi's paradox regarding extraterrestrial civilizations. Aimed at a general audience, *Fake Physics* touches on physics principles in an entertaining and engaging way. —CC

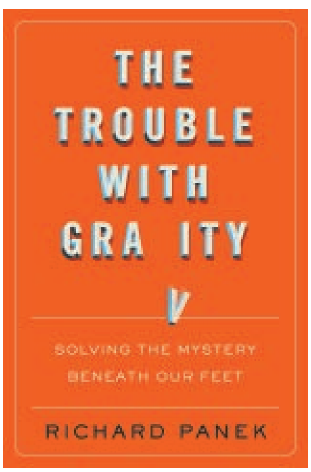
Underland

A Deep Time Journey

Robert Macfarlane
W. W. Norton, 2019. $27.95



"*Underland* is a story of journeys into darkness, and of descents made in search of knowledge." Thus writes author Robert Macfarlane, a fellow of Cambridge University. In this literary narrative, Macfarlane writes eloquently about some of the myriad mysterious spaces that lie beneath Earth's surface. Not only does he describe in lush detail the caves, catacombs, glacial ice, sinkholes, and other features he has explored, he also writes about their history and uses over time. Along the way, he meets and befriends fellow explorers, spelunkers, and diverse others. His numerous anecdotes and beautiful descriptions of natural phenomena make for a highly readable account of Earth's geography, history, and natural wonders. —CC



The Trouble with Gravity

Solving the Mystery Beneath Our Feet

Richard Panek
Houghton Mifflin Harcourt, 2019. $28.00

Nobody knows exactly what causes gravity, but to award-winning science writer Richard Panek, that's no obstacle to a fascinating discussion about its history. Despite the book's subtitle, Panek says early on that he has no solutions to the mystery of gravity. Instead, his book brings in research from philosophy, mythology, and the history of science to explore how the force of gravity has affected human bodies, thought, and culture. The first chapter, for example, considers how gravity affected the architecture of our religious worldviews: The gods are up there and we are down here. To be human is to be bound by gravity, and although some like Icarus may try to get into the divine realm, Panek says, we always fall in the end. This is not a book about the science of gravity, but if you want to wonder how gravity has shaped us and our world, Panek will wonder with you. –JO PT

NEW PRODUCTS

Focus on nanotechnology, lasers, and imaging

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

Andreas Mandelis

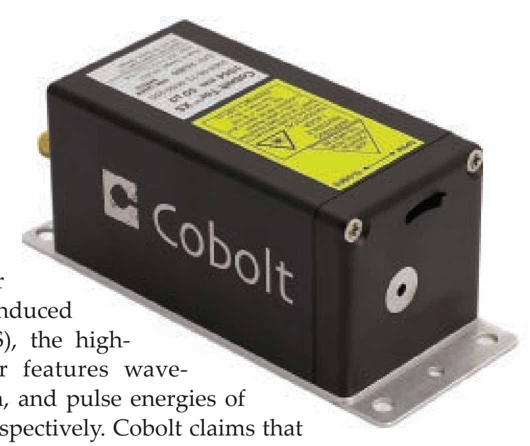
Flexible multiple-wavelength laser engine

The latest member of Toptica's iChrome multilaser engine family, the compact iChrome FLE, addresses the need for multiple-wavelength lasers in advanced biophotonics procedures, such as high-throughput screening. It is suitable for most microscopy techniques, such as confocal, superresolution, light-sheet, stochastic optical reconstruction, fluorescence recovery after photobleaching, and fluorescence resonance energy transfer. The iChrome FLE's extended platform can be configured with up to seven laser lines in the range of 405–647 nm and with one or two fiber outputs. Toptica's proprietary frequency-doubled diode-laser technology allows fast, direct modulation to the 532, 561, and 594 nm laser lines and is completely zero-emission when the laser is turned off. Previously, that capability was only available in a CW diode-pumped solid-state laser source combined with an acousto-optic modulator. ***Toptica Photonics Inc***, *5847 County Rd 41, Farmington, NY 14425, www.toptica.com*

