PHYSICS TODAY

November 2020 • volume 73, number 11

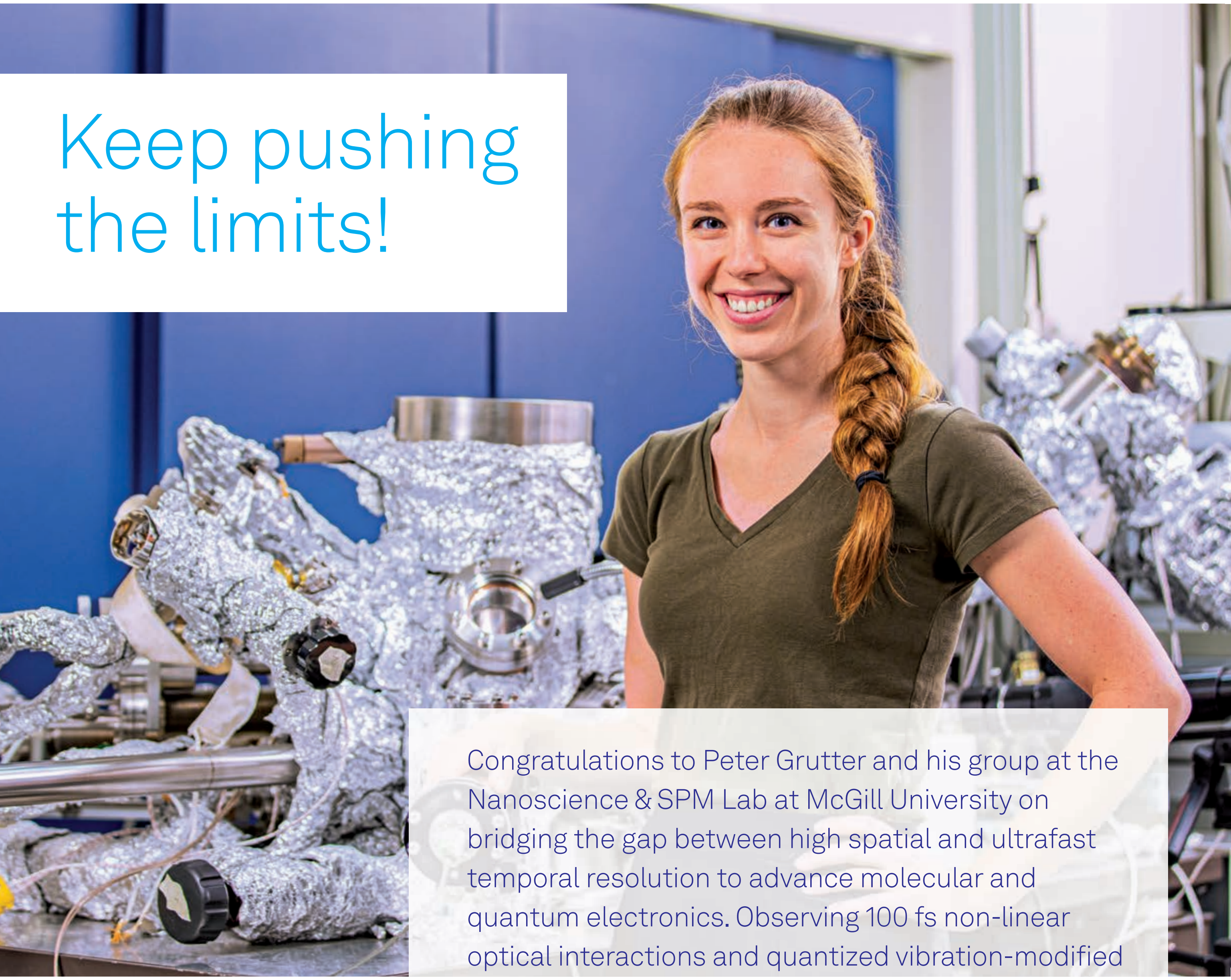
A publication of the American Institute of Physics

Caught in the wrong current

Commercializing quantum computing

The mysterious universe of James Jeans

Fermions behaving like bosons



Megan Cowie, Nanoscience & SPM Group,
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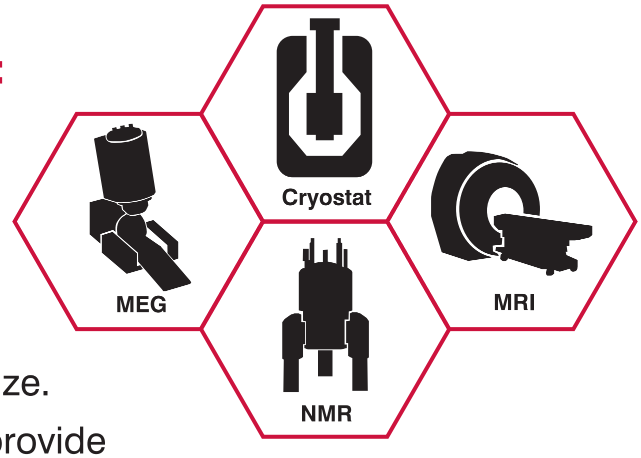

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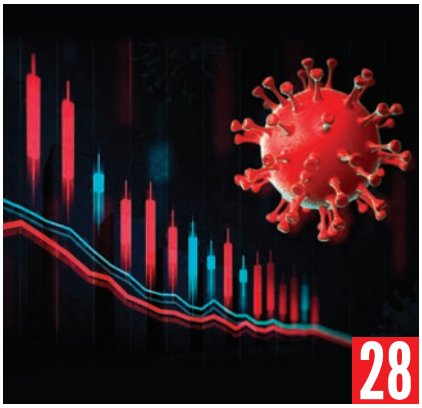
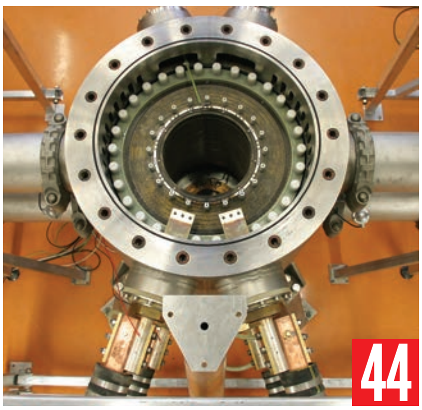


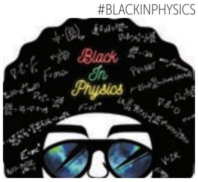


ON THE COVER: Found on seabeds around the North Atlantic Ocean, the common starfish (*Asterias rubens*) is easily recognized by its familiar five-armed shape and rusty coloration. But starfish begin their lives as tiny, free-swimming larvae that look nothing like their adult form. To learn about how that life cycle makes starfish—and dozens of other species—especially vulnerable to climate change, see the story on **page 17**. (Image by Andrey Nekrasov/Alamy Stock Photo.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org

#BLACKINPHYSICS



#BlackInPhysics Week

The last week of October was #BlackInPhysics Week, a series of events and initiatives hosted on social media that celebrated Black physicists and amplified their voices. The organizers of the week commissioned several essays that were published jointly by *Physics World* and PHYSICS TODAY.

physicstoday.org/Nov2020a

J. ESQUIVEL

NSF

Black physicists

Jessica Esquivel, Sekazi Mtingwa, and a dozen other Black physicists in the US talked to PHYSICS TODAY about their work and their experiences in the field. They describe encountering racism at every career stage and having to prove themselves over and over. They also share ideas for achieving lasting change.

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NASA/JPL-CALTECH

Phosphine on Venus

In the wake of the headline-grabbing finding of PH_3 in the clouds of Venus, Rachel Berkowitz reports on the next steps for confirming the detection and for understanding how the molecule could be produced, either biotically or abiotically, in the planet's still-mysterious atmosphere.

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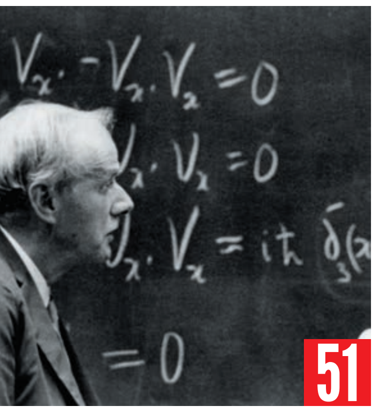

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Science and democracy

Charles Day

"Little else is requisite to carry a state to the highest degree of opulence from the lowest barbarism, but peace, easy taxes, and a tolerable administration of justice; all the rest being brought about by the natural course of things."

When Adam Smith wrote those lines in 1755, his native Britain was among the world's wealthiest nations. By avoiding costly foreign wars, Britain's prime minister Robert Walpole (in office 1721–42) and his Whig successors could afford to levy low taxes. Trial by jury, habeas corpus, and other aspects of the rule of law had abided in Britain for centuries.

In the 21st century, the countries with the highest GDP per capita, bar a handful of oil-rich monarchies, are all democracies. Smith's three requisites for prosperity are more likely to be satisfied in a democracy—because voters want peace, moderate taxes, and the rule of law. But as the examples of Shenzhen, Suzhou, and other wealthy Chinese cities attest, democracy is not essential for prosperity.

Nor is democracy essential for science to flourish. The Soviet Union was a physics powerhouse, as was the German Empire under its kaisers and chancellors. When Hideki Yukawa published his theory of mesons in 1935, Japan's chief executive was Keisuke Okada, an admiral serving in the Imperial Japanese Navy.

What are the requisites for cultivating science? Education is surely among them. But it's impossible and futile to identify which children might become scientists. All children should be given the opportunity to follow an educational path that leads, through school and university, to a career in science. And when someone takes that path, they should not face obstacles or hostility on account of who they are.

Adequate research funding is another requisite. Hong Kong's universities began producing abundant world-class research only after the territory's government recognized in the 1980s that its aspiration to become a center of higher education excellence in South China would require funding competitively selected grant proposals. "Adequate," though, is a squishy term. It means, I propose, that scientists face an encouraging prospect of their grant proposals being funded.

The ability to share one's research with peers is another requisite. Satisfying it doesn't necessarily mean publishing in peer-reviewed journals. As historian of science Melinda Baldwin has demonstrated, peer review did not become a standard feature of scientific publishing until the Cold War.[1] Still, journals of some kind are needed.

Scientists also need time to think. Teaching multiple courses, serving on multiple committees and panels, reviewing papers and grant proposals, worrying about career advancement—all those demands stifle creative thought. Lack of time was a complaint I heard from physicists in China when I visited the country in 2008 and 2009. "I keep having to go to meetings in Beijing," one Nanjing-based physicist told me. (The two cities are roughly 1000 km apart.)

Does freedom from political influence qualify as a requisite? In Norway, the country that the Economist Intelligence Unit ranked in 2019 as the world's most democratic, politicians ultimately determine funding priorities. The Research Council of Norway has three open proposal requests for new centers. One is for 11 centers of excellence in any field. The other two bear the stamp of politically mediated priorities: green wind power and special-needs education. Insofar as citizens should have a say in what science their taxes fund, political influence is inevitable and even desirable.

What's not acceptable is undermining confidence in science itself for political gain. President Trump has repeatedly dismissed climate change as a "hoax," even as Earth's temperature rises and forest fires, hurricanes, and flooding become more frequent and more damaging. Politics, not science, continues to drive his administration's response to the COVID-19 pandemic at a rising cost of avoidable deaths.

In discounting virology, epidemiology, and public health science, Trump is not alone among world leaders. President Alexander Lukashenko of Belarus urged his fellow citizens to combat COVID-19 by playing ice hockey, attending public steam baths, driving tractors, and drinking vodka.

Unlike Lukashenko, Trump faces the prospect of being voted out of office. As a proponent of democracy, I accepted his victory in 2016. Even if you disagree with his policies, Trump's tough stance on trade with China and his prodding of NATO countries to shoulder more of the cost of their own defense are rational and defensible. His denial of science is not.

Reference

1. M. Baldwin, *Isis* **109**, 538 (2018).

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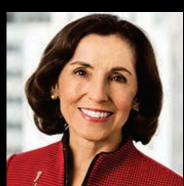

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International graduate students struggle amid COVID-19

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At a media briefing on 11 March, the director general of the World Health Organization (WHO) declared COVID-19 a global pandemic. While governments rushed to draft contingency plans to contain the virus, universities in Europe and the US worked to minimize the impact of COVID-19 on the higher education system. However, on 24 September, the Department of Homeland Security proposed limiting the duration of initial admissions for F and J visa holders and nonimmigrants to four years, which would have a huge negative impact on international students, especially international graduate students.

The more complex circumstances of graduate education and research have left graduate students surrounded by uncertainty with little to no instruction for how to cope during the crisis. With professional reputations, future job prospects, and even next semester's funding on the line, should they continue to conduct research as usual? Or should they socially distance themselves, halting hands-on experiments while focusing more on simulations and writing papers?

The confusion and angst in the broader graduate student community has only been exacerbated for international students. Some of them are trapped in their home countries because of the necessary international travel restrictions, which has prevented many of them from satisfying the enrollment criteria needed to maintain valid immigration status. Those away from home do not have family to care for them should they fall ill. What is clear is that their research is being affected in this global crisis, and the subtle dynamics between them and their advisers put them in a more vulnerable situation. They continue to struggle while their advisers expect progress.

With immigration policies that continue to aggravate the situation, the COVID-19 pandemic imposes unprecedented challenges for international graduate students. We hope academic authorities make extra efforts to create a more supportive environment so that international graduate students, especially during the pandemic, can manage with greater security and relief.

We gratefully acknowledge P. James Schuck at Columbia University for his valuable review and comments.

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On the stature of Cecilia Payne-Gaposchkin

Having recently published a book[1] with a chapter on Cecilia Payne-Gaposchkin, I read with interest David Weintraub's review of *What Stars Are Made Of: The Life of Cecilia Payne-Gaposchkin*, Donovan Moore's new book on the prominent astrophysicist (PHYSICS TODAY, April 2020, page 46). Although I have not yet read Moore's book, aspects of Weintraub's review took me aback.

I concur with Weintraub's claim that Payne-Gaposchkin "should have been Harvard University's first female recipient of a PhD in astronomy." But that understates her importance: It was due to

Payne-Gaposchkin that Harvard established an astronomy department in the first place. She should have been the first *person*, male or female, to receive a PhD in astronomy from Harvard.

In addition, Weintraub comments on Payne-Gaposchkin's "Forrest Gump–like habit of running into some of the greatest physicists of the 20th century." Gump careened from one famous encounter to another, as an outsider even when inadvertently influencing an event. Payne-Gaposchkin, on the other hand, was a first-rate scientist. Attending physics classes at Cambridge University provided her with the connections and training to land a fellowship at Harvard—should we be surprised that she encountered eminent physicists along the way? Would we ever characterize a male contemporary (say, J. Robert Oppenheimer) in that way?

Then there is the thorny matter of Payne-Gaposchkin's discovery that stars are made mostly of hydrogen. Several aspects of that history are not in dispute: that Payne-Gaposchkin made the discovery, that in later years it was often incorrectly attributed to Henry Norris Russell, and that Payne-Gaposchkin's gender was the primary reason for her lack of credit. But if we are to correct such injustices and prevent them from recurring, it is crucial to understand the mechanism by which they occur.

Much ink has been spilled on how Payne-Gaposchkin's discovery ended up credited to Russell; in my book, I examine six distinct explanations, all advanced at one time or another. Weintraub's review, however, includes several claims that are not backed up by the historical record.

That Payne-Gaposchkin's "accomplishments were initially pooh-poohed by her field's most eminent scientists" is incorrect. Her conclusion that the Sun was made mostly of hydrogen was indeed dismissed by Russell, but he and others consistently praised her accomplishments. In fact, Payne-Gaposchkin was one of only 250 scientists added to the 1927 edition of *American Men of Science*, which had last been updated in 1921.

Russell did not "[force] her to change the conclusion of her dissertation"; he made the suggestion that she change it, and she accepted his assessment. Saying that she was forced takes agency away from Payne-Gaposchkin, who in other contexts demonstrated that she was not afraid to challenge authority figures—including Russell—when she was sure of herself.

Weintraub also writes that Payne-Gaposchkin should have received a Nobel Prize, "but because of Russell, that was not to be." Although Payne-Gaposchkin's work was of Nobel caliber—hers is one of the most important doctoral dissertations in the history of astronomy—astrophysicists were not generally considered for Nobels in the first half of the 20th century. Thus, neither Payne-Gaposchkin nor Russell would have been considered serious candidates regardless of who received credit for Payne-Gaposchkin's discovery.

There is a long history of praising female scientists for their discoveries and abilities and then denying them the tangible benefits of such accomplishments, including fair pay, sufficient research funding and the ability to direct it, and such positions of authority as department chair. To the extent that we mischaracterize the historical record, I am concerned that we will not learn the lesson that recognition of accomplishment is not enough to prevent unfair treatment.

Reference

1. S. Calvin, *Beyond Curie: Four Women in Physics and Their Remarkable Discoveries, 1903 to 1963*, Morgan & Claypool (2017).

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David Weintraub's review (PHYSICS TODAY, April 2020, page 46) of Donovan Moore's *What Stars Are Made Of: The Life of Cecilia Payne-Gaposchkin* brought back several memories. When I was a freshman at Harvard University in September 1959, Payne-Gaposchkin was "chairman" of the astronomy department. Chain-smoking in her office, speaking with an English accent, and becoming as tall as I—six feet—when we stood up, she was intimidating. Only years later did I learn that she was the only woman regularly appointed to tenure on the Harvard faculty at the time.

Donald Menzel reported that when he became director of the Harvard College Observatory in 1956 and discovered "Mrs. G.'s" status and salary, he quickly improved both, pushing through her professorship with suitable compensation.

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▶ **Weintraub replies to Calvin:** The Forrest Gump metaphor was admittedly imperfect, as Scott Calvin suggests. But I disagree with Calvin's other criticisms. Whether Henry Norris Russell forced her or Cecilia Payne merely chose to modify her dissertation conclusions after Russell advised her to do so, her decision to capitulate is the nearly universal response to *force majeure*. When the most prominent scientist in one's profession dismisses the work of a graduate student as wrong, the student ignores that criticism at great peril to their career. This is true now and was certainly true a century ago.

Payne did what she had to do to secure a necessary signature and her doctoral degree and to transition into the next phase of her career. Any other decision would have been professional suicide. To imply that Russell made a suggestion Payne could ignore is to misrepresent the power dynamics of the situation, one in which Russell was extremely powerful and Payne was powerless.

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Majorana and the lone-genius myth

The June 2020 issue of PHYSICS TODAY contained an excellent article entitled "Majorana qubits for topological quantum computing" (page 44) by Ramón Aguado and Leo Kouwenhoven. It opened with a description of Ettore Majorana attributed to Enrico Fermi: "There are various categories of scientists, people of a secondary or tertiary standing, who do their best but do not go very far. There are also those of high standing, who come to discoveries of great importance, fundamental for the development of science. But then there are geniuses like Galileo and Newton. Well, Ettore was one of them."

Majorana was clearly an influential physicist who did exceptional work. However, that quote illustrates a pervasive and harmful belief, widely held among physicists, of the lone genius. According to the myth, the greatest advancements in physics are done by uniquely brilliant individuals working alone. That idea minimizes the many important discoveries made by numerous scientists in collaboration. It also devalues the careers of those who do solid and influential work over many decades but may never make "discoveries of great importance, fundamental for the development of science." The myth's implied corollary—that if you cannot do great work alone, there is no place for you in physics—contradicts the history of the field.

The lone-genius myth is harmful for everyone, but it is especially damaging for women, people of color, the LGBTQ+ community, and members of other minority groups. They frequently face impostor syndrome, negative cultural factors, the implicit biases of colleagues and institutions, and a climate that minimizes collaboration and inclusion. Perpetuating the myth only increases those feelings and further harms diversity and inclusion efforts in physics.

The lone-genius myth is rarely true. Although instances exist of scientists making breakthroughs while working alone, they are not common. The majority of scientists work in teams ranging from a few people to large collaborations spanning multiple continents. Even scientists who publish groundbreaking single-author papers usually acknowledge colleagues with whom they discussed their ideas. Now more than ever, science is a team effort that requires many people and multiple perspectives. I strongly encourage science writers to describe the contributions of outstanding scientists like Ettore Majorana without subscribing to the myth of the lone genius.

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Consequences absent from bomb assessment

An air of unreality overcame me as I read David Kramer's article about evaluation of new nuclear bomb technologies (PHYSICS TODAY, February 2020, page 23). The only concern mentioned is whether the physics of the new test facility will adequately ensure the reliability of the new designs without actual explosive tests being carried out. It's a neutral, objective presentation of some interesting physics.

But if ever those warheads were actually used, whether in error or in anger, PHYSICS TODAY and most or all of its readers would cease to exist. Presumably, about 25% of US residents would be fortunate enough to be vaporized instantly. Maybe another 25% would die in the next week from injuries and radiation sickness. And would any survive the ensuing nuclear winter without public supplies of electricity, fuel, food, and medicine? Russia's people would suffer the same, assuming they were hit in full retaliation by those well-designed US bombs. And what about the rest of the world? Could all memory of PHYSICS TODAY be wiped out along with humankind's accumulated knowledge of physics?

I suggest that PHYSICS TODAY follow up by publishing a neutral, objective, physics-based analysis of the consequences of full-scale nuclear war. It might, of course, raise the question, Why exactly do the world's "great powers" need to have thousands of nuclear weapons?

Garth van der Kamp
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Correction

September 2020, page 12—In "Units, for good measure," the area corresponding to 40 miles per gallon should have been about 0.06 mm^2. —Michael Albrow PT

Nonidentical fermions interact identically

The decoupling of electronic and nuclear spin states allows scattering fermionic atoms to rapidly cool.

Indistinguishable fermions don't typically interact much. Because their wavefunctions are antisymmetric, they tend to stay away from one another. That behavior manifests with particular strength in quantum gases cooled to ultralow temperatures, and it's a problem. Fermions' mutual avoidance limits the efficiency of evaporative cooling at low temperatures, as Deborah Jin observed 21 years ago when cooling potassium atoms (see PHYSICS TODAY, October 1999, page 17). Evaporative cooling relies on elastic collisions to nudge particles to lower energies, and it's an important technique for reaching the necessary temperatures to form Bose–Einstein condensates.

Bosons at ultralow temperatures can occupy the same energy state (see figure 1), which leads to physical proximity and much more scattering. What if fermions could act more like bosons? Not only would it be easier to evaporatively cool a Fermi gas down to the temperature needed for, say, quantum simulations, but there would also be new physics to explore. The challenge is finding fermions that don't mind sharing the same space.

Alkaline-earth fermionic atoms fit the bill. Because their nuclear spin states are decoupled from their electronic states, the energy levels and wavefunctions in an optical trap are identical for an atom in the $+9/2$ nuclear spin state, one in the $+7/2$ nuclear spin state, and so on. But the atoms aren't identical. As a result, fermionic atoms, each with a different nuclear spin value, can cluster together in the same energy state, as shown on the right in figure 1.

The interatom interactions are independent of the nuclear spin state, so for N atoms with different spins, the two-body interactions will have N-fold symmetry: The interaction is identical between any atom and each of the other $N-1$ atoms sharing its energy level. That so-called SU(N) symmetry enhances those interactions and boosts otherwise weak effects into pronounced ones, with N as a tuning knob. Researchers are interested in SU(N)-symmetric systems as a model to explore the physics behind a range of condensed-matter systems—for example, cuprates and other transition-metal oxides that display high-temperature superconductivity.

Research on SU(N) Fermi gases started only in the past decade, and previous studies kept the gases in temperature regimes for which the interactions didn't significantly alter the system's thermodynamic behavior compared with noninteracting Fermi gases that lack SU(N)-symmetric interactions. Now the University of Colorado Boulder's Jun Ye, his graduate student Lindsay Sonderhouse, and their colleagues have cooled an SU(N) Fermi gas down to a deeply degenerate regime, with all the states occupied below the Fermi level. Their ultracold strontium-87 gas with 10 distinct nuclear spin states shows clear signs of SU(N) interactions and demonstrates a new way to rapidly cool fermions.[1]

Clocking in

Ye and his colleagues have worked with ^{87}Sr gases for more than 16 years. Starting in 2014, they characterized the gas's scattering parameters and few-body elastic and inelastic interactions for clusters of up to five atoms.[2]

The Ye group's new study was motivated by three-dimensional optical lattice clocks, which were first demonstrated with a Fermi gas[3] in 2017. (For more on optical-lattice clocks, see PHYSICS TODAY, March 2014, page 12.) 3D lattice clocks have the best intrinsic stability of any clock today. But getting a Fermi gas to the required low temperatures is a slow process. Speeding it up would improve clock performance because the detrimental influence of laser frequency noise depends on the time spent preparing the atoms.

The researchers predicted that the en-

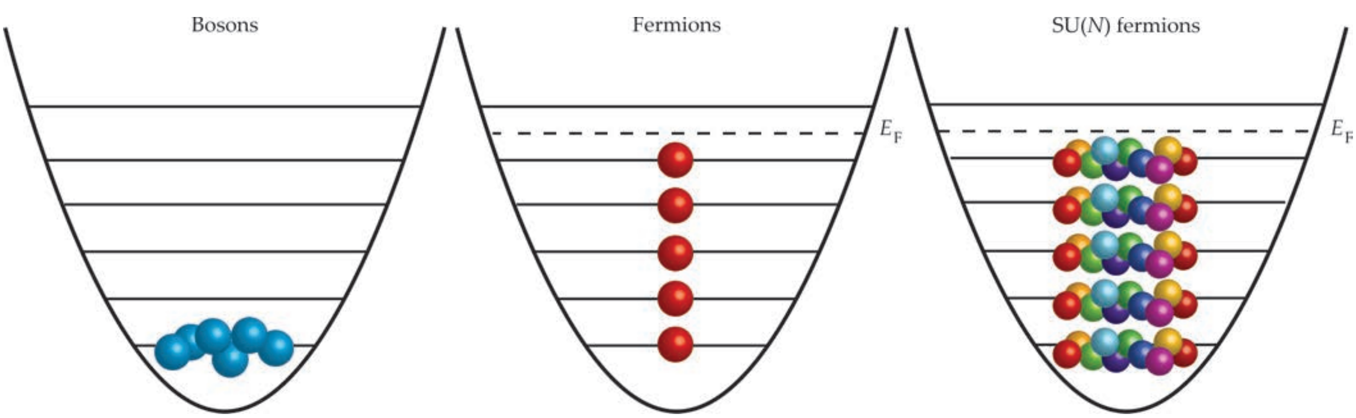

FIGURE 1. BOSONS, FERMIONS, AND SU(N) FERMIONS distribute themselves differently in energy levels at low temperatures. Whereas bosons can settle into the same state, fermions stick to separate levels below the Fermi energy E_F—unless they have interactions with SU(N) symmetry. Those SU(N) fermions can have N interacting particles in each level. (Adapted from ref. 1.)

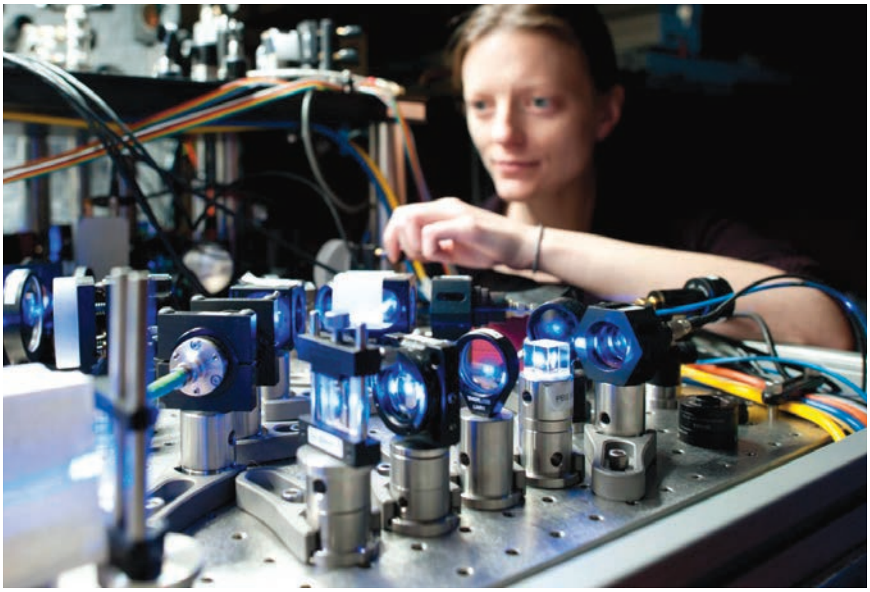

FIGURE 2. LINDSAY SONDERHOUSE adjusts optical components for the laser-cooling experiment in Jun Ye's lab at the University of Colorado Boulder. (Photo by Christian Sanner.)

hanced scattering in an SU(N)-symmetric Fermi gas would hasten cooling. So they timed it. To prepare their gas, the researchers used two stages of laser cooling to bring Sr atoms in a 2D potential down to 2 μK. (A photo of the experimental setup is shown in figure 2.) They then introduced a single dimple trap for the atoms to pool into.

