PHYSICS TODAY

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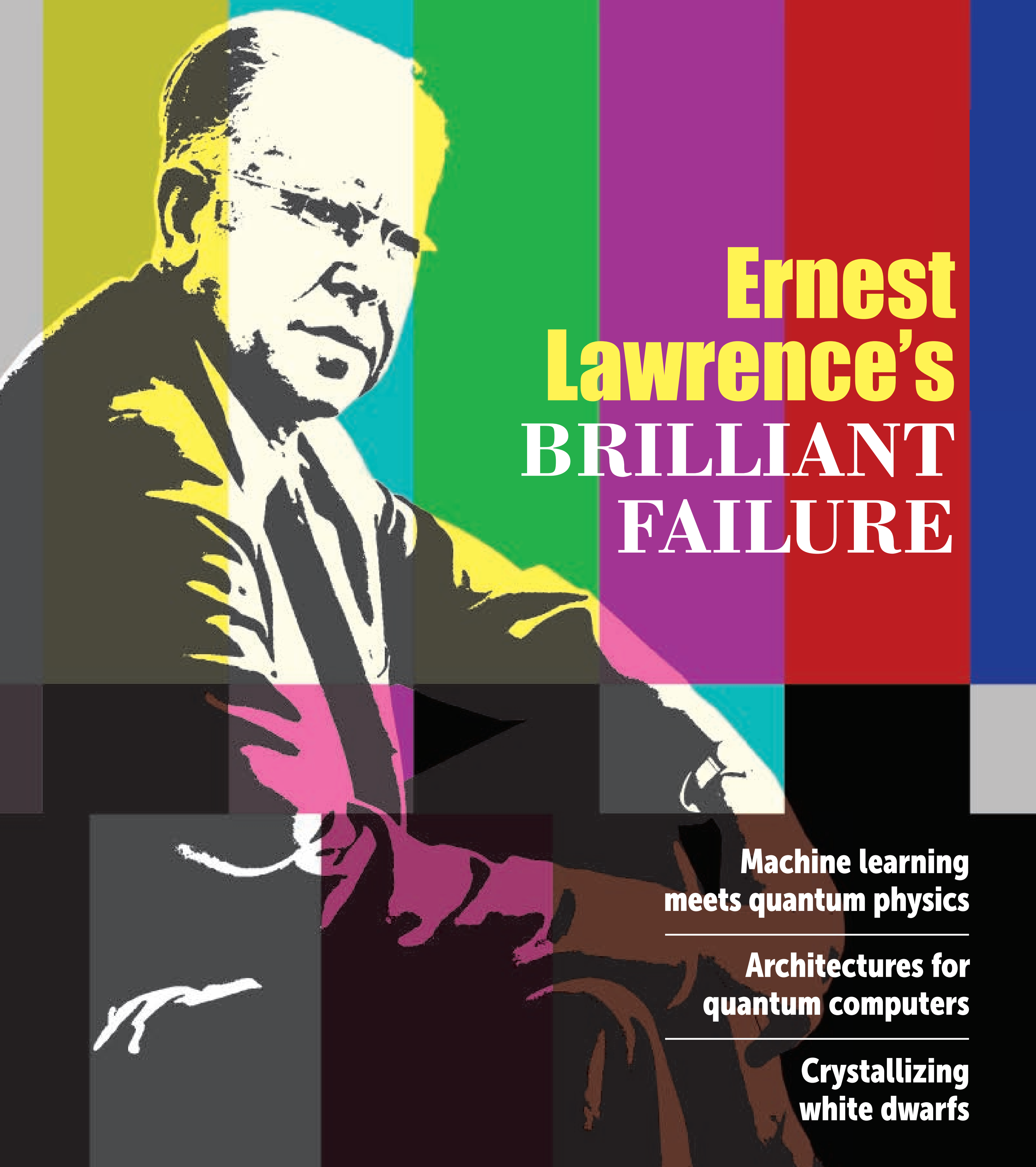

Ernest Lawrence's BRILLIANT FAILURE

Machine learning meets quantum physics

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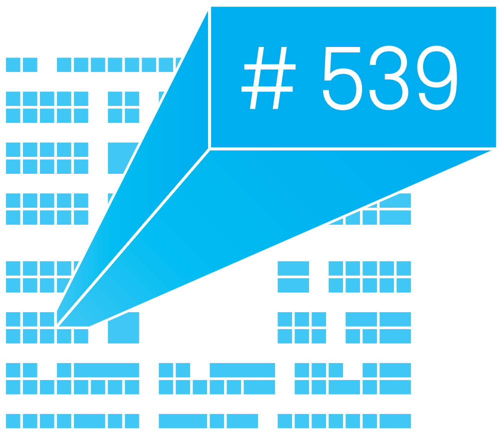

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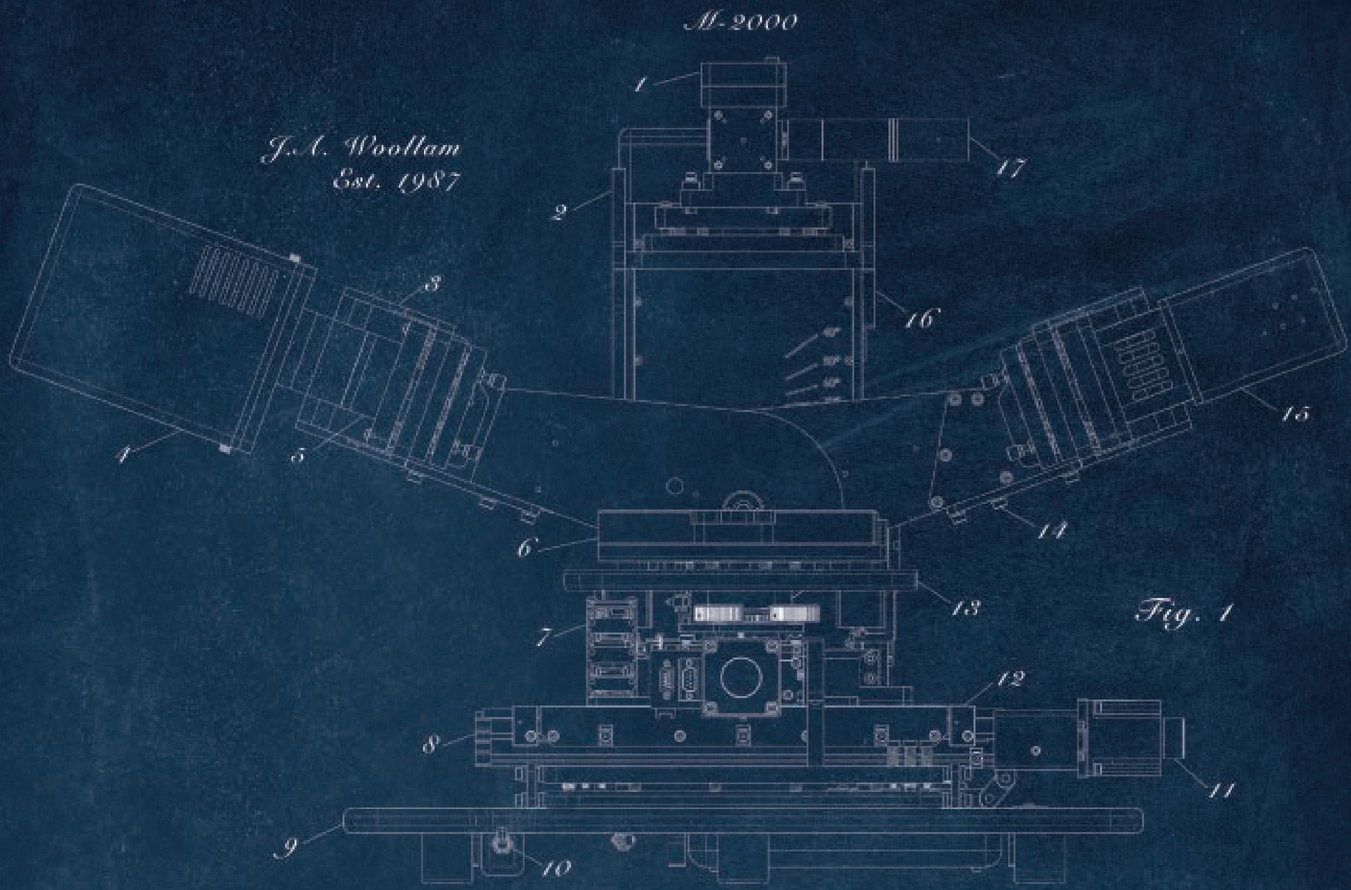

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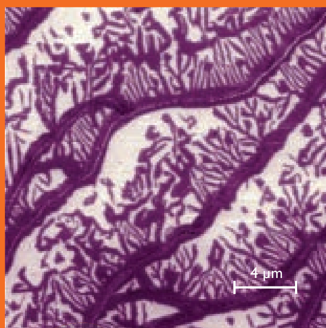

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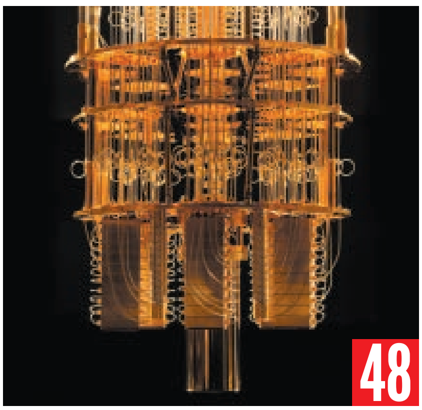
March 2019 | volume 72 number 3



FEATURES

ON THE COVER: Ernest Lawrence (1901–58) was awarded the 1939 Nobel Prize in Physics for his development of the cyclotron. But in the 1950s, Lawrence thought he would be remembered for another achievement: the development of color television. On **page 32**, Joshua Roebke explores the birth, growth, and eventual failure of Lawrence's television company. (Photo © 2010 The Regents of the University of California, Lawrence Berkeley National Laboratory.)

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NASA

▶ *Hubble* bias

The allocation of observing time on the *Hubble* telescope is a competitive process that, based on recent statistics, is not without gender bias. In response, the Space Telescope Science Institute established dual-anonymous review last year. Priyamvada Natarajan and Lou Strolger explain how it works and share the promising first results.

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▶ Physics in Africa

Launched in 2010, the African Physical Society has struggled to gain momentum as a force for the physical sciences on the continent. In a commentary, South African physicist Nithaya Chetty encourages the society to simplify its structure and focus on adding value to existing programs rather than replicating efforts.

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REAGAN WHITE HOUSE

▶ The UK and Star Wars

Despite its public support at the time, the British government had serious doubts about the US Strategic Defense Initiative, recently declassified documents show. Historian Aaron Bateman highlights the opposing approaches of the US and UK in integrating science and technology into national security policymaking.

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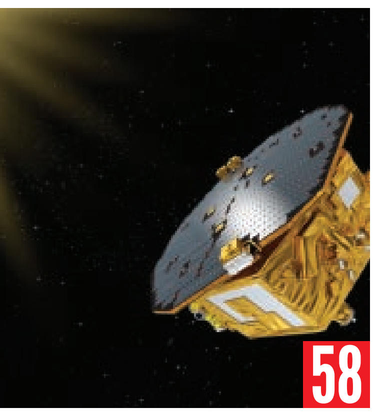

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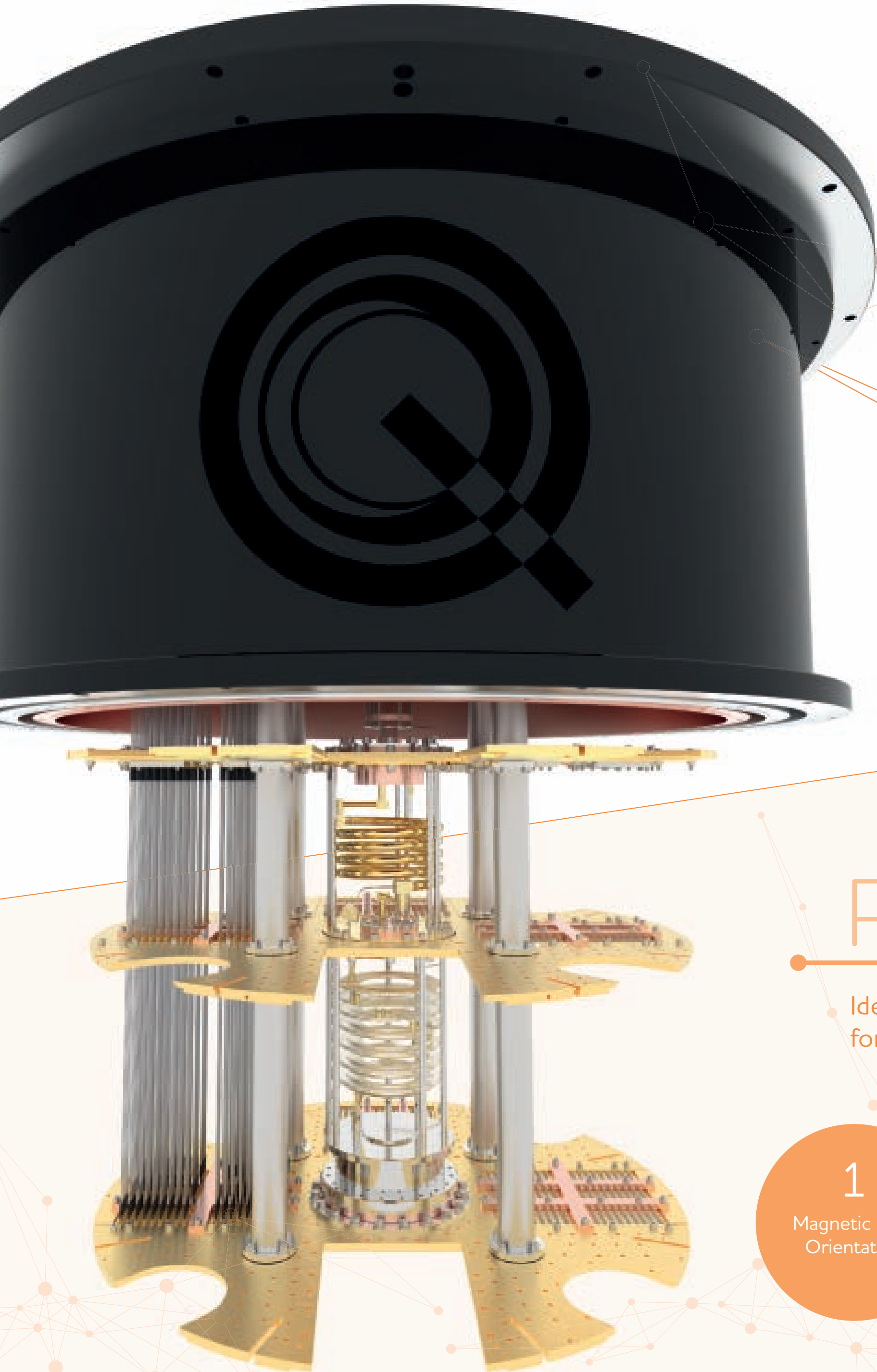

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FROM THE EDITOR

Let's talk about BL Lac objects!

Charles Day

When I was an astronomy graduate student, I heard a talk that mentioned a class of luminous variable galaxies called BL Lac objects. The name comes from the archetype of the class BL Lacertae. Audience members more versed in astronomical lore than I was would have recognized what the name entails, even if they were unfamiliar with BL Lac objects themselves. *Lacertae* is the genitive of *lacerta*, which is the Latin for "lizard," the constellation where BL Lac resides. "BL" designates the object as a variable star. That's because when Cuno Hoffmeister first observed BL Lac's variability in 1929, he thought he had discovered a variable star.