Piezo nanopositioning motion controller

Physik Instrumente (PI) now offers an EtherCat-compatible version of its E-727 digital piezo-controller family. It is suitable for use in piezo-based nanopositioning and scanning systems, optics and photonics, and semiconductor manufacturing. The controller delivers high bandwidth, linearity, and nanometer accuracy. It easily integrates into precision automation systems via EtherCat connectivity and can be operated as an "intelligent driver" for two- or three-axis piezo-based nanopositioning systems. Intelligent servo algorithms minimize settling times and allow repeatability into the subnanometer range. Advanced features include an integrated data recorder and subordinate, programmable drift compensation. PI also offers EtherCat motion controllers manufactured by ACS Motion for long-travel precision positioning stages. ***Physik Instrumente LP***, *16 Albert St, Auburn, MA 01501, www.pi-usa.us*

Pulsed lasers for LIBS and photoacoustics



Cobolt AB, a part of Hübner Photonics, has introduced its ultracompact Cobolt Tor XS laser. Intended for photoacoustic microscopy applications and for integration into handheld or portable instruments for laser-induced breakdown spectroscopy (LIBS), the high-performance Q-switched laser features wavelengths of 1064 nm and 532 nm, and pulse energies of 100 µJ/pulse and 50 µJ/pulse, respectively. Cobolt claims that for its size, the Tor XS provides a unique combination of kilohertz repetition rates, short pulse lengths less than 3 ns, and high pulse-to-pulse stability. The emission, which is generated in a TEM_{00} beam, can be externally triggered from single pulses at repetition rates up to 1 kHz. According to Cobolt, the lasers provide a high level of immunity to varying environmental conditions: They can withstand multiple 60 G mechanical shocks without degraded performance and exposure to temperatures higher than 100 °C. ***Cobolt Inc***, *2635 N First St, Ste 228, San Jose, CA 95134, www.coboltlasers.com*

Laser safety interlock shutters

Electro-Optical Products has launched new models of its economical laser and x-ray safety interlock shutters, the blades of which block a laser beam when the power is turned off. The small-size SH-66 laser shutter or low-frequency pulse picker can block a high-power laser beam up to 10 W. The low-vibration electromechanical device consists of a stepping motor with a mirror that smoothly turns from 0° to 45° to deflect a laser beam. The device produces no clicking or knocking noise, and no shock or vibrations are created when the mirror changes position. The SH-66 is offered in several variations, some with heat sinks, and in standard, custom, and OEM models. Aluminum mirrors with enhanced reflectivity are standard, and gold-, silver-, and dielectric-coated mirrors are optional. The shutter can also be used as a pulse picker for up to 20 Hz with a response time of 15 ms. ***Electro-Optical Products Corp***, *62-40 Forest Ave, 2nd Fl, Ridgewood, NY 11385, www.eopc.com*

Simplified fluorescence imaging software

PicoQuant and Zeiss have released a plug-in for Zeiss's ZEN imaging software (blue edition). The plug-in allows a Zeiss laser scanning microscope and an upgrade kit from PicoQuant to capture fluorescence lifetime imaging (FLIM) and fluorescence correlation spectroscopy data. Multidimensional imaging experiments such as z-stacks and time-lapse series can now be performed more simply, with FLIM acquisition measurements defined and started in the familiar ZEN imaging software environment. Time-resolved data are automatically acquired using the motorized laser combining unit and PicoQuant's SymPhoTime 64 software. After acquisition, the results can be analyzed with the easy-to-use SymPhoTime tools. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