Their goal was to reach the highest density possible inside the dimple. Unfortunately, once atoms were in the dimple, the cooling light created collisions and effective repulsion between them. To overcome that problem, Ye and his colleagues borrowed a technique used for bosons:[4] They added another laser that rendered the atoms inside the dimple transparent to the cooling laser. The transparency laser shifted the excited state of the atoms such that the cooling light was no longer resonant with the transition to the ground state. Atoms outside the dimple continued to be optically cooled, and the ones inside thermalized with them.

The researchers then left the SU(N)-symmetric Fermi gas to evaporate for either 600 ms or 2.4 s, depending on the desired temperature. That evaporation time is down from about 10 s for two-spin gases. They discovered that the more fermions that are colliding in each energy level in the dimple trap, the faster they cool; the total evaporation time scales approximately as $1/(N-1)$. The researchers prepared atoms with all 10 possible nuclear spin states—that is, 10 atoms per energy level—and 5×10^4 atoms per spin state by the end of a 2.4 s evaporation.

Dynamic changes

Although the fermion interactions are weak, they measurably change the system's thermodynamics. One example is the gas's compressibility. The SU(N) interactions are repulsive in ^{87}Sr. And although the compressibility depends only weakly on the number of atoms per spin state, it scales as $N-1$ with the number of spin states.

Ye and his group measured the gas's compressibility from its density fluctuations. To do so, they released the gas from the trap and performed absorption imaging, which gives a snapshot of the density profile. They found that the compressibility was reduced by 18% for $N=10$ compared with the model for a noninteracting Fermi gas at the same density and temperature.

But the density profile alone can't confirm that the system's constituents interact. The fluctuations for an interacting system look the same as a colder noninteracting system, although the mechanisms that limit compression are different: interaction-induced repulsion in the one case and filled energy levels in the other.

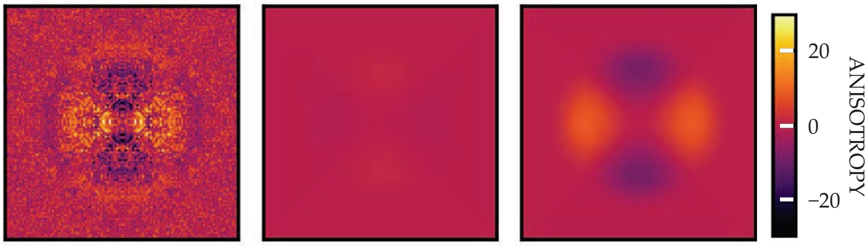

FIGURE 3. SIGNATURES OF FERMI INTERACTIONS in a strontium gas cloud show up as anisotropies in experimental data and theory. After the interacting Fermi gas is released from an optical trap, absorption images record a snapshot of the density profile that may appear anisotropic. But plotting the density profiles' anisotropy reveals a lobed structure in the experimental data and the interacting theory. (Adapted from ref. 1.)

Verifying the presence of interactions requires additional information, such as the expansion dynamics. When an ideal, noninteracting Fermi gas is released from a trap, even an asymmetric one, the gas's profile ends up isotropic because the isotropic momentum distribution produces uniform ballistic expansion. Interactions change the gas's kinetic energy and preferentially propel the atoms along the direction with the largest density gradient, arising from the asymmetry in the trap. As a result, an interacting Fermi gas has a nonuniform distribution. The researchers' gas of ^{87}Sr atoms with 10 different nuclear spin states yielded a noticeably elliptical cloud despite the weakness of the interactions.

Gases with an isotropic density distribution appear circular long after they're released from the trap. But the expansion dynamics of noninteracting and interacting gases still subtly differ. The team's kinetic theory calculations, performed by Ana Maria Rey, show that the density profile n of each gas appears to be circularly symmetric and therefore not indicative of interactions, or the lack thereof. But the differences become clear from the distributions' transpose anisotropy, defined as $n(x, z) - n(z, x)$, shown in figure 3.

In the interacting model and the experimental data, clear lobes emerge in the anisotropy that are not present in the noninteracting model. And because the lobes decrease with increasing temperature, integrals over the transpose anisotropy can be used as a temperature probe with an accuracy of $1/100$ of the Fermi temperature—the temperature at which thermal effects are comparable to quantum effects, defined as $T_F = E_F/k_B$ in terms of the Boltzmann constant and the Fermi energy, or the energy difference between the highest and lowest states occupied by noninteracting fermions at absolute zero temperature.

A new spin

With an efficient preparation method and a basic understanding of their properties, researchers are ready to tackle problems in condensed-matter and high-energy physical systems with SU(N)-symmetric gases. "One can almost think of a deeply degenerate Fermi gas as premium fuel for a quantum simulator," says Ye. Different combinations of kinetic energy, interaction energy, and nuclear spins can be used to systematically explore the phase diagram of, for example, the Fermi–Hubbard model (see the article by Gabriel Kotliar and Dieter Vollhardt, PHYSICS TODAY, March 2004, page 53), whose phase diagram is still unknown despite its common use to describe strongly correlated materials.

The system in the current study follows the Fermi-liquid model for interacting fermions, which describes the normal state of most metals at low temperatures. But in the future, SU(N)-symmetric gases may move to regimes where the theory isn't valid. Exploring the physics in that regime may help researchers understand the origins of the quantum phase transition in heavy-fermion materials.

Heather M. Hill

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Atlantic invertebrates are going the wrong way

Why, as the oceans warm, are seafloor animals moving to even hotter waters?

RLS PHOTO/SHUTTERSTOCK.COM

FIGURE 1. BLUE MUSSELS, seen here in Canadian waters, inhabit coastal regions around the world. In the Northwest Atlantic, they're among dozens of species now found to have a counterintuitive response to climate change.

Some species can save themselves from climate change simply by moving. Although organisms that are adapted to Earth's coldest climates may be left with nowhere to go in a warming world, those from temperate and tropical zones might find new homes in cooler regions: uphill for land species, in deeper water for aquatic ones, and toward the poles for both. Even if individual organisms, such as plants, can't migrate under their own power, their population as a whole can still shift, as offspring dispersed in cooler directions are more likely to survive.

But just because cooler homes exist doesn't mean species can or do reach them. Habitat destruction might obstruct their paths (see PHYSICS TODAY, September 2019, page 16). Or warming might be too rapid for a species to keep pace. Now Rutgers University's Heidi Fuchs and colleagues have identified yet another mechanism that not only blocks species from reaching cooler habitats but actually pushes them into warmer ones.[1]

The Rutgers study concerned several dozen species of bottom-dwelling marine invertebrates—including the blue mussels shown in figure 1 and the starfish shown on the cover of this issue—that inhabit the continental shelf off the east coast of North America. Like plants, the seafloor species are mobile primarily between generations. Their adults are mostly or entirely sessile. The newborn larvae can swim, but not well, so they drift at the mercy of the current for a few weeks before settling into their permanent homes.

The patterns of currents along the Northwest Atlantic continental shelf haven't been altered much by climate change—at least not yet. But they do vary with the seasons just as they always have.[2] Ocean warming, Fuchs and colleagues concluded, is triggering the animals to spawn at the wrong time of year, when the larvae encounter currents they're not evolutionarily accustomed to and are swept into warmer and shallower waters.

Range shift

The Rutgers project grew out of a study of two aquatic snail species. Although the species are related, their larvae respond differently to waves and turbulence. Fuchs and colleagues wanted to see whether that difference influenced their distribution over time. "I noticed that one of the snails had shifted to shallower water," says Fuchs. "I was curious whether other species had done the same."

Information abounds about where marine animals have lived over the years. Censuses of marine life are important not just to scientists but to the commercial fishing industry. Decades of worldwide records are now compiled into a single open-access searchable source, the Ocean Biodiversity Information System (OBIS).

But it can be hard to infer from the data which way species are moving or why. Oceans overall are warming more slowly than Earth's land surface, and that warming isn't uniform in space or time. The data are noisy, and species often seem to be shifting their ranges in unexpected ways: toward the Equator, east or west, or nowhere at all.

In 2013 Malin Pinsky (also at Rutgers, but not involved in the new research) and his colleagues showed that shifts in marine habitats were generally well explained by a concept called local climate velocity: Species go in whatever direction they need to, as far and as fast as necessary, to remain in a habitat of constant temperature.[3] If a species seems to be going in a counterintuitive direction, it may just be responding to unusual local conditions.

But that's not what Fuchs and her colleagues observed. For an undergraduate project, team member Emily Chen mapped the OBIS records over time for 45 species of seafloor-dwelling invertebrates in the Mid-Atlantic Bight, a subregion of the Northwest Atlantic. The rest

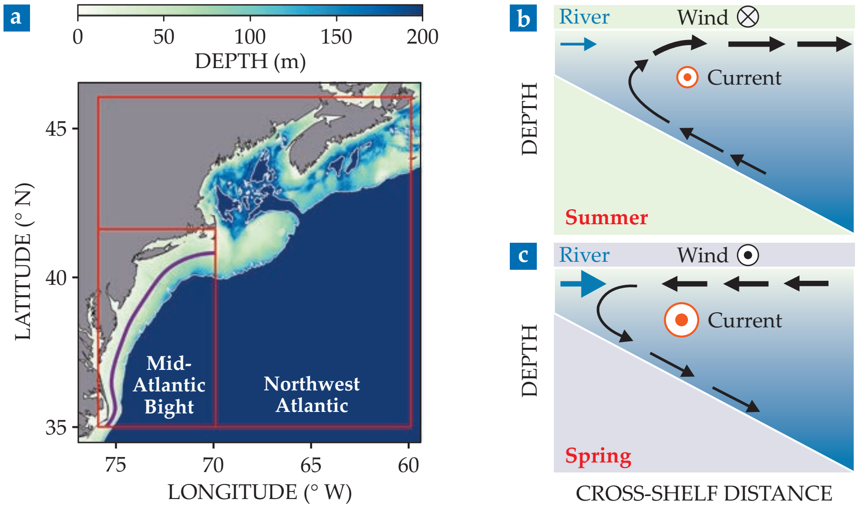

FIGURE 2. OFF THE EAST COAST OF NORTH AMERICA, the continental shelves of the Northwest Atlantic and the Mid-Atlantic Bight **(a)** are affected by seasonal wind, river, and current patterns. In the summer **(b)**, the southwestward current (orange, out of page) is modest and wind-driven surface waters (black arrows) flow away from the shore. But in the spring **(c)**, the current is stronger and surface waters flow toward the shore. When shellfish spawn too early in the year, their larvae are thus swept into warmer, shallower waters. (Adapted from ref. 1.)

of the group cross-correlated the range shifts with a model of ocean-bottom temperature. Over the 60 years of available data, 31 of the species ended up in warmer regions than when they started, and 25 of them saw temperature changes even greater than the overall regional trend. Not only were they not keeping up with climate velocity, they were moving in the wrong direction.

To help figure out what was going on, Fuchs turned to her colleague Robert Chant for his expertise in marine currents and transport processes. Unlike the currents of the open ocean, which are dominated by the clockwise-turning North Atlantic Gyre, currents of the shallow waters of the continental shelf are heavily influenced by local river discharge and wind patterns.

The seasonality of those patterns is shown schematically in figure 2, looking northeastward along the purple line in figure 2a. Key to understanding the dynamics is the Coriolis force, which in the northern hemisphere deflects flows to the right. So when rivers flow southeastward into the ocean, they produce a current to the southwest along the continental shelf, parallel to the shore (and out of the page in figures 2b and 2c, as shown by the orange symbols). Because river discharge is strongest in the spring, the current is too.

Wind-driven current works similarly. A process called Ekman transport, also related to the Coriolis effect, drives surface waters at a 90° angle to the prevailing wind (see the article by Adele Morrison, Thomas Frölicher, and Jorge Sarmiento, Physics Today, January 2015, page 27). In summer, winds in the Northwest Atlantic blow to the northeast, and the surface waters are pushed away from shore. In spring, southwestward winds push the waters toward shore. In both cases, the flow at the surface is compensated by a deeper flow in the opposite direction.

Out of time

Seafloor invertebrates usually spawn in the summer, when food for the larvae is plentiful. If spawning is triggered by temperature, then warming could push the spawning season earlier in the year—perhaps early enough for the larvae to get caught in the strong springtime current. If the larvae drift near the water's surface, then the springtime winds could also push them closer to shore.

The exact effect depends on the depth a species originally inhabited, the temperature at which it spawns, and whether its larvae occupy waters nearer the surface or the bottom. Those factors vary by species and aren't always known, so Fuchs and colleagues considered an array of possibilities. For most combinations of location and spawning temperature, ocean warming between 1960 and 2010 was sufficient to trigger spawning at a time when the larvae would encounter a significantly different current than their ancestors did.

The cycle reinforces itself: After one generation spawns too early, its offspring get swept southward and closer to shore, where they spawn earlier still. And shallower waters are not just warmer overall than deeper ones; they also warm up faster in the spring. All told, some species may be spawning up to a month too soon, and they're getting pushed to the limits of the temperatures they can tolerate. Continuation of that pattern could spell doom for the populations. Transporting them back to cooler regions would be difficult, expensive, and only a temporary solution.

Much remains unknown. Fuchs and colleagues' analysis is specific to the geography of the Northwest Atlantic; are similar feedback loops at work in other regions? The researchers found no evidence that the current patterns had changed over the half century they studied; will that constancy persist as the planet warms further? Could any of the species develop an evolutionary adaptation—perhaps spawning at a higher temperature—in time to save themselves?

The work highlights the complexity and fragility of the ecosystems currently being disrupted by climate change, as well as their interconnection with physical systems. "These species' complex life cycles mean they have to adapt to two completely different environments: the seabed where they spend their adult lives, and the water column they occupy as larvae," explains Fuchs. If either of those life stages becomes maladapted to its environment—due to too high a temperature, too strong a current, or anything else—the population as a whole suffers. And finding a new home in a warming world is not so simple.

Johanna Miller

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Nanodiamonds shine as subcellular thermometers

By taking advantage of the electron spin in nitrogen–vacancy centers and carefully tracking the centers, researchers detected temperature variations as small as 0.22 °C.

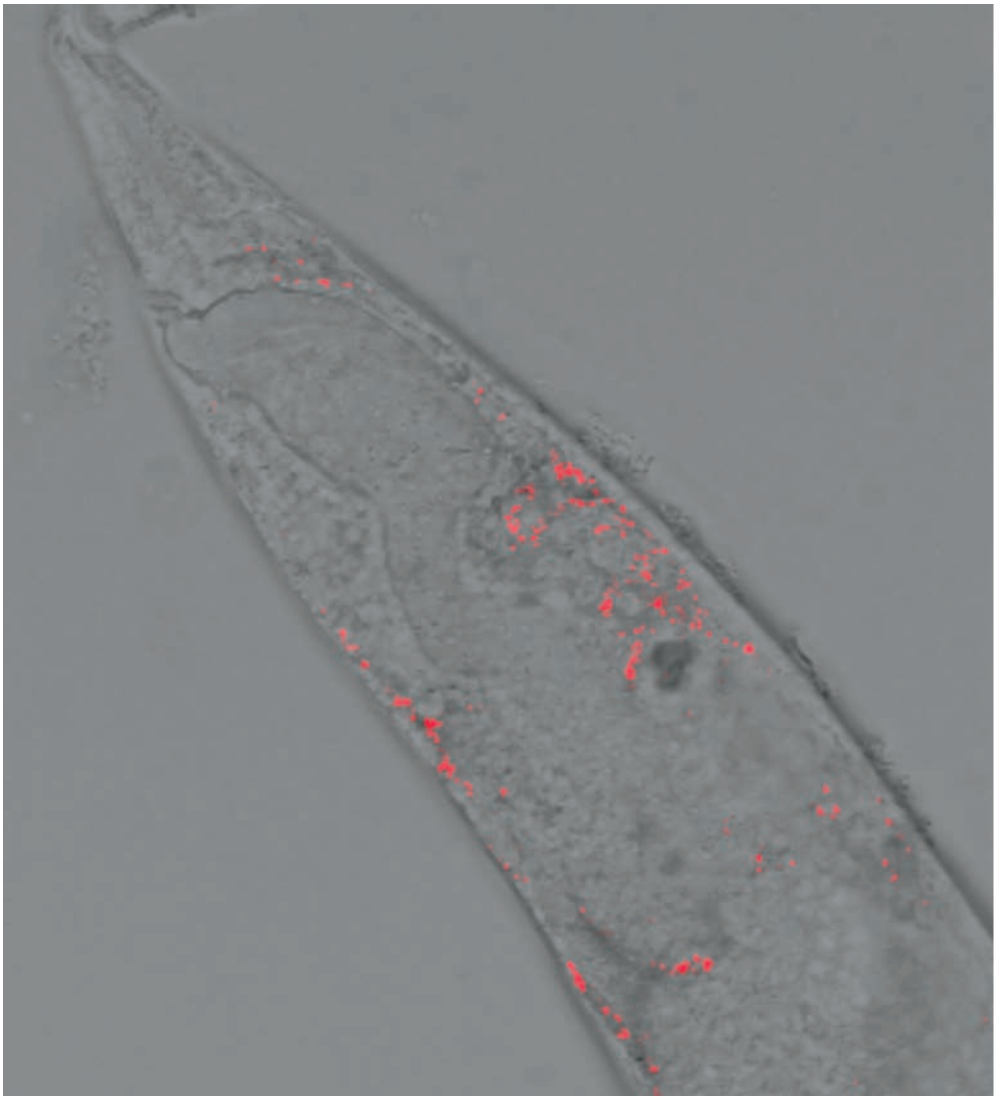

FIGURE 1. FLUORESCENT NANODIAMONDS (red dots) were injected into a *Caenorhabditis elegans* worm about 80 μm in diameter. This image was captured with a confocal fluorescent microscope after the specimen was placed in a glass-bottom dish and the nanodiamonds were excited with a green laser. (Image courtesy of Masazumi Fujiwara.)

Once in a while when a diamond forms, a nitrogen atom steals the place of a carbon atom next to an empty carbon site in the crystal lattice. Researchers call such impurities nitrogen–vacancy (NV) centers and often deliberately add them to a diamond lattice for various applications, including as a component in quantum information technology or as a microscopic biological sensor. (See the article by Lilian Childress, Ronald Walsworth, and Mikhail Lukin, PHYSICS TODAY, October 2014, page 38.)

The sensing ability arises from the centers' optical behavior. An NV center's electronic ground state is a spin triplet, and the energy difference between the sublevel with spin quantum number 0 and the degenerate −1 and +1 sublevels is temperature dependent. The splitting can be measured using optically detected magnetic resonance spectroscopy. Shining a green laser on an NV center will raise one of its two localized electrons to the first excited state, and the NV center fluoresces red as the excited electron relaxes back to the ground state. Applying microwave radiation that is resonant with the sublevel splitting will cause the fluorescence intensity to decrease, and temperature can then be estimated by that difference in intensity.

The spin state of a nanodiamond NV center has been used as a magnetometer to detect weak magnetic fields in cancer cells (see PHYSICS TODAY, August 2011, page 17). Nanodiamond NV centers have also been used as thermometers for *in vitro* cell cultures.[1] Now Masazumi Fujiwara at Osaka City University in Japan and his colleagues have demonstrated that NV centers can serve as precise quantum sensors to measure temperature changes *in vivo* in a complex organism.[2]

By tracking nanodiamond particles with a microscope, the researchers monitored, with fine spatial and temporal resolution, the temperature inside the cells of *Caenorhabditis elegans* worms. Compared with quantum dots—another nanoscale temperature-taking tool and one that often contains cadmium and arsenic—nanodiamonds are less toxic to living organisms, and their chemical stability makes them less disruptive to various biochemical processes in cells.

Follow the light

For decades, scientists have used *C. elegans* in molecular biology research. The transparent, multicellular nematode resides in a sort of goldilocks zone of study: The animal is more complex than simple one-celled organisms, but not so complicated that researchers struggle to disentangle the effects and mechanisms of various

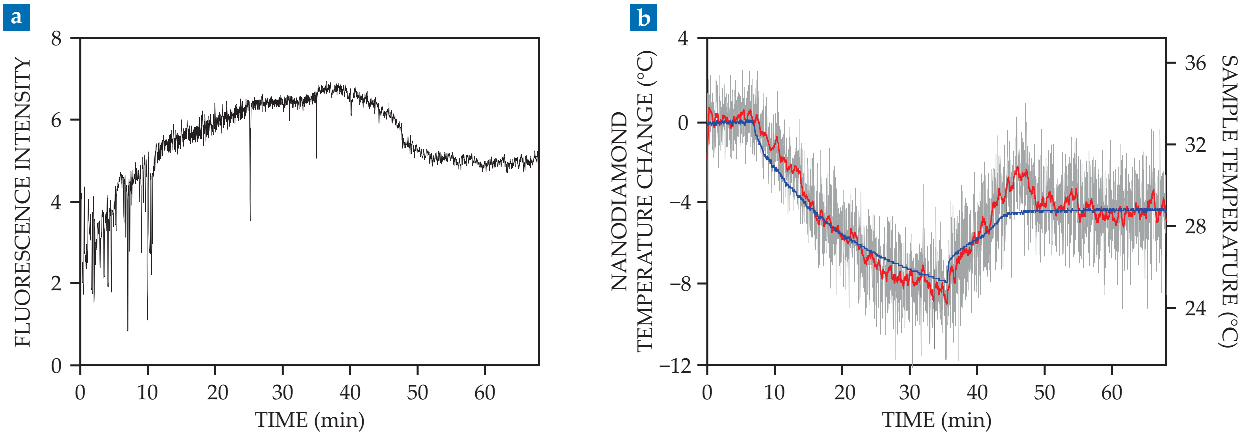

FIGURE 2. MONITORING SUBCELLULAR TEMPERATURE VARIATIONS. (a) The fluorescence generated by the nitrogen–vacancy (NV) centers in a nanodiamond after excitation by a green laser. Temperature affects the transition energy between the sublevels of the NV center's spin state and can be measured as an optically detected magnetic resonance when the excited electrons fluoresce as they relax back to the ground state. **(b)** The temperature estimated by the NV nanodiamond thermometer at 1 s intervals (gray line) and the 20-s running average (red line) are consistent with the independently labeled sample temperature (blue line). (Adapted from ref. 2.)

biological machinery. Two Nobel Prizes in Physiology or Medicine were awarded for research on the nematode, for example—in 2002 for studies of organ development and cell death and in 2006 for RNA interference. What's more, in December 1998 *C. elegans* became the first multicellular organism to have its genome sequenced.

Fujiwara and his colleagues were interested in using the model organism to test an improved nanodiamond thermometer. They first injected nanodiamonds with NV centers into 1-mm-long *C. elegans* specimens, one of which is shown in figure 1. Each sample was then placed in a glass-bottom dish mounted to a confocal fluorescence microscope.

The nanodiamonds were excited by a green laser, and the fluorescence intensity of the NV centers was measured at four closely spaced microwave frequencies. That tactic provided the researchers with the means not just to estimate temperature but also to correct for errors associated with changes to the total fluorescence rate.

The researchers measured the fluorescence intensity along all three axes of the microscope every few seconds to track the NV centers through the worm body. Nanodiamonds don't move all that much through *in vitro* cells. "Inside *C. elegans* or other animals, it's a more dynamic environment," says Fujiwara. "The technological breakthrough here was that we made a microscope system that can measure mobile nanodiamonds."

To test the sensitivity of their nanodiamond thermometer, the researchers subjected worms to thermal shocks, varying their body temperatures between 25 °C and 33 °C. Figure 2a shows representative fluorescence intensity observations. The time series in figure 2b plots real-time temperature estimates from the NV nanodiamond thermometer every second (gray line) and their 20-second running average (red line), which agrees with the independently measured worm temperature (blue line).

After observing induced temperature changes, the researchers used their nanodiamond thermometer to collect real-time measurements of heat generation with micrometer-scale spatial resolution. In a pharmacological experiment to treat cold exposure in a worm, the researchers introduced an uncoupling chemical that generates heat inside the mitochondria of a cell by interrupting the regular metabolic processes that operate there. Tracking the NV centers during the experiment showed that the worm moved a few micrometers, and the nanodiamond thermometer recorded a temperature increase of several degrees that persisted for about two hours.

Reconciling observations and theory

The temperature variations of a few degrees reported by Fujiwara and his colleagues agree with previous spectroscopic measurements of endogenous heat generation within a single living cell. But predictions based on the theoretical heat-generation rate and heat transfer in a cell showed temperature variations several orders of magnitude smaller.[3]

"There's no agreement among the researchers," says Yutaka Shikano at Keio University in Tokyo, a coauthor of the new paper. "But we've measured the temperature robustly, and this is the temperature increase that we've found." To close the gap between measured and predicted temperature changes, researchers will need to combine nanodiamond thermometry with other biological measurements, such as oxygen consumption rate. Such a combination of analyses promises to provide a better understanding of the biological mechanisms producing the temperature variations.

Besides *C. elegans*, Fujiwara and his coauthors suggest that a nanodiamond thermometer may also be useful for *in vitro* human stem cell studies. Researchers often use incubators to provide a lab environment for the cells to grow, but maintaining a stable temperature is challenging. Precise nanodiamond-based temperature measurements at the subcellular level could better determine local changes of the environmental temperature and help researchers better understand how those small differences affect cellular reproduction.

Alex Lopatka

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Quantum computing ramps up in private sector

Ridicule has given way to high hopes.

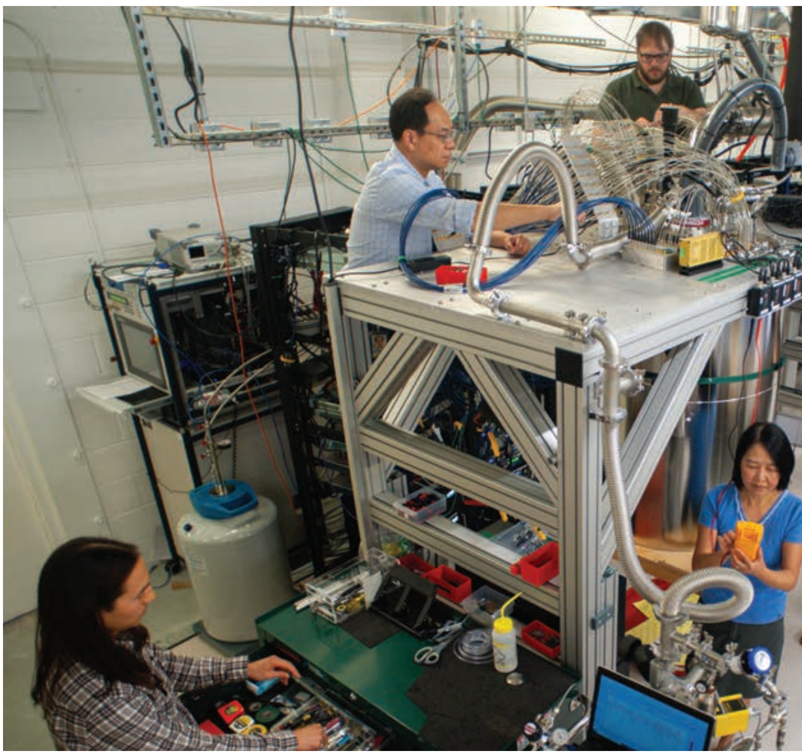
In the early days of quantum computing research, people working in the field routinely encountered skepticism. Twenty years ago eminent physicists told Susan Coppersmith, a theoretical physicist now at the University of New South Wales in Australia, that she was "wasting her time and that quantum computing would never work because of [the difficulties of] error correction." But advances have led to a gradual shift in attitudes.

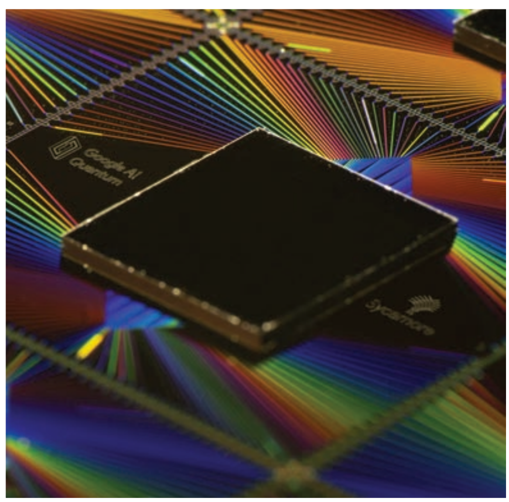
John Preskill of Caltech, a leading theorist in the field, says that over the past couple of years he has observed a shift in expectations about commercialization that is "reflected in a ramping up by tech companies and venture capital." The shift propels progress and creates opportunities for young people, he says. Still, he cautions, "nobody knows when we will have applications running on quantum platforms. I am concerned that the expectations may be inflated as far as time scale." Predictions for achieving a useful quantum computer span from a few years to a few decades; major players IBM and Google both aim for the end of this decade.