BL Lac objects are not the only confusingly named celestial bodies. Planetary nebulae have nothing to do with planets. Quasistellar objects are not like stars at all. It might be fun to mock astronomers for sticking with original names, but the rest of physics also has terms that, while not outright misleading, are not as helpful to students as they could be.

The constant that characterizes the strength of the electromagnetic interaction has a name—the fine-structure constant—that says little about its role to someone encountering it for the first time. On the contrary, "fine structure" suggests a refinement rather than something fundamental. Also confusing is the chemical potential as applied to condensed-matter physics, which is where I first encountered the term. What does a change in free energy when electrons are added or removed have to do with chemistry? Talking of chemistry, in my high school I learned that valence electrons are the outermost ones that participate in chemical bonding. Later, in an undergraduate physics class, I learned that a semiconductor's valence band lies beneath, not above, its conduction band.

BL Lac objects form one species in a zoo of active galaxies. Other species include Seyfert 1 and Seyfert 2, radio-loud and radio-quiet, blazar and quasar, and LINER and OVV. In the 1980s, when I first became acquainted with the zoo, astronomers were beginning to realize that some differences among the various species are a matter of viewing angle. The luminous plasma that swirls around a supermassive black hole looks different if you view it askance through an accretion disk or directly from above the disk. Although schemes to unify active galaxies remain incomplete, they nevertheless can simplify how we think of them—and, potentially, how we name them.

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The jeweled lacerta (*Timon lepidus*) inhabits southwestern Europe.

You might think I'm in favor of banishing antiquated and confusing names. I'm not, but with one proviso: If you're teaching physics and get to the part of your lecture when you first mention the fine-structure constant, don't just write the alpha on the blackboard and recite the name. Tell your students about its history and why it has the name it does.

In 1887 Albert Michelson and Edward Morley measured the spectrum of the hydrogen atom with unprecedented precision. They observed a splitting, a "fine structure," that remained puzzling until Arnold Sommerfeld extended Niels Bohr's treatment of the hydrogen atom to include special relativity and elliptical orbits. The name fine-structure constant reflects the crucial role of atomic spectroscopy in the development of quantum mechanics in the early 20th century.

Also potentially confusing (or at least unenlightening) is astronomers' tendency to give a group of seemingly similar things the same name until they find examples that aren't similar enough, in which case they introduce type I, type II, type III, and so on. Superconductors were initially classified in a similar way. In the case of supernovae, the first two types were identified when their optical spectra began to be routinely measured in the 1930s. Spectra that lacked hydrogen lines were denoted type I, and those with them, type II. Later, astronomers came to realize that the different spectra and light curves were manifestations of different types of progenitor: accreting white dwarf and collapsing massive star.

Exoplanets, which you can read about on page 24, have a range of names, such as hot Jupiters, super-Earths, and mini-Neptunes. Astronomers will eventually figure out how those and other exoplanets came to have their various characteristic properties. When they do, I suspect they'll retain the old names. PT

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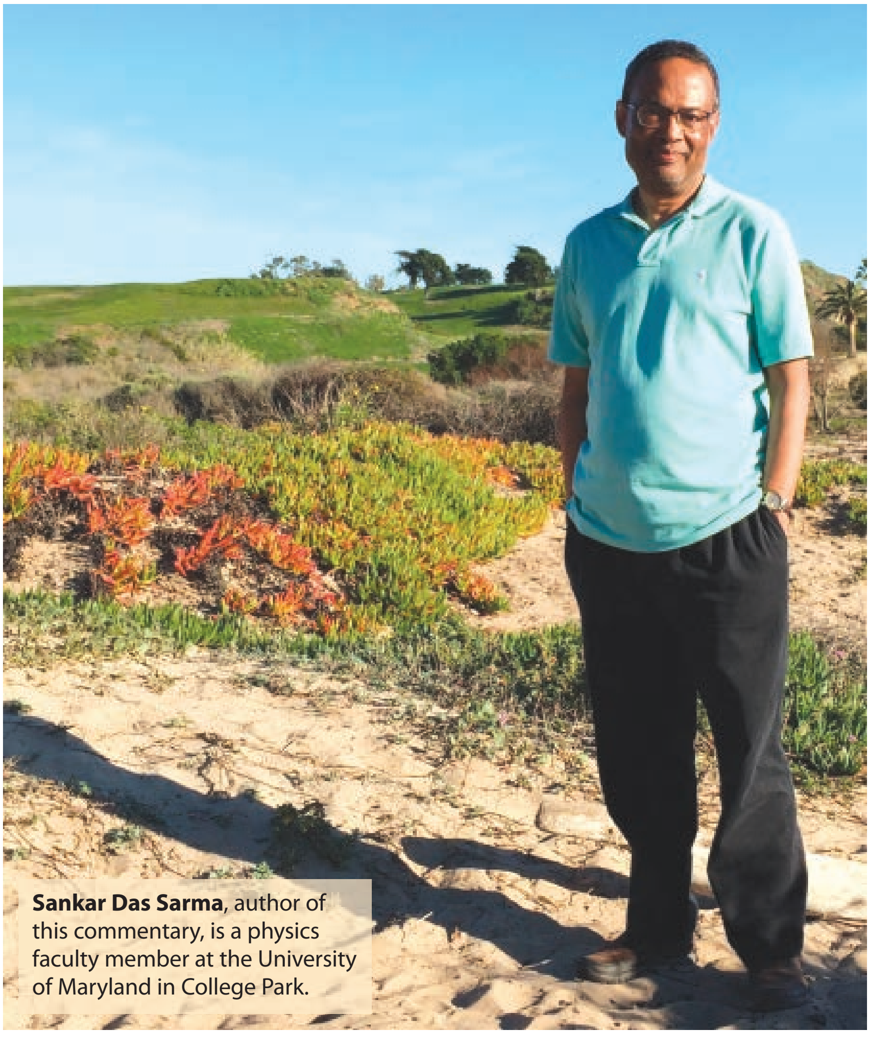
Commentary

Unity of physics perhaps not as grand as once thought

Most graduate physics departments have a qualifying exam that requires every graduate student to be well versed in all of basic physics—classical mechanics, quantum mechanics, statistical physics, electrodynamics, and other core areas—at a fairly advanced level. Here at the University of Maryland, for example, during two grueling four-hour sessions, graduate students had to answer five quantum problems and five classical problems with no options from which to choose. Requiring students to have such all-encompassing expertise merely to begin their thesis research is essentially unthinkable in chemistry, biology, mathematics, computer science, and other disciplines.

Implicit in broadly imposing such an exam is the dogma that physics is a unified pursuit. But how real is that unity of physics for today's practicing research physicists? More importantly, is it still relevant for truly cutting-edge studies?

I do not know of anyone who reads even the titles of all the papers published in *Physical Review Letters*, let alone the actual papers. Although some physicists, including me, have published in multiple *Physical Review* journals, they do so more from the multidisciplinary nature of certain research activities than from a deep intrinsic correlation among subdisciplines.



Sankar Das Sarma, author of this commentary, is a physics faculty member at the University of Maryland in College Park.

Of course, physics has unifying themes rooted in classical mechanics, quantum mechanics, statistical physics, and electrodynamics, and even more so in the shared language of mathematics: Much of physics is described by partial differential equations, integrals, linear algebra, and so on. One could also say that symmetry principles and conservation laws provide the underlying unification for physics, but they are quite broad and are equally operational in biology and chemistry. If they are all we have to connect all of physics, I am quite underwhelmed. "Unity" should mean more than just the common language of mathematics and the correlation of subjects—quantum mechanics, for example—that were already well developed by the 1930s.

When Isaac Newton integrated terrestrial and celestial mechanics by realizing that the same laws of inertia and gravitational forces control phenomena in the cosmos and on Earth, the unity of physics was manifestly obvious at a grand scale. In fact, I consider Newton's unification of the two disciplines to be the greatest leap in theoretical science ever; only Charles Darwin's theory of natural selection comes even close. Similarly, James Clerk Maxwell's unification of electricity and magnetism did not have to be announced; it was manifest.

Although it was a tremendous theoretical unification, Albert Einstein's insight that gravity and inertia are the same already has a much weaker unifying effect, compared with Newton's or Maxwell's, on various research areas of physics today. For example, condensed-matter physics, my chosen field of research, is essentially unaffected directly by general relativity. I find general relativity to be extremely beautiful, but I last had any direct contact with it in my beginning graduate year, more than four decades ago, when I decided to learn it on my own by studying Steven Weinberg's wonderful book on the subject, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity* (1972).

I do not believe that my in-depth graduate study of general relativity has had any more effect on my condensed-matter physics research than has my studying Jean-Paul Sartre's existential treatise *Being and Nothingness* in the early 1970s. Physics is now far too specialized for a theory to have any unifying effect on another part of physics just by virtue of its mathematical elegance. General relativity is extremely mathematically beautiful and is truly a grand theory, but that does not make it particularly relevant for understanding magnets or superconductors or transistors in any direct sense!

The standard model is the great paradigmatic success of the past 50 years of particle physics. But one could do outstanding work in condensed matter—and many do—without knowing anything about quarks. String theory, the purported Theory of Everything, has had little direct effect on condensed-matter physics regardless of the many speculative and brilliant suggestions on its possible role in condensed-matter phenomena. Theorists have used string dualities to produce many abstract answers in the field, but unfortunately, what the corresponding questions are (and why anyone should care) remain unclear.

One may argue that quantum field theory has been the unifying theme in physics over the past 70 years. That is partially correct for particle and condensed-matter physics. Quantum electrodynamics, the renormalization group, and topological quantum field theories provide a common language for many topics in condensed-matter and particle physics, but in vast areas of those fields, quantum field theories play no role whatsoever.

Much of materials physics, the most active branch of condensed-matter physics, is interpreted primarily in terms of mean-field band-structure theories, and the most cited papers in all of physics are all band-structure theories. Quantum field theory is essentially irrelevant to their practice and success. Once the quantum nature of photons is incorporated, most of atomic physics is also generally independent of quantum field theories. And, of course, substantial branches of physics—plasmas, fluids, soft matter, and biophysics, for example—are independent of quantum physics for all practical purposes.

I can go further. General unifying themes have not been particularly successful in either predicting or explaining the great experimental discoveries of condensed-matter physics. For example, there is nothing particularly beautiful or unifying about cuprates like lanthanum strontium copper oxide (LSCO) or yttrium barium copper oxide (YBCO) except that they are where high-temperature superconductivity was discovered through serendipity. Although there is an elegant and well-accepted long-wavelength topological quantum field theory for quantum Hall effects in which the boundary–bulk correspondence is fundamental, experiments have so far failed to establish that correspondence decisively.

Developments in physics, unlike in math, are not necessarily logical, and what may or may not work out cannot be predicted with certainty, despite the claims of stalwarts like Einstein and Paul Dirac that beauty and unification always reign supreme. After all, supersymmetry, despite its great allure and unifying power, is still undetected at the Large Hadron Collider. Natural phenomena may simply not care about our subjective feelings on the unifying importance of mathematical beauty!

So, is unification still germane in physics? Actually, yes. Unification is still very present, but how and where it will emerge is almost impossible to predict. The connection of quantum Hall effects to topological quantum field theories is one example. Who could have predicted that some of the most esoteric topological

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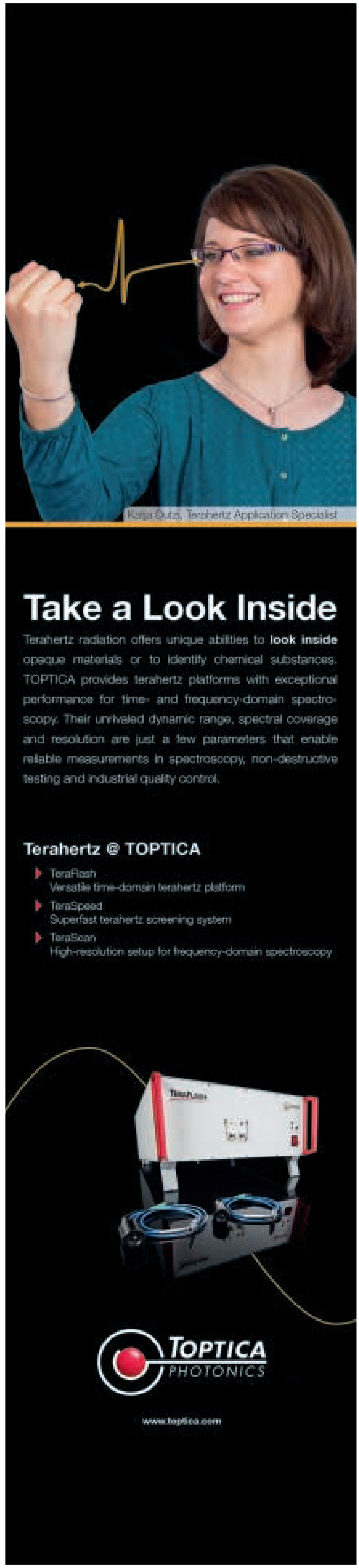

concepts, such as modular tensor categories, manifest themselves in the current–voltage measurements of two-dimensional transistors? Yet they do in quantum Hall effects, and they continue to be relevant in the emerging subject of topological materials and phenomena now dominating condensed-matter physics.

Similarly, the Dirac equation turned out to be the right description for electrons and positrons in vacuum, but the almost equally beautiful theories of Hermann Weyl and of Ettore Majorana languished in particle physics. Whether neutrinos are Majorana fermions—that is, whether they are their own antiparticle—remains unknown. But more than 80 years after Weyl, condensed-matter researchers are discovering solid-state Weyl materials, which exhibit massless, chiral charged quasiparticles. "Chiral two-dimensional massless Dirac equation" turns out to be an excellent continuum description for graphene. And Majorana particles are central to the concepts of non-abelian anyons and topological quantum computation. (See the article by Nick Read, PHYSICS TODAY, July 2012, page 38, and my article with Michael Freedman and Chetan Nayak, July 2006, page 32.) Microsoft has started a worldwide effort to build a quantum computer that has non-abelian Majorana modes and topological quantum field theories at its core.

Materials physicists, many of whom never heard of Weyl and his equation until recently, are busy publishing experimental papers on the search for chiral anomalies in certain types of semimetals. That is unification at its best, but it has not followed a planned, logical course. It has happened purely through general unifying concepts that are enabling us to connect phenomena that seem completely different on first sight. Newton's spirit of unification is still alive and well, but its scale is no longer as grand as it was in 1687, because physics itself is so much grander now.

Unification still rules physics, from the graduate qualifying exam to the creation of quantum computers. We may not see it in our everyday experience of physics, but when it shows up, we immediately realize it, accept it, and use it.

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LETTERS

A memoir on project-based learning

A story in the June 2017 issue of PHYSICS TODAY recently caught my eye. An Issues and Events story by Toni Feder (page 28) stated that project-based learning is gaining popularity. I am a retired industrial physicist with my PhD in atomic theory. I'd like to share a related story.

I think it was my junior year, 1966–67, at Colorado State University. I was taking a course on modern physics; the class had two parts. The lecture part was traditional and worth five credits, if memory serves me, and the laboratory part would now be called project-based learning. It was worth two credits.

On the first day of lab class, the professor took us to the basement of the physics wing, unlocked the doors of three rooms, and said, "You may use any materials in this room, the next one, and the one at the end of the hall. You are to design and execute five experiments in modern physics, record the data, and make a report on each. The notebooks and reports will be turned in at the end of the quarter and will determine your grade for the class." He then went back upstairs to his office. He was always available, but few needed to consult him.