Laser-grade aspheric lenses

Edmund Optics has announced a line of lenses with a λ/40 rms aspheric surface tolerance, which makes them suitable for high-precision laser-focusing applications. The aberration-free Techspec lenses are polished with a magnetorheological finishing, a process that selectively removes material in a highly repeatable and controlled manner. That enables diffraction-limited performance and a guaranteed exceptional Strehl ratio greater than 0.8 at the wavelengths of the neodymium-doped yttrium aluminum garnet lasers. According to the company, the lenses can maximize throughput with high-performance laser line V-coatings for less than 0.25% reflection at the laser wavelengths. The aspheres feature fused silica substrates and are available in standard imperial sizes with f/2 designs. ***Edmund Optics Inc****, 101 E Gloucester Pike, Barrington, NJ 08007, www.edmundoptics.com*

DFB laser diode module

OSI Laser Diode has developed a 1650 nm distributed-feedback (DFB) laser diode module for optical test equipment applications in which high-peak-pulsed optical power is required. The SCW 1731F-D40R's stabilized wavelength is unaffected by operational pulse width, making it suitable for use as an optical spectrum analyzer or in optical time-domain reflectometry (OTDR). The module also features a broader spectrum than is available in traditional DFB lasers and exhibits less noise in OTDR and other similar applications, according to the company. The new product complies with the Restriction of Hazardous Substances directive. It is optically coupled to a single-mode fiber pigtail and includes a thermoelectric cooler and an electrically isolated temperature-sensing thermistor. ***OSI Laser Diode Inc****, 4 Olsen Ave, Edison, NJ 08820, www.laserdiode.com*

Compact ultrafast lasers

Coherent has designed its Axon family of compact femtosecond lasers to be less expensive and complex and to address demanding applications, such as multiphoton microscopy, material nanoprocessing, two-photon polymerization, terahertz spectroscopy, and semiconductor and thin-film metrology. The first two models of the air-cooled lasers have fixed output wavelengths of 920 nm and 1064 nm; future models will offer additional wavelengths. The Axon lasers feature 1 W of average power with integrated, software-controlled group-velocity-dispersion precompensation. The output features a pulse width of less than 150 fs and an 80 MHz pulse repetition rate. The 920 nm model is designed for green fluorescent protein and related imaging probes and Ca^{2+} indicators. The 1064 nm version matches well with red-shifted Ca^{2+} indicators and red fluorescent proteins. ***Coherent Inc****, 5100 Patrick Henry Dr, Santa Clara, CA 95054, www.coherent.com* PT

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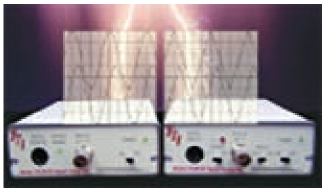

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NATIONAL HIGH MAGNETIC FIELD LABORATORY

Dirac Postdoctoral Fellowship in Theoretical Condensed Matter Physics

The National High Magnetic Field Laboratory (NHMFL) invites applications for the ***Dirac Postdoctoral Fellowship***, a two-year postdoctoral fellowship in condensed matter theory. The program is designed for Ph.D.'s with a research interest in any of the condensed matter areas represented by the three sites of the NHMFL. Successful applicants are expected to demonstrate high aptitude for theoretical research as well as to draw on the close connection with the ongoing experimental program. Extension for a third year is possible, contingent upon exemplary performance.

The expectation is that upon appointment the successful 2020 candidate will be located at the NHMFL in Tallahassee. The appointment includes a highly competitive salary and benefits, $5000 annually in discretionary funds to cover research and/or travel expenses, and the opportunity to travel to the other two NHMFL sites at Los Alamos National Laboratory and the University of Florida at Gainesville. Members of underrepresented groups are encouraged to apply.

Applicants should submit the following: (1) A brief (two-pages maximum) statement of prior research activities and future research interests that will be pursued at the NHMFL if granted the Dirac Postdoctoral Fellowship. (2) Curriculum vitae including publications. (3) At least three letters of reference in support of the application. (Official undergraduate and graduate transcripts will be required from successful applicants to whom offers are extended).