Milestones leading to the shift in attitude include the first commercial quantum computers, marketed in 2015 by the Canadian company D-Wave, and the first publicly accessible cloud-based quantum computer, introduced in 2016 by IBM (see "IBM proclaims 'the beginning of the quantum age of computing,'" Physics Today online, 4 May 2016). That same year, error rates with some ion-trap systems dipped below 0.1%. And in October 2019, to great fanfare, Google demonstrated quantum supremacy by performing a calculation deemed impractical or impossible for a classical computer: With 53 quantum bits, or qubits, it solved a math problem in 200 seconds that would have taken much longer on a high-performance computer. The actual time a supercomputer would need is debated, with Google claiming thousands of years and IBM saying its Summit supercomputer could do it in 2.5 days.

Still, hurdles remain to achieving useful quantum computers. The number of qubits needs to be scaled up. The qubits are needed not only for computations but also for correcting errors due to decoherence of the fragile quantum state. Engineering infrastructure must be designed and built. Algorithms must be created.

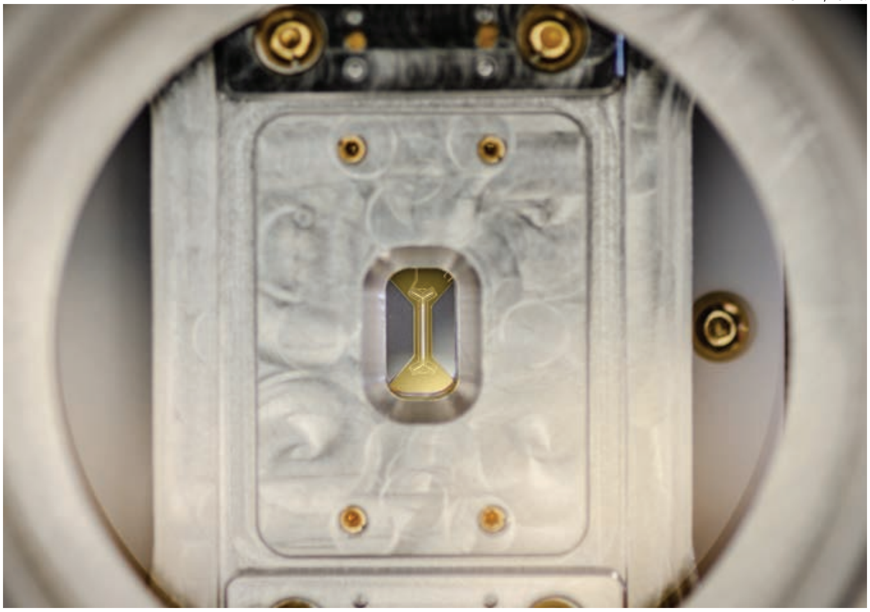
Hartmut Neven, who in 2013 founded Google's Quantum Artificial Intelligence





GOOGLE DEMONSTRATED QUANTUM SUPREMACY in October 2019. Above, scientists and engineers at the company's laboratory in Santa Barbara, California, maintain the dilution refrigerator housing the Sycamore chip (right) that performed the milestone calculation. The chip's 53 superconducting qubits performed in minutes a calculation that would have taken much longer on a classical computer. (Images courtesy of Google AI Quantum.)

KAI HUDEK, IONQ



CHAINS OF YTTERBIUM-171 IONS are loaded into ion traps to serve as qubits at the Maryland-based startup company IonQ. The qubits are controlled with a laser tuned to the frequency difference between the ground state and an excited state of the ions. The thin strip at the center where the ions are trapped measures 1.2 mm by 4 mm.

laboratory, compares the state of quantum computing to the pre-discovery days of the Laser Interferometer Gravitational-Wave Observatory: "It was very difficult to build such a precise instrument, but the bigger concern was, Will there be enough black holes or neutron stars to observe with it?" Sooner or later a reliable quantum computer will be achieved, he continues. "I'm more nervous about the discovery risk: Will we find scientifically and commercially valuable algorithms to make the investments worthwhile?"

Initialize, manipulate, measure

The power of quantum computing lies in the quantum nature of qubits. In classical computing, a bit can take the value 0 or 1; a qubit's value can be 0, 1, or a superposition of 0 and 1. With 2 qubits, there are 4 possible states; with 3, there are 8, and with N, there are 2^N. At 50 qubits, computing power exceeds that of a classical supercomputer, says experimental physicist John Martinis of the University of California, Santa Barbara. "By the time you get to 300 qubits, 2^{300} is more than the number of atoms in the universe, so you could never make a classical computer that could do computations comparable to what quantum computers will likely do some day."

Quantum logic gates for implementing the various steps of a computation can operate on individual qubits or pairs. To create quantum algorithms, "you have to learn new rules," says Martinis, who parted ways with Google in the spring and in September joined the Australian startup company Silicon Quantum Computing as an in-house consultant for six months. "It's going from checkers to chess. With qubits, you have an enhanced set of rules, a richer set of gates."

Several approaches are being pursued for realizing physical qubits. Many are based on superconducting tunnel junctions (see PHYSICS TODAY, July 2009, page 14) or on semiconductor quantum dots (see the article by Lieven Vandersypen and Mark Eriksson, PHYSICS TODAY, August 2019, page 38). Such fabricated qubits can be made in quantity, and researchers can adjust their energy levels to tune their behavior. Other implementations use the spins of trapped ions or neutral atoms. (See the PHYSICS TODAY articles by Ignacio Cirac and Peter Zoller, March 2004, page 38, and by David Weiss and Mark Saffman, July 2017, page 44.) In a trapped-ion or neutral-atom system, the qubits are inherently identical and they maintain their coherence longer than superconducting or semiconductor qubits typically do.

"You can find many quantum mechanical two-state systems in nature," says Neven. "If you can initialize, manipulate, and measure them, it's a qubit. You can form an abstract programming language, and the end result will look the same regardless of what's under the hood." What's under the hood, though, can determine what quantum gates and algorithms are suitable.

For now, ion traps and superconducting qubits are widely considered the leading candidates for quantum computers, says Raymond Laflamme, founder and former director of the Institute for Quantum Computing at the University of Waterloo in Ontario, Canada. He studies NMR systems for quantum computation. The approach is interesting for learning about controlling qubits in general, he says, but NMR is not in the running to build large quantum computers.

Isolation versus interaction

The last few years have seen the debut of quantum computers of increasing size and power. "It's getting to the stage where quantum computing is not yet useful," notes Martinis, "but it's useful for research on quantum computing, and that is in itself really interesting." He cites such questions as, What is the physics of a qubit? What are the constraints? Can you solve problems with qubits that you can't solve in any other way? "The difficulty is that quantum computers are hard to build." Typically, the more qubits get linked together, the faster the decoherence. "It's a tradeoff between getting qubits to talk to each other but not talk to the outside world," says Martinis. For Google's quantum supremacy demonstration, he adds, "we were able to solve the problem through chip design."

"The speed at which decoherence occurs can make or break a qubit," says Coppersmith, whose focus is on semiconductor qubits. "Understanding quantum coherence will have huge consequences for quantum computing."

Possible initial applications that many researchers anticipate are in quantum chemistry and materials science. Simulations with quantum computers could lead to more efficient batteries and molecules deployed for cleaning the environment. (See, for example, "Quantum computer models a chemical reaction," PHYSICS TODAY online, 8 September 2020.)

Another class of problems that quantum computing may ace is optimization, such as the well-known "traveling salesman" problem, in which the aim is to find the shortest route to knock on a large number of doors. "The hope is that quantum computing can do better by looking at all states at the same time," explains Martinis. Optimization problems—how to route planes, diversify investment portfolios, and so on—are ubiquitous.

How can one know whether the results from a quantum computer are correct? For some tasks, such as factoring numbers, checking the answer is easy. And that's an important task: Implementing Peter Shor's 1994 algorithm for factoring large numbers could help crack encrypted information and encrypt future data. Other simple calculations can be tested too. For more complex, nontestable algorithms, researchers have to make the jump to trusting their quantum computers.

Errors and noise

Such trust requires error correction, which in turn means building in redundancy. (See the article by Preskill, Physics Today, June 1999, page 24.) And for many qubit approaches, redundancy can be bulky and costly. The qubit error rate for superconducting systems is currently around 0.5%. For error correction to be effective, Martinis says, "you need to get down to 0.1%." A system can be sampled for errors by checking whether redundant qubits—which together function as a single logical qubit—are in the same state, without disturbing the system by actually reading them out.

In a recent arXiv preprint, University of Maryland experimental physicist Chris Monroe and colleagues report achieving a 0.3% error rate for a logical qubit encoded with 13 physical qubits. The small number of physical qubits—compared with the redundancy employed by other quantum computing approaches—was possible because of the low error rate and dense connectivity in ion-trap systems, says Monroe, cofounder of the Maryland-based startup company IonQ. "This gives trapped ions a clear path to scale up."

In the meantime, many researchers are looking for possible applications with current systems. In the noisy intermediate-scale quantum (NISQ) computing regime, the idea is to write algorithms with few gate operations so they can run before the system is overwhelmed by decoherence. "NISQ is what we do before we can do error correction," says Duke University physicist and IonQ cofounder Jungsang Kim. (See the article by Anne Matsuura, Sonika Johri, and Justin Hogaboam, Physics Today, March 2019, page 40.)

"We have to find out what NISQ is useful for and then generate value so that people reinvest," says Kim. "That will trigger economic development." Preskill, who coined the terms "quantum supremacy" and "NISQ," agrees: "We need practical applications to ignite a virtuous cycle." This past summer Amazon tapped Preskill for the company's quantum computing initiative.

A possible dark horse in the race to useful quantum computers is the five-year-old Palo Alto–based PsiQuantum, which takes a photonics approach to qubits. The company is leapfrogging NISQ and aiming directly for error correction. "The magic is how to come up with architecture that is compatible with the semiconductor industry," says Jeremy O'Brien, company cofounder and a former professor of physics and electrical engineering. The company patterns silicon wafers into thousands of photonic components containing waveguides for carrying the single photons that encode the qubits. "We are going for 10 000 physical qubits to distill into one logical qubit," he says. "It's expensive, but a price well worth paying."

O'Brien predicts that PsiQuantum will have a useful quantum computer with a million logical qubits in just a handful of years—faster than people working with other qubit types are committing to. This past spring the company reached the quarter-billion-dollar mark in venture-capital investments. "I no longer have to convince people it's interesting," O'Brien says. "I have to fend them off with a stick."

The question about which approach to qubits succeeds comes down to who manages to put all the necessary parts together to make the quantum computers do what computer scientists want them to do, says David DiVincenzo. The theoretical physicist is based at Germany's Jülich Research Center, the hub of a consortium working toward a quantum computer as part of the European Union (EU) Quantum Flagship initiative.

Multisector effort

Companies, university researchers, and governments are entering the quantum computing arena. China, Japan, and other countries are investing in quantum computing. In December 2018 President Trump signed into law the National Quantum Initiative, which, among other things, set a 10-year plan for the field. As part of the initiative, in August the US announced awards for new artificial intelligence and quantum information science research institutes. Both the initiative and the EU flagship, launched in 2018, are roughly $1 billion bets on the future commercial potential of quantum information science.

"The community is growing rapidly, and companies can pull off meaningful engineering that is hard to do at universities," says Frank Wilhelm-Mauch, Jülich-based coordinator of the EU quantum computer effort. Companies can also bring large interdisciplinary teams together. "That is extremely hard to do in academia and on academic time scales," he says. Some large companies are investing huge sums, and they can do so more nimbly than governments or academic researchers.

A growing number of companies are offering quantum computing via the cloud—so far, in addition to IBM, the list includes Microsoft, Honeywell, Alpine Quantum, D-Wave, Rigetti Computing, QuEra, and Atom Computing. Google is planning to host a supremacy-level system soon. In August, IonQ opened an 11-qubit quantum computer to the public via the Amazon Braket cloud platform, and on 1 October it unveiled a 32-qubit version. In putting quantum computers in the cloud, Wilhelm-Mauch notes, companies have sparked interest among computer programmers, venture capitalists, and students who want to explore. "This was a great service, and has pulled the field along faster," he says. The wide access could accelerate the discovery of useful algorithms.

Jan Benhelm leads product management at Zurich Instruments, a company that develops control electronics and software to connect qubits to higher software and applications. Universities are an excellent place to develop new, risky technologies, he says, "for exploring new qubits, new gates, new algorithms." But given academia's emphasis on publishing and the fact that many university researchers don't have permanent positions, he says, "the incentive patterns in universities are not supportive when you want to scale up."

More and more startups and larger companies are populating the quantum computing landscape. One is Quantum Benchmark in Kitchener, Ontario, which provides software diagnostics for qubit designers to test whether their computations are performing as expected. And Tabor Electronics makes arbitrary waveform generators integrated with digitizers to control and read out superconducting qubits.

"The field is making good progress," says Martinis. "It's a mixture of well-placed optimism and a bit of hype." It's still hard to say when quantum computers will become useful, says Wilhelm-Mauch. For now, though, with the range of components available, "It's like during the Gold Rush: The ones benefiting are the shovel makers."

Toni Feder

ARPA–E can't reach the promised land alone

Evaluating the success of an upstart agency that swings for the fences on clean-energy technologies isn't straightforward.

The Advanced Research Projects Agency–Energy (ARPA–E), the 10-year-old Department of Energy program designed to foster high-risk clean-energy technologies, has had limited success in moving them toward commercialization, according to a recently published study. But ARPA–E managers, former program officials, and even the lead author of the study agree that the program is performing as it was intended in advancing potentially game-changing solutions for decarbonizing energy. Additional government programs and market incentives are needed, they say, to attract the investments that will bring those innovations to market.

Anna Goldstein of the University of Massachusetts Amherst and colleagues compared the success of 25 startups, all part of the initial 2010 cohort of 60 ARPA–E awardees, to 1262 other cleantech startups of the same age. The researchers used acquisitions by other companies, initial public offerings, survival through 2019, and the amount of venture capital (VC) raised through 2017 as indicators of successful business outcomes. They found that the ARPA–E startups fared no better than the clean-energy startups that didn't apply for ARPA–E grants. Goldstein and her group published their analysis in *Nature Energy* on 14 September.

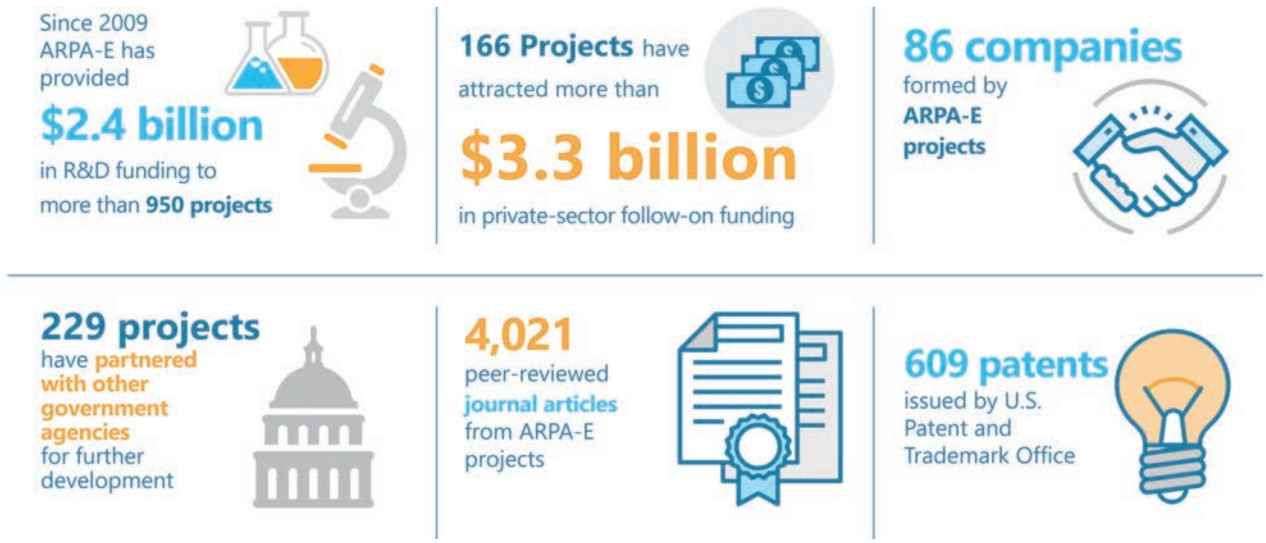
The comparison set comprised three groups: startups that had been rejected for ARPA–E grants, ones that had received grants in 2010 from DOE's Office of Energy Efficiency and Renewable Energy (EERE), and startups that didn't apply to ARPA–E or receive EERE funds. The authors said that of those, only the group of rejected ARPA-E applicants had worse business outcomes than the ARPA–E sponsored startups. No significant differences were identified between the success rates of the ARPA–E awardees and those of the EERE awardees. Nor did measures of success differ from those of the "other" group.

The findings "suggest that ARPA–E was not able to fully address the 'valley of death' for cleantech startups within 10–15 years after founding," the paper states. The "valley of death" is a widely used term for the difficulty of obtaining the investment required to move an innovative technology from development to full-scale demonstration and commercialization.

The report concludes, however, that the ARPA–E startups showed a high degree of innovation by obtaining significantly more patents than any of the other groups. "They are patenting at twice the rate after their award, even accounting for other factors that we know influence the patenting rate. That's what I see as the important finding," Goldstein says.

Failure is an option

Patterned after the successful Defense Advanced Research Projects Agency, ARPA–E was created in 2007 legislation to support high-risk technologies that could greatly reduce greenhouse gas emissions. The new agency was initially funded through the American Recovery and Reinvestment Act of 2009, and its first awardees were announced in fiscal



THE ADVANCED RESEARCH PROJECTS AGENCY–ENERGY was created to support the development of high-risk but potentially transformational clean-energy technologies. Housed in the US Department of Energy, ARPA–E issued its initial awards in fiscal year 2010. (Courtesy of ARPA–E.)

year 2010 (see PHYSICS TODAY, December 2009, page 26). President Trump has repeatedly proposed eliminating it (see PHYSICS TODAY, June 2017, page 34). Congress instead has steadily increased the agency's appropriation; its budget for FY 2020 was $425 million.

Unlike traditional R&D grant programs, ARPA–E empowers its program managers to take a hands-on approach. If a project fails to progress, it can be quickly terminated at the manager's discretion. Given the high-risk nature of the R&D, failure rates are expected to be higher than for grants from EERE or DOE's other applied energy research programs.

Goldstein says it's important to compare the startup successes of ARPA–E programs with those of less risky research projects. "If you got political opposition to ARPA–E that asks why the government should be taking high-risk bets, it bakes in the assumption that these high-risk projects are going to do worse and be more of a loss for public dollars. It's important to know that's not the case."

An ARPA–E spokesperson says the *Nature Energy* study failed to take into account startups that resulted from university research sponsored by ARPA–E. One such project at Stanford University led to the advanced-battery startup QuantumScape, which recently announced it will go public in December at an anticipated evaluation of $3.3 billion.

David Danielson, of the Bill Gates–backed Breakthrough Energy Ventures investment firm, says he identified $230 million more in VC that was raised through 2017 by the ARPA–E startups that wasn't included in the study's total. If that sum were added to venture funding raised by QuantumScape, three other university spinoffs, and Vionx, a spinoff from United Technologies, all of which were backed by ARPA–E, total VC would nearly double the $984 million listed in the study. Goldstein replies that the study's methodology considered only startups that were already incorporated at the time of the award, "so we could be comparing apples to apples" between ARPA–E recipients and the other categories.

In his own analysis of the study, Danielson, a former assistant secretary of EERE and the initial program director at ARPA–E, also counted more startup failures than Goldstein found. But he says higher failure rates are expected from ARPA–E's "high-risk moonshots."

Acquisitions, another metric used in the Goldstein study, more often than not are an indication of failure, Danielson says. When startups throw in the towel, they will usually find someone willing to buy the technology they failed to commercialize—for far less than the sellers had sunk into it.

Breakthrough Energy Ventures itself has invested in 10 ARPA–E startups, including QuantumScape.

The innovation ecosystem

Arunava Majumdar, a Stanford engineering professor who was the inaugural ARPA–E director, says the agency was never intended to bridge the valley of death. "ARPA–E's job is not to create businesses. It is to do research on breakthrough technologies that could eventually become the foundation of entire new industries." He says the Goldstein report highlights a systemic issue in the innovation ecosystem: "There are these valleys of death. I don't think anyone is immune to it. You may have the best technology you can develop . . . but it will still have to go through the same gauntlet of trying to raise money and face the valleys of death beyond ARPA–E. That needs fixing."

In September ARPA–E announced the initial awards of a new program meant to help bridge that gap by supporting full-scale technology demonstrations. The SCALEUP program (Seeding Critical Advances for Leading Energy technologies with Untapped Potential) will provide $19.9 million to Natron Energy for sodium-ion battery development and $4.6 million to Bridger Photonics for the aerial detection of methane leaks from oil and gas infrastructure. More SCALEUP awardees are expected to be announced in January.

Norm Augustine, a retired Lockheed Martin CEO, chaired a 2007 report from the National Academies Press that urged ARPA–E's creation. The agency's greatest achievement, he says, has been to add more than $3 billion in new research funding for clean energy, but he added that its budget should be three times larger. As for evaluating its performance, "the ideal measure would be how many tons of carbon were removed from the atmosphere or how many tons per joule were not put into the atmosphere due to ARPA–E, but that's probably impossible to figure."

Augustine discounts patents as a performance metric. "It's common practice in some places that where one patent would do, you get four or five because it makes you look better to your funder or boss. On the other hand, some large companies are very reluctant to get patents because it just gives it away to the world the avenue of research you are pursuing." Augustine puts more weight on the number of startups created and the amount of industry investment attracted.

Danielson thinks ARPA–E may be best judged not by the number of successes and failures, but by its "transformational outcomes," measured by the number and frequency of companies valued at $1 billion or more that have resulted from sponsored projects. In addition to QuantumScape, two other companies fit that bill: advanced-battery company Sila Nanotechnologies, privately valued at more than $1 billion, and the custom-organism-engineering company Gingko Bioworks, which he says is privately valued at $4.2 billion. The total $8.5 billion valuation of the three is about 2.5 times the $3.3 billion total ARPA-E funding to date. "That can be loosely thought of as a 19% equivalent annual rate of return on taxpayer funds," he says.

Investors needed

Organizations such as the Engine, launched in 2016 by MIT to be an incubator and source of long-term capital for disruptive technologies, and Breakthrough Energy Ventures are evidence of growing investor interest in clean energy since the 2010–17 investment window covered in the Goldstein study, says Addison Stark, a former ARPA–E acting program director now with the Bipartisan Policy Center. "The fundamental story is that ARPA–E has existed for 10 years and we know that innovation in hard technology and energy technology occurs over decades," he says.

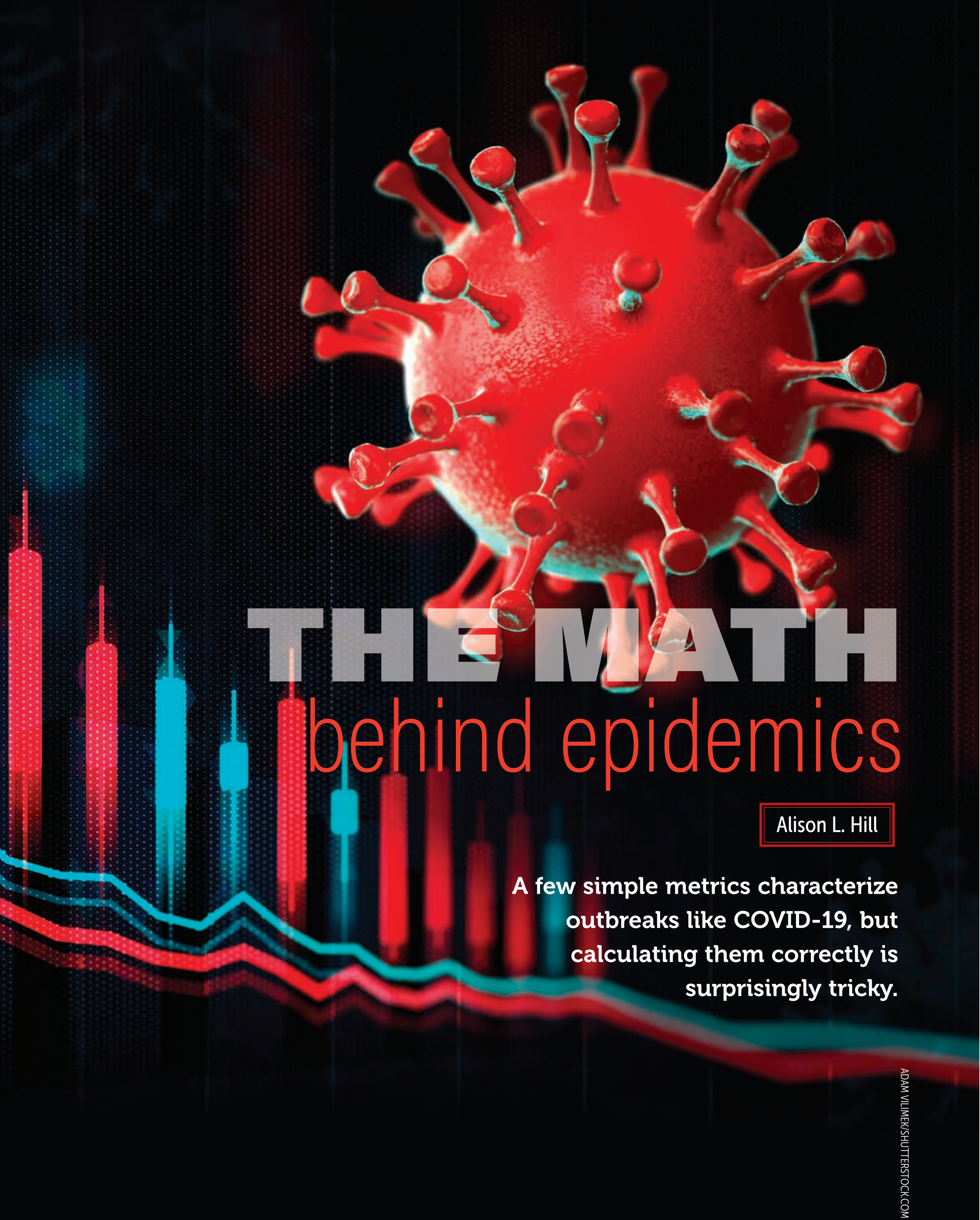
The market demand to attract more private investment could be generated by a tax on carbon emissions or by regulations such as clean energy standards, says Majumdar. Demand could also be created by government procurement of low-carbon products. "Anyone who wants to create something needs a place to sell. Without selling, the pipeline is clogged."

As for financing, Majumdar says the VC model doesn't work for energy technologies, given that VC can get factor-of-six returns in five years from investing in software. "That whole ecosystem needs to be fixed, and that's not the job of ARPA–E. It's the job to some extent of the federal government to prime the pump and provide the incentives for private capital to be unleashed."

"We know the private sector has struggled with funding full-scale technology demonstrations," says Stark. Of five carbon capture technology demonstrations that were initiated with government funding, only the smallest, the Petra Nova plant south of Houston, Texas, was a success.

On the other hand, the five utility-scale solar energy demonstrations that were built by companies and private consortiums with the help of $4.6 billion in federal loan guarantees continue to operate today. Solar has benefited from decades of federal R&D, tax credits, and consistent policies. But carbon capture has been plagued by technical difficulties, cost and schedule overruns, and inconsistent support from government.

David Kramer PT



THE MATH behind epidemics

Alison L. Hill

A few simple metrics characterize outbreaks like COVID-19, but calculating them correctly is surprisingly tricky.

ADAM VILIMEK/SHUTTERSTOCK.COM

Alison Hill is an assistant professor in the Institute for Computational Medicine and the infectious disease dynamics group at Johns Hopkins University in Baltimore, Maryland. She is also a visiting scholar at Harvard University in Cambridge, Massachusetts.

The year 2020 has been defined by the COVID-19 pandemic: The novel coronavirus responsible for it has infected millions of people and caused more than a million deaths. Like HIV, Zika, Ebola, and many influenza strains, the coronavirus made the evolutionary jump from animals to humans before wreaking widespread havoc. The battle to control it continues.

When a disease outbreak is identified—usually through an anomalous spike in cases with similar symptoms—scientists rush to understand the new illness. What type of microbe causes the infection? Where did it come from? How does the infection spread? What are its symptoms? What drugs could treat it? In the current epidemic, science has proceeded at a frenetic pace. Virus genomes are quickly sequenced and analyzed, case and death numbers are visualized daily, and hundreds of preprints are shared every day.

Some scientists rush for their microscopes and lab coats to study a new infection; others leap for their calculators and code. A handful of metrics can characterize a new outbreak, guide public health responses, and inform complex models that can forecast the epidemic's trajectory. Infectious disease epidemiologists, mathematical biologists, biostatisticians, and others with similar expertise try to answer several questions: How quickly is the infection spreading? What fraction of transmission must be blocked to control the spread? How long is someone infectious? How likely are infected people to be hospitalized or die?