We were teamed up into groups of two. In addition to choosing from several "canned" experiments, each group took on at least one original experiment. My partner and I chose to measure the stopping potential of the photoelectron. We found a regulated DC power supply with shielding, a student spectroscope, and a few odds and ends, and we cobbled together a credible experiment. The result was within 20% of the accepted value, a quite good result for the equipment available to us.

That class served me well throughout my career. It taught me to read what others had done, adapt their work, and solve problems with the equipment at hand, and it developed in me a passion for the projects I encountered. I had an exciting career that involved topics from programming a direct-reading spectrograph for analytical chemistry to studying iron aluminides. The work was an equal mix of the theoretical and the experimental and was highly interdisciplinary. For example, one summer I was a student hire at Aerojet General to work on Project NERVA, an effort to develop nuclear propulsion for spacecraft.

Among other things, the project-based lab fostered a can-do attitude in me. I strongly applaud the efforts described in Feder's story.

Jack R. Woodyard
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Norton, Kansas

Assumptions about climate change skeptics

In his editorial in the August 2018 issue of PHYSICS TODAY (page 8), Charles Day writes about his interaction with a climate change skeptic. Like all of us, he has made some assumptions. The most troubling of those is that the skeptic has some understanding about the nature of science.

Day writes, "I can point out that the current mean temperature is 1 °C higher now than it was in the 1950s." Were he to make that point and then ask the skeptic what temperature indicates, he would get some insight into how shallow the skeptic's understanding is. If he were to ask the difference between heat and temperature, Day would undoubtedly be even more dismayed.

When giving presentations to teachers and the public, I am careful to make sure the participants understand the difference between temperature and heat. I then emphasize the enormous amount of energy (heat) it takes to raise the temperature of Earth's atmosphere, oceans, and surface by just 1 °C.

I would not qualify Day's acquaintance from the embassy as a legitimate skeptic unless that person has some basic understanding of climate science.

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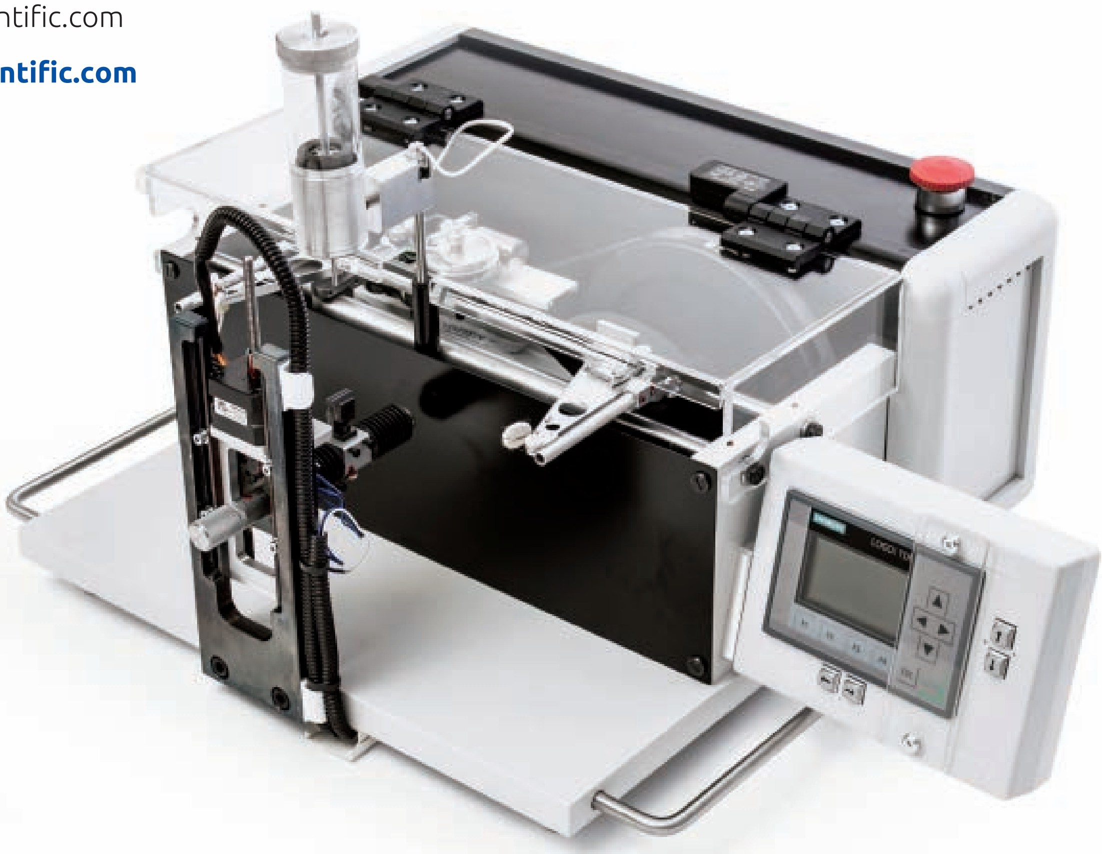

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White dwarfs crystallize as they cool

A new star survey and statistical analysis vindicate a 50-year-old theory.

A white dwarf is the final stage in the evolution of all but the most massive stars in the sky. Before then, as the last of a star's hydrogen and helium fuel is exhausted, nuclear burning can no longer support it from its considerable gravity, and it contracts to a diameter comparable to Earth's. A white dwarf packs the mass of the Sun into a millionth of its volume. Densities inside reach 10^9 g/cm^3—a billion times that of water—and the only thing preventing further implosion is the pressure of degenerate electrons, which, obeying Pauli's exclusion principle, cannot get any closer to each other. (See the article by Hugh Van Horn, PHYSICS TODAY, January 1979, page 23.)

Fifty years ago Hugh Van Horn predicted that as a white dwarf radiates and cools, electrostatic interactions between the ionized nuclei in the star's interior cause the nuclei to freeze into a lattice—even at temperatures as high as a few million kelvin—through a first-order phase transition.[1] One consequence of that transition is the release of latent heat, an effect Van Horn realized ought to be observable, if not in individual stars then in a statistical ensemble. Because they radiate through a surface area 1/10 000 the size of the Sun's, white dwarfs are faint, and prior to two years ago star surveys had found fewer than 200 at accurately measured distances.

The paucity ended in September 2016 with the first publication of data from the European Space Agency's (ESA's) *Gaia* observatory, a satellite that provided astrometric information for 1.1 billion stars. In April 2018 ESA released the celestial positions of an additional 1.7 billion stars (see figure 1 and PHYSICS TODAY, January 2019, page 19).[2] The number of white dwarfs at well-known distances shot up beyond 200 000, more than enough to hunt for the predicted release of latent heat. From that bounty, Pier-Emmanuel Tremblay of the University of Warwick, Gilles Fontaine (Van Horn's first doctoral student) of the University of Montreal, and their colleagues have presented the first empirical evidence that white dwarfs crystallize.[3]

They took a subset of *Gaia*'s data—about 15 000 white dwarfs that reside within 100 parsecs (roughly 330 light-years) from Earth—and populated a Hertzsprung–Russell (HR) diagram with the stars (black dots in figure 2). The white dwarfs were so varied—spanning a wide range of masses, luminosities, temperatures, and ages—that Tremblay and company were able to search the HR diagram for a telltale pattern in the number density predicted by theory. A histogram of the number of white dwarfs per unit volume per unit luminosity confirmed that a few thousand of those stars had likely been caught in the act of going through the phase transition.

From apparent to absolute

The first satellite-based astrometric survey was conducted by ESA's *Hipparcos*, which was launched in 1989 (see the article by Michael Perryman, PHYSICS TODAY, June 1998, page 38). Its more capable successor, *Gaia*, collects more than 30 times the light and measures stellar positions and motions 200 times as accurately. More importantly, thanks to its advanced CCD cameras, *Gaia*'s parallax measurements resolve far smaller angles, and thus more accurate distances, than *Hipparcos* could. With those better distance measurements, astronomers convert each star's apparent brightness into an absolute magnitude—a proxy for luminosity, the total energy radiated per unit time.

Figure 2 plots the absolute magnitude

FIGURE 1. THE OUTER REACHES OF THE MILKY WAY, in color. This map is a reconstruction of the total integrated light flux measured by the *Gaia* space observatory. To date, the European Space Agency, which built, launched, and manages the satellite, has released astrometric measurements of nearly 3 billion stars. (Adapted from ref. 2.)

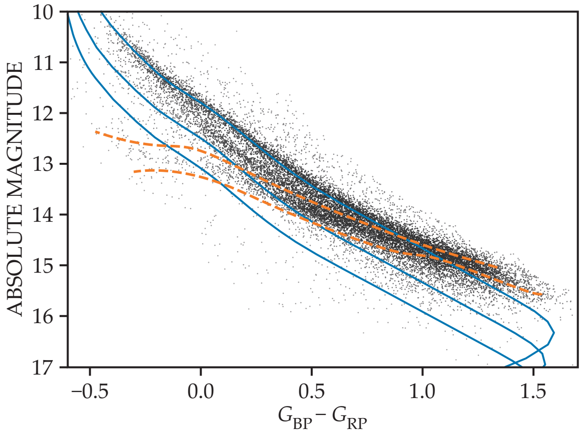

FIGURE 2. THIS HERTZSPRUNG–RUSSELL DIAGRAM plots the absolute magnitude of some 15 000 white dwarf stars (black dots). Its horizontal axis, as explained in the text, is a proxy for temperature. The more massive a white dwarf, the smaller and less luminous it is. The blue curves illustrate the cooling sequences for three masses of stars (0.6 $M_\odot$, 0.9 $M_\odot$, and 1.1 $M_\odot$, from top to bottom, where $M_\odot$ is the mass of the Sun). The two orange dashed lines delimit the regions where models predict that 20% (top) and 80% (bottom) of the white dwarf masses would crystallize. The liquid-to-solid phase change is accompanied by a release of latent heat that slows the stars' cooling and causes a pileup in their number density. (Adapted from ref. 3.)

for each of the 15 000 white dwarfs and the difference in their magnitude in two wavelength passbands, G_{BP} (blue) and G_{RP} (red). That difference is a proxy for color or temperature. The HR diagram captures stars of different ages as they progress along their cooling tracks.

As white dwarfs become cool enough to crystallize, the concomitant release of latent heat from the phase transition slows their cooling rate. The slowing, in turn, causes a statistical pileup—an above-average density in the number of stars at the luminosity where the heat is released. The two orange dashed lines in figure 2 delimit the regions where most stars undergoing crystallization are theoretically expected to occur.

The higher number density isn't evident to the naked eye in the HR diagram, so to confirm it, the researchers plotted the raw data as an integrated histogram: Figure 3 shows the number of white dwarfs per unit volume per unit luminosity as a function of luminosity.

White dwarfs start hot and cool quickly at first. Not surprisingly, their plotted number density (red dots) steadily rises as total luminosity drops. After a few billion years, when the luminosity is below one thousandth that of the Sun, the number density locally peaks (the shaded region)—a direct signature of the pileup—only to briefly fall again as the dwarfs resume cooling at a faster pace after most of their mass has solidified and the latent heat is spent.

After rising again to a second peak at the far right, the number density plummets, a result of the finite age of the universe; few dwarfs have cooled to such a low luminosity. The local peak in the

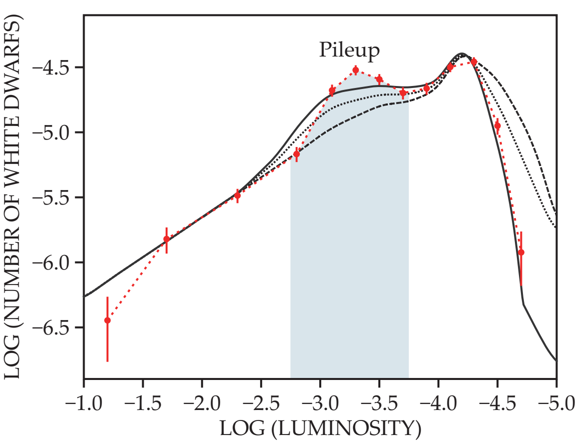

FIGURE 3. THE NUMBER OF WHITE DWARFS (RED DOTS) per unit luminosity per unit volume versus luminosity $L/L_\odot$ for stellar masses 0.9–1.1 $M_\odot$, where $L_\odot$ and $M_\odot$ are the luminosity and mass of the Sun. The number steadily rises as the luminosity falls until the stars cool to less than 1/1000 of the Sun's luminosity. The plot's peak in the shaded region is a direct observational signature of crystallization. Three model simulations (black lines) approximate the experimentally observed number of white dwarfs. The best fit (solid line) includes both latent heat released by crystallization and the gravitational energy released by oxygen sedimentation. The dotted curve neglects phase separation but includes latent heat, whereas the dashed curve neglects both. (Adapted from ref. 3.)

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shaded region caught the researchers' attention for its relevance to crystallization. White dwarfs on the left, more luminous side of that peak are primarily liquid, and those to the right, less luminous side are primarily solid.

A metal that unmixes

Devoid of nuclear burning, a white dwarf is thought to exist as a homogeneous mixture of carbon and oxygen whose nuclei are liquid. (In the star's ionized-plasma state, the electrons remain a Fermi gas and the nuclei are either liquid or solid.) When the nuclei freeze, the elements start segregating. Oxygen nuclei carry a higher charge than carbon, so they are the first to solidify—into a body-centered-cubic metal, according to calculations. Oxygen also has a higher density than carbon, and after nucleating, it "snows out" of the liquid and sinks to the core.

Tremblay and colleagues hope the new work will help them disentangle the energetics of sedimentation—the segregation of the two phases—from the energetics of crystallization. The carbon in the liquid phase is forced outward by the growing, solid oxygen-enriched core. The release of gravitational potential energy from the sedimentation further delays cooling.