Application review will begin on Oct. 15, 2019 and continue until the position is filled. The appointment will commence on or about Aug. 31, 2020. All application packets should be submitted, preferably by email in PDF electronic format to: *Mr. Arshad Javed (ajaved@magnet.fsu.edu), Administrative Specialist, Condensed Matter Sciences, A300 NHMFL FSU, 1800 E. Paul Dirac Dr., Tallahassee, FL 32310-3706.* The Florida State University is an Equal Opportunity, Affirmative Action employer, committed to diversity in hiring, and a Public Records Agency.

Burton Richter

Burton Richter, influential experimental particle physicist and international scientific leader, died from congestive heart failure on 18 July 2018 in Palo Alto, California.

Burt is indelibly linked to the 1974 discovery of a new type of subatomic particle. It was observed in two quite different experiments: One, under Burt, was performed at SLAC on the weekend of 9–10 November. It continued for several years and revealed new physics of the standard model, and its approach became an exemplar for future collider experiments. The other, led by MIT's Samuel Ting, was done at Brookhaven National Laboratory and used more conventional approaches. On 11 November, Ting happened to be visiting SLAC and met Burt; in their ensuing discussion, they each described their team's analysis of what turned out to be the same particle, now called J/ψ. They issued a joint announcement of the discovery, which immediately created intense activity among particle physicists. Public recognition came soon after, and in 1976 Richter and Ting received the Nobel Prize in Physics.

Burt was born in Brooklyn, New York, on 22 March 1931 to immigrant parents. He entered MIT in 1948, settled on physics, and graduated in 1952. He stayed on and used the 350 MeV MIT electron synchrotron for his PhD research. Helping run that machine sparked Burt's interest in accelerator physics.

In 1956 Burt accepted a postdoc position with Wolfgang Panofsky at Stanford University's High Energy Physics Laboratory; he was attracted by the potential of its Mark III linear electron accelerator. Another freshly minted PhD, Gerard O'Neill, then at Princeton University, visited Panofsky in 1957 to discuss two powerful ideas: that head-on collisions of particle beams produce substantially higher energies than a fixed target struck by a single accelerated beam and that accelerated electron beams naturally avoid certain instabilities that limit performance of proton accelerators due to damping by synchrotron radiation. O'Neill asked whether Stanford would consider building an electron–electron collider to validate those concepts.

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Panofsky supported the idea; Burt changed his research to focus on colliding beams; a small team of physicists joined with Burt and O'Neill to work on what became the first-ever colliding beam experiment (CBX); and the Office of Naval Research supported the project in 1958. The technical challenges were substantial, but by the time it ended in 1965, the CBX published scientific results on electron–electron scattering and provided a technical basis for all future colliders.

By 1965 Stanford's two-mile linear accelerator project, SLAC, directed by Panofsky, was nearly complete. Burt, now a professor and group leader at SLAC, said he always tried to hire physicists whom he thought were smarter than he was. Burt conducted high-energy-physics research and led the design of SLAC's first electron–positron collider, SPEAR. Such colliders have distinct advantages over the CBX in potential and practicality: More interesting physics questions can be addressed, and a single storage ring can contain both counter-rotating beams. When SPEAR finally received funding in 1970, Italian, French, and Soviet labs were already operating e^+e^- colliders; the Italian collider at Frascati had observed surprising results that would be confirmed and extended at SPEAR.

Burt's strategic leadership came to the fore with SPEAR. Incorporating his CBX experience, he oversaw the accelerator design, engineering, and construction efforts. He had the vision to recognize that a new scale for experimental collaborations would be needed to build a suitable detector and analyze its data. Accordingly, he recruited a second SLAC experimental group, led by Martin Perl, and groups, led by William Chinowsky, Gerson Goldhaber, and George Trilling, from Lawrence Berkeley Laboratory (LBL). Thus began the SLAC–LBL collaboration.

A new type of particle-detector system would be needed to exploit SPEAR: a magnet and tracking chamber ideally covering the entire 4π solid angle surrounding the collision point to measure momenta, other sensors to determine energies and directions of neutral particles, and means to determine particle identities. Despite challenges, Burt was unwavering in his vision to build a 4π magnetic detector, a vital capability missing at the earlier colliders.