Physics is often considered the most mathematical science, but theory and rigorous mathematical analysis also underlie ecology, evolutionary biology, and epidemiology.[1] Ideas and people constantly flow between physics and those fields. In fact, the idea of using mathematics to understand infectious disease spread is older than germ theory itself. David Bernoulli of fluid-mechanics fame devised a model to predict the benefit of smallpox inoculations[2] in 1760, and Nobel Prize–winning physician Ronald Ross created mathematical models to encourage the use of mosquito control to reduce malaria transmission.[3] Some of today's most prolific infectious disease modelers originally trained as physicists, including Neil Ferguson of Imperial College London, an adviser to the UK government on its COVID-19 response, and Vittoria Colizza of Sorbonne University in Paris, a leader in network modeling of disease spread.

This article introduces the essential mathematical quantities that characterize an outbreak, summarizes how scientists calculate those numbers, and clarifies the nuances in interpreting them. For COVID-19, estimates of those quantities are being shared, debated, and updated daily. Physicists are used to distilling real-world complexity into meaningful, parsimonious models, and they can serve as allies in communicating those ideas to the public.

Transmission dynamics

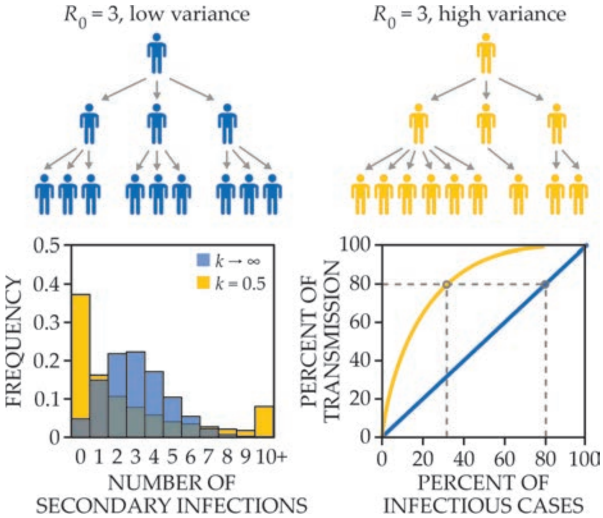
Few scientific fields have a single metric that both insiders and outsiders obsess over as much as infectious disease epidemiology's basic reproductive number, R_0. The unitless number is defined as the average number of new cases, or secondary infections, caused by a typical infected individual in a susceptible population.[4] It's a single quantity that describes how infectious a given pathogen is and how difficult it will be to control. (See box 1 for more about how models incorporate R_0.)

Infectious disease dynamics almost always display criticality or threshold behavior, whereby spread only takes off under certain conditions. Absent those conditions, the outbreak fizzles out, similar to a nuclear chain reaction. The value of R_0 determines which outcome occurs. If disease spread is modeled by continuous differential equations, R_0 helps determine when an equilibrium condition is stable or unstable. If the spread is instead captured as a series of stochastic reactions, R_0 affects whether extinction or establishment is more likely.

Roughly speaking, R_0 depends on the product of three factors: the contact rate, or the number of people an infected individual interacts with each day; the transmissibility, or the probability per unit time that any given contact results in transmission; and the infection duration. The goal of most infectious disease control efforts is to reduce R_0 by altering one or more of those components. For example, the contact rate can be reduced by limiting an infected individual's connections through general social distancing or targeted isolation. The transmissibility can be reduced by limiting the chance of infection during each interaction through measures such as mask wearing. (For more on the physics of respiratory infection spread, see the Quick Study by Stephane Poulain and Lydia Bourouiba, PHYSICS TODAY, May 2019, page 70.) The duration of an infection can often be reduced by microbe-clearing therapies, like antibiotics for strep throat, but such drugs aren't yet available for COVID-19. Another way to decrease R_0 is to reduce the number of susceptible individuals, which a vaccine could eventually do.

As a metric, R_0 has several important limitations. It doesn't say anything about a disease's virulence, which characterizes how deadly it is. Infections with small R_0 values, like SARS

BOX 1. QUANTIFYING TRANSMISSION DYNAMICS

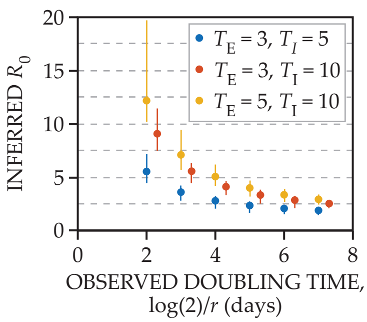


A disease's basic reproductive number R_0 describes the average number of secondary infections generated by a single infected individual introduced into a susceptible population. For an epidemic to take off, R_0 must be greater than 1. An epidemic will tend to slow if the fraction f of the population that's protected from infection is sufficiently large: $f > 1 - 1/R_0$.

The variance in secondary infections can be large and can lead to superspreading events.[9] The number of secondary infections is often summarized by a negative binomial distribution,

$$P(x; R_0, k) = \Gamma(k+x) / \Gamma(k)\,\Gamma(x)\, p^k (1-p)^x,$$

with mean R_0, where k parameterizes the dispersion of secondary infections, $p = (1 + R_0/k)^{-1}$, and Γ is the gamma function. If all individuals have the same intrinsic infectiousness—that is, the variance is low (blue scenario on the right)—then the number of secondary infections is expected to have a Poisson distribution ($k \to \infty$). If the infectiousness is heterogeneous, the distribution is said to be overdispersed and has a lower k. Overdispersion implies that a small number of individuals are responsible for a large percentage of secondary infections (dotted lines), whereas most others infect no one, which causes infection chains to go extinct. For COVID-19, a few studies have estimated $k \approx 0.5$ (yellow at right), albeit with high uncertainty.



Estimating R_0 directly is difficult. Instead, its value is usually inferred from the disease's exponential growth rate r early in the epidemic and from the infection's time scale[10] (figure 2). For example, if the average duration of the latent and infectious periods (T_E and T_I, respectively) are known and one assumes that the periods have exponential distributions, then $R_0 = (1 + rT_E)(1 + rT_I)$ (dots on the lower graph). Other distribution shapes lead to different estimates for R_0 (error bars). Country-level epidemic growth rates in the range of 0.1–0.4 per day have been observed for COVID-19, which corresponds to doubling times of 2–8 days. Estimates of R_0 have generally been between 2 and 3, although they are sometimes much higher depending on the setting observed and the assumptions about the transmission intervals. (Images created using code from ref. 8.)

(severe acute respiratory syndrome), can be extremely lethal; others with high values, such as chicken pox, rarely lead to death. Some infections, like smallpox, have both a high R_0 and a high risk of death. Also, R_0 doesn't reflect the time scale over which a disease spreads. The average number of new cases described by R_0 could occur over a few days, as with the common cold, or many years, which is typical for HIV.

Contrary to popular belief, R_0 is not an intrinsic property of an infection any more than the Reynolds number is a characteristic of a fluid. It is highly dependent on the population in which a disease spreads. The same infection could have a high R_0 in a crowded population with poor hygiene and immune systems weakened by malnutrition but a much lower value in a population with better living conditions and general health. Even demographic details, such as the proportion of people in high-risk groups or patterns of social mixing, can influence R_0. The average number of secondary infections can also change dramatically over the course of an epidemic and is reflected by the effective reproductive number, which adjusts as individuals change their behavior to avoid infection.

Despite the limitations, knowing a disease's reproductive number is still useful in an outbreak. For example, Stephen Kissler and Christine Tedijanto at Harvard University found that with an estimated R_0 of 2.2, people in the US would need to reduce their contacts by 60% through social distancing for at least 70% of the epidemic to avoid overflowing its current intensive care unit capacity. Luca Ferretti and Chris Wymant at Oxford University calculated that with their estimate of $R_0 = 2.0$, testing and contact tracing could control the epidemic only if 75% of confirmed and suspected cases were isolated within two days.

After estimating $R_0 = 5.7$ early in the outbreak in Wuhan, China, Steven Sanche and Yen Ting Lin at Los Alamos National Laboratory calculated that control would require isolating 50% of infected people along with a 50% reduction in all contacts through social distancing. Huaiyu Tian at Beijing Normal University and colleagues estimated that early in the outbreak R_0 was, on average, 3.1 in Chinese cities but that it quickly decreased to about 1 in cities that rapidly implemented control measures and further decreased to about 0.04 under more intense controls.

But where did those R_0 values come from? Estimating R_0 is notoriously difficult. A complete chain of transmission events starting from a single individual is rarely observed. That is often only possible when infection is still relatively rare, the symptoms are relatively unique, good diagnostic tests are available, and a high proportion of the population can be sampled (see figure 1). In contact-tracing studies, as soon as an individ-

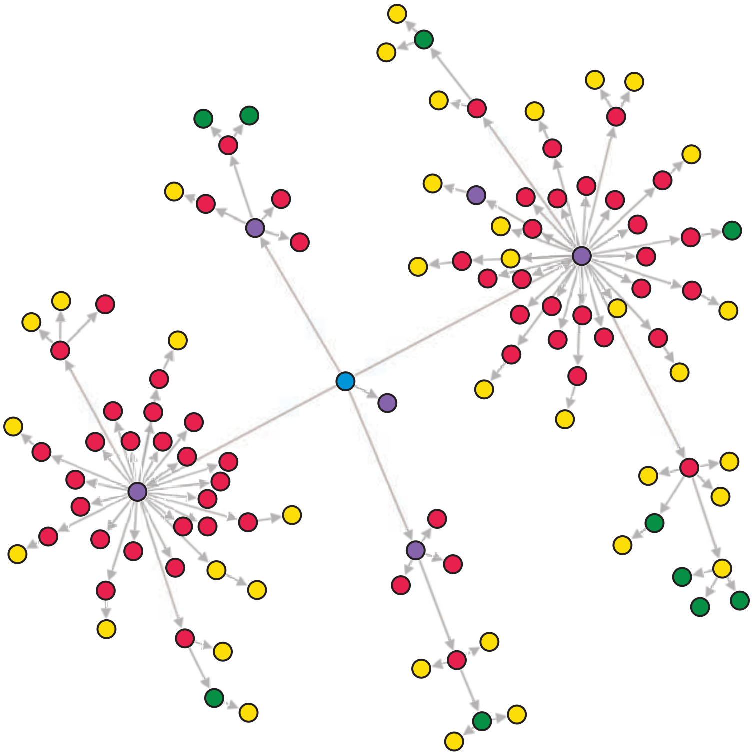


FIGURE 1. EXAMPLE TRANSMISSION NETWORK FOR COVID-19. This transmission cluster was seeded by an unknown infected individual (blue) who attended a training course with other fitness instructors (purple). They in turn spread the infection to students in their exercise classes (red), to family (yellow), and to coworkers (green). (Created from data in ref. 7 using code from ref. 8.)

ual is diagnosed, public health professionals track down anyone that person might have contacted during his or her infectious period and test them for the disease; researchers use the data to estimate R_0 for a single generation of infection.

But direct estimates of R_0 can be biased. For example, outbreaks are more likely to be detected when many individuals were infected by a single source—a superspreading event—so estimates could be biased upwards. Alternatively, individuals enrolled in studies may be more likely than the average person to be diagnosed and isolated quickly, leading to underestimates of the true R_0. Indirect estimates are therefore more common and may give more representative values.

A common way of indirectly estimating R_0 involves observing an epidemic's growth rate. Alone, R_0 does not determine how quickly a disease spreads. It also depends on the time scale over which an individual's secondary infections occur. However, if the average time a person is infectious can be determined, then it's generally possible, with some mathematical tricks, to estimate a population's R_0 from the rate of disease spread (see box 1).

Time scale of infection

Exponential growth in the number of infections is a defining feature of epidemics early in their course. Estimates of the growth rate r, or alternatively the doubling time $T_2 = \log(2)/r$, can inform short-term projections of the epidemic.

Like R_0, r is not an intrinsic property of an infection; it varies across regions and over time. Usually variation in r occurs for the same reasons as in R_0, such as changes in human behavior that reduce spread. But estimates of r are also subject to other factors. Dramatic changes in testing capacity that alter the proportion of cases detected and reported can lead to biased estimates of r, as can changes in reporting delays.

Observed exponential growth rates can be used to back out R_0, which has a more intuitive interpretation and is more directly connected to the underlying process of disease transmission. Researchers have derived mathematical equations to relate r to R_0 under different assumptions about transmission (see box 1). In general, those formulas require knowing how long a typical individual is infectious and the delay between when someone is infected and when they become infectious, known as the latent period (see figure 2). A high observed exponential growth rate of infection implies a high R_0 if either the latent period or infectious period is long, whereas it could imply a much smaller value if both those intervals are short.

A disease's latent and infectious periods can be estimated by following individual patients with known infection exposure dates. But more than just the intervals' average durations is needed to determine the relationship between r and R_0: Enough patients must be studied to get a reasonable estimate of the full distribution.

For many infections, the latent and infectious periods are easily identified because they correspond with disease symptoms. However, for COVID-19 that is not the case: Individuals often shed the virus in their respiratory secretions and are highly infectious before they develop symptoms, such as a cough or fever. The incubation period—the time until symptoms develop—is therefore generally longer than the latent period (see figure 2). Furthermore, it appears that many of the symptoms of COVID-19 extend far beyond the infectious period. Epidemiological information, rather than symptom tracking, is therefore needed to estimate when someone was infectious.

Infectious disease epidemiologists often use observed transmission chains to determine the timing of infectiousness relative to the disease course. They do so by estimating either the generation interval, the time between when an individual was infected and when he or she infected a secondary case, or the serial interval, the time between when symptoms start in the first person and in the person they infected (see figure 2). Measuring the serial interval is more common because the onset of symptoms is generally easier to discern than the infection time.

The serial interval is a mathematical convolution of the incubation and infectious periods, so if one is known, the other can be calculated. Researchers have developed formulas that directly relate the serial-interval distribution to r and R_0 without first recovering the individual periods. Those formulas have become the most common way to estimate R_0. However, the calculated R_0 values are subject to biases in estimates of the serial interval. For example, individuals enrolled in research studies are often isolated shortly after diagnosis, which reduces the time they have to infect others.

Estimating the durations of infection stages provides information beyond R_0 for epidemic control. The distribution of incubation periods indicates how long exposed individuals should be quarantined to safely rule out symptomatic infection. The

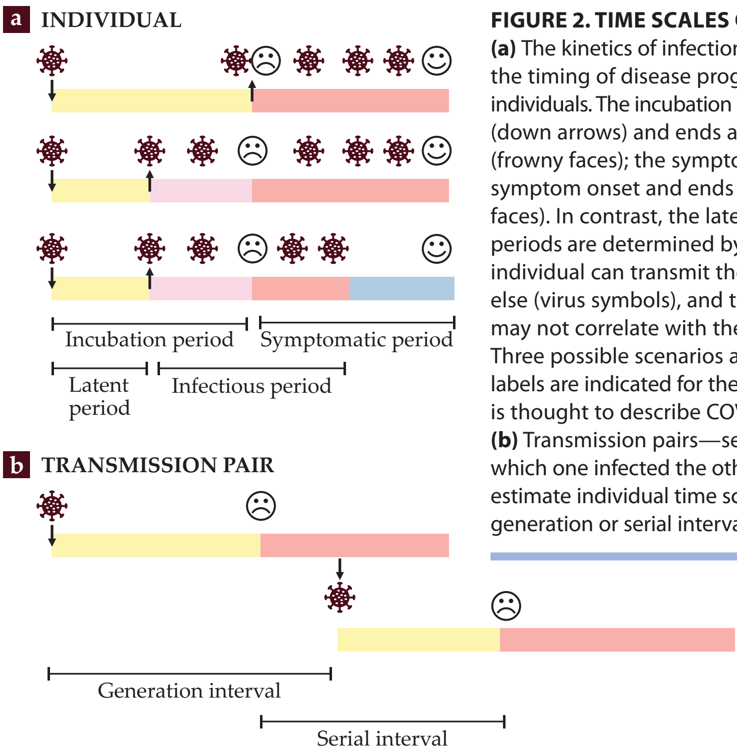


FIGURE 2. TIME SCALES OF EPIDEMIC SPREAD. **(a)** The kinetics of infection spread depends on the timing of disease progression in infected individuals. The incubation period starts at infection (down arrows) and ends at symptom onset (frowny faces); the symptomatic period starts at symptom onset and ends at resolution (smiley faces). In contrast, the latent and infectious periods are determined by when an infected individual can transmit the disease to someone else (virus symbols), and the periods may or may not correlate with the timing of symptoms. Three possible scenarios are shown. Timeline labels are indicated for the third scenario, which is thought to describe COVID-19 infections. **(b)** Transmission pairs—sets of individuals in which one infected the other—are often used to estimate individual time scales through either the generation or serial interval. (Figure by Alison Hill.)

distribution of infectious periods determines how long infected individuals should be isolated to prevent them from infecting others.

How deadly is it?

So far we've characterized epidemics using the basic reproductive ratio R_0, which summarizes an infected person's transmission potential; the exponential growth rate r, which reveals how fast the epidemic is growing; and infection time intervals, which capture how the disease's course in one individual determines the time scale of infection at the population level. But those metrics miss a key feature: how deadly the disease is.

The lethality of an infectious disease is typically defined as the probability that an infected individual will eventually die of the disease and is commonly reported as the case fatality risk (CFR; see box 2). The CFR for COVID-19 has been hotly debated, and although scientists have generally converged on an estimate of around 1%, researchers, the press, and the general public continue to scrutinize that value. Some insist that COVID-19 is "just another flu," whereas others present evidence for total excess deaths far exceeding official reports. To understand the debates, it is important to understand the complications in estimating the CFR.

A common mistake in estimating a disease's CFR is to simply divide the cumulative number of deaths occurring up to a certain day by the cumulative number of cases diagnosed up to that same day. That ratio is a biased estimate of the likelihood of death given infection, especially during a rapidly growing epidemic. (See box 2 for a simple model illustrating that point.) To correctly ascertain the risk of death, researchers can use cohort studies in which they monitor a group of recently infected individuals until each one either recovers or dies. Performing such studies is difficult during an ongoing outbreak. Alternatively, simple death ratio measurements can be adjusted to account for epidemic growth and time to death.

Another complicating factor when calculating the CFR is determining who counts as a case. Definitions of the CFR in epidemiology literature make it clear that a case is someone diagnosed with infection, either by a specific test or at minimum based on symptoms. But that's a problem for infections like COVID-19, since true cases are underreported because of testing limitations and asymptomatic infections. If researchers truly want to estimate the probability of death given infection, then they need to correct for that undercounting. The quantity being estimated is then more correctly termed the infection fatality risk (IFR). To estimate the degree of undercounting and calculate the IFR for COVID-19, epidemiologists either look at populations with near-universal testing or conduct random population-level testing to estimate the prevalence of current or past infection.

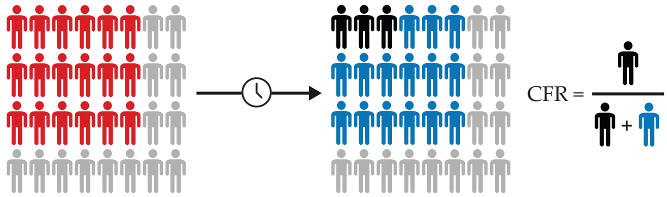
Other challenges, such as correctly identifying a cause of death, also affect estimates and interpretations of CFR and IFR values for COVID-19 and other infections. But more importantly, metrics like the CFR only count deaths; they don't include the many other harms that survivors suffer. The long-term complications of COVID-19 and the care required for serious cases, such as mechanical ventilation, are still under investigation, and simple metrics are unlikely to capture those effects.

From description to prediction

Metrics like R_0, r, and the CFR help classify and compare infections and quickly communicate risk. But their ability to predict the full burden of an epidemic is limited. For example, how many people an infection kills and the time scale over which that occurs depend not only on the CFR but also on how many people get infected, which itself depends on how easily the infection is transmitted, what fraction of the population is susceptible, and the efficacy of control measures. The number of new daily infections depends on the number of people currently infected and how long ago they were infected, which determines how many of them have already entered their infectious period. To put those ideas together and make informed predictions, mathematical models are needed.

Most dynamical models used to track infection spread in a population are compartmental models, in which individuals are classified into one of a few discrete states, such as susceptible, infectious, or recovered, based on their infection status[5,6] (see figure 3). The model tracks changes in the number of individuals in each state, usually with differential equations or discrete or continuous stochastic processes. The equations are inherently nonlinear because pairwise interactions between susceptible and infectious individuals generate new infections.

BOX 2. ESTIMATING THE RISK OF DYING DURING AN EPIDEMIC

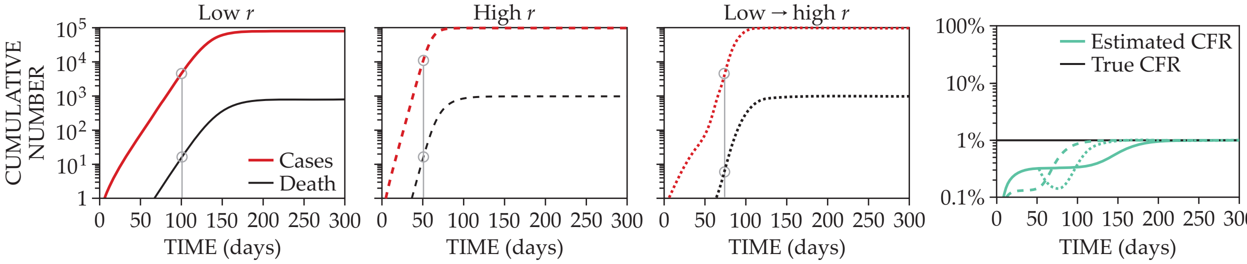


Epidemiologists use a disease's case fatality risk (CFR) to describe the percentage of individuals confirmed to be infected (red, top right) who will eventually die of the disease (black) rather than recover (blue). The true CFR can be accurately established only by following a cohort of infected individuals until their final outcome is observed.

The ratio of the number of deaths observed up to a certain time to the number of cases reported up to that same day (gray circles on graphs below) can give a biased estimate of the true risk of death. The risk estimate is especially skewed when the epidemic has a high exponential growth rate *r*, when *r* changes rapidly, and when a long delay exists between infection and death. That's because the pool of cases from which the observed deaths were drawn occurred in the past, when the epidemic was smaller.

In the simple infection model shown here, individuals are only infectious for about five days, but it may take an additional two weeks for them to die. The true CFR is 1%, which is dramatically underestimated by the ratio of deaths to cases early in the epidemic (right graph). In real data, the ratio can further be confounded by underreporting or reporting delays.

A note on terminology: The abbreviation CFR is confusing because the R can stand for rate, ratio, and risk. In epidemiology, the three words have precise meanings. A rate generally implies a unit of inverse time and is rarely used to describe a short-term infection affecting only a portion of the population. A ratio compares two distinct populations. Only a risk metric describes a proportion in which individuals counted in the numerator are a subset of those in the denominator. That is what's needed to measure an infected person's chance of death. (Images created using code from ref. 8.)



Some simple standard epidemic models will be familiar to physicists from introductory dynamical systems courses and are named for the acronyms of their compartments. For example, the SIS model describes infections, like many sexually transmitted diseases, that don't produce long-term immunity: susceptible (S) individuals can become infectious (I) but then return to the susceptible state when they recover. In the SIR model, recovered (R) individuals are assumed to be permanently immune, a good approximation for many short-term viral infections like measles or yellow fever. (An online simulation tool that uses a compartmental SIR-type model to understand COVID-19 transmission is available at https://alhill.shinyapps.io/COVID19seir.)

Just like physicists, infectious disease researchers balance creating simple, understandable models with generating useful predictions. Compartmental models are always oversimplifications because in reality, the infection in one person's body is a continuum of states—the microbe multiplies and migrates between tissues, the immune system mounts a response, and symptoms develop. And the process of disease transmission can be much more complicated than the simple reaction-rate terms used in many equations. It depends on personal contacts and the highly structured nature of social networks (see box 3).

The level of detail needed for a model to be useful depends on its purpose. Some researchers modeling COVID-19 are interested in understanding the potential burden on the

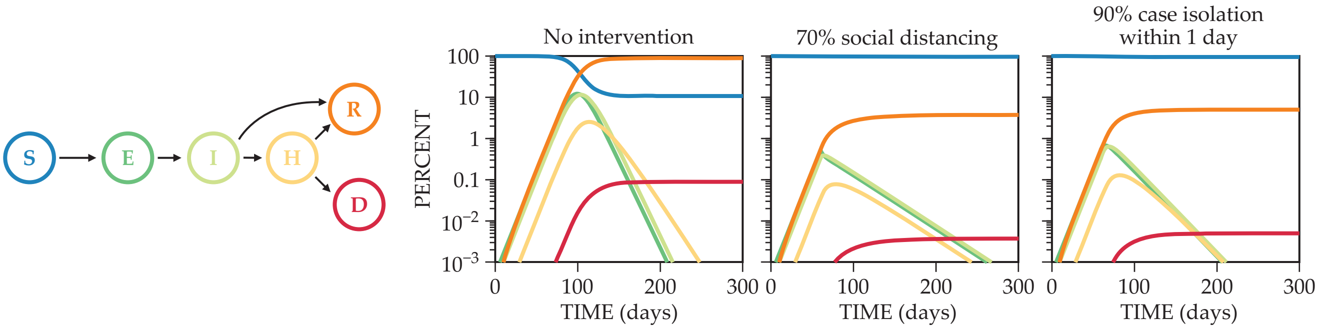


FIGURE 3. A MODEL OF COVID-19 SPREAD WITH AND WITHOUT INTERVENTIONS. The compartmental model shown here classifies individuals as susceptible (S), exposed (E), infectious (I), hospitalized (H), recovered (R), or dead (D). At day 60, one of two interventions is implemented: either a general social distancing policy that reduces contact between infected and susceptible individuals by 70% or another case-based policy in which 90% of infectious individuals are isolated an average of one day after they become infectious. (Images created using code from ref. 8.)

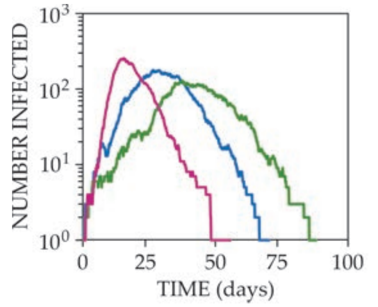
BOX 3. SIMULATING INFECTION SPREAD IN NETWORKS

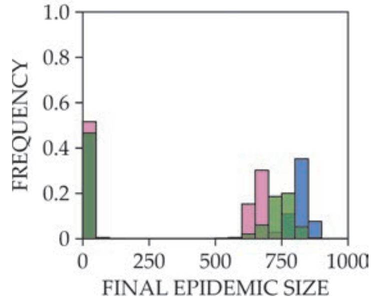
Human contacts are not random or uniformly distributed. They can be described by a contact network that determines which transmission paths are possible if an infection is introduced into the population. The structure of the network can heavily influence the extent of disease spread.[11]

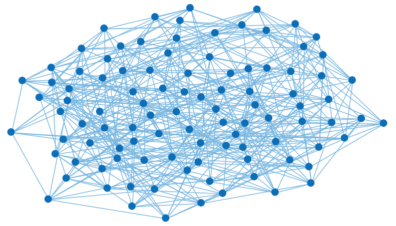
Here, a simple, stochastically simulated susceptible-infected-recovered (SIR) model demonstrates that idea on three idealized networks: a uniform random network in which each individual is connected to 10 other randomly chosen people, a highly clustered small-world network that uses the Watts–Strogatz algorithm to preferentially connect individuals to 10 neighbors and then randomly rewires 10% of connections, and a heterogeneous network in which the number of neighbors for each individual is drawn from a gamma distribution with mean and standard deviation of 10. All epidemics started with one infected individual.

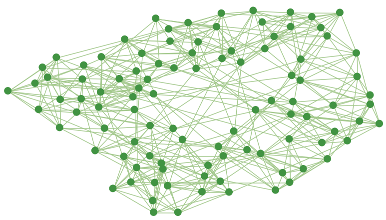
Epidemic growth is fastest in the heterogeneous networks and boosted by highly connected superspreaders. It's slowest in the small-world network, where the high degree of interconnectedness limits the susceptible contacts seen by an infected individual. The final epidemic size—the percentage of recovered individuals when the infection eventually dies out—varies across simulations because of stochastic effects, but it is generally highest in the uniform network and lowest in the heterogeneous network. (Images created using code from ref. 8.)

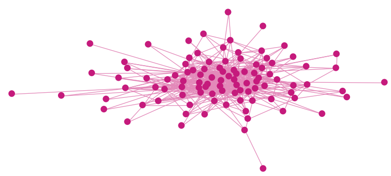
(For more details on the physics of networks, see the article by Mark Newman, PHYSICS TODAY, November 2008, page 33.)