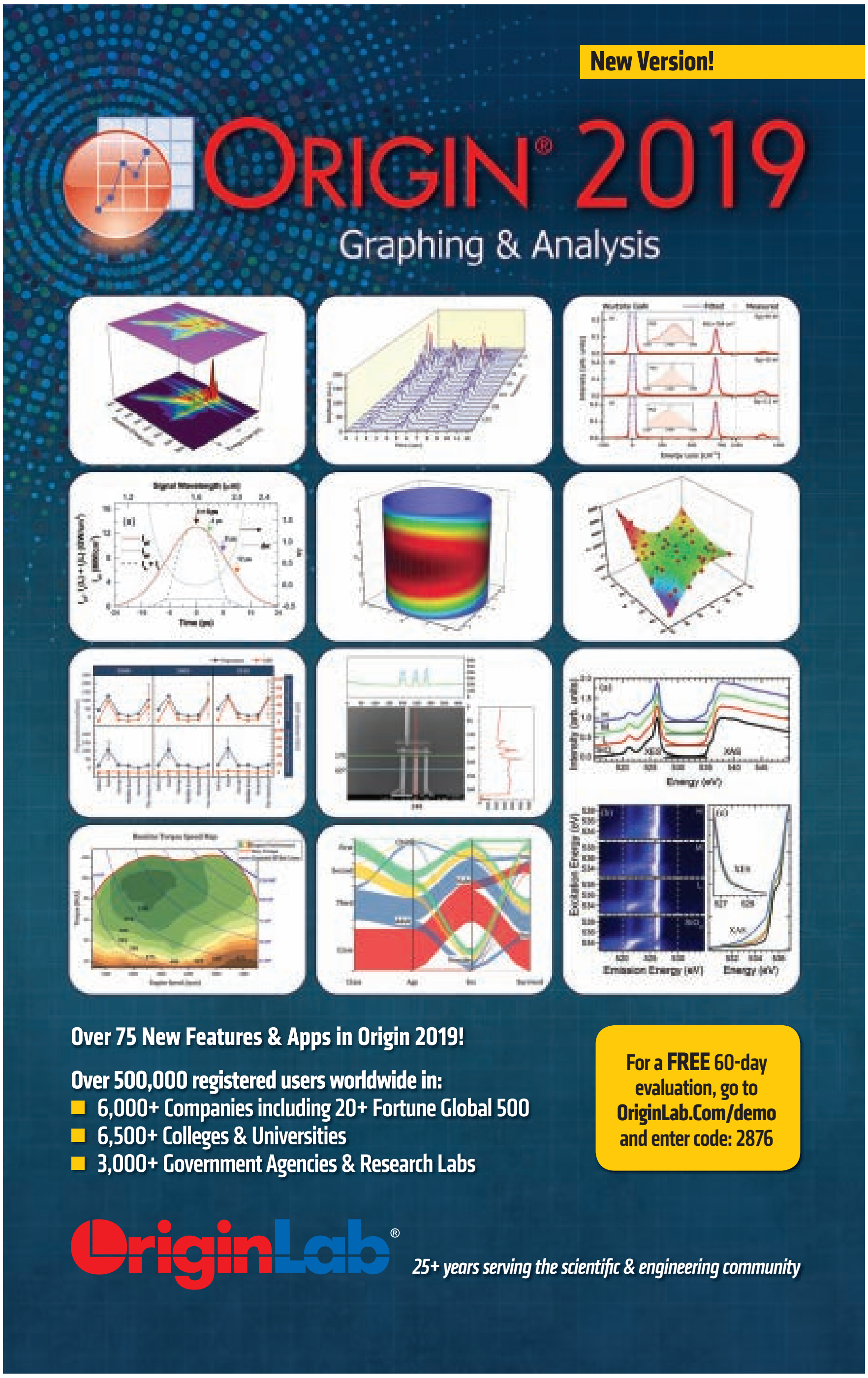
The absence of latent-heat release is ruled out in white-dwarf evolution: Simulations that neglect latent heat and sedimentation produce the poorly fitting dashed black line in figure 3. Progressively better simulations—accounting for the effects of latent heat, either alone (dotted black line) or with sedimentation (solid black line)—approach, but do not match, the experimental results (red).

"I would have been astonished had our theoretical predictions perfectly reproduced the white dwarfs' number density," says Fontaine. "The mismatch may, in fact, open the door to a keener understanding of stellar processes." For example, theorists can test whether modifications to the initial mixture of carbon and oxygen improve the fit. Judging by the narrowness of the crystallization peak, the phase transition also occurs more quickly than simulations predict.

Improvements to the theory will likely yield payoffs. White dwarfs are near-perfect thermal conductors, and since 1987, their uniform temperatures have made them reliable clocks to gauge the ages of various classes of star systems—globular clusters, galactic disks, and others—that contain them.[4] Although the ubiquity of white dwarfs has made the technique common, its accuracy is limited to 15–20% of the white dwarfs' actual age because of their intrinsic faintness.

The new work shows that many of the white dwarfs we see today cool more slowly and are thus older than previously thought—by as much as 2 billion years. Why should the better age estimates matter? Matt Caplan, a postdoc at McGill Space Institute and unaffiliated with the work, puts it succinctly: "Stars' ages largely tell us when and in what amounts they make certain elements. Only then can we trace the chemical evolution of the universe we live in today."

Mark Wilson



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Boosting the resolution of neutron backscattering spectroscopy

Replacing silicon crystals with gallium arsenide ones quadruples energy resolution, the biggest jump the technique has seen in its half-century history.

BERNHARD FRICK

FIGURE 1. KRISTIJAN KUHLMANN (front) and Markus Appel (back, almost hidden) examine part of a gallium arsenide analyzer in a proof-of-concept neutron backscattering spectrometer. In a fully functional spectrometer, the hexagonal GaAs facets will cover about 20% of the surface area of a sphere centered on the sample (right foreground).

Experiments with subatomic particles don't often have to account for gravitational potential energy. A proton or neutron moving through Earth's gravitational field gains or loses just 100 neV for every meter of altitude change. For many purposes, that's an insignificant amount.

But a new proof-of-concept neutron backscattering spectrometer is so sensitive to tiny changes in energy that gravitational effects matter.[1] The spectrometer (whose vertical scale is shown in figure 1) is located at Institut Laue–Langevin in Grenoble, France, and was devised and developed by a team led by ILL scientist Bernhard Frick and Andreas Magerl of Friedrich–Alexander University of Erlangen–Nuremberg in Germany. Its energy resolution, 78 neV, is an order of magnitude better than a typical instrument of its type and a factor of four better than the best currently available.

Neutron backscattering spectroscopy is used to measure the minute energy shifts in neutrons that scatter off a sample. Those energy changes can result from sample resonances, such as phonons or hyperfine excitations. They can also arise from random motions such as diffusion: Neutrons scattering off moving molecules acquire positive or negative Doppler shifts, and the resulting broadening of their energy spread provides information about the mobility of molecules in the sample.

The technique has been used to study, among other things, the diffusion of protons in fuel cells and the movement of water in biological and geological specimens. Improved energy resolution opens the door to studying dynamics that are slower or more complicated—such as different components of the sample diffusing at different rates—and wider ranges of temperature, pressure, and other parameters.

Bragg backscattering

The ILL is one of several user facilities worldwide that are dedicated to neutron research. Neutrons are produced in a central nuclear reactor and distributed among several dozen instruments, on which users can book time for their experiments.

The beamline neutrons have too broad a kinetic energy spread for the slight shifts imparted by the sample to be discernable. Neutron backscattering spectroscopy uses Bragg reflection to pick out neutrons of a particular energy. As shown in the schematic in figure 2, the beam first reflects off a crystalline monochromator. By Bragg's law, only those neutrons whose de Broglie wavelength is commensurate with the lattice spacing constructively interfere and reach the sample.

After scattering off the sample, which may or may not involve a slight change in energy, the neutrons collide with a large spherical shell of crystalline analyzers. If and only if the Bragg condition

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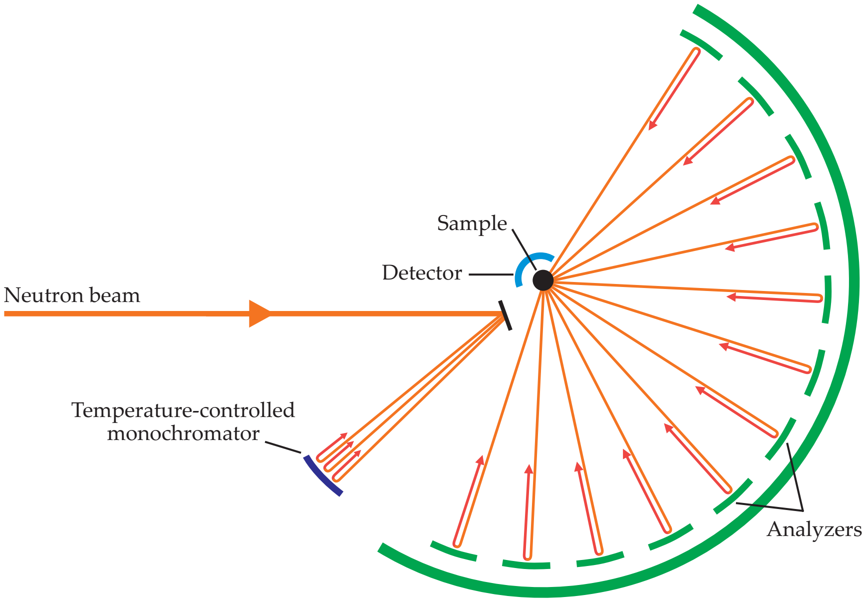

FIGURE 2. THE NEUTRON BACKSCATTERING SPECTROSCOPY SETUP, shown schematically. Incoming neutrons first reflect off the temperature-controlled monochromator, then scatter off the sample, then reflect off the analyzers. Neutrons reach the detector only if their energies satisfy the Bragg condition at both the monochromator and the analyzer—that is, if the energy gained or lost by scattering in the sample matches the temperature shift imparted by the monochromator.

is satisfied again are the neutrons reflected back toward the detector. If the monochromator and analyzers are made of identical crystalline materials, then, the detected neutrons are the ones that neither gain nor lose energy in the sample. By adjusting the monochromator's temperature, one can select for neutrons that gain or lose a specific amount of energy: Warmer crystals have slightly larger lattice spacing, so they reflect slightly longer-wavelength neutrons.

The material chosen for the monochromator and analyzers needs to be one that can readily be fabricated into large-area, high-quality crystalline wafers. Ever since the first prototype[2] in 1969, neutron backscattering spectrometers have used the (111) surface of silicon. And from the beginning, spectrometers were almost perfectly optimized for that material: The 1969 prototype had an energy resolution of 620 neV, and the best Si(111) spectrometer today has a resolution of 300 neV.

That resolution is largely limited by the intrinsic linewidth of the Si(111) reflection. The Si atoms scatter neutrons strongly: Neutrons with resonant energy penetrate just 34 μm into the crystal, so only 10^5 atomic layers participate in the reflection, and the destructive interference at off-peak energies is incomplete. It's been known since the 1990s that the reflection off the (200) surface of gallium arsenide could potentially do better.[3] Because that material scatters neutrons less strongly, the beam penetrates 10 times as far into the crystal. As a result, the peak reflection intensity is the same as for Si(111), but the stronger extinction at off-peak energies makes the reflected energy range much narrower.

Realizing resolution

In the 1990s GaAs fabrication wasn't yet sufficiently advanced for a large-area perfectly crystalline analyzer to be feasible. Now it is. But building the analyzer is a lot more involved than piecing together some commercially available GaAs crystalline wafers. Several other resolution-limiting effects—including facet alignment, beam geometry, and crystal strain—had to be controlled more precisely than in a conventional Si(111) spectrometer. "If any one of them was neglected," says postdoc Markus Appel, who worked on the project, "progress would be stalled. We often had to take a step back and shift our attention to identifying and working on the current weakest link in the chain."

One of those potential weak links is the effect of gravity. All else being equal, neutrons scattered from the sample toward the top of the analyzer end up with 300 neV less energy than those scattered toward the bottom. Leaving that effect uncorrected would obliterate all other resolution-improving advances. To compensate for gravity's influence, the researchers introduce a thermal gradient such that the bottom of the analyzer is 10 K cooler than the top.

To test the energy resolution, the researchers made some proof-of-concept measurements, including the hyperfine spectrum of cobalt. But the new spectrometer isn't ready for users yet. The analyzers constructed so far represent just 3% of the area of a fully furbished instrument. And there's still some room for improvement in resolution: The theoretical limit for an ideal GaAs(200) crystal is just 13 neV.

Johanna Miller

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Spin excitations in a cavity hop coherently over long distances

Virtual photons mediate nonlocal interactions between cold atoms.

Quantum mechanics is as counterintuitive as it is in large part because of its nonlocality. Particles can be entangled with other particles, no matter how far away (see PHYSICS TODAY, August 2017, page 14), with information stored not in the state of one particle or the other but in their correlations. A measurement on one particle instantly changes the state of its distant entangled partner. That spooky action at a distance isn't technically an interaction between the particles. But it looks enough like one that it's difficult to reconcile with physical intuition.

Stanford University's Monika Schleier-Smith (shown in her lab in figure 1) and colleagues are using a cloud of cold rubidium atoms in an optical cavity to engineer and study nonlocal interactions. They've now induced a collective spin excitation to act at a distance on a faraway part of the cloud by having it hop more than a quarter millimeter, skipping over all the identical atoms in between.[1] With the combination of nonlocal interactions and local control and imaging, they hope to create a new platform for exploring the limits of how quantum systems can behave.

DAWN HARMER

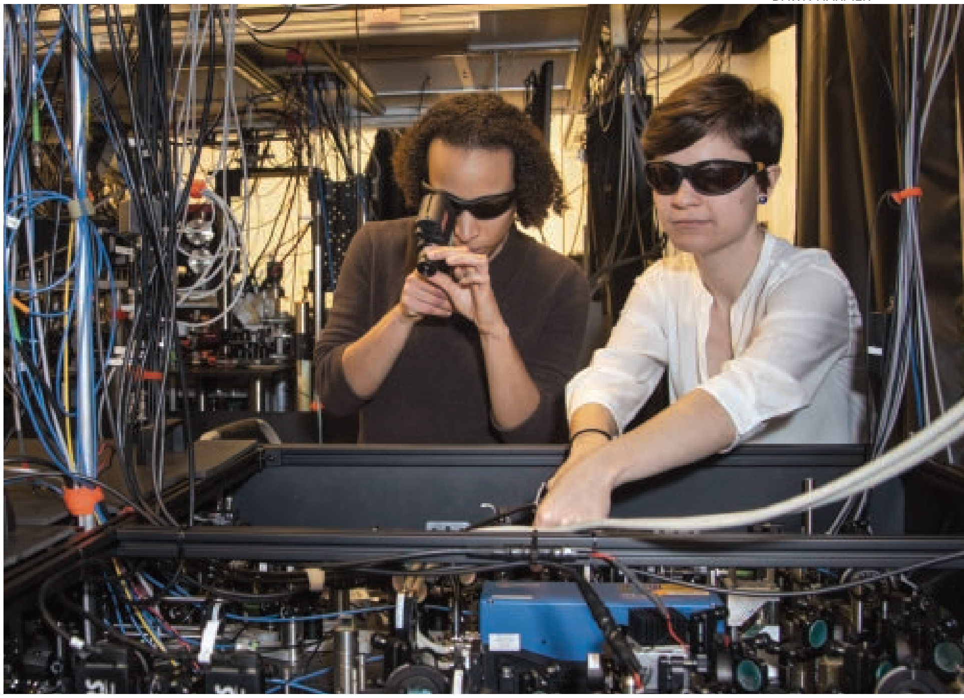

FIGURE 1. MONIKA SCHLEIER-SMITH (left) observes with an IR viewer as her student Emily Davis adjusts a pair of mirror mounts. In the background is a second table where the researchers cool and trap a cloud of rubidium atoms. Optical fibers carry light between the two parts of the experimental setup.

Driving a spin exchange

The experimental setup is shown schematically in figure 2a. A cloud of some 10^5 spin-1 atoms is held in a one-dimensional array of optical traps created by the standing wave in the optical cavity. An applied magnetic field **B** produces Zeeman splitting of the atoms' $m = +1$, 0, and −1 spin states.

By driving the cavity with a laser pulse of a suitably chosen wavelength, the researchers set off a flip-flop process like the one shown in figure 2b. When a drive-pulse photon inelastically scatters off an atom, it changes the atom's spin state and creates a virtual photon of a different wavelength. The virtual photon then induces a change of spin of equal and opposite energy elsewhere in the cavity, and the photon returns to the original wavelength.

The drive-pulse wavelength is chosen so that the virtual photons are almost, but not quite, resonant with a cavity mode. If they were exactly on resonance, they would be able to exit the cavity without ever completing the spin flip-flop. The slight detuning ensures that the virtual photons have nowhere to go but to scatter off another atom.

Several recent experiments have used similar setups to produce collective spin interactions among atoms in cavities.[2] But until now they've focused on controlling and probing the atoms through global degrees of freedom, such as the total magnetization or the intensity of the light exiting the cavity. Schleier-Smith and colleagues introduced the new capability to manipulate and measure the spin states locally so they can directly see where in the cloud the spin excitations are located.