R. B. PALMER

Burton Richter

The SLAC–LBL collaboration, its magnetic detector, and SPEAR came together and began accumulating data in 1973. The ψ discovery, J results, and a rapid confirmation by the Frascati collider were published simultaneously in *Physical Review Letters* in December 1974. Among the other significant discoveries made at SPEAR was the τ lepton, for which Perl received one-half of the 1995 Nobel Prize in Physics.

For the remainder of his life, Burt used his skills to serve science in various capacities. He was SLAC's laboratory director after Panofsky's retirement in 1984, and he developed new collider concepts. In 1994 he served as president of the American Physical Society. Burt influenced US science policy by publicly advocating for all fields of science in Congress and the press, and as a member of JASON he advised US agencies on technical matters related to national security. His 2010 book *Beyond Smoke and Mirrors: Climate Change and Energy in the 21st Century* is an original and accessible work. His was a rich scientific life, well lived.

Roy F. Schwitters
University of Texas at Austin

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QUICK STUDY

Jay Pasachoff is Field Memorial Professor of Astronomy at Williams College in Williamstown, Massachusetts, and chair of the International Astronomical Union's working group on solar eclipses. He is coauthor with Alex Filippenko of the textbook *The Cosmos: Astronomy in the New Millennium* (5th edition, 2019).

Eclipse science today

Jay M. Pasachoff

Observations during total solar eclipses may help unlock the remaining mysteries of the solar corona.

Our sun is a celestial laboratory only 8 light-minutes from Earth. Its close proximity means that we can see details there that we cannot see in other stars. The Sun's energy, formed by nuclear fusion deep inside, travels to the surface by radiation and convection until it reaches a layer in which the gas is especially transparent. The visible and IR radiation emitted from that photosphere is what heats Earth to habitable temperatures.

Just above the photosphere is the chromosphere, about one-thousandth as bright and composed of spiky structures about 10 000 km high; the name comes from the colorful, mainly hydrogen and helium emission lines seen during solar eclipses when the chromosphere is silhouetted against a dark background. (See the Quick Study by Charles Kankelborg, PHYSICS TODAY, April 2012, page 72.) Above it is the solar corona, one-thousandth as bright as the chromosphere. The visible light from the photosphere is so bright that it turns the daytime sky blue and prevents us from observing those faint outer solar layers. The upshot is that the corona is visible from Earth only when the Sun is up but the blue sky is absent. That situation happens only during a total solar eclipse.

Observing the corona

About every 18 months, the Sun, Moon, and Earth align in a syzygy in which the Moon—1/400 the size of the Sun but also about 1/400 as far from Earth—passes centrally over the solar disk and blocks out the entire photosphere. (Also about every 18 months, the Moon is farther from Earth than it usually is and a ring of photosphere remains in the sky; during almost all such annular eclipses, the sky is too bright for anyone on Earth to see the solar corona.) Figure 1 shows a map of the paths of totality that will cross Chile and Argentina in 2019 and 2020, Antarctica in 2021, and the US in 2024. Only within those narrow strips, each hundreds of kilometers wide, can people observe the solar corona.