Uniform random network


Small-world network


Heterogeneous network

healthcare system, so they extend SIR-type models to include advanced stages of infection that require hospitalization or admission into an intensive care unit. They also track the portion of individuals who die (see figure 3). In studies that make policy recommendations about social distancing strategies, modelers simulate detailed infection networks that describe individuals' interactions at home, school, and work and among friends. To understand the effectiveness of symptom-based isolation with or without additional quarantining of contacts, scientists augment basic models to track infectiousness over the disease's course.

Scientists continuously debate the relative merits and caveats of different modeling approaches for COVID-19. They refine models as their understanding of the disease changes and try to determine how to best communicate to the public the inherent uncertainty in model predictions. (For more on uncertainties in COVID-19 modeling, see PHYSICS TODAY, June 2020, page 25.)

Mathematical analysis and modeling are key tools in the study of infectious diseases and have been critical in our response to the COVID-19 pandemic. Estimating even seemingly simple metrics—R_0, the CFR, and the incubation and infectious periods, among others—requires strict attention to nuances in the data and careful formulation of mathematical relationships. When designing complex models of epidemic dynamics, modelers make trade-offs between keeping things simple enough to facilitate understanding and realistic enough to make accurate forecasts. Getting the numbers right is always a priority for scientists. During a public health crisis, the stakes are higher than ever.

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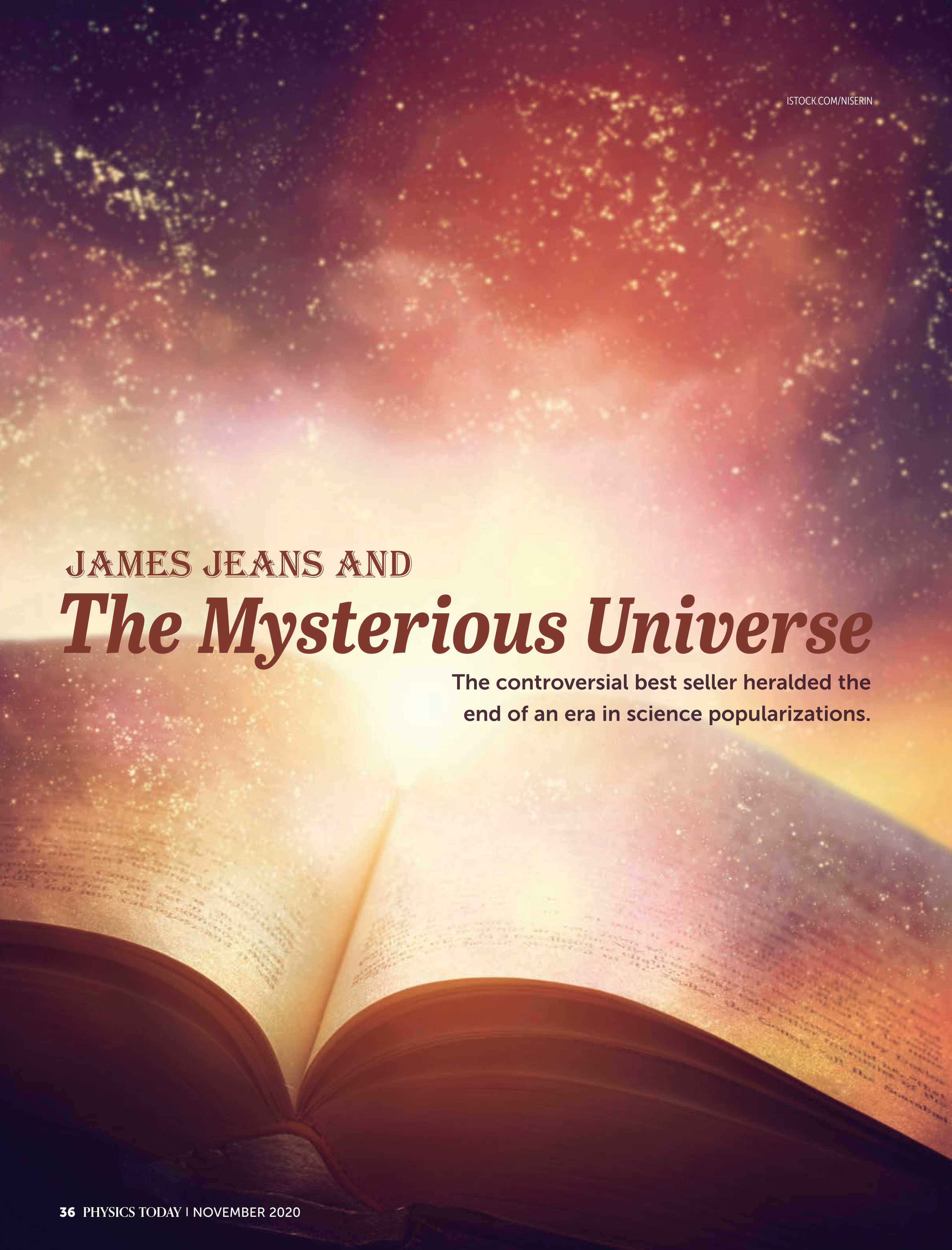

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JAMES JEANS AND *The Mysterious Universe*

The controversial best seller heralded the end of an era in science popularizations.

Daniel Helsing received his PhD in literature from Lund University in Sweden in 2019. He is a freelance critic and translator and teaches comparative literature at Linnæus University in Växjö and Karlstad University, both in Sweden.

Daniel Helsing

Can physics help answer questions about who we are, why we are here, and what the meaning of life is? In the UK in the 1920s and 1930s, many writers expounded the new physics of the time—relativity and quantum mechanics—in popular books with philosophical leanings. Some of those books were popular in both senses of the term: They explained physics to laypeople, and they sold extraordinarily well. That booming market turned some popularizers into celebrities. Of those authors and their books, none were as successful as James Jeans and *The Mysterious Universe*, published in 1930.

In the first chapter,[1] Jeans reflects on the meaning of life in a seemingly indifferent universe. And for him, modern physics does have something to say on the matter: It leads people to recognize an intimate connection between human beings and the universe. The philosophical framework underpinning Jeans's work—a form of metaphysical idealism, in which ultimate reality is "mind-like" rather than "matter-like"—may strike modern readers as odd.

Many present-day popularizers, from Neil deGrasse Tyson to Sean Carroll, would probably agree with Jeans on the importance of addressing existential questions, since they frequently explore such questions in their own books and television shows. But they would likely take issue with Jeans's idealism. Reading Jeans today illuminates a long tradition of existential, best-selling popular science and inspires an investigation into the philosophical assumptions in current popularizations.

Who was James Jeans?

Born into a family of journalists in 1877, James Hopwood Jeans was a precocious child who learned how to read and count at an early age. In 1896 he left his childhood home in London for Trinity College at the University of Cambridge. After completing his studies in mathematics and physics in 1903 and briefly working as a lecturer in mathematics, he accepted a position as a professor of applied mathematics at Princeton University in 1905. He stayed there for four years before returning to Cambridge to become the Stokes Lecturer in applied mathematics.

During the first half of his scientific career, Jeans did research in statistical mechanics and blackbody radiation. He is perhaps best known today for the Rayleigh–Jeans law—originally derived by Lord Rayleigh in 1900 and amended by Jeans in 1905—which describes the radiation intensity of a blackbody at a given temperature as a function of wavelength. The law was derived in a classical framework and is valid only for long wavelengths. For shorter wavelengths, the function goes to infinity; that problem became known as the ultraviolet catastrophe.

Jeans tried to avoid the ultraviolet catastrophe within a classical framework by introducing additional hypotheses, but he eventually concluded that the attempted solution was a dead end. In his *Report on Radiation and the Quantum-Theory*, written for the Physical Society of London in 1914, Jeans argued that quantized energy, as suggested by Max Planck in 1900, was necessary. The report aided in the development and acceptance of quantum physics in the UK.

From 1914 on Jeans shifted his research from the very small to the very large—from atoms and molecules to stars and the universe. He received the University of Cambridge's Adams Prize for his essay "Problems of cosmogony and stellar dynamics," which was published as a book in 1919. Jeans went on to serve as the honorary secretary of the Royal Society of London for a decade, all while keeping up his prolific research on stellar dynamics. He published more than 35 astronomical papers between 1913 and 1928. One of his last technical publications was the book *Astronomy and Cosmogony*, in which he summarized his astrophysical research and attempted to survey the field generally. After 1929 Jeans diverted his energy to science popularization.[2]

The Einstein boom

Physics came to the forefront of the British public imagination during the final decade of Jeans's career as a researcher. Astronomers Arthur Eddington and Frank Dyson organized expeditions to test Albert Einstein's general theory of relativity during the solar eclipse of May 1919 (see the article by Daniel Kennefick, PHYSICS TODAY, March 2009, page 37). After the results were made public in November 1919, the world experienced what has been described as a "relativity circus."[3] Almost overnight Einstein became a global superstar and an icon of genius, international science, and the

JAMES HOPWOOD JEANS (1877–1946) was a prolific physicist and science popularizer. (Courtesy of the AIP Emilio Segrè Visual Archives.)

modern world (see the article by Paul Halpern, PHYSICS TODAY, April 2019, page 38).

Demand was growing for texts explaining the new, revolutionary picture of the universe. Eddington wrote one of the earliest book-length popularizations, *Space, Time and Gravitation: An Outline of the General Relativity Theory*, published by Cambridge University Press in 1920. It was favorably but not widely reviewed. The book sold well and was reprinted several times during the 1920s.

Einstein, too, wrote a popularization of relativity, *Über die spezielle und die allgemeine Relativitätstheorie* (*Relativity: The Special and General Theory)*, published in German in 1916 and translated to English in 1920. But he lacked Eddington's gift for marketing physics to laypeople; his book was dry and did not sell as well. The slew of books on relativity that followed initiated what literary scholar Elizabeth Leane calls the "Einstein boom" in popular physics publishing[4] in the 1920s and 1930s.

As early as 1922, interest in relativity seemed to be waning. Magazines and journals claimed that Einstein was "last season" (*Nouvelle Revue Française*, January 1922) and that "even philosophers have had enough of relativity" (*Mind*, October 1922; both quotes are from reference 5, page 56). But two developments saved the genre. First, most popularizers widened their scope to include the other modern-physics revolution, quantum mechanics. Second, they discussed the new physics' significance and implications for philosophy and spirituality.

Although popularizations of relativity continued to appear—some of them written by famous writers such as Bertrand Russell and John W. N. Sullivan—the books that dominated the market took the broader view. Literary scholar Michael Whitworth singles out three books, all published by Cambridge University Press, as particularly influential: Alfred North Whitehead's *Science and the Modern World* (1925), Eddington's *The Nature of the Physical World* (1928), and Jeans's *The Mysterious Universe* (reference 5, page 62). Of those, *The Mysterious Universe* was by far the most successful.

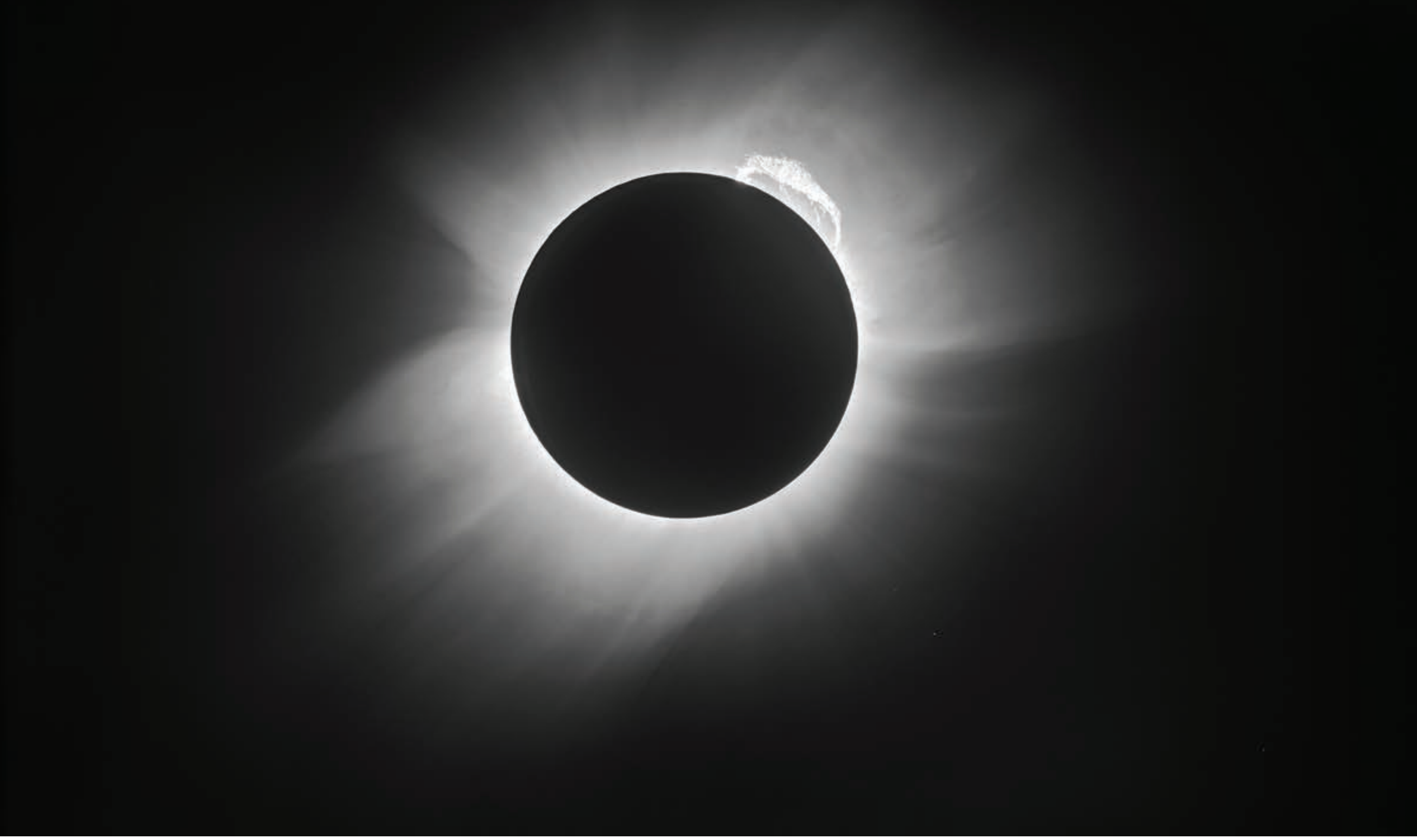
The making of a popularization

The Mysterious Universe was not Jeans's first popular science book. Sydney C. Roberts, the secretary at Cambridge University Press, persuaded Jeans to write one in 1929. The result, *The Universe Around Us*, became an immediate best seller and sold more than 11 000 copies in the first few months alone (reference 6, page x). In comparison, Eddington's *The Nature of the Physical World* sold only around 10 000 copies in the UK in over a year.[7] But both those figures pale in comparison with those of *The Mysterious Universe*.

In 1930 Allen Ramsay, vice chancellor of the University of Cambridge, invited Jeans to deliver the Rede Lecture, the university's prestigious annual public address whose roots go back to the 16th century. Encouraged by the success of *The Universe Around Us*, Jeans agreed to publish an expanded version of the lecture as a book, *The Mysterious Universe*. It was published on 5 November, the day after Jeans gave his highly anticipated talk. An editor at the *Times*, Harold Child, reported that "the whole office is buzzing about Jeans." In anticipation of its popularity, Cambridge University Press printed 10 000 copies for the initial release. But those were not enough. "For the next few weeks," Roberts says, "our chief concern was to keep *The Mysterious Universe* in stock" (reference 6, page xi).

Shortly after the Rede Lecture, the BBC aired six weekly lectures, "The Stars in Their Courses," by Jeans. The first one was promoted on the 14 November cover of the BBC's weekly magazine *The Radio Times*. The following week's issue featured an article by Richard Church—with the eye-catching title "Einstein: Why don't we boil him in oil?"—about Jeans and the changing attitudes toward scientists.[8] That media attention boosted the sales of *The Mysterious Universe*, and by the end of 1930, the book had sold 70 000 copies in the UK. The sales remained high into 1931, and by the end of that year, *The Mysterious Universe* had been reprinted eight times along with a second, revised edition (reference 5, page 71).

Before settling on the title, Jeans considered two alternatives: "The Wasting Universe" and "The Shadowland of Modern



THE 1919 SOLAR ECLIPSE provided the first experimental evidence of the theory of general relativity. Using glass photographic plates, Arthur Eddington and Andrew Crommelin imaged the eclipse, as shown here after restoration and modern processing. When stars were close to the Sun—and visible during the eclipse—they appeared displaced due to the bending of light by the Sun's gravity, as predicted in general relativity. The observation created demand for popular science books explaining the topic. (Courtesy of ESO/ Landessternwarte Heidelberg-Königstuhl/F. W. Dyson, A. S. Eddington, and C. Davidson.)

Physics" (reference 7, page 52). Those titles hint at different aspects of Jeans's vision of the universe and at his intentions beyond explaining science for laypeople. The philosophical ambitions of *The Mysterious Universe* are apparent already in the first few pages of the first chapter, ominously named "The Dying Sun."

After emphasizing "the littleness of our home in space" and the isolation of most stars as they wander "blindly through space," Jeans reveals that the universe provokes "something akin to terror" in him: "We find the universe terrifying because of its vast meaningless distances, terrifying because of its inconceivably long vistas of time which dwarf human history to the twinkling of an eye, terrifying because of our extreme loneliness, and because of the material insignificance of our home in space—a millionth part of a grain of sand out of all the seasand in the world" (reference 1, pages 1 and 3).

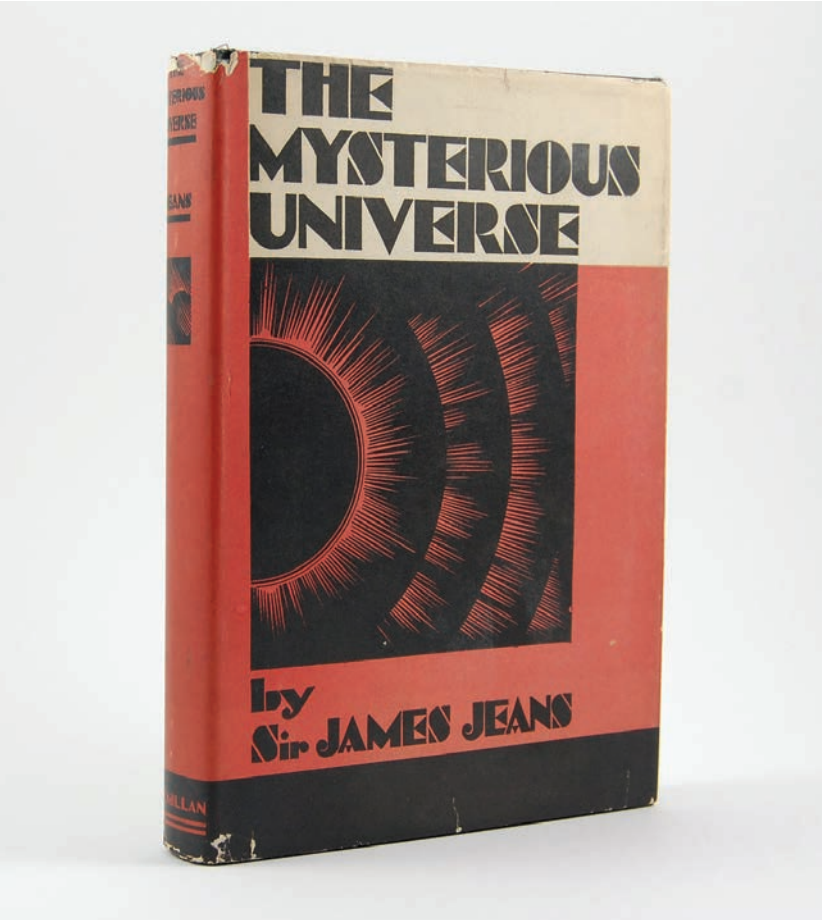
Questions about the meaning of life amid that abundant meaninglessness preoccupy Jeans and inspire him to use poetic language. "Is this, then, all that life amounts to," he asks, "to stumble, almost by mistake, into a universe which was clearly not designed for life, and which, to all appearances, is either totally indifferent or definitely hostile to it, to stay clinging on to a fragment of a grain of sand until we are frozen off, to strut our tiny hour on our tiny stage with the knowledge that our aspirations are all doomed to final frustration, and that our achievements must perish with our race, leaving the universe as though we had never been?" But rather than turning to religion for an answer, Jeans turns to science: "Astronomy suggests the question, but it is, I think, mainly to physics that we must turn for an answer" (pages 11–12).

The answer, however, is not straightforward

On the one hand, thermodynamics suggests that the universe is heading inexorably toward dissolution. The eventual heat death of the universe—a uniform, homogeneous state in which life is impossible—was a popular idea in the Victorian era.[9] For Jeans, that fate was as certain as anything in science, although in the last chapter, he does allow for the possibility that the idea may prove to be mistaken. The approaching heat death inspired Jeans's sense of life's meaninglessness. In a universe bound for destruction, we live on "a fragment of a grain of sand" (page 11) next to that dying Sun.

To Jeans, physics suggests that planets and life are exceedingly rare. The mechanisms of planetary formation were unknown at the time, and Jeans used his platform to promote his own theory, the tidal theory originally formulated in 1917. In it, a star happened to pass by the Sun some 2 billion years ago, and that near collision created huge stellar tidal waves, which ejected fragments of solar matter into space—and thus the planets were formed. Jeans estimated that near collisions between stars are extremely rare, and as a result, so are planets and life. That rarity adds to his sense of "our extreme loneliness."

On the other hand, according to Jeans, physics also holds the key to understanding the universe and ourselves. In the last chapter, "Into the Deep Waters," Jeans develops his vision of the philosophical implications of emerging physics. He suggests that we are similar to the cave dwellers in Plato's allegory of the cave: We see and study the shadows of reality, not reality itself. But through physics and mathematics, we are beginning to glimpse reality.



THE FIRST EDITION OF *THE MYSTERIOUS UNIVERSE* came out in 1930 and sold 70 000 copies in the UK by the end of that year. In the book, Jeans explains to a lay audience the latest research on quantum mechanics and general relativity with a philosophical bent. (Courtesy of Laura Massey/Alembic Rare Books.)

Jeans emphasizes that science is incomplete and that we may yet see "the river of knowledge" turn in unexpected ways. But he contends that physics has shown that some ideas we took for granted are almost certainly wrong. In particular, Jeans argues that we must give up science's long-cherished materialistic and mechanical worldview, which posits that nature operates like a machine and consists solely of material particles interacting with each other. The "age of mechanical science had passed," Jeans says, but we still have "a bias towards mechanical interpretations" (pages 98 and 135). The new physics is counterintuitive and reveals a universe more mysterious than expected.

What, then, does science say about the nature of the universe? Jeans uses modern science in his speculations, but he cautions that he is "a stranger in the realms of philosophical thought" (page viii). And those speculations are what many critics interpreted as Jeans going off the deep end.

Jeans embraces a variant of metaphysical idealism. Not only does the universe begin "to look more like a great thought than like a great machine" (page 137), but some kind of active agent seems to be involved: "If the universe is a universe of thought, then its creation must have been an act of thought" (pages 133–134). Although Jeans does not think that such a creative act of thought necessarily had humans or human emotions in mind, he does posit the existence of some kind of creator—a "Great Architect" who appears to be a "pure mathematician" (page 122). And if true, then the mind "no longer appears as an accidental intruder into the realm of matter; we are beginning to suspect that we ought rather to hail it as the creator and governor of the realm of matter" (page 137).

The upshot of Jeans's philosophy is that the sensations of terror and alienation described in the first chapter may be unwarranted. As it evolves, life approaches ultimate reality: "Those inert atoms in the primaeval slime which first began to foreshadow the attributes of life were putting themselves more, and not less, in accord with the fundamental nature of the universe" (page 138). And we humans, with our capacity for mathematical thought, are more in accord with the fundamental nature of the universe than any other life-form on planet Earth. In other words, physics leads us toward, not away from, a deity. In the end, physics provides our souls with a home in the cosmos in the form of metaphysical intimacy with the Creator.

The descent of Jeans

As sales of *The Mysterious Universe* skyrocketed, critics started opining on Jeans's vision of the universe. The press homed in on the speculative qualities of the last chapter and tended toward sensationalist interpretations. The *Daily Herald*, for example, framed Jeans's conclusions as science versus religion, as evidenced in the title "Scientist challenges the churches: Mankind just an accident" (reference 5, page 70).

Scientists and highbrow critics started to distance themselves from *The Mysterious Universe*, in large part because the book's success provoked them to air their concerns publicly. Physicist Herbert Dingle, writing in *Nature*, expressed admiration for Jeans's ability to explain physics in lay terms but criticized his philosophical speculations. Dingle argued that since Jeans had the means to reach large numbers of laypeople "who seek guidance in matters of philosophy and religion," Jeans had a responsibility not to overstep the boundaries of science. Dingle did acknowledge the importance of putting forth hypotheses in science, but not hypotheses that "pose as the sole prophets of God." And in that regard, Jeans failed. Dingle wrote, "we feel strongly that he is darkening counsel, not by words without knowledge, but, much more dangerously, by knowledge without equivalent balance of judgement."[10] Many scientists agreed with Dingle's assessment.

Philosophers also criticized Jeans. Ludwig Wittgenstein told his students that he loathed *The Mysterious Universe* and charged it with "a kind of idol worship, the idol being Science and the Scientist."[11] In her 1937 book *Philosophy and the Physicists,* L. Susan Stebbing criticized Jeans and Eddington for invoking emotions when explaining science. She also argued that Jeans's understanding of idealism and materialism were outdated and thus his attempt to explore the "'philosophical implications' of the new physics" resulted in "cloudy speculations" rather than substantial insights.[12]

The broader philosophical landscape in the UK was chang-

CARL SAGAN (1934–96), the prominent science popularizer, on the set of his 1980 TV show *Cosmos*. In his show and book of the same name, Sagan injects existential questions into his scientific discussion, similar to James Jeans. (Courtesy of Science History Images/Alamy Stock Photo.)

ing at the time. Idealism had dominated academic philosophy starting in the 1860s. But shortly after the turn of the 20th century, philosophers G. E. Moore and Bertrand Russell started to attack idealism, and by 1930 it was rare in the British philosophical world. Most philosophers eschewed the idealists' emphasis on metaphysics and questions about the nature of being and turned instead to logic, positivism, and linguistic analysis. While idealism was common among physicists in their popularizations in the 1920s—Eddington and Whitehead, the other best-selling authors at the time, also had idealist views—the general trend among philosophers was to turn away from it.[13]

The scientific and philosophical critiques of Jeans and idealism affected the entire genre of popular physics books. Although many popularizers kept publishing, the hype and the excitement surrounding the genre had waned. Eddington's and Whitehead's idealist views had not met with as much resistance in the 1920s; it was Jeans's book that brought the criticism to the fore and spelled the end of idealism in popular science. Whitworth comments that the "very blurring of science, philosophy and art, which had stimulated the science books of the mid-1920s, was now seen by philosophers and scientists alike as an unwelcome breaching of disciplinary boundaries" (reference 5, page 72).

Popular science did not disappear. But following World War II and the creation of the nuclear bomb, it transformed as scientific institutions and journalists sought to restore public faith in science. As a result, much popularization focused on the social implications and practical applications of science. Space exploration and astronomy remained popular—for example, the works of Fred Hoyle and Arthur C. Clarke[14]—but grand philosophical and poetic narratives didn't attract similar levels of public attention as *The Mysterious Universe* did for a few decades.

Finally at home in the cosmos?

This year marks not only the 90th anniversary of *The Mysterious Universe* but also the 40th anniversary of Carl Sagan's *Cosmos*, the best-selling popular science book and television series, which helped create the modern celebrity scientist.[15] Sagan guided readers and viewers through the world of modern science and created a grand narrative in which humanity is the product of natural processes reaching all the way back to the Big Bang. Similar to Jeans, Sagan not only explained science, he also used it to address existential questions. Also like Jeans, Sagan posited a connection between human beings and the universe. In the opening sequence of the first episode, standing on a cliff by the sea, he says, "The cosmos is also within us. We're made of star stuff. We are a way for the cosmos to know itself."

After the enormous success of Sagan and *Cosmos*, popular science books that present grand narratives and address existential questions have had a sustained market. But popularizers rarely express philosophical views of Jeans's flavor; idealism has broadly remained out of favor since the 1930s. Instead, contemporary popularizers typically promote some version of naturalism, which philosopher David Papineau defines as the view that "reality is exhausted by nature, containing nothing 'supernatural', and that the scientific method should be used to investigate all areas of reality, including the 'human spirit.'"[16] That view often has the implication that meaning and purpose are human inventions with no objective existence.

In his 2016 best-selling book *The Big Picture*, cosmologist Sean Carroll develops and supports that aspect of naturalism: "Purpose and meaning in life arise through fundamentally human acts of creation, rather than being derived from anything outside ourselves. Naturalism is a philosophy of unity and patterns, describing all of reality as a seamless web."[17] In other words, people construct meaning in an inherently meaningless universe. And engaging in science is one of the primary ways of making life meaningful.