State-sensitive imaging is a standard technique in cold-atom physics: The spin states are mapped by driving them, one at a time, through a closed-cycle excitation loop that produces detectable fluorescence. But it's challenging to implement in the context of an optical cavity. Traditionally, when researchers use an optical resonator to concentrate light in a small space, they make the whole resonator small. Schleier-Smith and colleagues used a different setup, a so-called concentric configuration, with curved mirrors separated by nearly twice their radius of curvature, a distance of several centimeters. A concentric cavity is extremely sensitive to misalignment of its mirrors. But it concentrates light tightly at its center while leaving plenty of room to introduce imaging laser beams from the side.

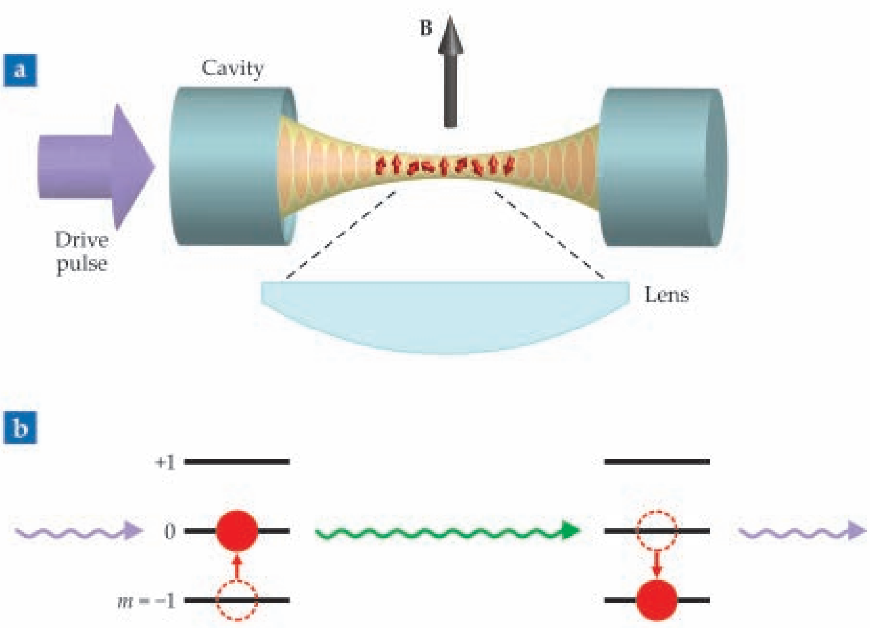

FIGURE 2. SPIN-EXCHANGE INTERACTIONS among atoms in an optical cavity. **(a)** A cloud of atoms (red) is held in a one-dimensional array of optical traps (orange). A magnetic field **B** induces Zeeman splitting, and the lens enables imaging of the cloud from the side. **(b)** When a photon (purple) from a drive pulse scatters inelastically off an atom, it changes the atom's spin state and creates a virtual photon (green) of a different energy. The virtual photon then induces a spin change of equal and opposite energy elsewhere in the cloud. (Adapted from ref. 1.)

Toward spatial control

Figure 3 shows the results of one experiment. After initializing the cloud in the $m = -1$ state, the researchers locally excite atoms at position A. When the drive pulse is introduced to turn on the spin-exchange interactions, the excitation quickly hops to position B, 250 μm away. It slides back to A, and then it hops to B again.

The hop destination is always position B because that's the part of the cloud nearest the cavity center, where the light intensity and thus the light–atom coupling is strongest. The subsequent sliding is a more complicated effect, but it too is explained by the inhomogeneity of cavity light. Over the course of the experiment, the overall excitation density goes up; that's because the experimental conditions aren't quite perfect for ensuring that the flip-flops are complete. The virtual photons are close enough to resonant that some of them do leak out of the cavity, so some spin excitations are not matched with de-excitations elsewhere.

Despite those complications, the results are reproducible. The data in figure 3 weren't collected in real time during a single trial—the nature of the imaging method makes that impossible. Rather, the figure is a patchwork of time slices from many trials with the same initial state prepared each time. Experiment and theory agree well.

The researchers are working on ways to control where the hopping spin excitations end up. For example, by making the applied magnetic field (and thus the Zeeman splitting) spatially inhomogeneous, they could restrict which pairs of atoms can mutually interact to participate in a flip-flop. Another possibility is to replace the end-on drive pulse with drive lasers incident from the side of the cavity to target specific regions of the atom cloud. Between those two approaches, it should eventually be possible to engineer any desired pattern of interactions between pairs of atoms.

Excitation hopping is at its heart a classical phenomenon: Although the atoms interact nonlocally, no nonlocal correlations are involved. But the same physics of the spin flip-flop can also be used to generate and manipulate entangled states. For example, when the cloud is initialized in the $m = 0$ state, the drive pulse creates correlated pairs of +1 and −1 spins: The number of atoms in both states must be the same, but it's not known which atom is in which state. The long-term goal is to combine pair creation, spin exchange, and spatial control to engineer arbitrarily complicated quantum states in large numbers of atoms.

Black hole connections

Schleier-Smith's inspiration for her experiment came from her background in quantum control: creating entangled states for specific practical purposes.[3] For example, squeezed states, in which quantum fluctuations in one variable are reduced at the expense of increasing them in another variable, have applications in metrology. (See the Quick Study by Sheila Dwyer, PHYSICS TODAY, November 2014, page 72.) That's still an area of interest. "But as we were setting up the lab," she says, "we learned about another possible application that could potentially take things in a totally new direction"—the black hole information paradox, an unsolved problem in quantum gravity. (See the article by Steve Giddings, PHYSICS TODAY, April 2013, page 30.)

What happens to quantum information when it falls into a black hole? It can't just disappear without violating the unitarity of time evolution, a fundamental property of quantum mechanics: Any quantum state can be uniquely propagated forward or backward in time. In the absence of a wavefunction collapse

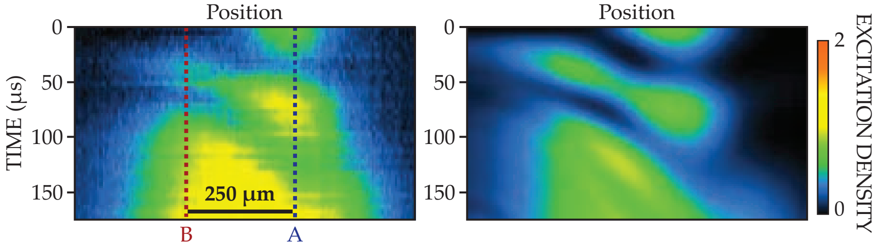

FIGURE 3. NONLOCAL HOPPING of a spin excitation as captured by experimental data (left) and a theoretical model (right). The excitation was prepared at position A at time 0. Turning on the drive pulse causes the excitation to quickly hop to position B, closer to the cavity's center. It then slides back to A, and at time 100 μs hops again. (Adapted from ref. 1.)

associated with an observation, information can't be created or destroyed.

Nor can the information stay inside the black hole's event horizon forever—at least, not necessarily. If a black hole doesn't take in enough new mass to balance out the energy it loses to Hawking radiation, it will eventually evaporate away to nothingness. Where will the information go?

Some mechanism must seemingly exist to allow information to leak out past the event horizon. Figuring out how that mechanism works is a daunting theoretical challenge. But experiments may be able to help, thanks to the duality, or mathematical correspondence, between gravitational systems and quantum many-body systems. (See the article by Igor Klebanov and Juan Maldacena, PHYSICS TODAY, January 2009, page 28.) Experimenters can't build a black hole in the lab, but they may be able to construct its dual.

Which physically realizable quantum systems are the duals of black holes is itself an open theoretical question. But Schleier-Smith is hopeful that her cold-atom spin-exchange experiment could provide the answer.[4] Theoretical models that attempt to solve the black hole information problem often do so by bending the familiar rules of physical locality. "They can look very strange," she says, "because they include all these nonlocal hopping effects," reminiscent of the hopping of spin excitations induced by nonlocal atomic interactions. "In the future, maybe we can build something in the lab that processes information like a black hole."

Johanna Miller

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Measurements of elusive mineral could explain mantle discontinuity

A predicted phase transition shows up in high-pressure experiments.

As Earth's tectonic plates shift and collide, slabs of cold, dense oceanic crust get pushed down into the mantle. The subduction process carries volatile compounds and water into the mantle along with crustal material that has a different isotopic signature from primitive mantle material. Heat and pressure in Earth's interior can transform the subducted crust into different minerals and may eventually return it to the surface in the magma that upwells and forms new crust. However, the depth to which crust material descends during that cycling is still a subject of debate among geophysicists and is key to understanding heterogeneities in the mantle structure.

Knowledge of Earth's interior structure is based on inferences of how seismic waves travel at different depths. The boundary between the upper and lower mantle is marked by a sharp change in density, and therefore of seismic-wave velocities, at a depth of 660 km. Toward the bottom of the upper mantle, at a depth of 410 km, is another density change that

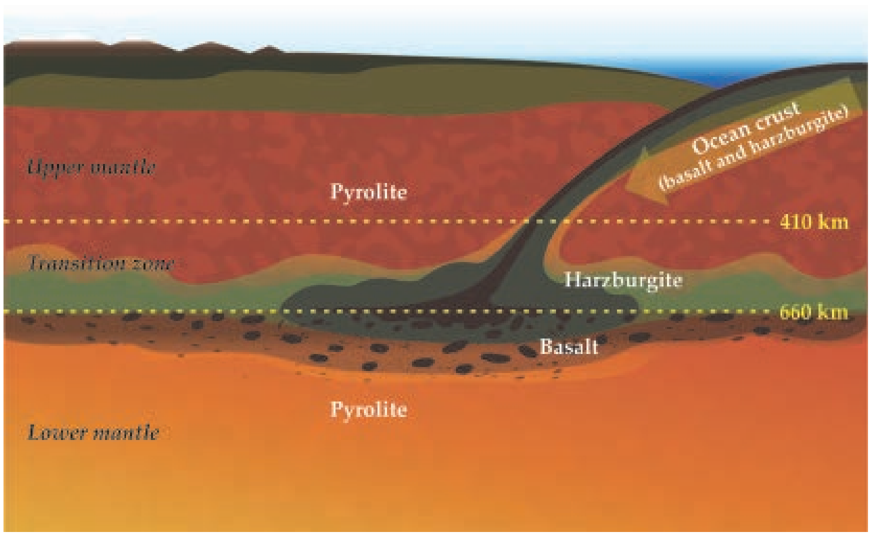

FIGURE 1. SLABS OF BASALTIC OCEANIC CRUST and underlying mantle rocks of harzburgite sink into Earth's mantle during tectonic processes. The boundary between upper and lower mantle is marked by sudden slowing in seismic-wave velocities at depths of around 660 km. New sound-velocity measurements of high-pressure minerals believed to exist in subducted ocean crust suggest that the crust accumulates at the bottom of the mantle transition zone. (Image by Steeve Gréaux.)

marks the beginning of a transition zone. Geophysical simulations suggest that as cold crust material sinks, it undergoes mineral transformations that render it buoyant near the lower boundary of the upper mantle.[1] However, little evidence has been available to support that theory.

Now Steeve Gréaux and colleagues at Ehime University and the Tokyo Institute of Technology in Japan have synthesized a laboratory sample of a calcium–silicon compound that models say should be prevalent in crust rocks that plunge past depths of 560 km. Gréaux and his team have made the first measurements of how sound waves travel through the compound.[2] The measurements match seismic results at the mantle boundary.

Seismic snapshots

Seismic tomography is an important tool for mapping Earth's interior structure. It uses networks of seismometers that detect surface movements caused by waves both from earthquakes and from controlled explosions generated at the surface. Based on the readings, researchers can calculate the locations of reflection and refraction of the paths the waves took through the interior. Seismic travel-time data are compared to an initial model of Earth's compositional layering, tectonic structure, and thermal variations. The model is modified to find the best fit between predictions and observations. From the modified model, three-dimensional maps of velocity differences inside Earth are created. Changes in velocity are caused by local density variations in the material and may be correlated with its structure, temperature, or composition.

Seismic tomography reveals several density discontinuities that divide Earth's mantle into layers. As shown in figure 1, the upper mantle extends 410 km down from the base of the crust and the transition zone spans depths from 410 to 660 km. The lower mantle covers the region from 660 km down to the outer core at approximately 2900 km. Laboratory measurements of seismic properties of rocks and minerals serve as a reference for translating wave characteristics into mineralogy.

In 1962 Alfred Edward Ringwood of Melbourne University developed a model for the mantle's composition. He proposed that bulk mantle material is a mixture of basalt and peridotite. He called the hypothetical mixture pyrolite. Researchers who have synthesized pyrolite in the lab have found that ultrasonic wave velocities in pyrolite agree with seismic velocities for depths down to 560 km and below 800 km.[3] But between the two depths, pyrolite can't be responsible for the seismic behavior.

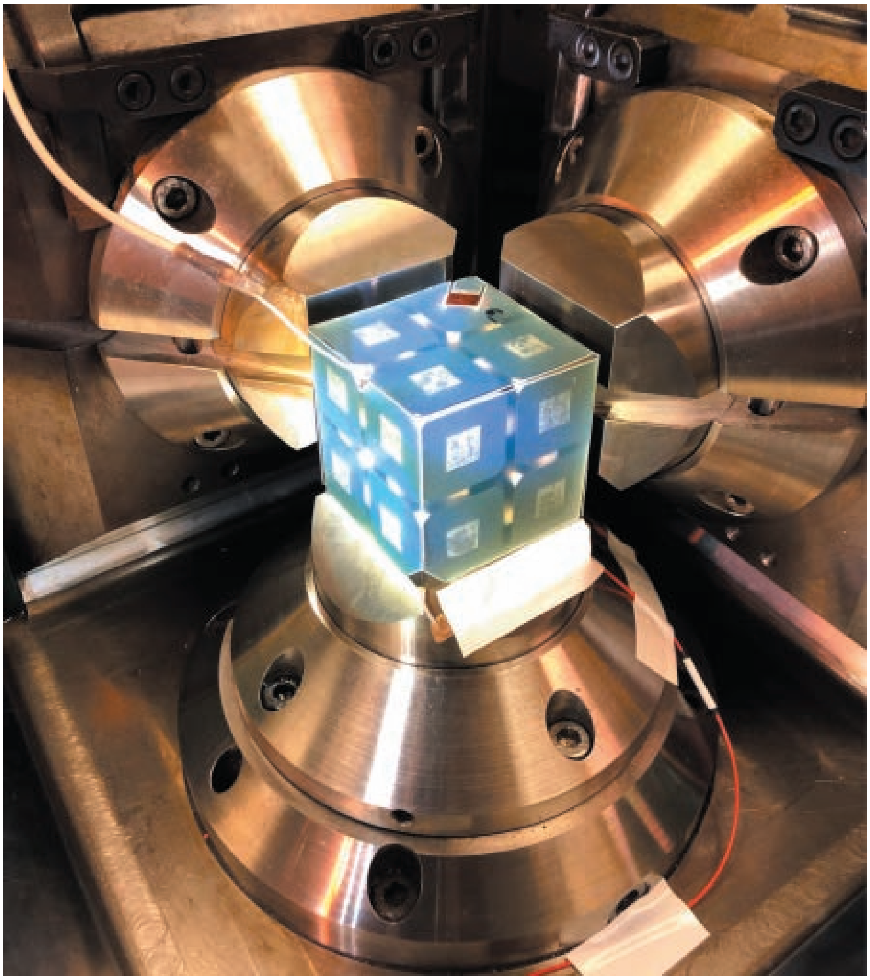

FIGURE 2. MULTI-ANVIL PRESS APPARATUS at the Japan Synchrotron Radiation Research Institute. Hydraulic rams drive six first-stage steel anvils and distribute force on a cubic arrangement of eight second-stage tungsten carbide anvils. The second-stage anvils compress an octahedral high-pressure cell. (Photo by Steeve Gréaux.)