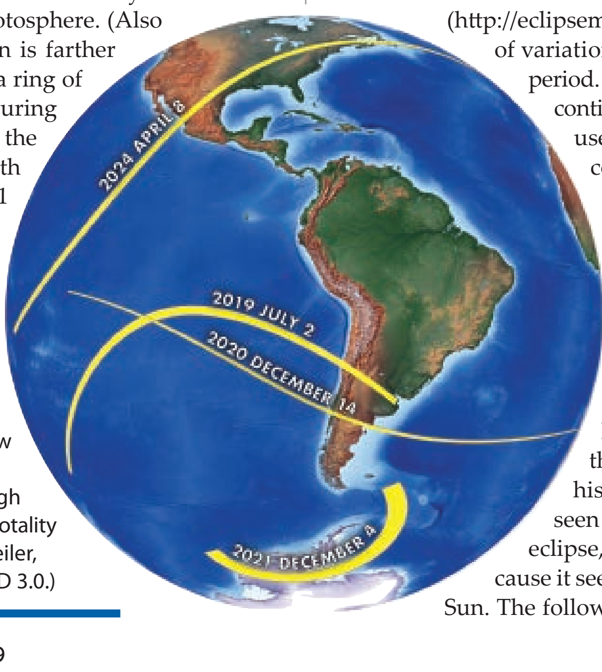

FIGURE 1. MAP OF TOTAL SOLAR ECLIPSES, 2019–24. Only within the narrow path of totality can the corona be seen by the unaided eye. During annular eclipses or partial phases close to totality, even the few percent of the photosphere that remains visible brightens the sky enough to hide the corona. The 2023 path of totality is not shown. (Courtesy of Michael Zeiler, www.eclipse-maps.com, CC BY-NC-ND 3.0.)

The corona varies greatly in brightness: Its magnitude falls by a factor of a thousand in the first solar radius outside the solar disk. Because that range in brightness is too great for any single detector (usually a CCD) to capture, detailed images of the corona are often composites of perhaps dozens of individual images taken with different exposure times or apertures.

In the 2017 eclipse, shown in figure 2, the path of totality stretched from coast to coast of the US. Although totality lasts only a few minutes at any given location—2 minutes in Oregon during the 2017 eclipse but up to about 7 minutes in principle—the Moon's shadow, the umbra, takes about 90 minutes to cross the US. In 2017 my own team was able to compare fine details in the coronal features obtained from our location in Oregon with those captured some 65 minutes later. We discerned changes in the streamers and in the polar plumes, all of which are held in space by the corona's magnetic field, which is not otherwise directly measurable.

In anticipation of that 2017 eclipse, Hugh Hudson, Scott McIntosh, Shadia Habbal, Laura Peticolas, and I proposed a citizen science effort that ultimately included more than a thousand contributors spaced across the region of totality from coast to coast. The resulting movie of still photographs (http://eclipsemegamovie.org) provides an archive of variations in the corona over a 90-minute period. A separate effort—Citizen CATE, for continental-America telescopic eclipse—used 60 identical telescopes across the country and had more uniform observations to compare.

Coronal heating

To appreciate the evolution of solar physics, it helps to know some eclipse history. During the total eclipse of 1868, French astronomer Jules Janssen was in India and observed a yellow line in the chromospheric spectrum with his newfangled spectroscope. Later seen by Norman Lockyer outside the eclipse, the line was named "helium" because it seemed at the time to exist only on the Sun. The following year in the US, Charles Young

FIGURE 2. A COMPOSITE IMAGE made from dozens of individual frames taken in Salem, Oregon, on 21 August 2017. During the recent 2 July 2019 eclipse, the corona was even more extended at the Sun's equator than at high solar latitudes. (Image courtesy of Williams College Solar Eclipse Expedition/NSF/NatGeo. Computer synthesis by Vojtech Rusin and Roman Vanur for Jay Pasachoff.)

Young spectroscopically observed a green emission line in the solar corona. (For more on that 19th-century eclipse expedition, see the article by Deborah Kent on page 46.)

A later-discovered red emission line joined the green line in being attributed to coronium. But it took about 70 years before anyone realized that the original coronium lines actually came from highly ionized iron—the green line from Fe XIV (iron that is ionized thirteen times from neutral Fe I), and the red line from Fe X. Coronal gas must be more than a million kelvins for such extreme ionization to occur. Scientists aboard NSF airplanes flown during the 2017 and 2019 eclipses took observations in the near-IR to look for additional coronal emission lines beyond the few now known. They were searching for lines that are especially sensitive to magnetism for use in future measurements of the coronal magnetic field.