Contemporary readers of popular science may find naturalism almost self-evidently true—of course we create meaning and project it onto the universe; of course meaning and purpose do not exist objectively. But Jeans's extension of idealism to physics was similar. He developed his views when idealism was prevalent among his fellow popularizers and had been commonplace in academic philosophy for decades, just as naturalism is today. Could the feeling of naturalism's self-evidence say more about our moment in time than the universe itself? Our scientific models and explanations may be naturalistic, but does that mean that ultimate reality is too?

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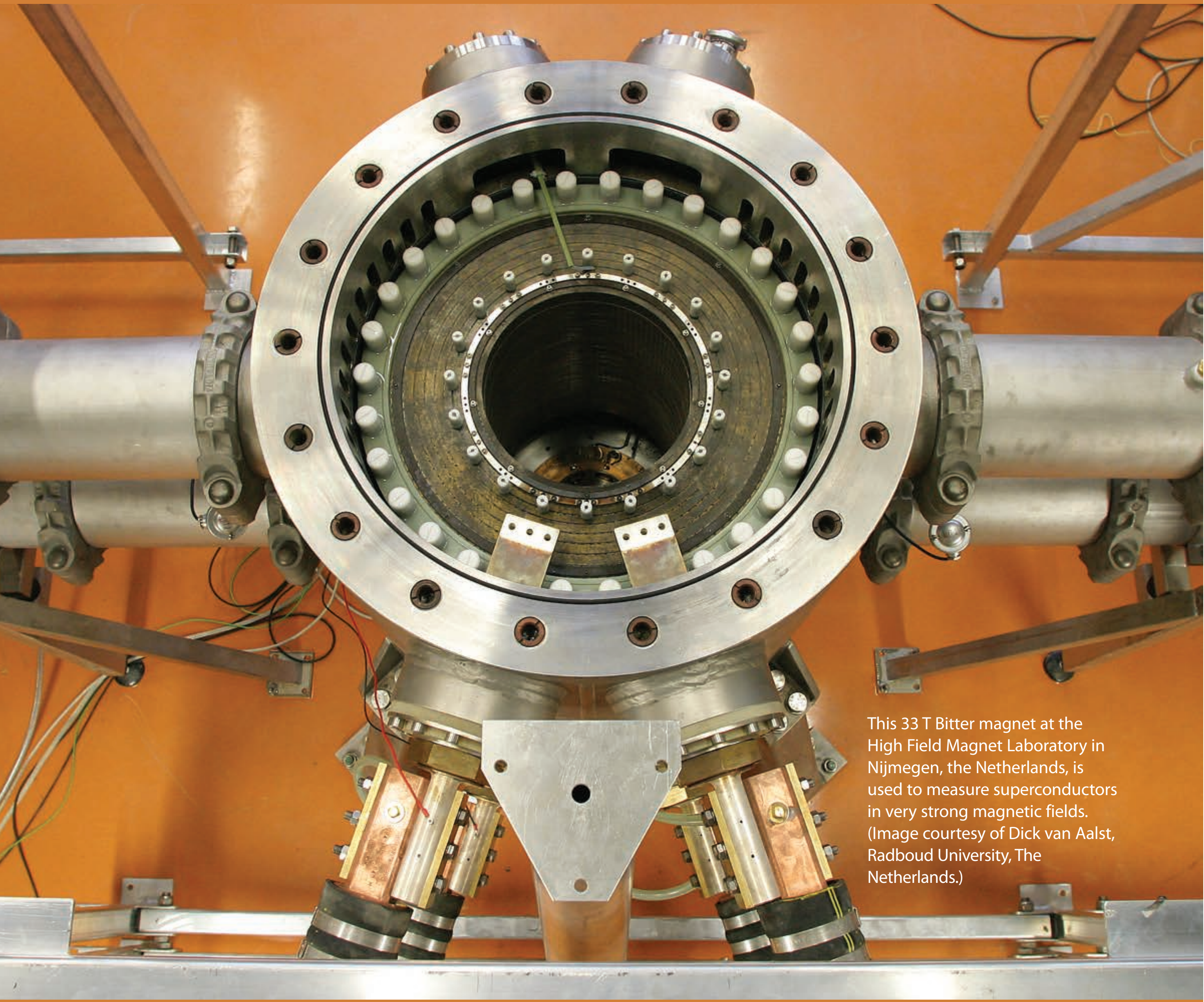

This 33 T Bitter magnet at the High Field Magnet Laboratory in Nijmegen, the Netherlands, is used to measure superconductors in very strong magnetic fields. (Image courtesy of Dick van Aalst, Radboud University, The Netherlands.)

Magnetic field–boosted SUPERCONDUCTIVITY

Anne de Visser is an associate professor at the Van der Waals–Zeeman Institute at the University of Amsterdam in the Netherlands.

Anne de Visser

Although a magnetic field gradually destroys the superconducting state in most materials, a small family of uranium compounds bucks the trend.

During his 1911 discovery of superconductivity Heike Kamerlingh Onnes made a simple observation: The electrical resistance of a metal—mercury in his experiment—dropped to zero below a critical temperature, T_c. (For a historical account, see reference 1 and the article by Dirk van Delft and Peter Kes, PHYSICS TODAY, September 2010, page 38.) Two decades later, in 1933, Walther Meissner and Robert Ochsenfeld discovered a second fundamental property of superconducting materials while they were investigating the magnetic properties of tin and lead. When the samples were cooled below T_c in a small magnetic field, the field was expelled from their interiors.

The Meissner effect is explained by screening currents that flow in a thin surface layer of a superconductor and produce a magnetic field that is directed opposite to the applied field. Therefore, the net magnetic field inside the superconductor is zero. With those two central properties—the complete loss of electrical resistance and the Meissner effect—at its heart, the phenomenon of superconductivity turned out to be a most difficult puzzle in condensed-matter theory. It wasn't until 1957, almost half a century after its discovery, that John Bardeen, Leon Cooper, and J. Robert Schrieffer developed the theory, now known as BCS, that resolved how it works. (See reference 1 and the article by Schrieffer, PHYSICS TODAY, July 1973, page 23.)

In the conventional BCS theory, lattice vibrations, or phonons, create an attractive interaction between electrons and bind them into so-called spin-singlet Cooper pairs. Composed of zero-angular-momentum states with spin-up and spin-down electrons, the pairs collectively lower the ground-state energy of the electron ensemble and form the superconducting condensate. The condensate is what gives rise to dissipationless transport. But the story does not end there.

Unconventional superconductivity

In the first 60 years after Kamerlingh Onnes's discovery, superconductivity research focused on materials that followed BCS behavior. Starting in the 1970s, though, superconductors were found that veered from that behavior.[2] Some of them, such as the Chevrel phases, borocarbides, and heavy-fermion superconductors, had a low T_c; others, such as the fullerenes, pnictides, and cuprates, exhibited a high T_c. More recently, metal hydrides at pressures up to 2 million atmospheres have brought the transition temperature to a record high of 250 K (see the article by Warren Pickett and Mikhail Eremets, PHYSICS TODAY, May 2019, page 52).

Some of those superconductors are genuinely unconventional. For example, in a conventional BCS superconductor below T_c, only the global phase symmetry of the wavefunction is broken; in an unconventional superconductor, spatial symmetry or time-reversal symmetry, or both, is broken as well.[3] The additional types of symmetry breaking allow exotic Cooper-pair states to emerge with finite angular momentum $L = 1$ (*p*-wave superconductivity) or $L = 2$ (*d*-wave superconductivity). Such unconventional superconductors have extraordinary properties: For instance, *p*-wave superconductors can sustain very strong magnetic fields, which is the topic of this article. *D*-wave superconductivity is found in the high-T_c cuprates, whose properties cannot be explained by BCS theory alone. The pairing mechanism is thought to be nonphononic,

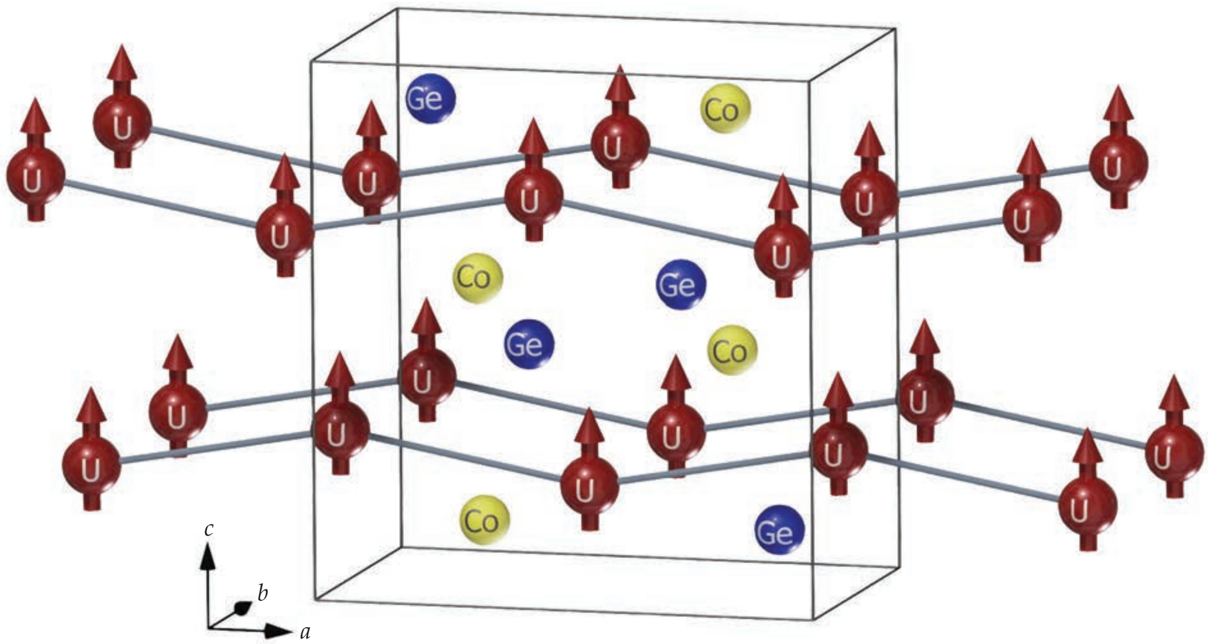

FIGURE 1. THIS VIEW OF THE CRYSTAL STRUCTURE of UCoGe shows the uranium atoms on zigzag chains. Red, yellow, and blue balls represent uranium, cobalt, and germanium atoms, respectively. The magnetic moments indicated by the arrows all point along the *c*-axis of the orthorhombic structure, an orientation that makes the magnetic structure uniaxial. Fluctuations of the moments along that direction are predicted to stimulate *p*-wave superconductivity. (Figure by Udo van Hes.)

and researchers are currently scrutinizing new theoretical scenarios that bear out that expectation.

An exceptional toolbox for probing unconventional superconductivity can be found in a small family of uranium-based metallic ferromagnetic compounds.[4] The first, UGe_2, was discovered by Siddharth Saxena and collaborators at Cambridge University in 2000. Dai Aoki and coworkers at the Atomic Energy Commission in Grenoble, France, reported a second, URhGe, one year later. And the third family member, UCoGe, was discovered by Nguyen Thanh Huy and colleagues at the University of Amsterdam in 2007. In all those compounds, the 5*f* electrons of the uranium atoms carry a magnetic moment. At high temperature, they are paramagnets—that is, the magnetic moments are oriented in random directions. However, they become ferromagnets below the transition temperature T_{Curie} of 53 K for UGe_2, 9.5 K for URhGe, and 3.0 K for UCoGe. Below T_{Curie}, the magnetic moments of each material point in the same direction and produce a net internal magnetic field.

In the BCS model, an internal magnetic field is incompatible with the Meissner effect, and it was long thought that ferromagnetism and superconductivity were competing ground states. The discovery of superconductivity in the three uranium-based ferromagnets below the Curie temperature was therefore unexpected. Those exceptions to the long-standing belief reveal an alternative route to explore in the field of superconductivity. Indeed, recent cutting-edge experiments that use nuclear magnetic resonance techniques[5] and strong magnetic fields[6] demonstrate that the superconducting condensate in those ferromagnets is unconventional.

As I explain in this article, the superconductivity involves spin-triplet Cooper pair states, which in their simplest form consist of two spin-up or two spin-down electrons or a linear combination of them. In a 2019 comprehensive review, Aoki, Kenji Ishida, and Jacques Flouquet collected compelling evidence that those pair states are mediated by quantum critical spin fluctuations rather than by the usual lattice vibrations.[7] Thus superconducting ferromagnets provide a rare case of superconductivity without phonons, an alternative route to superconductivity pioneered by Gilbert Lonzarich at Cambridge University.[8]

A peculiar order

Ferromagnetic order in these compounds has two special features that give rise to superconductivity. First, the magnetic order has a band character.[4] Prime examples of band ferromagnets are simple metals, such as iron, cobalt, and nickel. Band magnetism is caused not by the magnetic moments localized at atoms but by electrons occupying energy bands at the Fermi level. The exchange interaction splits the energy of electron states with different spins, which gives rise to an imbalance in the number of spin-up and spin-down electrons at the Fermi level. That imbalance produces a spontaneous magnetization associated with ferromagnetism.

In the case of band magnetism, it turns out that the Curie temperature and the ordered moment are highly tunable. For instance, in UCoGe, both the ordered moment $m_0 = 0.07\ \mu_B$/U-atom and $T_{Curie} = 3$ K are quite small and can easily be depressed[8] to 0 K by a moderate external pressure of 1.0 GPa. In UGe_2, an applied pressure[4] of 1.6 GPa suffices to reduce T_{Curie} from 53 K to 0 K. And for UTe_2, a recently discovered nearly ferromagnetic superconductor[9] with $T_c = 1.6$ K, T_{Curie} is already (accidentally) close to zero.

That proximity shows that those uranium-based alloys are close to a magnetic instability, a so-called quantum critical point on the phase diagram where T_{Curie} becomes 0 K. In the vicinity of such a critical point, quantum fluctuations of the order parameter—here, the magnetic moment—control the ground state. The band nature of the ferromagnetic order plays a pivotal role in triggering superconductivity. The energy bands at the Fermi level constitute the conduction bands that are involved in the superconducting state. Hence the same electrons that bring about ferromagnetism also produce superconductivity.

A second special feature of the materials lies in their orthorhombic crystal structure. In UCoGe, shown in figure 1, the U atoms form zigzag chains and their magnetic moments point in the same direction. Such magnetic order is called uniaxial. And its reduced dimensionality supports a special type of fluctuation in the magnetic moments along the moment direction, which favors superconductivity.[7]

An everyday, conventional superconductor, such as niobium, exhibits two distinct phases when exposed to a magnetic field, as shown in figure 2. If the field is small, Meissner currents on the surface screen the field from the material's interior. Above a certain critical field, called the lower critical field B_{c1}, the magnetic field starts to penetrate the superconductor in the form of flux lines, or vortices. Each vortex carries a quantum of flux $\Phi_0 = h/2e$, where e is the charge of an electron and h is Planck's constant. Because the flux lines repel each other, they arrange themselves on a triangular lattice—the well-known Abrikosov lattice—whose lattice constant a_Δ is proportional to $(\Phi_0/B)^{1/2}$. That second superconducting phase is known as the vortex, or mixed, state.

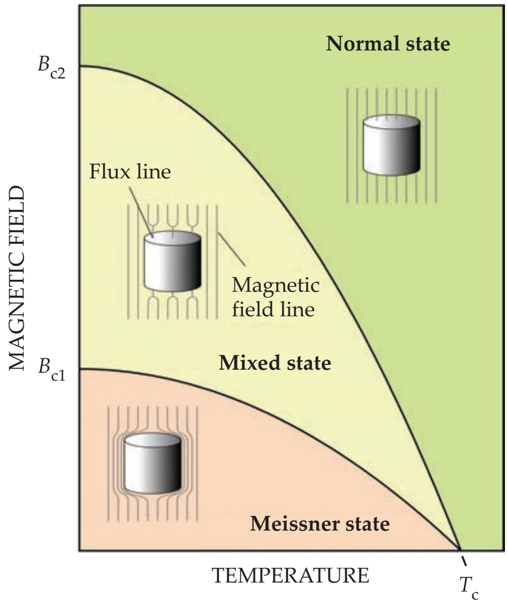

FIGURE 2. THE PHASE DIAGRAM OF A CONVENTIONAL BCS SUPERCONDUCTOR. In the Meissner phase, the magnetic field is expelled from the material's interior. In the mixed (or vortex) phase, the magnetic flux penetrates the material in the form of quantized vortices. In the normal phase, the magnetic field passes through the material uniformly. The fields B_{c1} and B_{c2} are known as the lower critical field and the upper critical field, respectively, and T_c refers to the superconductivity critical temperature. (Figure by Anne de Visser.)

By raising the magnetic field higher still, more vortices penetrate the material at the expense of superconducting regions until a_Δ becomes so small that the vortices eventually touch, at which point superconductivity disappears. That suppression field is called the upper critical field B_{c2}. For niobium, which has a T_c of 9.25 K, $B_{c1} = 0.17$ T and $B_{c2} = 0.40$ T. Measuring the upper critical field provides a way to determine the strength of the superconductor. In the limit where T goes to 0 K, $B_{c2}(0) = \Phi_0/2\pi\xi^2$, where the coherence length ξ is the distance over which the two electrons in a Cooper pair are bound together. A large value of $B_{c2}(0)$ implies a relatively small value of ξ and thus a strongly bound Cooper pair.

In a superconducting ferromagnet well below the Curie temperature, the electrons at the Fermi level team up into Cooper pairs and superconductivity sets in. Upon cooling the material in the absence of an external magnetic field, something peculiar happens: the spontaneous creation of a vortex lattice. The flux lines are produced by the weak internal magnetic field, which is caused by magnetic moments. The existence of such a self-induced vortex lattice implies that the Meissner effect is absent. When an external magnetic field is applied, it penetrates the superconductor in the form of the usual vortex lattice. Thus superconducting ferromagnets only have a mixed state.

Surprises in large fields

In superconductors, the temperature variation of the upper critical field $B_{c2}(T)$ is routinely measured. Normally, $B_{c2}(T)$ is a smooth, monotonous function that gradually drops to zero at T_c, as shown in figure 2. But in the case of superconducting ferromagnets, measurements of $B_{c2}(T)$ yield a surprise: Superconductivity is revived—that is, strengthened or reinforced by the magnetic field—and may persist up to the highest fields produced in the laboratory (see figure 3). In 2005, Florence Lévy and colleagues[6] found that in URhGe superconductivity is revived at fields between 10 T and 13 T. Four years later, Aoki and coworkers reported an exotic upward slant in the $B_{c2}(T)$ curve in UCoGe.[6] In that alloy, superconductivity strengthens above 6 T (in the form of subtly higher values of T_c) until it is again suppressed at 17 T. And this past year, Georg Knebel[10] and Shen Ran,[11] separately with their coworkers, discovered that T_c in UTe_2 suddenly increases above 16 T and that superconductivity survives up to a spectacularly high 35 T, above which it suddenly disappears.

It's important to note that very strong magnetic fields are required to completely suppress superconductivity. The $B_{c2}(0)$ values reached in figure 3 are much larger than one would expect in a conventional superconductor. To appreciate why, consider how the magnetic field interacts with the electrons of the Cooper pairs in a conventional spin-singlet superconductor. Figure 4 illustrates the situation schematically. The B field acts on the Cooper pair via the electrons' spin and charge. In the first case, presented in figure 4a, the field acts on the antiparallel spins of the electrons via the Zeeman effect. When the field is small, the antiparallel arrangement is unaffected and the spin-singlet state is stable. However, in a strong enough magnetic field, one of the spins flips and both spins then align with the field direction. At that point the spin-singlet Cooper pairs are broken and superconductivity is lost. The phenomenon is dubbed spin pair breaking.

The threshold field B^P where the pairs break is known as the Pauli limiting field,[1] and it's easy to show that $B^P(0) = 1.84 \times T_c$. That rule of thumb predicts the maximum critical magnetic field in which a spin-singlet superconductor may survive once T_c is known. The $B^P(0)$ values for UCoGe, URhGe, and UTe_2 are 0.5 T, 1.1 T, and 2.9 T, respectively, whereas the experimental $B_{c2}(0)$ values are 16 T, 14 T, and 35 T. The upshot is that $B_{c2}(0) > B^P(0)$ implies that the Cooper pairs cannot be of the spin-singlet type, but must instead be of the spin-triplet type. The spins of the two electrons in such Cooper pairs are parallel and cannot be broken by the Zeeman effect.

Besides bringing about spin pair breaking, the magnetic field acts on the momenta of paired electrons via the electron charge. As the magnetic field becomes larger, the resulting Lorentz force will eventually exceed the binding force between the two electrons and break the Cooper pair. That process, illustrated in figure 4b, is termed orbital pair breaking. Since the Lorentz force acts on the charge of the electrons but not their spin, orbital pair breaking will have a similar effect in spin-singlet and spin-triplet superconductors.

For a conventional spin-singlet superconductor, that behavior is well understood and captured by the Werthamer-Helfand-Hohenberg (WHH) model.[12] Its curve is a smooth function of temperature: In an applied field, T_c decreases and gradually drops to zero at the orbital critical field $B_{c2}^{orb}(T)$, as shown in figure 2. For most superconductors, $B_{c2}^{orb}(0) < B^P(0)$ and orbital pair breaking is the main reason that T_c is suppressed by the field.

The initial depression of T_c as a function of magnetic field for the three alloys shown in figure 3 is attributed to orbital pair breaking. But at higher fields, T_c is no longer depressed. Indeed, the revival of superconductivity in URhGe, the unusual upward slant in the B_{c2} curve for UCoGe, and the sudden increase of T_c in UTe_2 are at odds with the WHH model. That's mainly because an important parameter in the model—the electron–phonon coupling parameter λ_{ep}, a measure of the pairing strength—is a constant and does not depend on the magnetic field. But assuming a fixed value for λ_{ep} cannot lead to a revival of superconductivity in strong magnetic fields.

Spin fluctuations

In 2017 Beilun Wu and coworkers proposed an elegant solution to capture the revival of superconductivity.[13] They replaced λ_{ep} in the WHH model with a new field-dependent coupling parameter $\lambda_{sf}(B)$. By letting λ_{sf} increase in the magnetic field, which implies a stronger pairing interaction, T_c is increased. The subscript sf refers to spin fluctuations of the magnetic moments and reflects another important aspect of unconventional superconductivity in ferromagnets: The attractive interaction between electrons is mediated not by phonons but by spin fluctuations.

Magnetically mediated superconductivity has been a challenging research field in past decades, especially in the context of heavy-fermion superconductors and the high-T_c cuprates.[8] The reason is that close to the border of a magnetically ordered phase, the magnetic moments are not static but fluctuate in space and time. Those fluctuations can enhance the spin susceptibility, which also varies. The resulting dynamic, magnetic landscape—on the scale of tens of interatomic spacings—can induce, in special cases, an attractive potential and a binding force between neighboring electrons in the spin-triplet channel. If the interaction is strong enough to defeat the electrons'

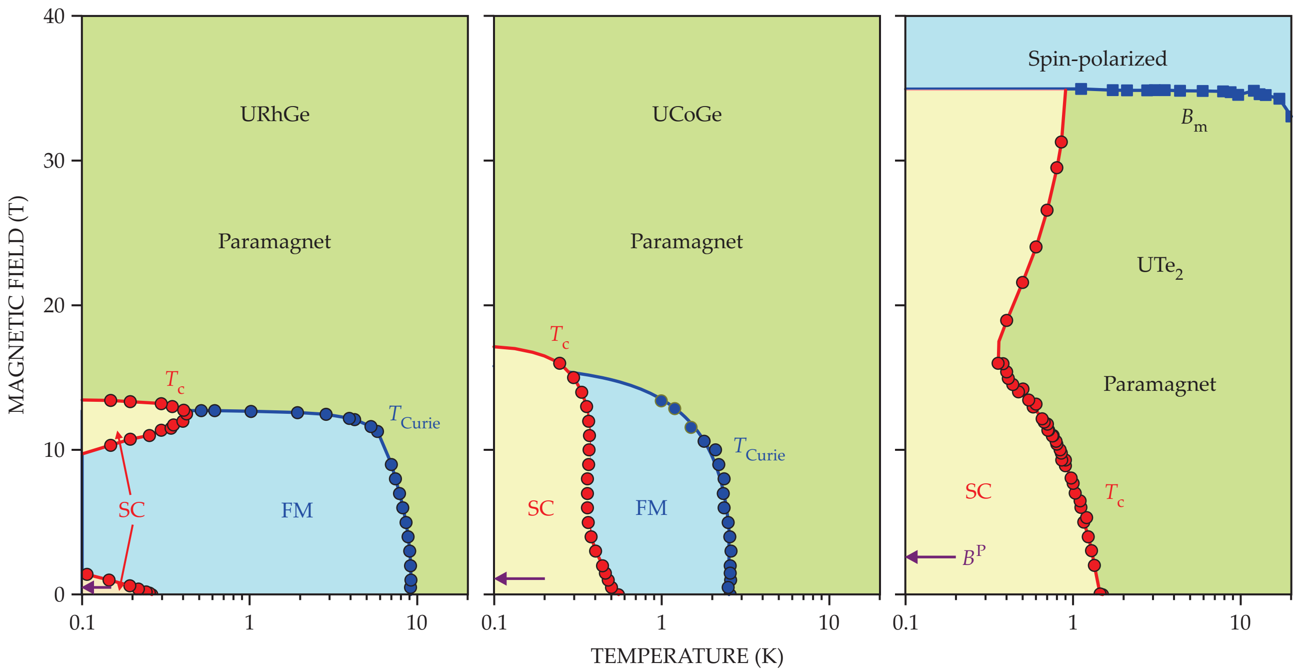

FIGURE 3. THE MAGNETIC FIELD–TEMPERATURE PHASE DIAGRAM OF THREE URANIUM-BASED ALLOYS. In these plots, the superconductivity (SC) phase is shown in yellow, the magnetic normal phase (FM or spin-polarized) is in blue, and the paramagnetic normal phase is in green. In URhGe (left), SC is revived between 10 T and 13 T. In UCoGe (middle) and UTe_2 (right), the superconducting critical temperature T_c (red dots) exhibits a pronounced upturn above 6 T and 16 T, respectively. SC persists for $B > B^P$, the Pauli-limiting field (purple arrows) at which spin-singlet Cooper pairs break apart. For URhGe and UCoGe, SC coexists with FM; the blue dots, which mark the Curie temperature T_{Curie}, delimit the border of the FM phase at which SC is strengthened by the abundance of spin fluctuations. For UTe_2, blue squares mark the transition to the spin-polarized phase above the metamagnetic transition field B_m. In all diagrams, the magnetic field is aligned along the *b*-axis, perpendicular to the direction of the magnetic moments. (Figure adapted from refs. 7 and 16.)

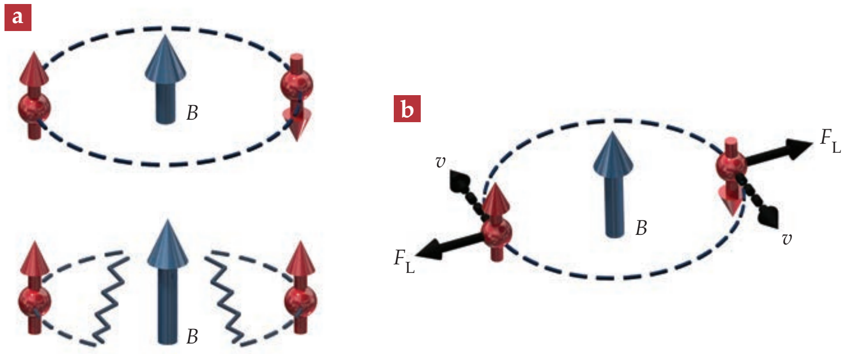

FIGURE 4. COOPER PAIR BREAKING, ILLUSTRATED. (a) In a small magnetic field B, the spins of the two electrons (red) in the Cooper pair are antiparallel (top). But in a large magnetic field, the electron spins will align due to the Zeeman effect and the pair breaks apart (bottom), a phenomenon known as spin pair breaking. **(b)** In orbital pair breaking, an applied magnetic field produces a Lorentz force F_L on two electrons with opposite momentum and velocity $\pm v$. When the magnetic field increases, the oppositely directed Lorentz forces eventually exceed the binding force of the electrons and the Cooper pair breaks. (Figure by Udo van Hes.)

Coulomb repulsion, Cooper pairs may form. Keep in mind that superconductivity here is driven by quantum fluctuations of the magnetic moments, and those fluctuations become most pronounced as the temperature approaches 0 K. An appealing way to induce magnetically mediated superconductivity is by tuning the magnetic ordering temperature to 0 K with hydrostatic pressure. That has been achieved[4] in UGe_2 with a modest pressure of 1.6 GPa.