Mineral transformations

A gravitationally stable layer of chemically distinct material could account for the observed seismic discrepancies. Ocean crust consists mainly of basalt and an underlying layer of the igneous rock harzburgite, on top of a peridotite layer. The peridotite may be reabsorbed in the mantle early during subduction, whereas the basalt and harzburgite can travel down to the deep mantle. But ocean crust at mantle temperatures and pressures is transformed into an assemblage of different minerals. The seismic velocities for key minerals thought to occur in that assemblage have not been measured.

One suspected transformation would rearrange calcium and silicon—common elements in the basalt in ocean crust—into a calcium silicate ($CaSiO_3$) phase with a cubic perovskite structure (cubic CaPv) at transition zone depths. A perovskite has the chemical formula ABX_3, where A and B represent cations and X is an anion bonded to both. Mineralogy studies suggest that $CaSiO_3$ in its cubic perovskite structure should constitute 30% of any basaltic crust material that has reached the lower mantle. The crust composition offers a possible explanation for the observed slowing of seismic waves just above the boundary at 660 km.[4]

Cubic CaPv, though, is not stable under ambient conditions. At room temperature and pressure the mineral is amorphous, and at high pressure and room temperature it takes on a tetragonal structure. Velocity extrapolations based on tetragonal CaPv do not match seismic values in the mantle. The elusive cubic CaPv was first found in 2018 in a South African mine, trapped and encased in a diamond during the diamond's formation deep in the mantle.[5]

Gréaux and colleagues have now met the challenge of measuring the seismic properties of cubic CaPv at conditions akin to those in Earth's mantle. The researchers compressed a 2-mm-diameter $CaSiO_3$ glass rod at a temperature of 1700 K to a pressure of 23 GPa using a multi-anvil press at the Japan Synchrotron Radiation Research Institute (figure 2).

The researchers measured the time it took for ultrasonic waves to travel through the CaPv in the pressure cell at various temperature and pressure combinations. They used x-ray diffraction to verify that during the experiments the sample had and maintained its cubic structure. By combining the *in situ* sound-wave travel times and diffraction patterns, the researchers derived sound-wave velocities and elastic moduli for CaPv.

Gréaux's team found that the shear modulus of cubic CaPv at 23 GPa was 26% lower than estimates calculated from first principles.[6] The unexpectedly low rigidity means that seismic waves travel significantly more slowly in CaPv than previously thought. The velocities match seismic observations at the boundary depth of about 660 km between the upper and lower mantle.

Stagnant slabs

The experiments demonstrate that seismic-wave velocities through subducted oceanic crust are much slower at depths around 660 km than the global average velocities through pyrolite. The results are consistent with oceanic crust stagnating at the top of the lower mantle.

The results do not preclude other possible explanations for slow seismic velocities at the boundary between upper and lower mantle. Hydrated rocks can release water as they are pushed downward. The resulting aqueous fluids can trigger melting in the lower mantle, and melted material could also lead to low seismic velocities. Water-containing minerals encased in diamonds that originated at similar depths provide evidence for dehydration melting. (See the article by Marc Hirschmann and David Kohlstedt, Physics Today, March 2012, page 40.) However, dehydration melting remains a controversial concept due to questions about water solubility in certain key minerals at relevant pressures and depths. Minerals at 660 km might not contain enough water to have an effect.

"The deep interior of our planet is still largely unknown, and of particular interest is how it interacts with Earth's surface over geologic time scales," says Hauke Marquardt (University of Oxford). Understanding the fate of subducted slabs helps reveal how material is transported deep in the mantle. For example, any crust that accumulates at the bottom of the upper mantle would play a different role in the convective processes that carry molten material back upward than if it reached the core–mantle boundary at 2900 km. (See the article by Eugene Humphreys and Brandon Schmandt, Physics Today, August 2011, page 34.)

The research combines seismologic observations with experimentally determined properties of minerals to find former oceanic crust in Earth's mantle. More detailed seismological studies could help map regions of the mantle that have low seismic velocities at a range of depths. Localized maps would reveal differences between shear and compressional wave velocities relative to the surrounding mantle. Additional measurements of sound-wave velocities in single crystals of CaPv and of the polycrystalline samples in Gréaux's experiments could explain how observed velocities change depending on the direction of travel through the crystal lattice.

Rachel Berkowitz

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Exoplanet research evolves with statistical and technological advances

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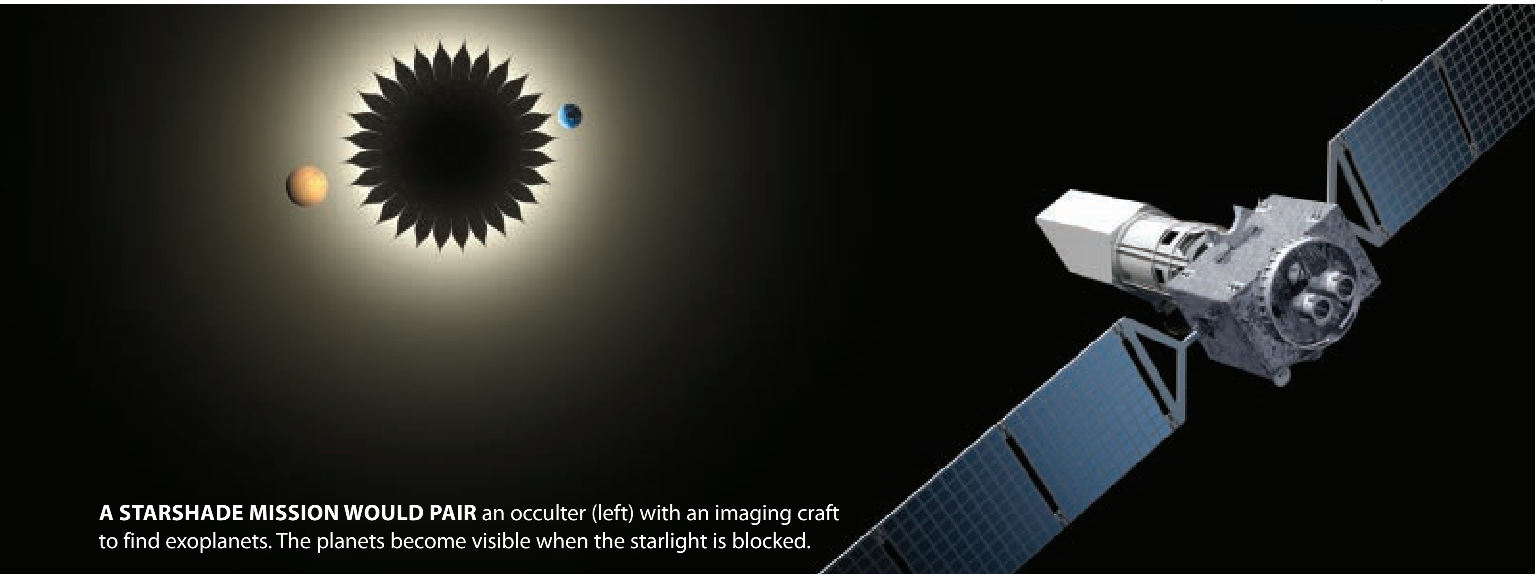

A STARSHADE MISSION WOULD PAIR an occulter (left) with an imaging craft to find exoplanets. The planets become visible when the starlight is blocked.

"Planet finding has become mainstream," says MIT astrophysicist Sara Seager. "It's remarkable how quickly it went from being hard and challenging to 'Hey, let's train the next student to find planets.' "

In the roughly quarter century since the first exoplanets were discovered, astronomers have found thousands of them. And the field is shifting from tallying celestial bodies to unraveling mysteries: How do planetary systems form? How do planets form? How typical is our solar system? Is there life elsewhere?

In the decade following the first discoveries, scientists studied exoplanets one at a time. Then statistical studies ramped up because of the many planets found by NASA's *Kepler* mission, which monitored a 115 square-degree patch of sky from 2009 to 2018. The *Transiting Exoplanet Survey Satellite* (*TESS*), launched last year, marries the two approaches. *TESS* will scan 85% of the sky to identify candidate planets, which astronomers can then study in detail with other instruments; the planets that *Kepler* found are typically too distant and faint for detailed characterization. "The science is maturing," Seager says. "If we get enough planets with *TESS* and measure mass, orbital properties, atmospheric properties, and so on, we'll be able to solve some of the growing list of puzzles." (See also the interview with Seager at http://physicstoday.org/seager.)

Beyond *TESS*, the community is planning future space missions and ground-based instruments to understand formation of planetary systems and identify possible signs of life. A pathway, including possible missions, is laid out in *Exoplanet Science Strategy*, a report by the National Academies of Sciences, Engineering, and Medicine, released last September. Its recommendations will be submitted to the 2020 decadal survey of astronomy and astrophysics.

Stars and planets

The transit method is responsible for the most exoplanet detections to date—out of some 3891 confirmed detections as of press time, the *Kepler* satellite found 2695 and *TESS* spotted 3. Slight periodic dimming in a star indicates an orbiting planet that partially blocks light from its host star, from which the planet's diameter can be obtained. (See the article by Jonathan Lunine, Bruce Macintosh, and Stanton Peale, PHYSICS TODAY, May 2009, page 46.) And by spectroscopic comparison of light that comes directly from the host star and light that has passed near the planet, the planet's atmospheric composition can be probed.

Other methods for spotting planets include radial velocity, direct imaging, astrometry, and gravitational microlensing. The methods are sensitive to different types, sizes, and orbital separations of planets and stars, and they reveal different characteristics of the systems. *Kepler* found planets mostly within 1 AU (the mean distance between the Sun and Earth) of their host star. The radial-velocity method goes out to roughly 5 AU, and direct imaging is most sensitive to planets with orbits greater than about 20 AU (the orbit of Uranus). The gap from 5 AU to 20 AU can be observed by gravitational microlensing, in which an exoplanet introduces a blip in the way its host star bends a background star's light. Gravitational microlensing can spot small and distant planets. To date, the method is credited with finding 72 exoplanets.

With the radial-velocity method, a periodic Doppler shift in starlight indi-

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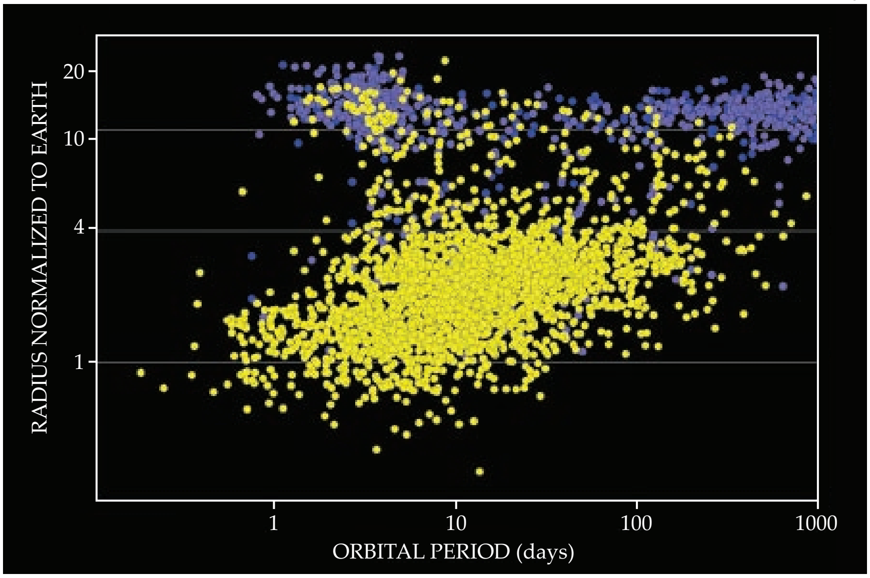

THE *KEPLER* MISSION GAVE THE FIELD OF EXOPLANETS a big kick, from pure counting to statistical studies. This plot shows the 3567 confirmed exoplanets that had been discovered as of 14 December 2017. Yellow dots represent the 2525 planets found by *Kepler*, with blue and violet dots indicating planets found before and after *Kepler*.

cates the back-and-forth pull on the star by an orbiting planet. The method gives a lower limit on the planet's mass, which can be obtained if the orbit inclination is known. The approach is best suited to high-mass planets with low-mass host stars because their gravitational pull is greater and therefore more easily detected. If the same system is observed with the transit and radial-velocity methods, the size and mass give the planet's density. From that, scientists can glean whether the planet is rocky or gaseous.

The two most important findings about exoplanets so far are their sheer numbers—the galaxy contains many more planets than stars—and their diversity, says Ignas Snellen of Leiden University in the Netherlands. In particular, the planetary systems that have been discovered are unlike our solar system, so then the question is, "Are we unique?" The jury is still out on whether Earthlike planets and planetary systems similar to our solar system are actually rare. "It could be that our instruments have not been sensitive to the right-sized planets at the right distance from the right type of star," Snellen says.

Super-Earths and hot Jupiters

"Solar systems are hard to see," says Stanford University's Bruce Macintosh. "And the realization that our solar system may not be typical is spectacularly exciting." It was lucky for *Kepler* that there are so many medium-sized planets at 1 AU or closer, he adds.

Those medium-sized planets—larger than Earth by a factor of 1.6 to 4—are a perplexing discovery. They are very common, so astronomers wonder why our solar system doesn't have one and what they are. From the density alone, astronomers can't tease out whether those exoplanets are mostly rocky with a lightweight atmosphere made of hydrogen and helium or are mostly water and methane and resemble ice giants like Neptune.

Figuring out the composition of the super-Earths—or mini-Neptunes—would help answer where they formed, says Andrew Vanderburg of the University of Texas at Austin. If they are mostly water, they probably formed far from their host star, where water and methane exist as ice. If they are mostly rocky with a layer of hydrogen and helium, they probably formed close to their host star. "It's a really challenging question," he says. "We are left grasping."

Hazes have stymied efforts with the *Hubble Space Telescope* to obtain direct spectroscopic measurements of individual exoplanet atmospheres. But the *James Webb Space Telescope* (*JWST*), which is scheduled to launch in 2021, is more sensitive and, because it will observe in the IR, is better able to peer through planetary haze. Another approach to studying the super-Earths is to look for correlations between planet size and temperature. A

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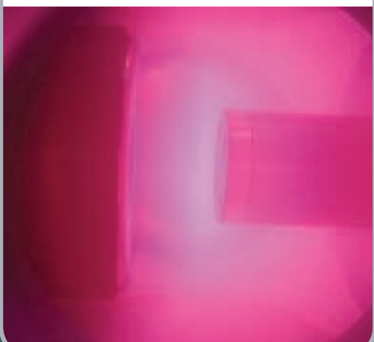

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theory that is gaining traction, Vanderburg says, relates to how hydrogen gas evaporates: Planets shrink if the gas around them evaporates, so close to their host star, smaller planets are hotter.

Astronomers are also trying to crack the super-Earth/mini-Neptune puzzle by looking at planets with special characteristics. The planet WASP-47e, for example, has a short orbit of 19 hours. That means it's hot, so any hydrogen gas it may once have had would be gone, and there is one less variable to worry about. If it started off as rock, its density should be close to that of Earth, whereas if it started with methane, water, and hydrogen, a lower density is expected. For WASP-47e, "spectroscopic observations suggest water or methane," says Vanderburg. The bottleneck in understanding the super-Earths is characterizing them, he says. "When *JWST* launches, we'll look at individual planets and then leverage what we learn to get hints about what to study next."