The high temperature indicates extraordinarily fast motion of the coronal gas. But the gas itself is sparse, which makes the heat capacity of the corona low and raises the question, How does the coronal gas get heated to millions of kelvins? Scientists are considering more than a dozen possible answers, though the most likely processes implicate the Sun's magnetism. (See Physics Today, May 2009, page 18, and the article by Jack Zirker and Oddbjørn Engvold, August 2017, page 36.)

During eclipses, my team often carries out subsecond observations through filters that transmit only the red and green coronal lines. The power spectra of that emission can be searched for the periods of vibrations on the magnetically constrained coronal loops that are visible in the lower corona.

The sunspot cycle

The corona has been drawn or photographed for 150 years. Pictures reveal helmet streamers, named for their resemblance to 19th-century police helmets. Wider at the base and narrow higher up, the streamers are bright loop-like structures whose gas is held in space by closed magnetic fields. Between them the magnetic field is open, which allows the solar wind to escape more easily. Near the solar poles, the magnetic field resembles that of a bar magnet, and plumes of streamers bristle radially.

At times near the maximum of the 11-year sunspot cycle—the most obvious visual manifestation of the Sun's repeating magnetic activity—electrons in streamers even at high solar latitudes scatter ordinary sunlight and make the overall shape of the corona almost round. Near sunspot minimum, streamers are constrained to lower latitudes and the polar plumes are visible. Earth has now entered sunspot minimum, and the polar plumes were quite visible during the 2017 and 2019 total eclipses. Monitoring the overall shape of the corona traces the solar-activity cycle. The past three cycles have been diminishing in intensity, which has prompted varying predictions of how weak the next one might be.

Heliophysicist Zoran Mikić at Predictive Science Inc and his colleagues have used measurements of the photospheric magnetic field from the Zeeman effect to make predictions in the week or so before an eclipse of what the corona will look like. My team at Williams College made composite photographs of 2017's and 2019's eclipses that closely matched those predictions. The differences we found are being used to improve the theories behind the predictions and to better understand the corona and its magnetic field.

Additional resources

▶ L. Golub, J. M. Pasachoff, *The Sun*, U. Chicago Press (2017).

▶ J. M. Pasachoff, A. Fraknoi, "Resource Letter OSE-1: Observing solar eclipses," *Am. J. Phys.* **85**, 485 (2017).

▶ J. M. Pasachoff, "Heliophysics at total solar eclipses," *Nat. Astron.* **1**, 0190 (2017).

▶ J. M. Pasachoff, "Science at the Great American Eclipse," *Astron. Geophys.* **59**, 4.19 (2018).

▶ J. M. Pasachoff et al., "Images and spectra of the 2017 total solar eclipse corona from our Oregon site," *Front. Astron. Space Sci.* **5**, 37 (2018).

▶ Z. Mikić et al., "Predicting the corona for the 21 August 2017 total solar eclipse," *Nat. Astron.* **2**, 913 (2018).