Another way to push the border of a ferromagnetic phase to low temperatures is by field tuning the critical point T_{Curie}, an approach that was successfully achieved in UCoGe and URhGe. As the critical point approaches 0 K, the quantum-critical spin fluctuations at the magnetic phase boundary become more pronounced and revive the superconductivity. In the adapted WHH model, the intensity of the spin fluctuations is captured by the field-dependent coupling parameter λ_{sf}. The field variation of λ_{sf} can also be extracted from the normal-state properties, such as electrical transport and heat capacity. Spin fluctuations, which provide low-energy excitations, give an additional contribution to the low-temperature electronic heat capacity. Measurements of the heat capacity in a magnetic field confirm the direct link between the revived superconductivity and the strength of the ferromagnetic spin fluctuations.[13]

Magnetic-field direction

Magnetic field–boosted superconductivity is one of the most remarkable features of superconducting ferromagnets. But modeling new phenomena on the microscopic level is a great challenge, and no unifying model is yet at hand. For one thing, calculating λ_{sf} is notoriously difficult. All the current models use superconductivity stimulated by critical spin fluctuations at the border of a magnetic phase, but they differ in details.[7] An important ingredient in the models is the low dimensionality of the spin fluctuations along the direction of the magnetic moment (see figure 1). The uniaxial nature of the moments imposes a precise tuning of the magnetic field direction in single crystal samples. For UCoGe and URhGe, that tuning was demonstrated by magnetic-field angle-dependent transport measurements that probed the superconducting transition via electrical resistance.

Figure 5 illustrates those results in the case of UCoGe, as measured by Aoki and coworkers.[14] The critical field $B_{c2}(\theta)$ exhibits a sharp peak when the field angle θ aligns with either the a- or b-axis in the crystal. At either of those orientations, the magnetic field is perpendicular to m_0, which points along the c-axis. The strong reduction of B_{c2} when the magnetic field is not exactly aligned along the a- or b-axis confirms the uniaxial nature of the spin fluctuations, as any small component of the field along m_0 will relentlessly depress those fluctuations and hence superconductivity. For a field along the c-axis, $B_{c2}(0)$ amounts to just 1 T. On the microscopic scale, strong support for the key role of those spin fluctuations comes from NMR data.[5] When the field is applied along the a- or b-axis, pronounced longitudinal spin fluctuations along the c-axis stimulate superconductivity. But when the field is rotated toward the c-axis, the longitudinal mode is depressed, as is the superconductivity.

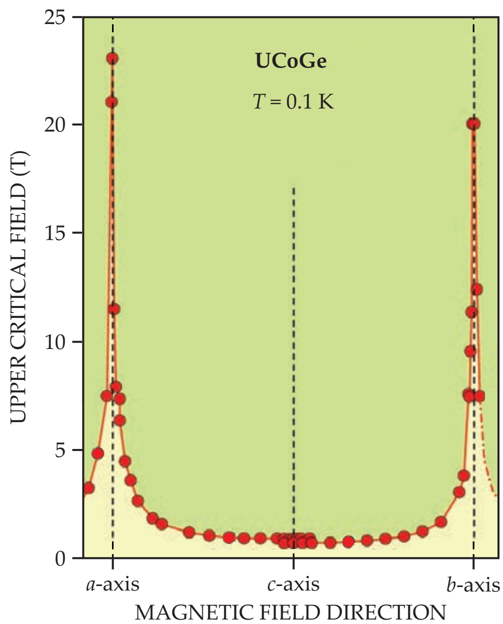

FIGURE 5. ANGULAR VARIATION OF THE UPPER CRITICAL FIELD B_{c2} of UCoGe at low temperature. When the field is aligned with the crystal's a- or b-axis, B_{c2} exhibits sharp peaks. As soon as the field is rotated toward the c-axis, the magnetic field–boosted superconductivity is suppressed. (Courtesy of Dai Aoki, adapted from ref. 14.)

The experimental phase diagrams of the uranium-based alloys differ in important details. UCoGe presents the simplest case. The magnetic phase boundary, $T_{Curie}(B)$, bends toward lower temperatures for fields above about 6 T. At the same time, superconductivity becomes stronger—that is, T_c increases, as shown in figure 3. That result is in line with the scenario of spin-fluctuation-mediated superconductivity sketched above. In URhGe, the magnetic phase boundary at low temperatures is due to a rotation of the magnetic moments at a field of 12.7 T. At that field, the accompanying spin fluctuations cause a revival of the superconductivity and a maximum in T_c.

For UTe_2, a different theoretical treatment might be required because long-range ferromagnetic order is absent. And yet a ferromagnet-like spin-polarized phase is induced above the metamagnetic transition field, $B_m = 35$ T. The alloy holds other surprises as well, such as a second revived superconducting phase, reported to exist in the range of 35–65 T for a field directed between the *b*- and *c*-axes,[11] and multiple superconducting phases that were observed under pressure.[15]

All in all, the discovery of the family of superconducting ferromagnets has led to momentous progress in our understanding of unconventional superconductivity, with magnetic field–boosted superconductivity its ultimate litmus test. An obvious question is, Are there any other family members? Researchers are also considering what their strategy should be to unearth new ferromagnetic superconductors. Evidently, the necessary ingredients include band ferromagnetism, uniaxial magnetic moments, and strong spin fluctuations in close proximity to a quantum critical point. Critical transition temperatures reported so far are so low that new experimental tests are needed down to those very low temperatures.

Unraveling the superconducting and magnetic parameters of such complex superconducting materials also necessitates their preparation in high-quality, single-crystal form. So far, all materials in the family contain the element uranium. That apparent requirement restricts the research to dedicated laboratory space. Nonetheless, researchers with new, creative ideas will undoubtedly succeed in adding new superconductors to the toolbox. The unforeseen marriage of superconductivity and ferromagnetism has already produced unprecedented discoveries that have found their place in modern textbooks. Many more are likely on the horizon.

I thank Udo van Hes for preparing figures 1 and 4 and Dai Aoki, Kenji Ishida, Jacques Flouquet, George Knebel, Jean-Pascal Brison, Daniel Braithwaite, Andrew Huxley, and Nick Butch for fruitful discussions.

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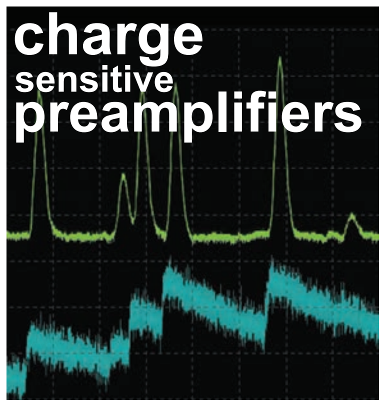

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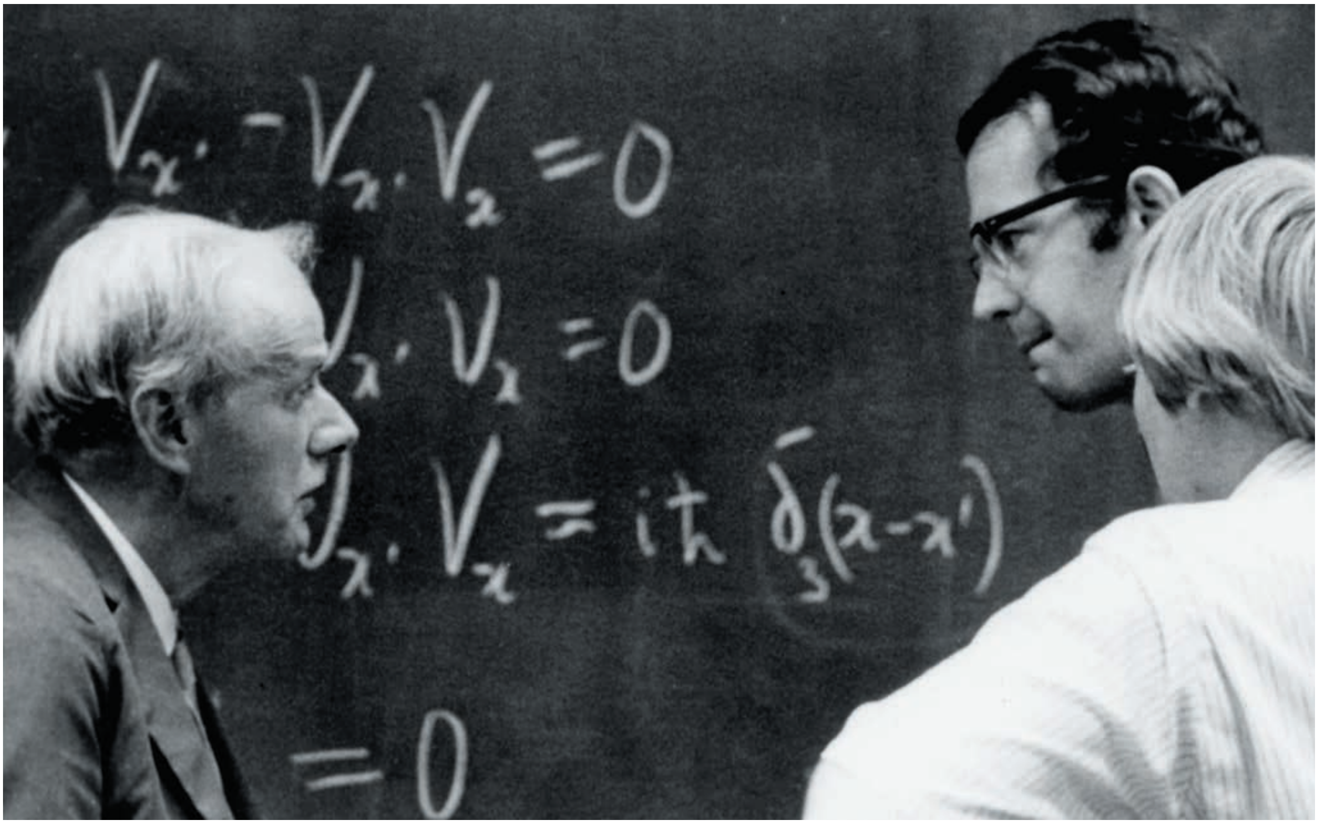


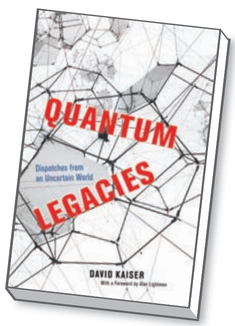
PAUL DIRAC, JOHN RAY, AND JACK HENEISEN discuss quantum mechanics in 1971.

More than a quantum chimera

Similar to oscillating neutrinos, MIT's David Kaiser is in a superposition of distinct academic states: Germeshausen Professor of the History of Science in the program in science, technology, and society; professor of physics in the physics department; and associate dean for social and ethical responsibilities of computing in MIT's Stephen A. Schwarzman College of Computing.

Kaiser's latest book, *Quantum Legacies: Dispatches from an Uncertain World*, illustrates the depth and range of his unique chimerical superposition. In 19 short vignettes, which represent a distinguished career of scholarship and popular science writing, Kaiser weaves a story of quantum mechanics that reflects his multiple vocational interests. He moves seamlessly from explaining his work as a particle cosmologist on ingenious Bell test experiments to tracing the history of the expression "the physicists' war."

Quantum Legacies
Dispatches from an Uncertain World
David Kaiser
U. Chicago Press, 2020. $26.00



Two decades after completing PhDs in both physics and the history of science, Kaiser has put together a thoughtful interdisciplinary investigation of the legacies of quantum mechanics. Although an edited volume with multiple authors might have offered more perspectives, Kaiser presents a work of coherence, accessibility, and rhetorical power not generally found in those volumes. The chapters in *Quantum Legacies* are organized, roughly by topic, into four parts: "Quanta," "Calculating," "Matter," and "Cosmos." But what makes the book stand out is how Kaiser weaves those topics together using three rhetorical threads: conceptual development, historical analysis, and reflective memoir.

Kaiser is a popular science writer with a clear command of his subject matter and deep pedagogical sensibilities. He deftly teaches a lay audience about the foundational quantum principles and paradoxes that have made the topic so exciting and perplexing over the past century. But he doesn't stop at the well-trodden foundations; Kaiser also introduces readers to more speculative cosmological theories, including multiverses. Those nontechnical, conceptual discussions run alongside insightful and probing historical analyses that reveal the inner workings of scientific practice.

The selected episodes in the history of quantum mechanics reveal the social and contingent nature of scientific research. Kaiser does not paint idealized caricatures of solitary scientific heroes toiling toward inevitable discovery. He instead creates nuanced portraits of scientists, such as Paul Dirac, carefully situated within their proper contexts and constrained by institutional and social forces. Kaiser's quantum actors are driven not by random fits of isolated inspiration but by conversation and collaboration with colleagues.

The final rhetorical thread running through the book is Kaiser's use of reflective memoir. He complements his conceptual and historical analyses with his experiences as a physics student and as a particle cosmologist. For example, readers are transported to the front lines of Kaiser's cosmic Bell collaboration with, among others, physicist Anton Zeilinger. Whether he's describing cosmic entanglement experiments in Vienna or the final data collection at the Roque de los Muchachos Observatory in the Canary Islands, Kaiser is fully immersed and infuses his narrative with firsthand accounts and expertise. His personal interjections are at times disarming; we see his vulnerability in asides about his twins, wife, sister, and mother. Overall, the use of memoir gives *Quantum Legacies* a refreshing sense of accessibility and legitimacy.

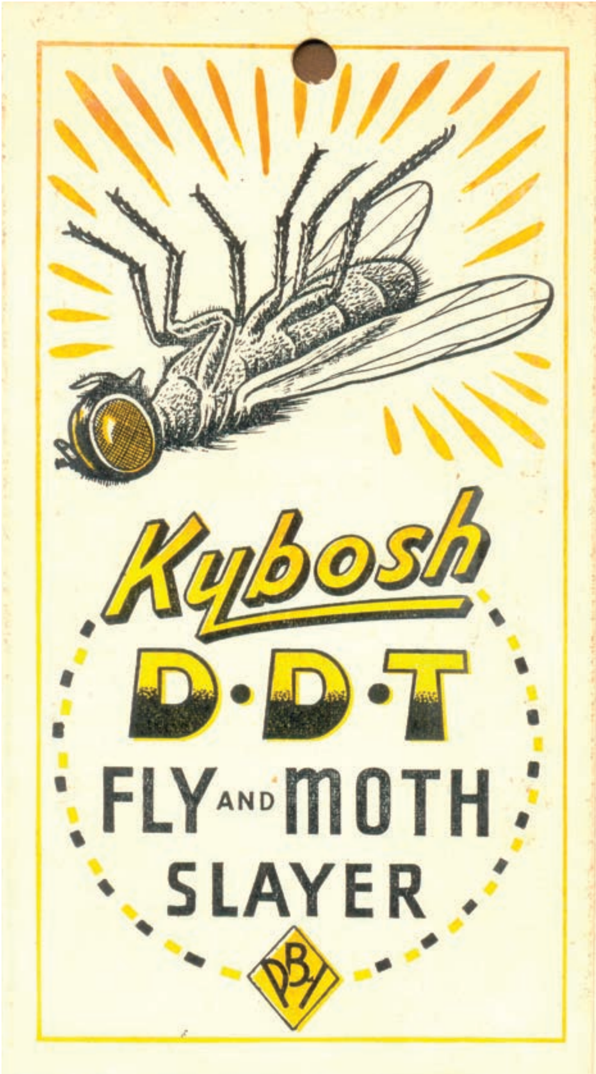
Those distinct threads help reinforce and articulate a rigorous examination of physics pedagogy and training in the context of evolving Cold War tensions. With exacting historical analysis, Kaiser tracks the shifting meaning of the phrase "the physicists' war." When it was first invoked by James Conant, the phrase referenced a "massive, urgent educational mission" to teach elementary physics to enlisted men. However, by the end of the war, the phrase evoked visions of heroic physicists taming nuclear energy and inventing radar. The spotlight made physicists vulnerable to political attacks during the McCarthy-era Red Scare, but it also drove an unchecked inflation in physics funding—and university course enrollments.

As "the cold war of the classrooms" escalated, a "'standing army' of physicists" was stockpiled like any other war commodity. Kaiser treats that physics inflation as a speculative bubble that eventually ruptured around 1970, briefly re-formed as a secondary bubble in the 1980s, and then ruptured again at the end of the Cold War. In subsequent discussion, he illustrates the uneven impact of those speculative cycles on physics textbooks, pedagogy, creation of subfields, scientific institutions, and the scope and effectiveness of physics research.

Kaiser has woven together a unique, compelling, and kaleidoscopic portrait of the quantum revolution and its implications. He doesn't hide from the messiness of science but embraces the challenge of understanding its underlying human and social conditions. The book isn't perfect; Kaiser repurposes some shorter essays that appear analytically thin. For example, the account of LIGO's detection of gravitational waves seems to me a missed opportunity to reveal the institutional dynamics and intrigue surrounding the observatory's history and funding. But in the context of the whole book, that criticism is a quibble. Students in my quantum seminar this fall will certainly be grappling with *Quantum Legacies*.

José G. Perillán
Vassar College
Poughkeepsie, New York

AMORET TANNER COLLECTION/ALAMY STOCK PHOTO



A MID-20TH-CENTURY advertisement for DDT emphasizing its potency.

The two faces of modern chemistry

The Chemical Age
How Chemists Fought Famine and Disease, Killed Millions, and Changed Our Relationship with the Earth

Frank A. von Hippel
U. Chicago Press, 2020. $29.00

Are we living in the Anthropocene? Enduring the atomic age? Or weathering the next major extinction event? There is no shortage of terms to describe our environmental present. The term "Anthropocene" first entered the English vocabulary in 2000, at the suggestion of atmospheric scientists Paul Crutzen and Eugene Stoermer. Twenty years later, scholars continue to devise names for our current era of unprecedented environmental change. Environmental historian Jason Moore recently coined the phrase "Capitalocene" to emphasize industrial capitalism as the primary cause of environmental degradation, whereas journalist Elizabeth Kolbert has given our era the morbidly apt moniker of the "Sixth Extinction."

Biologist Frank A. von Hippel adds to the abundance of neologisms in *The Chemical Age: How Chemists Fought Famine and Disease, Killed Millions, and Changed Our Relationship with the Earth*, which highlights the roles that chemists played in public health campaigns, warfare, and environmental transformation from the mid 19th century to the present. Although not explicitly defined, the titular "Chemical Age" nevertheless captures the widespread application of chemistry to real-world problems and the related belief that chemistry can solve them. Von Hippel reprises for a popular audience the familiar story of technological optimism and its unintended consequences; his text is a welcome addition to the growing corpus of environmental histories.

A professor of ecotoxicology by day, von Hippel aims to promote scientific literacy and environmental consciousness among the general public. *The Chemical Age* builds on the author's penchant for environmental activism. Its strongest chapters are those that adhere most closely to its motivating theme: chemistry's promise and peril. The book is full of tragic characters like German-Jewish chemist Fritz Haber, who developed a class of insecticides later used by the Nazi regime for genocidal purposes. Von Hippel also highlights chemists complicit in environmental harm, such as the less well-known Thomas Midgley, who developed leaded gasoline in an effort to improve automobile engines. His invention inadvertently polluted the atmosphere with lead.

The role of chemistry itself as a tragic character comes across most clearly in the author's discussion of DDT. Once heralded as a magic bullet for malaria and typhus, a boon to agriculture, and a necessity for suburban living, DDT was synonymous with environmental degradation by the early 1960s. That attitudinal change occurred largely because of marine biologist Rachel Carson, whose 1962 book *Silent Spring* depicted the environmental consequences of indiscriminate pesticide use. As Carson's warnings provoked widespread debate about pesticide safety, chemical companies mobilized to discredit her claims. Their gendered critiques of Carson's "emotional" tone and their pleas to present "both sides" of the controversy resonate strongly with contemporary environmental politics and make von Hippel's analysis both incisive and timely.

Readers interested in the history of chemistry must approach the book with patience. *The Chemical Age* is divided into four sections. The first two discuss the Irish Potato Famine and several epidemic diseases, including malaria, yellow fever, typhus, and the bubonic plague. In each case, the author meticulously reconstructs dominant theories of disease transmission at the time and follows scientists' efforts to identify pathogens, but he only briefly mentions chemical prophylactics and cures. Those appear in a much later chapter discussing the use of synthetic chemicals like DDT and atabrine to curb malaria transmission during World War II.

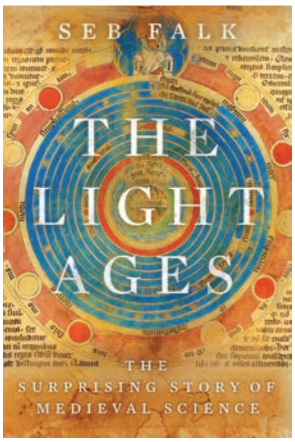
The chemical age began during the age of late imperialism, and chemical cures did not universally benefit the global population. As von Hippel puts it, they often underpinned "nineteenth- and twentieth-century imperial ambitions." European states relied on anti-malarial drugs to colonize African nations in the 19th century. Similarly, the US depended on a steady supply of quinine to extend its influence into the Panama Canal Zone.

As von Hippel reconstructs imperial public health campaigns, he frequently quotes colonial officers' frustrations that colonized people would not cooperate with directives. Those passages would benefit from further context. Chemistry and imperialism intersected during military invasions, to be sure, but they also intersected in the day-to-day exercise of imperial power, which forced uncertain chemical cures on indigenous people and used the language of public health to support claims of racial difference. By glossing over those elements, the author misses an opportunity to show the Janus face, or two sides, of modern chemistry, so crucial to the book's argument, and to credit those who resisted its incursions into their daily lives.

Likewise, the author misses the mark when discussing chattel slavery and mosquito-borne illnesses. He twice remarks that West Africans' moderate immunity to illnesses like malaria and yellow fever "ensured" their enslavement at the hands of plantation owners, but he makes no mention of factors like racial ideologies or Euro-American profit motives. As more scholars look to scientific disciplines for perspectives on history, they should be wary of focusing too narrowly on chemical and biological causation and thus diminishing the role of human agency and responsibility. When we speak of the chemical age, we inevitably speak about synthetic molecules. But we should also look with a critical eye at those who wielded them, their motives, and the effects of their choices. In its analysis of modern environmentalism, von Hippel's monograph fulfills that task. *The Chemical Age* is a timely exploration of our environmental present.

Alison McManus
Princeton University
Princeton, New Jersey

NEW BOOKS & MEDIA



The Light Ages

The Surprising Story of Medieval Science

Seb Falk

W. W. Norton, 2020. $30.00

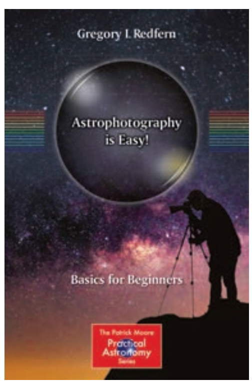
Claiming that Dark Ages is a misnomer, Cambridge University science historian Seb Falk says that the Middle Ages saw the development of numerous scientific achievements. In *The Light Ages*, Falk takes the reader on a "journey through medieval science" as experienced by a 14th-century monk named John Westwyk, who trained at St Albans monastery in the UK. While not much is known about him, other than that he annotated at least two astronomy texts, Westwyk serves as a jumping-off point for a discussion of medieval and monastic life and advances in astronomy. Falk illustrates how those astronomical developments were applied in such areas as religious practices, timekeeping and the calendar, weather forecasting, navigation, and agriculture. –CC

Astrophotography Is Easy!

Basics for Beginners

Gregory I. Redfern

Springer, 2020. $27.99 (paper)



True to its title, this comprehensive how-to book tries to cover everything a novice astrophotographer needs to know: cameras, lenses, and telescopes; imaging methods, mountings, and software; and techniques and tips for capturing such celestial objects and events as the Sun, Moon, stars, eclipses, and auroras. Gregory Redfern draws on his more than four decades of experience as an astrophotographer to provide key guidance to even the most rank amateur and launch them on a lifetime of celestial exploration. An extensive list of reading material and internet links supplements the text. –CC

Space Stations in Action

An Augmented Reality Experience

Rebecca E. Hirsch

Lerner, 2020. $31.99

Part of Lerner's Space in Action: Augmented Reality series, *Space Stations in Action* is a 21st-century pop-up book aimed at readers in grades 3–6. Focusing on the International Space Station (ISS), it features not only images from NASA, Roscosmos, and the European Space Agency but also four augmented-reality experiences, which require a cell phone or tablet and the Lerner AR app. When the handheld device is waved over the designated icon, a 3D interactive image appears, such as one that allows 360-degree views inside different parts of the ISS. The text, written by science writer Rebecca Hirsch, discusses the history of space stations, the ISS, and what it's like to live and work there. –CC PT

Massachusetts Institute of Technology

Faculty Positions

The Department of Nuclear Science and Engineering (NSE) at the Massachusetts Institute of Technology (MIT), Cambridge, MA, invites applications for faculty positions starting July 1, 2021 or on a mutually agreeable date thereafter.

The Department is a world leader in the generation, control and application of nuclear reactions and radiation for the benefit of society and the environment. NSE faculty educate and conduct research in fields from fundamental nuclear science to practical applications of nuclear technology in energy, security and quantum engineering. We are seeking exceptional candidates broadly engaged in these areas. All candidates who demonstrate excellence in the multidisciplinary landscape of the department's research and education areas will be considered. These areas include, but are not limited to: **advanced modeling, simulation, and theory of complex nuclear systems; integrated design for nuclear fission energy systems; advanced thermal hydraulics; radiation sources and technology; nuclear security; plasma physics and fusion engineering; materials for extreme environments; and quantum computing, engineering and control.** See http://web.mit.edu/nse/. The search is for candidates to be hired at the assistant professor level; under special circumstances, however, an untenured associate or senior faculty appointment is possible, commensurate with experience.

We welcome applications from a wide range of disciplines, including **nuclear engineering, physics, chemistry, materials science, mechanical engineering, computational science and engineering, environmental engineering, and electrical engineering.** However, a commitment to excel in teaching in the Department is essential. Faculty duties will include teaching at the graduate and undergraduate levels, research, and supervision of graduate students. Applicants must have a doctorate in an Engineering or Scientific field relevant to research in the Department by the beginning of employment, and must have demonstrated excellence in research and scholarship in a relevant technical field.

Applications are being accepted electronically at https://faculty-searches.mit.edu/soe/nse/. Each application must include: a curriculum vitae, the names and addresses of three or more references, a two-page strategic statement of research interests, a one-page statement of teaching interests, and electronic copies of no more than three representative publications. In addition, candidates must provide a statement regarding their views on diversity, inclusion, and belonging, including past and current contributions as well as their vision and plans for the future in these areas. Each candidate must also arrange for three or more reference letters to be uploaded electronically.

Recognizing MIT's strong commitment to diversity in education, research and practice, minorities and women are especially encouraged to apply.

Applications received before January 31, 2021 will be given priority.