The most common stars in the Milky Way are red dwarfs, or M stars. They are smaller, dimmer, and cooler than the Sun, so the so-called habitable zone, where the temperature is consistent with life, is closer in (see the Commentary by David Stevenson, Physics Today, November 2018, page 10). Radial-velocity and astrometry measurements, which look for a star's tiny movements that result from a planet's gravitational tug, produce better signals for M stars than for larger stars.

"A lot of people are looking for planets around M stars because it's easier to find planets that are more Earthlike," says Andreas Quirrenbach of the University of Heidelberg. "And with the technology in 10 years, it will be possible to get spectra and study their atmospheres." (See the article by John Johnson, Physics Today, March 2014, page 31.) Planetary systems centered on red dwarfs may help astronomers understand planet formation, but it would be a surprise if they host life, he says. "Red dwarfs are active, they have outbursts," and the radiation would be harmful to life.

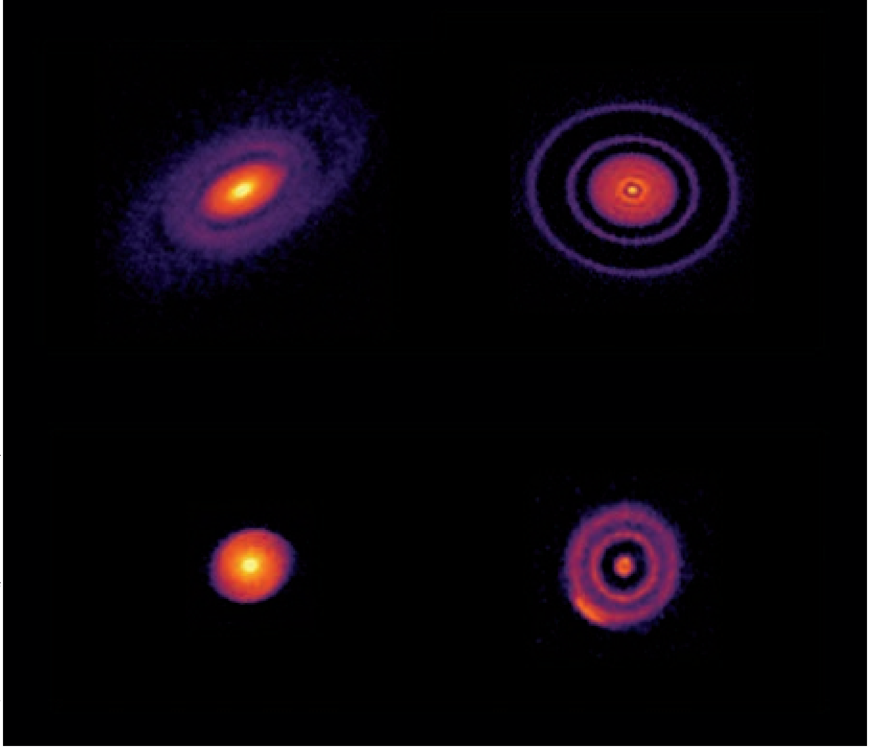
Hot Jupiters—gas giants that are close to their host star—are another type of exoplanet not found in our solar system. How and where they form are open questions. It's widely held that the early stage of planet formation involves the clumping of dust, small rocks, and ice. (See Physics Today, November 2015, page 16, and the article by Robin Canup, April 2004, page 56.) If a clump gets big enough, its gravitational pull on gases and other materials makes it grow more. But the medium stage of formation is still a mystery.

"I am interested in planets of all shapes and sizes. Right now, I focus on gas giants because the larger the planet relative to the star, the larger the signal," says Laura Kreidberg, who studies planetary atmospheres as a junior fellow at the Center for Astrophysics | Harvard & Smithsonian. "The amount of water in a planet's atmosphere provides a fossil record of the formation of the planet." With current instruments, she says, water is the easiest molecule to detect, but with future facilities, methane, carbon dioxide, and other chemical species will be observable. (See the Quick Study by Heather Knutson, Physics Today, July 2013, page 64.)

"Hot Jupiters can't form near their stars because there isn't enough material, but if they form far from the star, how do they get close in?" says Anne-Marie Lagrange of the University of Grenoble Alpes in France. Do they fall into the star by gravitational pull and lose energy due to friction? Are they pulled in by the gravity of another planet? Studying how well the orbits line up may give clues to planet formation. "Thirty years ago we knew little about how planetary systems form. We still have many questions, but the progress is incredible," Lagrange says.

Atmospheric disequilibrium

Atmospheric composition is also the best shot astronomers have of detecting life on exoplanets. "Disequilibrium is a hallmark of life," says Scott Gaudi of the Ohio State University and the cochair of the National Academies study on exoplanet research. Methane and oxygen react to form water and carbon dioxide. For both methane and oxygen to be abundantly present in a planetary atmosphere requires living sources—oxygen can come from photosynthesis and methane from bacteria, for example. The most likely scenario would be to find simple life, as was the case on Earth for most of its existence. "Knowing if there is life on other worlds is a big-picture question," says Gaudi, "and the fact that we can answer it soon makes this time



ALMA (ESO/NAOJ/NRAO); S. ANDREWS ET AL.; N. LIRA

SOME OF THE MANY PROTOPLANETARY SYSTEMS that have been imaged by the Atacama Large Millimeter/Submillimeter Array in Chile are shown here. By studying them, astronomers hope to learn more about planetary formation.

different from any other time in human history."

For now, the exoplanet community is making hay with the data that started flowing in from *TESS* last summer. Dozens of ground-based facilities worldwide are targeting for study stars *TESS* finds that seem likely to harbor planets. As extremely large ground-based telescopes, with mirrors 20–40 meters in diameter, begin coming on line next decade, it will become possible to measure masses of smaller planets and to image and characterize atmospheres of both transiting and nontransiting planets. And current and future space-based observatories will bring to bear additional astrometry and microlensing tools for the search and study of exoplanets. The European Space Agency's *Gaia*, for example, is using astrometry to identify likely planetary systems. And NASA's *Wide Field Infrared Survey Telescope*, now scheduled for a mid 2020s launch, will help complete the exoplanet census with its microlensing survey.

The US community is pursuing possible missions with launch dates foreseen in the 2030s. The National Academies report recommends that NASA "lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars." The two most-studied missions that could fit that bill are the *Habitable Exoplanet Observatory* and the *Large UV Optical Infrared Surveyor*.

A leading proposed method for directly imaging planets involves a starshade with a pair of spacecraft working together: One carries the shade and the other does the imaging (see page 24). Current specifications put the shade at tens of meters in diameter and tens of thousands of kilometers from the imaging craft.

The studies of stars and exoplanets all feed into questions about the physics of planetary surfaces, atmospheres, and interiors; how planetary systems formed; why there is such a diversity; and, ultimately, the search for life. Four pillars make up the broader field, says Gaudi. (See the article by Mario Livio and Joe Silk, PHYSICS TODAY, March 2017, page 50.) The first pillar is to complete the census of exoplanets. Next is to understand the various planet types in detail. The third is to look for Earthlike planets orbiting Sunlike stars and search their atmospheres for biosignatures, specifically for the telltale disequilibrium of certain chemicals. The fourth pillar differs in that it focuses on advanced life, not signs of life in general: SETI, the search for extraterrestrial intelligence, "is more risky," Gaudi says. "The probability that it pays off is small, but if it does, the implications are enormous and far-reaching. I believe in a balanced portfolio."

Toni Feder

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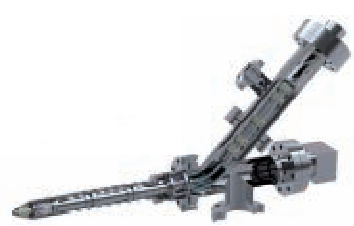

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DOE uranium contract raises fairness concerns

Agency is criticized for conducting an apparently piecemeal process to satisfy its future requirements for enriched uranium. Stipulation that material have US origin is also questioned.


CENTRUS ENERGY

CENTRUS ENERGY IS BEING AWARDED a no-bid contract from the Department of Energy to demonstrate the production of high-assay low-enriched uranium using 12-meter-tall centrifuges, shown here.

The US Senate's third-ranking member has challenged the Department of Energy's decision to award a $115 million no-bid contract to Centrus Energy to demonstrate a uranium enrichment process and produce a small quantity of a little-used fuel for the agency's advanced reactor R&D program.

DOE says Centrus is the only company capable of producing so-called high-assay low-enriched uranium (HALEU) by 2020 while adhering to US policy requiring that enrichment for military consumption be performed with US-origin technology. In a 23 January letter to Energy secretary Rick Perry, Senator John Barrasso (R-WY), who chairs the Committee on Environment and Public Works, asked Perry to explain why US-origin policy should apply to HALEU, which contains up to 19.75% of the fissionable uranium-235 isotope.

Barrasso, whose state has the most uranium reserves in the US, said the contract "appears to use American taxpayer funding to bailout Centrus, an unsuccessful business that relies on commercial relationships with Russian state-owned corporations to stay in business." He added that the contract had not been authorized by Congress, nor had funding been appropriated.

In addition to advanced reactor development, HALEU is used to fuel some research reactors. All US commercial reactors use low-enriched uranium (LEU), which contains about 4% ^{235}U.

Barrasso also inquired of Perry why the Centrus contract for HALEU shouldn't be considered part of the much larger need for uranium enrichment that has been identified by DOE's National Nuclear Security Administration (NNSA) for both tritium and naval reactor fuel. (See PHYSICS TODAY, March 2018, page 29.)

The Centrus contract calls for a pilot plant consisting of 16 centrifuges. NNSA officials have indicated they intend to build an enrichment plant capable of supplying both DOE's defense and HALEU needs. In a 2015 report to Congress, NNSA said their plan would require 1440 Centrus centrifuges. The January contract award, however, was made by DOE's Office of Nuclear Energy, which supports civilian R&D, and covers only HALEU.

Uranium used for civilian purposes isn't subject to domestic-origin limitations. Soon after the Centrus award announcement, Urenco USA, a foreign-owned US enrichment plant operator, said it is preparing to supply HALEU to the US market.

The US and other nuclear weapons states have long abided by policies to clearly delineate military and civilian nuclear assets. The rationale is that intermingling the two would encourage other countries with civilian programs to start nuclear weapons programs. But the US has crossed the civilian–military line on at least three occasions in the past.

Centrus CEO Daniel Poneman, from 2009 to 2014 DOE deputy secretary, acknowledges there is no "inherent logic in balkanizing the uranium requirements into a bunch of segments, so that you don't do something that the country by universal consensus is going to require in due course." But he says the HALEU contract is "a logical step on the road to restoring a broader domestic capability" for enrichment. "You crawl before you walk; you walk before you run."

Although Barrasso requested a response from DOE by 8 February, a spokesperson said he had not received one by press time. DOE did not respond to a request for comment on Barrasso's letter.

Barrasso has previously questioned DOE's dealings with Centrus. In 2015 he wrote to then Energy secretary Ernest Moniz expressing "serious concerns" with Poneman's hiring by Centrus, saying it "epitomizes the inappropriate and legally questionable relationship that DOE has had with this private company." In his January letter to Perry, Barrasso cited Government Accountability Office (GAO) findings that DOE had illegally traded publicly owned uranium to the US Enrichment Corp (USEC) to pay the company for environmental cleanup activities. USEC, now known as Centrus, had operated two now-shuttered DOE-owned enrichment plants. The trades also harmed uranium producers in Wyoming and other states by depressing uranium prices, he said.

Centrus spokesperson Jeremy Derryberry says the uranium barters were DOE's idea. "We were a contractor and that's how they chose to pay us. We weren't circumventing anything."

From producer to broker

Centrus emerged from the 2013 bankruptcy of USEC and marketed enriched uranium from retired Russian warheads to US utilities through 2013. Today Centrus is a uranium broker to US nuclear-power utilities. Its main source of enriched uranium is the Russian state-owned TENEX.

USEC and Centrus, with funding from DOE, developed very large, 12-meter-tall

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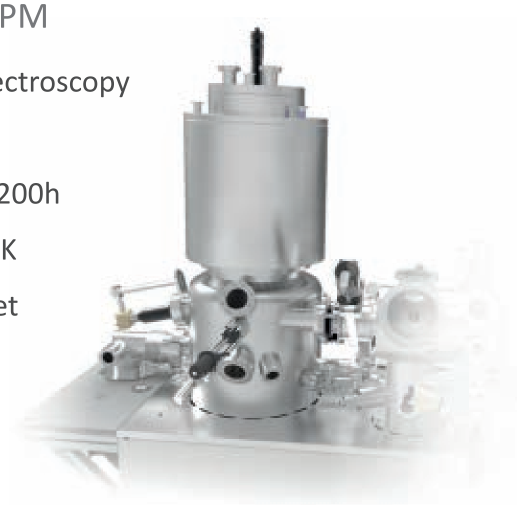

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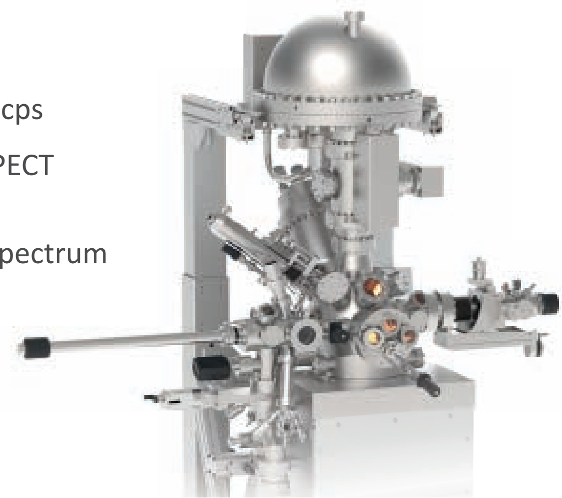

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enrichment centrifuges called AC100s. Other modern centrifuges are believed to be no more than 5 meters in height. In 2009 DOE rejected USEC's request for $2 billion in loan guarantees to commercialize the AC100; the centrifuges weren't then sufficiently developed, according to DOE.

After several more years of technology development, DOE in 2013 funded a three-year demonstration of a 120-centrifuge AC100 pilot plant located alongside DOE's former enrichment plant in Piketon, Ohio. The plant and the centrifuges were then dismantled, and Centrus continued to refine the technology, now known as AC100M, with DOE funding.

Derryberry says a global overcapacity and depressed prices for enrichment services have prevented Centrus from attempting to build a commercial plant in recent years.

DOE's 14 January notice of intent to award the HALEU contract says that Centrus "is in this unique position because it developed the AC100M centrifuge and associated equipment; it possesses proprietary data associated with advanced designs related to that technology; and it has demonstrated technical expertise in operating the AC100M equipment and technology. In sum, [Centrus] is the only US-owned and controlled entity capable at this time to demonstrate and operate the only existing US-origin uranium enrichment technology on the required schedule."

Both Ohio senators, Rob Portman (R) and Sherrod Brown (D), issued statements welcoming DOE's award. The Centrus plant will be located at Piketon.

The US has lacked the capability to enrich uranium with a domestic-origin technology since the 2013 shutdown of the USEC-operated plant in Paducah, Kentucky. The gaseous diffusion process used at Paducah and Piketon was not competitive with centrifuges, and NNSA has said that restarting it would be more costly than building a new centrifuge facility.