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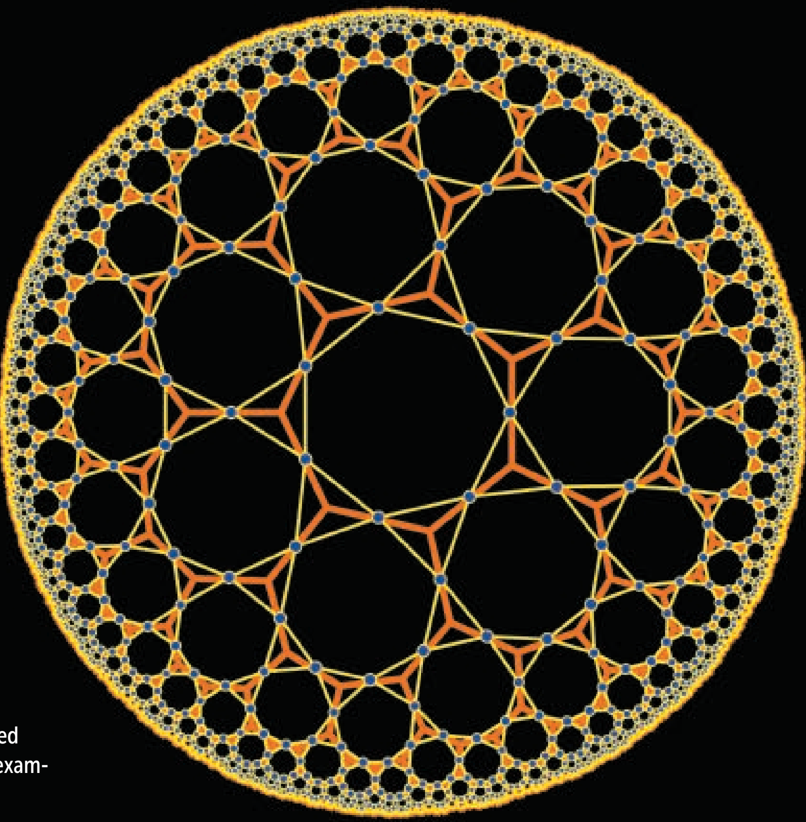
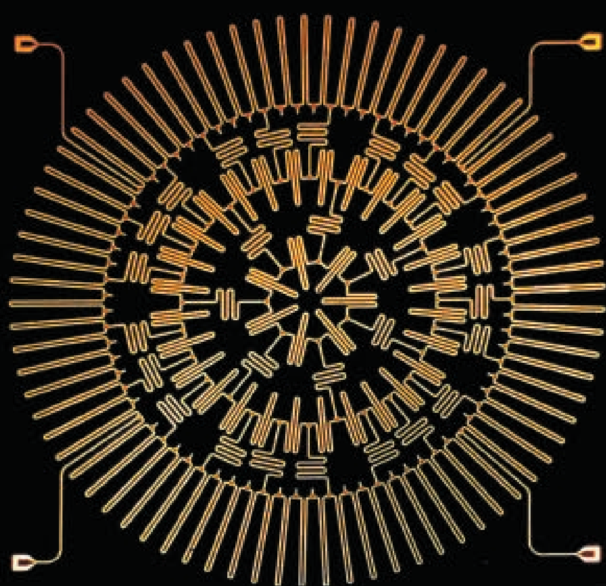
BACK SCATTER



Non-Euclidean geometry on a chip

Equal-sized squares or hexagons can be arranged to fully tile a flat, two-dimensional plane, which has zero curvature. Pentagons can't tile a plane, but they can be wrapped into a 3D dodecahedron and cover a sphere. Heptagons can't be tiled at all, at least in familiar Euclidean geometry. A regular tiling of heptagons would require a hyperbolic surface with negative curvature—every point is a saddle point where space curves away from itself. Unlike a sphere, which has positive curvature, a hyperbolic surface cannot be realized in Euclidean space without distorting it. The top panel shows an example: a 2D projection (orange) of a regular heptagonal tiling.



Alicia Kollár (now at the University of Maryland) and colleagues at Princeton University have demonstrated a novel way of fabricating an effective hyperbolic space using a 2D network of superconducting circuits. Each circuit is a coplanar waveguide resonator, a platform for so-called cavity quantum electrodynamics (see PHYSICS TODAY, November 2004, page 25). As is the case for coaxial cables, bending the resonators doesn't change their behavior, which is determined only by the length of the meander. The arrangement of 140 resonators, each 7.5 mm long, in the bottom photo corresponds to the 29 innermost orange tiles of the top image. Photons hop from resonator to resonator along paths that correspond to the yellow lines in the top image. Together, the paths define what the researchers call a heptagon-kagome lattice. The result is an artificial photonic material in an effective hyperbolic curved space. Many standard approaches of solid-state physics break down in non-Euclidean space; the researchers had to resort to numerical simulations to find their material's band structure: a rare combination of a flat band and an energy gap. Adjusting the resonator layout and couplings will allow exploration of a large variety of other lattices and curved spaces. (A. J. Kollár, M. Fitzpatrick, A. A. Houck, *Nature* **571**, 45, 2019.) —RJF