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Focus on lasers, imaging, and microscopy

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

Andreas Mandelis

Intensified sCMOS neutron cameras

According to Photek, its N-Cam incorporates the latest neutron-imaging technology. The intensified neutron camera system significantly reduces image-acquisition time while maintaining excellent spatial resolution. With a gadolinium oxysulfide layer directly applied to the image intensifier, the N-Cam simultaneously provides greater sensitivity and excellent spatial resolution and yields fast integration times and a high signal-to-noise ratio. It features gating down to 50 ns, which improves precision for time-of-flight energy-specific imaging. The standard N-Cam comes with a 4.2 MP cooled sCMOS camera and a 75-mm-diameter field of view capable of high-speed or energy-specific radiography and tomography with greater than 10 line pairs/mm resolution. Applications include neutron radiography; computed tomography; and dynamic, energy-specific, and stroboscopic imaging. ***Photek USA LLC**, 313 W Liberty St, Ste 256, Lancaster, PA 17603, www.photek.com*

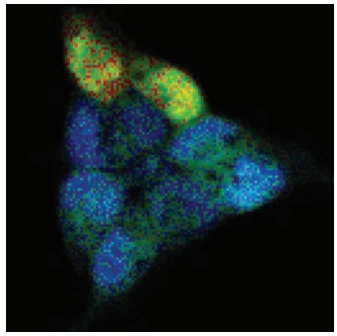
Turnkey frequency combs

Vescent has unveiled its FFC-100 erbium-based fiber frequency comb. At its heart is the company's MLL-100 mode-locked laser, which features a passive semiconductor saturable absorber mirror. Designed for longevity, it delivers sub-100 fs seed pulses to a highly nonlinear fiber for supercontinuum generation. For long-term stability, the company locks f_{CEO} and f_{opt} of its octave-spanning comb, which will support the requirements of the next generation of optical clocks. Fitting into a 2U 19-inch rack-mount chassis, the FFC-100 features more than 30 mW of power in the supercontinuum spectrum, factory-matchable repetition rates to better than 5 kHz, and high-bandwidth control over repetition rate. It is a suitable source for multicomb spectroscopy, low phase noise RF generation, frequency ruler work, and more. ***Vescent Photonics LLC**, 14998 W 6th Ave, Ste 700, Golden, CO 80401, www.vescent.com*

Nanolithography software

Park Systems has added new software to the Park SmartScan operating system for its atomic force microscopes (AFMs). Park SmartLitho is a next-generation technology that controls nanolithography processes via a user-friendly interface. Objects can be easily drawn, resized, and moved by manipulating a mouse, and bitmap images can be imported for raster and vector nanolithography. Using Park SmartLitho, a bias-assisted nanopatterning of complicated structures can be readily produced by locally oxidizing the surface of a silicon wafer and switching ferroelectric domains of a lead zirconate titanate film. A high-voltage mode allows the AFM system to be connected to an external voltage amplifier so experiments or measurements can use a tip or sample bias exceeding the normal ±10 V nanolithography mode. SmartLitho also produces vector nanolithography, crucial for today's advanced circuit designs and structures. Applications for SmartLitho include the creation of integrated circuits and parts for semiconductor device circuit technologies. ***Park Systems Inc***, *3040 Olcott St, Santa Clara, CA 95054, https://parksystems.com*

Fast fluorescence lifetime imaging



PicoQuant developed rapidFLIM$^{\text{HiRes}}$ to combine rapid data acquisition speed and high time resolution in visualizing dynamic processes in cells or tissue. RapidFLIM$^{\text{HiRes}}$ can be used to study fast processes such as protein interactions, Förster resonance energy transfer dynamics, ion fluxes, and quickly moving species. It enables imaging of samples at up to 15 fps with a time resolution of 10 ps. RapidFLIM$^{\text{HiRes}}$ overcomes the limitations of classic FLIM, which is based on time-correlated single photon counting (TCSPC). Instead, the new imager uses hardware that includes hybrid photomultiplier detectors that can handle count rates of about 78 Mcps and the MultiHarp 150 4P TCSPC module with four parallel detection channels. Memory management and processing time in the SymPhoTime data-acquisition and analysis software have been improved, and correction algorithms reduce decay-curve distortions due to very high count rates and artifacts of the detector pulse pileup. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

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       Average* 11 794 August** 10 233
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       Average* 71 593 August** 63 955
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       Average* 10 167 August** 12 032
    F. *Total distribution (sum of C and E)*
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       Average* 1 319 August** 245
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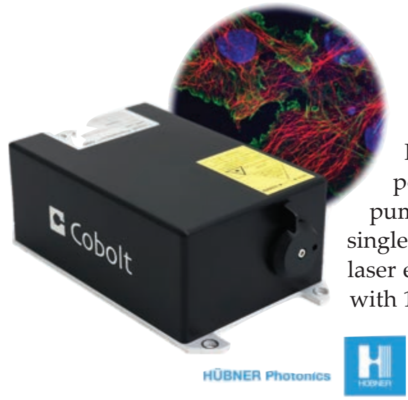
NEW PRODUCTS



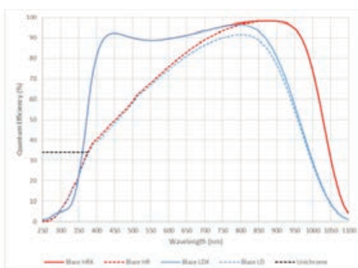
CW diode-pumped 640 nm laser

Hübner Photonics has introduced the Cobolt Rogue 640 nm laser. The multimode, high-power Cobolt Rogue series of CW diode-pumped lasers complements the Cobolt 05-01 single-frequency series. The Cobolt Rogue 640 nm laser emits in multiple longitudinal TEM_{00} modes with 1 W of output power and spectral half width less than 150 GHz. It is suitable for super-resolution and fluorescence microscopy, flow cytometry, and DNA sequencing. All Cobolt lasers are manufactured using proprietary HTCure technology; according to the company, the resulting compact, hermetically sealed package improves the laser's reliability and performance under varying environmental conditions. ***Hübner Photonics Inc****, 2635 N 1st St, Ste 202, San Jose, CA 95124, https://hubner-photonics.com*

Digital laser modules

ProPhotonix has expanded its PROdigii digital laser module range by five wavelengths at output powers up to 500 mW. The new wavelengths allow the company to offer digital laser solutions for additional applications: The 375 nm PROdigii digital laser is suitable for UV curing and fluorescing. There are two wavelengths in the blue range, a 405 nm digital laser appropriate for 3D printing and particle measurement and a 450 nm laser module suitable for spectroscopy. The 905 nm and 940 nm IR digital lasers can be used in robotics, gesture recognition, and lidar applications. The compact, high-performance PROdigii laser modules are available with a uniform-line, elliptical-spot, or diffractive pattern. According to the company, the configurable lasers offer straightforward integration into most systems, high wavelength stability, and excellent thermal management in challenging environments. ***ProPhotonix Ltd****, 13 Red Roof Lane, Ste 200, Salem, NH 03079, www.prophotonix.com*

Fast, high-sensitivity CCD cameras



To meet the needs of cutting-edge scientific research, Teledyne Princeton Instruments has increased the wavelength coverage of its Blaze models HRX and LDX spectroscopy CCD cameras. At −95 °C, the Blaze CCD cameras can achieve greater than 90% quantum efficiency at 450 nm, 98% at 900 nm, and 75% at 1000 nm and can maintain high frame rates and low dark current. For broad wavelength coverage (190–1100 nm), the Blaze also comes with Unichrome coating. Improvements are attributed to the addition of the company's eXcelon technology to the Blaze models' sensors, which provides highly sensitive spectroscopic imaging coverage across a broad spectrum. With dual-port, high-readout speeds of 16 MHz and ultralow noise, the Blaze spectroscopic cameras are suitable for applications such as pump–probe experiments, new materials research, Raman spectroscopy, and small-animal imaging. ***Teledyne Princeton Instruments****, 3660 Quakerbridge Rd, Trenton, NJ 08619, www.princetoninstruments.com*

Flat-field diffraction grating

A new flat-field diffraction grating improves the efficiency and range of McPherson's model 251MX soft x-ray spectrometer for measurements of deep-UV and vacuum-UV radiation and emission spectra with subnanometer spectral resolution. Designed to minimize astigmatism and coma, flat-field concave grating grooves are neither parallel nor equidistant. With a digital camera and adjustable slits, the 251MX now works from less than 1 nm up to more than 200 nm (5 eV to 1500 eV). The newly mastered gold-coated diffraction grating is suitable for work from 50 nm to 200 nm. With aberration correction and a flat-field spectrum, the optical system is suitable for use with direct-detection CCD or microchannel-plate-intensified detectors. The 251MX can be used in such fields as plasma physics and astrophysics and in such applications as spectral test and calibration, attosecond-pulse and high-harmonic laser generation, and extreme UV lithography semiconductor source and process development. ***McPherson Inc***, *7A Stuart Rd, Chelmsford, MA 01824, https://mcphersoninc.com*

Self-optimizing Raman imaging microscope

The second generation of WITec's alpha300 apyron automated Raman imaging microscope features AutoBeam technology that enhances its optical, analytical, and operational capabilities and improves automation and user-friendliness. Because of AutoBeam's optomechanical components, which can be configured to create the optimal experimental setup for every investigation, the alpha300 apyron can self-align and self-calibrate; less user input eliminates potential sources of error. Other new functionalities provided by AutoBeam modules include polarization-dependent measurements with motorized polarizer and analyzer rotation, push-button spectrometer connection and signal maximization, and automated adjustment of both iris diaphragms. ***WITec Instruments Corp***, *130G Market Place Blvd, Knoxville, TN 37922, www.WITec-Instruments.com*

Ultrathin vibration-isolation platform

Minus K designed its CT-2 to be the thinnest low-frequency-vibration passive isolator for micro- and nanomicroscopy. Its negative-stiffness isolation aims to minimize the low-frequency vibrations that can be problematic for sensitive instrumentation, particularly at the nanometer level, without involving compressed air or electricity. Operating purely in a passive mechanical mode, the tabletop unit delivers ½ Hz vertical and ~1½ Hz horizontal natural frequencies—better vibration-isolation performance at low frequency than air tables and active systems, the company claims. With no motors, pumps, or chambers, there is nothing to wear out and no maintenance, and the small size—just 2½ inches high—mitigates space constraints. Besides various microscopy techniques—including scanning probe, scanning electron, and atomic force—the CT-2 can be used in laser, optical, biological, and neuroscience systems and in applications such as microhardness, nanoindenter, and spacecraft ground testing. ***Minus K Technology Inc***, *460 Hindry Ave, Unit C, Inglewood, CA 90301, www.minusk.com* PT

Thomas B. Sanford

Physical oceanographer Thomas B. Sanford died from heart failure on 12 July 2020 in Seattle, Washington. He was an innovative scientist who pioneered a suite of measurement techniques that use motional electromagnetic induction and have revealed new facets of ocean physics. For his contributions, Tom was awarded the American Meteorological Society's Henry Stommel Research Medal in 2010 and the US Navy's SECNAV/CNO Chair of Oceanographic Sciences in 2008.

When Michael Faraday lowered electrodes into the river Thames in 1832, he doubtless thought he was ushering in a new era of fluid-transport measurements. But the inventor of the electric motor and discoverer of electromagnetic induction was mistaken. His equipment had limited sensitivity and the conducting riverbed reduced the amplitude of the motional signal, so Faraday's measurement did not in fact quantify the river's flow.

Later experimenters verified that seawater flowing through Earth's magnetic field produced voltages that could be measured using electrodes attached to submarine telegraph cables or towed behind a ship. But the interpretation of those measurements continued to present challenges and provoke disagreements until Tom's 1967 PhD thesis, "Measurement and interpretation of motional electrical fields in the sea." Tom's theory correctly determined the appropriate simplifications for geophysical flows and the different interpretations of voltage measurements from fixed, towed, drifting, or vertically falling platforms. That enabled the exploration of the vertical, horizontal, and temporal structure of the ocean velocity field on which he built his career.

Born on 22 April 1940 in Toledo, Ohio, Tom received his bachelor's in physics from Oberlin College in 1962 and his PhD from MIT in 1967 under William von Arx. Undaunted by the fact that previous generations had essentially given up on getting anything useful from motionally induced voltages, Tom set out to build the instruments that would reestablish geomagnetic induction as a viable tool and uncover a wealth of dynamical processes in the ocean. He did that work first at the Woods Hole Oceanographic Institution and then at the University of Washington's Applied Physics Laboratory.

Tom's theory and careful experimental methods in 1969–75 led to the establishment of submarine cable monitoring of the Florida Current—the headwaters of the Gulf Stream and a key component of the North Atlantic Gyre circulation. His work resulted in what is now one of the longest continuous time series of ocean transport.

With the free-falling electromagnetic velocity profiler, Tom and engineers Robert Drever and John Dunlap set out in the late 1960s to measure the electrical signals from vertical gradients of horizontal water velocity as small as 1 mm/s over a few meters of depth. They realized that the instrument required a sensitivity of 40 nV, a difficult challenge for an autonomous instrument then. Tom's success in decomposing the profiles into oppositely polarized spirals, sometimes called the oceanographer's double helix, revealed the predominantly downward propagation of internal waves, as expected from wind forcing at the surface. In collaboration with one of us (Gregg), Tom built a composite velocity and microstructure profiler that established a widespread relationship between internal wave shear and turbulence. That relationship underpins our current understanding of how vertical mixing occurs in most of the ocean interior.

Although customized instruments were Tom's specialty, he also wanted his motional induction techniques to help the broader oceanographic community. The adaptation of his profiler to a low-cost expendable format enabled multiple groups in the 1990s and 2000s to use it for surveys of internal waves, eddies, and energetic dense gravity currents that form in intermediate and deep waters of the world's oceans. Subsequent air-deployable versions captured the intense upper-ocean response to hurricanes. In 2004 Tom's group added velocity-measurement and air-deployment capabilities to robotic profilers that could send data ashore via satellite. They have now been used in long-duration studies; in hostile and remote environments, including under tropical storms and Antarctic ice; and in concentrated swarms to simultaneously capture spatial and temporal variability.

Thomas B. Sanford

Tom's innovations continued unabated. In 1995, for example, he used a fixed magnet and a set of electrodes in a vertical plane to quantify the horizontal vorticity of the flow; that work led to a new characterization of boundary-layer stress and its scales. In 2008 Tom developed a controlled-source electromagnetic sounding device for remote measurement of the conductivity profile in the water column. And his motional induction transport instrument was incorporated in 2014 into a seafloor fiber-optic network for real-time telemetry of ocean variability.

Even after retiring in 2015, Tom continued to work on new projects. Most recently he was developing creative approaches to analyze autonomous-profiler data; that paper will be published posthumously.

Tom's work was always highly collaborative, and he inspired his team of engineers to use unorthodox problem-solving approaches and create truly novel devices. He was a gracious contributor of observational data and insight to fellow scientists across the US and the world; he often let students and collaborators take first authorship on papers describing his best results. And he worked tirelessly to pass on his wisdom to others, including at least 23 students in their graduate and postdoctoral work. He will be sorely missed.

James B. Girton
Michael C. Gregg
University of Washington
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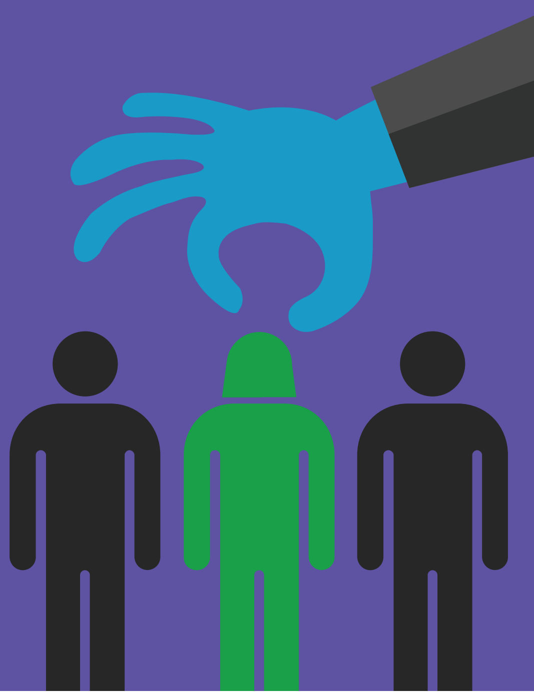

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PHYSICS TODAY | JOBS

Adam Fortais is a doctoral candidate studying the physics of soft matter at McMaster University in Hamilton, Ontario, Canada.

Soft electronics with liquid-metal veins

Adam Fortais

Deformable circuits whose resistance changes when stretched could set the stage for bio-inspired robots and soft tactile logic devices.

Over time, nature can improve the effectiveness of its designs with adaptations that produce uniquely functional organs. Examples abound: our eyes, skin, nerve networks, and brain, all of which are built entirely from soft tissue. Despite the ubiquity of such organs, creating similarly smart robots that are also robust and deformable is an engineering challenge. Evolution transforms soft tissues into the functional organs of thriving organisms. Unfortunately, engineers aren't given millions of years to refine their work. Instead, a common approach is to look to nature for inspiration.

Take the octopus, for example. Its eight strong, deformable arms are capable of complicated and independent tasks, such as capturing prey and opening jars while remaining coordinated and untangled. Indeed, research has shown that the animal can even respond to stimuli—and by some accounts capture and deliver prey to a location where its mouth would be—even after being decapitated. That behavior is possible because the majority of the octopus's neurons are distributed throughout its arms, which allows it to sense and react locally.

A lot can be learned by trying to replicate the octopus's features. By sensing and responding to stimuli locally, robots could simplify more difficult tasks, such as balancing mammal-like on feet or slithering snake-like across a desert, while reducing the computational load on central processors needed to decipher visual cues, make decisions, and store memories.

However, distributing sensors and actuators throughout a synthetic device can be complicated. Electronics and wires are usually bulky and stiff, and replicating the nervous system of an organism may require covering a robot's entire surface. But what if a robot could sense and respond to stimuli locally while remaining deformable and adaptive to its environment? This Quick Study explores one approach researchers are following to make just such devices.

Liquid-metal veins

An octopus's adaptability comes largely from its ability to deform elastically. Because of recent advances, it's now possible to create thin and flexible sensors that connect wirelessly to a computer. Used in medicine, they can be applied to patients' skin like a bandage—in some cases adhering via van der Waals forces alone—flexing with a patient's movement and increasing comfort (see PHYSICS TODAY, May 2019, page 16). Even so, flexible sensors may still not be as deformable and adaptable as human skin or an octopus's arm. For electronics to mimic all the deformation modes of an animal, they need to be soft and stretchable in addition to being thin and flexible.

To appreciate the distinction between flexible and stretchable, consider aluminum foil. Because it is only 0.01–0.02 mm thick, foil is easily bent and crumpled, but it cannot stretch without permanently deforming. Soft polymers like silicone have been used as the base of some electronic devices for years now—just as a silicon wafer is the base for computer chips. But polymers are typically insulators, and incorporating wires and solid-state electronics in a deformable system isn't easy (see PHYSICS TODAY, March 2017, page 14).

Engineers have proposed other approaches, such as reformulating the polymer's composition. By blending carbon nanotubes, liquid-metal droplets, or some other conductive particles into the elastic material, microscopic conductive wiring can form through a process called percolation (see PHYSICS TODAY, October 2008, page 18). Including a high enough concentration of conductive particles in the polymer produces winding channels that allow electrical current to travel through its bulk. Although such systems are promising for some applications, they don't conduct electricity as well as traditional wiring. What's more, the polymer's elasticity drops when the particles are added.

This past year a different approach was proposed by a re-

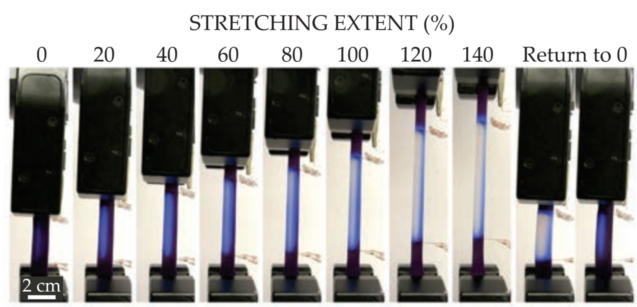

FIGURE 1. THERMO/MECHANOCHROMISM. Stretching a liquid-metal-filled polymer wire narrows its width and thus its electrical resistance. Photographs of the stretched wire reveal the concomitant Joule heating as a color change—from purple to white—as current is held constant but current density rises. In the two panels on the far right, the wire returns to its original shape and resistance. (Image adapted from Y. Jin et al., *Nat. Commun.* **10**, 4187, 2019.)

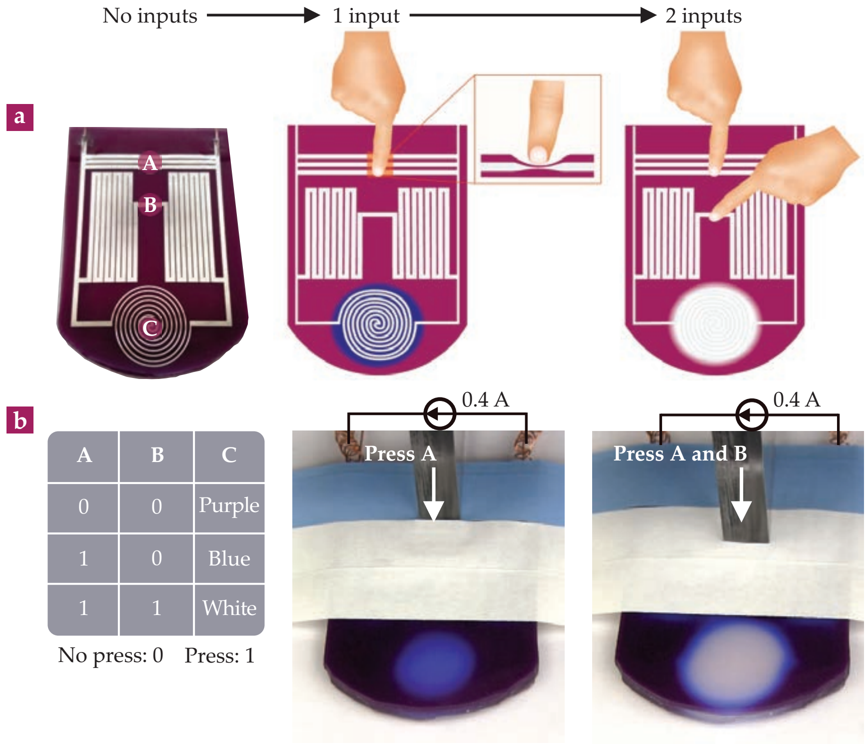

FIGURE 2. THIS LOGIC GATE is made from liquid metal embedded in pigment-treated polymer wires. **(a)** Regions A and B are pressure sensors, and C presents the visual response to truth-table options. **(b)** Responses depend on whether A and B are pressed (1) or not (0). The resistance in the compressible wires connecting A and B determines which color appears at C. (Figure adapted from Y. Jin et al., *Nat. Commun.* **10**, 4187, 2019.)

search group led by chemical engineer Michael Dickey from North Carolina State University. The group paired a metal alloy made of gallium and indium that is liquid at room temperature (above 15.7 °C) with a soft skeleton made of polydimethylsiloxane (PDMS)—the chemical equivalent of bathtub caulk. The liquid metal allows current to flow through the polymer, just as it would flow through a circuit. But unlike a conventional wire, the alloy's liquidity allows the veins to stretch and twist with the PDMS they're embedded in.

That design did not come without complications, as changing the shape of the conducting veins altered the resistance of the wire. However, the variable resistance turned out to be useful in both sensing stimuli and providing local responses. The researchers demonstrated a simple device that could perform logical operations independent of a central processor. In that sense, much like an octopus arm, the device straddled the line between computer and soft robot.

Tuning resistance through shape

When an elastic band is stretched in one direction, it contracts in the other to conserve volume. That principle also extends to other types of deformations, such as bending and compressing, and to materials, such as polymers and metals. Stretching a liquid-metal wire makes it thinner, increases its electrical resistance, and thus increases the power dissipated by a constant current. The power dissipation leads to local heating, and that Joule heating is how Dickey and coworkers observed the change in resistance in their liquid-metal wires.

By measuring the local heating as a wire is deformed, the researchers determined the resistance along it. The trick was to incorporate a temperature-sensitive pigment into the PDMS and monitor the change in color as a stand-in for temperature, and thus resistance, in the elongating region. It's possible to tune devices by adjusting the initial resistance, so that the color change happens at a particular strain. Figure 1, which illustrates the idea, shows a current-carrying liquid-metal-filled PDMS strip stretching up to 140% of the polymer's natural length before being allowed to relax. Higher resistance, and thus temperature, along the strip caused the pigment to fade to white.

Thinking by feel

Some simple computers can be built exclusively with Boolean operations, which apply conditional statements to a set of inputs in a truth table and return a true or false response. For example, the output of an AND operation yields "true" if both inputs are true and "false" if either (or both) of them are false. Although deformation-sensitive veins are capable of continuous changes in resistance, they can also be used to carry true or false signals by controlling the resistance at different locations, as shown in figure 2.

Pressing A or B will increase the resistance at those points and redirect current into C, which is observed as a change in either temperature or color. The device can take two inputs and create one of three responses, independent of any processor. Although the device's output is limited to color, many materials expand, contract, or change their shape in response to heating. Combining certain materials can create many mechanical feedback loops. Imagine the foot of a robot, whose skin could sense and respond to changes in pressure. As the robot moves or the ground shifts, tiny adjustments could be made to the foot to stabilize the robot's balance. The result is not a robotic octopus, but by combining our understanding of solid-state electronics with soft materials, we could soon be seeing devices approach the capabilities of the organic ones that nature already makes.

Additional resources

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▶ P. Ehrlich, J. Reed, dir., *My Octopus Teacher*, Netflix (2020).
▶ F. Angelini et al., "Decentralized trajectory tracking control for soft robots interacting with the environment," *IEEE Trans. Robot.* **34**, 924 (2018).
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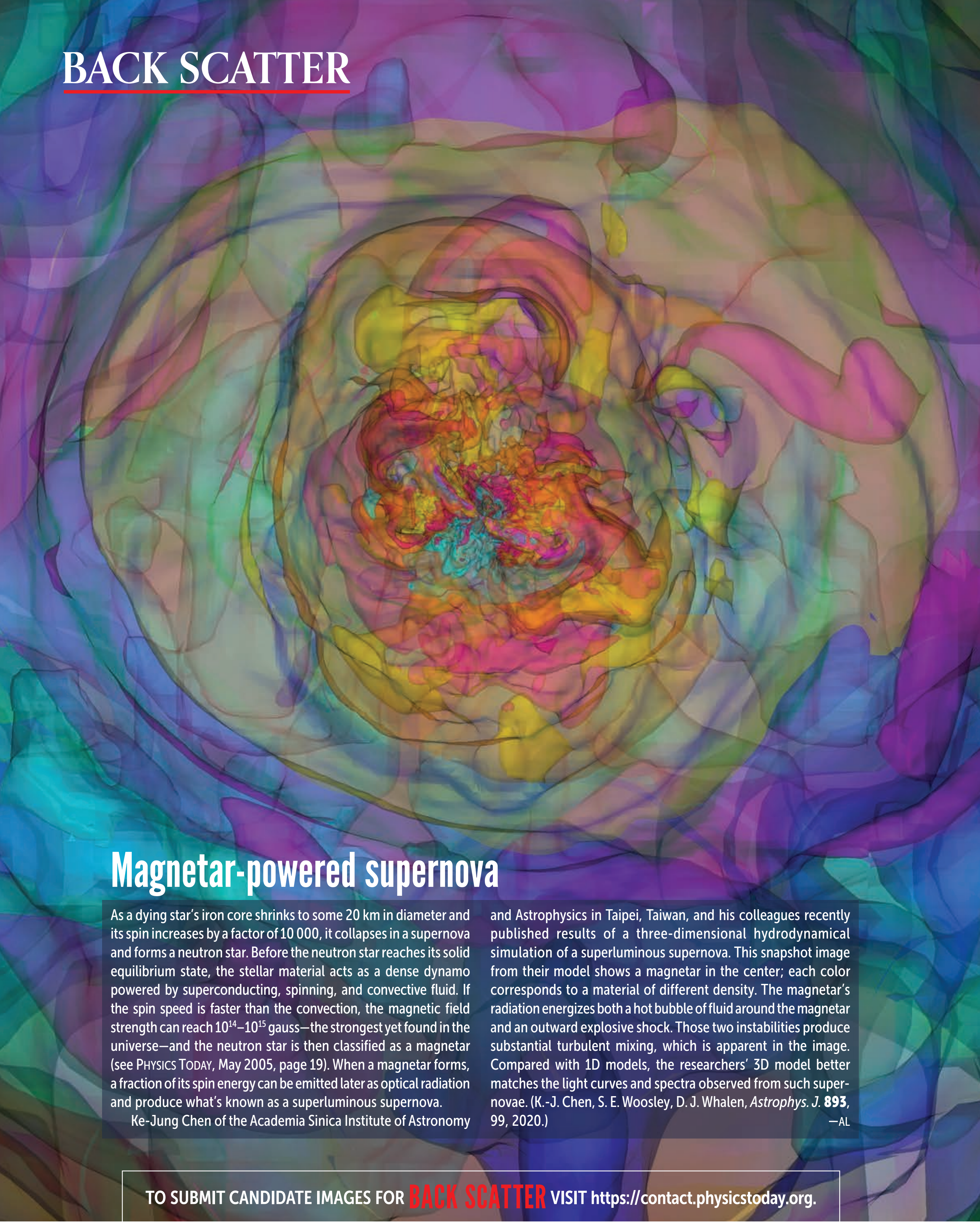

Magnetar-powered supernova

As a dying star's iron core shrinks to some 20 km in diameter and its spin increases by a factor of 10 000, it collapses in a supernova and forms a neutron star. Before the neutron star reaches its solid equilibrium state, the stellar material acts as a dense dynamo powered by superconducting, spinning, and convective fluid. If the spin speed is faster than the convection, the magnetic field strength can reach 10^{14}–10^{15} gauss—the strongest yet found in the universe—and the neutron star is then classified as a magnetar (see PHYSICS TODAY, May 2005, page 19). When a magnetar forms, a fraction of its spin energy can be emitted later as optical radiation and produce what's known as a superluminous supernova.

Ke-Jung Chen of the Academia Sinica Institute of Astronomy and Astrophysics in Taipei, Taiwan, and his colleagues recently published results of a three-dimensional hydrodynamical simulation of a superluminous supernova. This snapshot image from their model shows a magnetar in the center; each color corresponds to a material of different density. The magnetar's radiation energizes both a hot bubble of fluid around the magnetar and an outward explosive shock. Those two instabilities produce substantial turbulent mixing, which is apparent in the image. Compared with 1D models, the researchers' 3D model better matches the light curves and spectra observed from such supernovae. (K.-J. Chen, S. E. Woosley, D. J. Whalen, *Astrophys. J.* **893**, 99, 2020.)

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