An alternative source

Urenco USA operates the sole US uranium enrichment plant, which uses centrifuges developed by a UK-Dutch-German consortium. Urenco officials announced on 5 February that the company has begun design engineering and licensing activities to produce HALEU at its New Mexico plant. Melissa Mann, president of Urenco USA, says the company's centrifuge technology has demonstrated capability to produce HALEU, but building a dedicated module for HALEU will require an amended license from the Nuclear Regulatory Commission.

Producing HALEU will require new procedures and processes to prevent a criticality, in which a mass of fissile material becomes sufficient to sustain a nuclear chain reaction. Higher levels of safeguards and security also are required, since HALEU's ^{235}U content, close to the 20% threshold that defines highly enriched uranium (HEU), presents an increased proliferation concern. Further, notes Mann, new containers must be developed and licensed to transport HALEU, in the form of gaseous uranium hexafluoride, from the plant to facilities where it will be converted to metal or oxide and fabricated into fuel. The container-licensing process could take up to seven years, she says.

According to US interpretations of international nonproliferation agreements, Urenco's European-developed centrifuges bar it from supplying uranium for US military purposes.

Only Russia currently enriches HALEU, but it does not offer it commercially. DOE has been obtaining HALEU by diluting small amounts of its 500-ton-plus stockpile of HEU with unenriched uranium. DOE estimated in 2017 that it will require 3–7 metric tons of HALEU annually in 2019–34 and 7–9 tons per year thereafter. But it said a new HALEU source wouldn't be needed before 2025.

Separately, DOE announced in January its intent to fabricate up to 10 tons of HALEU fuel at its Idaho National Laboratory. The HALEU should be obtained by reprocessing spent HEU fuel from a former experimental breeder reactor at the site. It's unclear whether the Idaho material was factored into DOE's 2017 forecast.

DOE's notice of intent to award the Centrus contract does not identify military uses for HALEU. However, in January the Department of Defense requested proposals from industry to develop small mobile reactors that could be transported by truck to power temporary military installations and provide off-the-grid electricity to permanent bases. Known as Project Dilithium, the DOD program specifies that the mobile reactors are to be HALEU-fueled.

In his letter to Perry, Barrasso asked whether US-origin requirements apply to uranium used to generate electricity for the military. US military bases currently use power from the commercial grid. In 2017 93% of the uranium purchased by US nuclear power plant operators was imported, according to the Energy Information Administration.

A second potential military application for HALEU is in a conceptual design effort by DOE's naval reactors program for a propulsion reactor. All US nuclear ships currently are fueled with weapons-grade HEU, which is 93% or greater ^{235}U. Although Congress ordered the HALEU design development, the US Navy has made clear in reports and testimony its preference to continue using HEU in future reactors.

A larger enrichment need

The AC100 technology is favored to be chosen by the NNSA to provide LEU for the production of tritium used in nuclear weapons and ultimately to produce new HEU for naval reactors. But an alternative small-centrifuge technology is under development at Oak Ridge National Laboratory, and NNSA expects to complete a detailed comparison of the two centrifuges this year. In the 2015 report to Congress, NNSA said it has enough stockpiled LEU to meet tritium requirements until at least 2038 and sufficient HEU to meet naval reactor needs until 2064.

In 2016 NNSA put the cost of the AC100 plant at between $7.5 billion and $14 billion and estimated that a plant using the less mature Oak Ridge technology would cost $3.8 billion to $8.3 billion. A 2018 GAO report called those estimates outdated and unreliable.

The need for a new enrichment plant was debated at the highest levels within the Obama administration, and Moniz was a strong advocate. There were concerns over its expense, and time ran out for the administration before a decision was reached. One source who was involved in those deliberations says that DOE's record on building new facilities indicates that a plant capable of meeting all DOE needs could cost $50 billion or more.

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Ernest Lawrence's brilliant failure

Joshua Roebke

Lawrence, the creator of the cyclotron, also tried to bring the first color TV to American consumers. The story of his efforts reveals how the history of television was connected to physics and the military.

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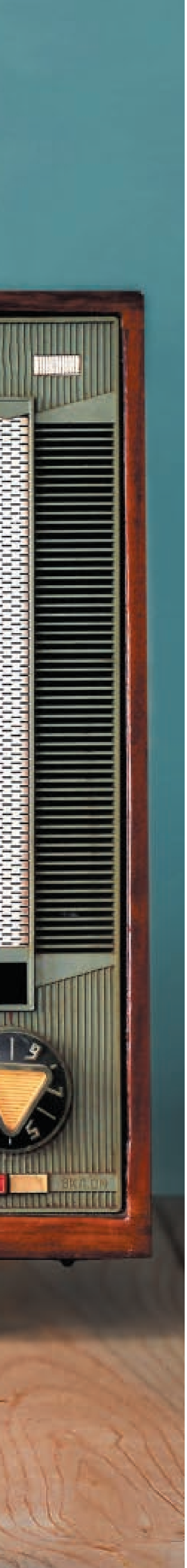
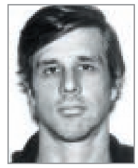


Joshua Roebke is an author and researcher who also teaches at the University of Texas at Austin. His book *The Invisible World: The Story of Particle Physics and the Forces That Shaped the 20th Century* won a Whiting Foundation Creative Nonfiction Grant in 2016 and is forthcoming from Farrar, Straus and Giroux.



There are more television sets in the United States than there are people. Three-quarters of American households include a personal computer or tablet, more than those with either a cat or a dog. And nearly two-thirds of all Americans—yes, counting children—now own a smartphone. Screens are the windows through which we look at the world; they are the glassware through which we work, communicate, and play.

Just 60 years ago, however, it was barely possible to transmit color images to electronic screens. For two decades after World War II, companies spent hundreds of millions of dollars trying to display moving images in living color. Their brilliant failure only began to fade during the 1960s because of the gradual refinement of vacuum tubes and electronics. Some of the best tubes originated from an unexpected source: Ernest Lawrence (see figure 1) and other physicists from the Radiation Laboratory at the University of California, Berkeley.

Physicists largely remember Lawrence for his development of the cyclotron, which earned him the Nobel Prize in Physics in 1939. Historians typically recognize him for another activity that made him infamous: his advocacy for nuclear weapons. The labs that he established in California to support both endeavors are still named after him today: Lawrence Berkeley and Lawrence Livermore National Laboratories. But Lawrence believed that he would always be remembered for a third pursuit—the development of color television. He even feared that it would be all that he was remembered for.

In 1948, when his subordinates at the Radiation Laboratory began to construct the Bevatron, the largest accelerator at that time, Lawrence had already begun to direct his energy elsewhere. He dedicated himself to his other, dueling passions: hydrogen bombs and color televisions. His devotion to the first was attributed to patriotism, and his interest in the second was dismissed as a hobby, but it was not so easy to disentangle his motives. Color screens could display more than variety shows and evening news; they could highlight foreign rockets and incoming bombers. His work on color television also bespoke his patriotism, and, as with atomic weapons, it was an outgrowth of his physics.

Television sets used to be particle accelerators. Electromagnetic fields propelled beams of charged particles across vacuum tubes and toward their intended targets, the color phosphors on glass screens. Families gawked at the light radiating from such collisions, much as physicists scanned the images of scattering events hoping for discoveries. The physics of beams applied equally well to the electrons that transmitted sitcoms and to those that revealed the existence of quarks.

Physicists readily adapted their expertise to improving broadcasts and sets. Lawrence even founded a television company that employed dozens of physicists, including two future Nobel laureates—Luis Alvarez and Edwin McMillan. The history of color television was thus rooted in Lawrence's physics and his fears throughout the early Cold War.

Black and white to color

At the end of World War II, there were 3000 televisions in the continental US, and the images they displayed, as in most photographs and theaters, were wan and black and white. Three years later US companies were producing nearly a million televisions a year. The growth in television happened so fast that the Federal Communications Commission (FCC) stopped issuing station licenses so as not to exhaust the bandwidth.

Senator Edwin Johnson (D-CO) wanted a physicist to compel the FCC to increase its bandwidth and permit the manufacture of color sets. So in May 1949 he instructed Edward Condon, the director of the National Bureau of Standards, to investigate ultra-

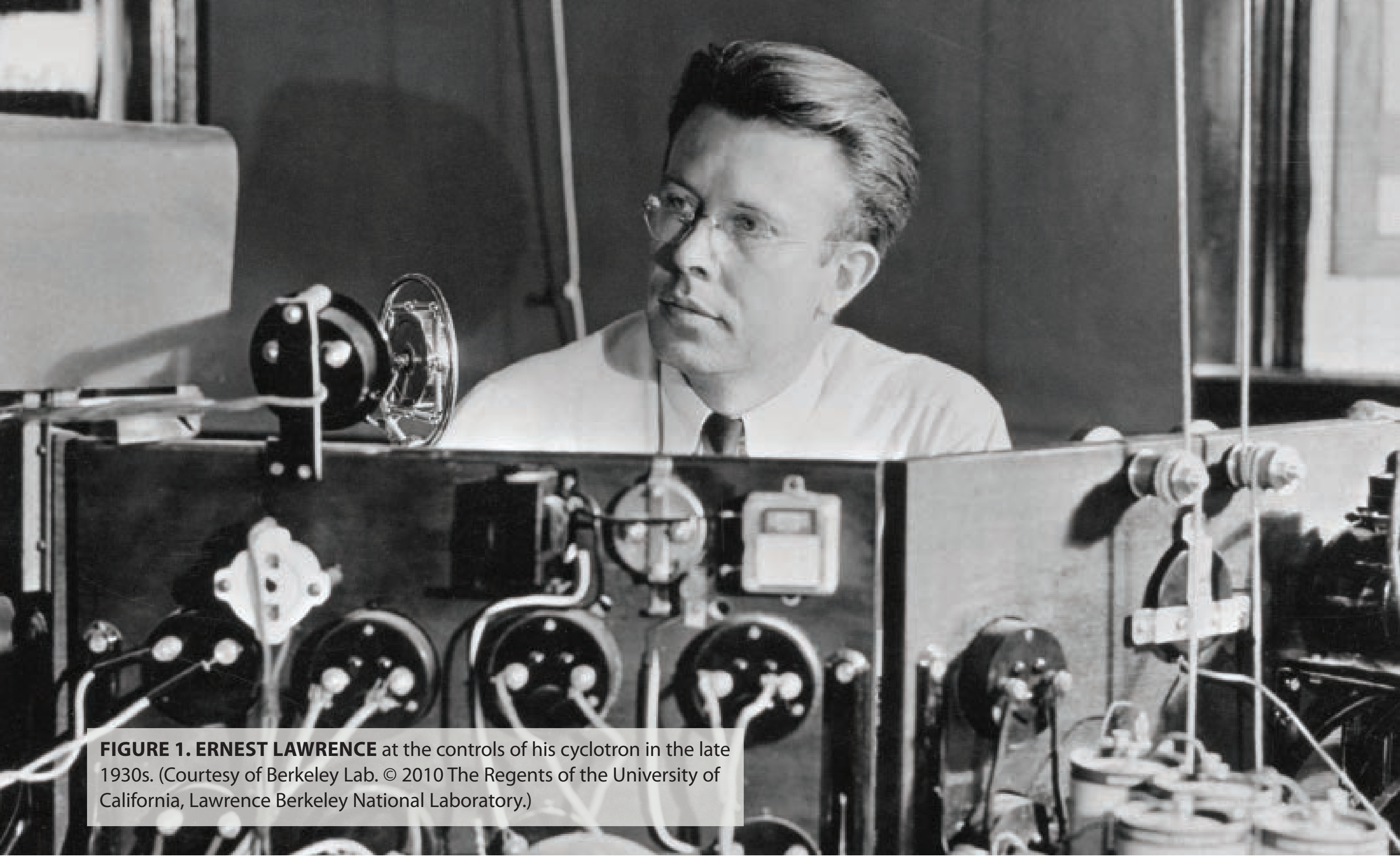


FIGURE 1. ERNEST LAWRENCE at the controls of his cyclotron in the late 1930s. (Courtesy of Berkeley Lab. © 2010 The Regents of the University of California, Lawrence Berkeley National Laboratory.)

high-frequency broadcasts and a standard for color television. Six days later, the FCC invited three companies—RCA, CBS, and Color Television—to demonstrate color prototypes. Lawrence rushed to compete with them.

The story that Lawrence later told journalists about the origin of his television company, like most creation stories in business, was either an exaggeration or a lie. His interest was not piqued one Christmas morning when his children asked why their television set glared in black and white yet the world shone in color. And he did not jot down his first ideas on wrapping paper.

In the spring of 1948, George Everson, the director of personnel at Lawrence's Radiation Laboratory, introduced his boss to Philo Farnsworth, a television pioneer and the subject of a biography that Everson was writing. Lawrence had once designed a black-and-white television before Farnsworth's model superseded it. Lawrence was thinking of trying again, in color, so he conferred with Farnsworth and a few knowledgeable colleagues in Berkeley. Alvarez, for one, was already a popular consultant on television technology because of his innovations to radar systems during the war.

Later that spring Lawrence traveled to Mexico with Seeley Mudd, a notable physician and philanthropist. Aboard his private plane, Mudd told Lawrence that the head of engineering at Color Television, George Sleeper, was developing electronic screens that would display in either black and white or color.

After he returned from Mexico, Lawrence was driving south along California's coastal highway to his summer house on Balboa Island, and he had an idea. He imagined a television in which charged wires deflected a beam of electrons to fluorescent compounds on a glass screen. Earlier that spring, Lawrence had begun taking notes in a ledger to revolutionize the cyclotron. But his beloved accelerator had already been surpassed by the designs of Alvarez and McMillan. So Lawrence jotted down his television idea and dedicated his ledger instead to revolutionizing color screens.

When Lawrence returned to the Bay Area, he visited the law offices of Lippincott & Smith. Donald Lippincott represented Alvarez and Farnsworth and was preparing to file the patent on Sleeper's color television, so Lawrence met with the other partner, Samuel Smith. Smith warned that RCA had already patented a tube like the one that Lawrence imagined. The next day, Lawrence designed a pair of glasses with a rotating color wheel for watching TV. But Peter Goldmark, who had just introduced LP records, was already installing such wheels inside televisions for CBS.

Lawrence asked Alvarez to help devise an original idea. In San Francisco, they witnessed Sleeper's working set and, a day or two later, Sleeper's lawyer showed them its pending patent. The next day Lawrence sketched a new television tube, with color phosphors arrayed much like Sleeper's. Lawrence then did what he had done with the cyclotron; he directed two young men from his laboratory—Dick Mack and William Ross Aiken—to build a working device.

Other designs

Motion pictures were once successions of photographs—moments in time recorded on frames of film. Projectors advanced static frames in synchrony with the original recording and shined a light through them onto a screen. Our brains then set those frames in motion.

Television cameras minced images. They scanned what was in front of them—side to side, top to bottom—and converted the intensity of light into electronic signals. The signals were then transmitted serially as radio waves to sets. The procedure was complex, so the television was not developed until decades after the cinema. And color only compounded the problem. The electronic signal was multiplied by three, once for each of the primary colors—red, blue, and green.

There is no single way to parse visual information, so each company did it differently. RCA divided images into dots. Color Television cut them into lines. CBS projected whole images through mechanical color wheels. The different systems, however, were incompatible; the signal from one could not be displayed on the set of another.

So while his assistants were struggling to realize a prototype in 1949, Lawrence worked toward a better way to encode signals and compress information that would comply with every system. Lippincott told Lawrence that the idea was timely and shrewd.[1] If he could build a working set that displayed the signal from any system, his television would be competitive, whatever standard the FCC approved later in the year.

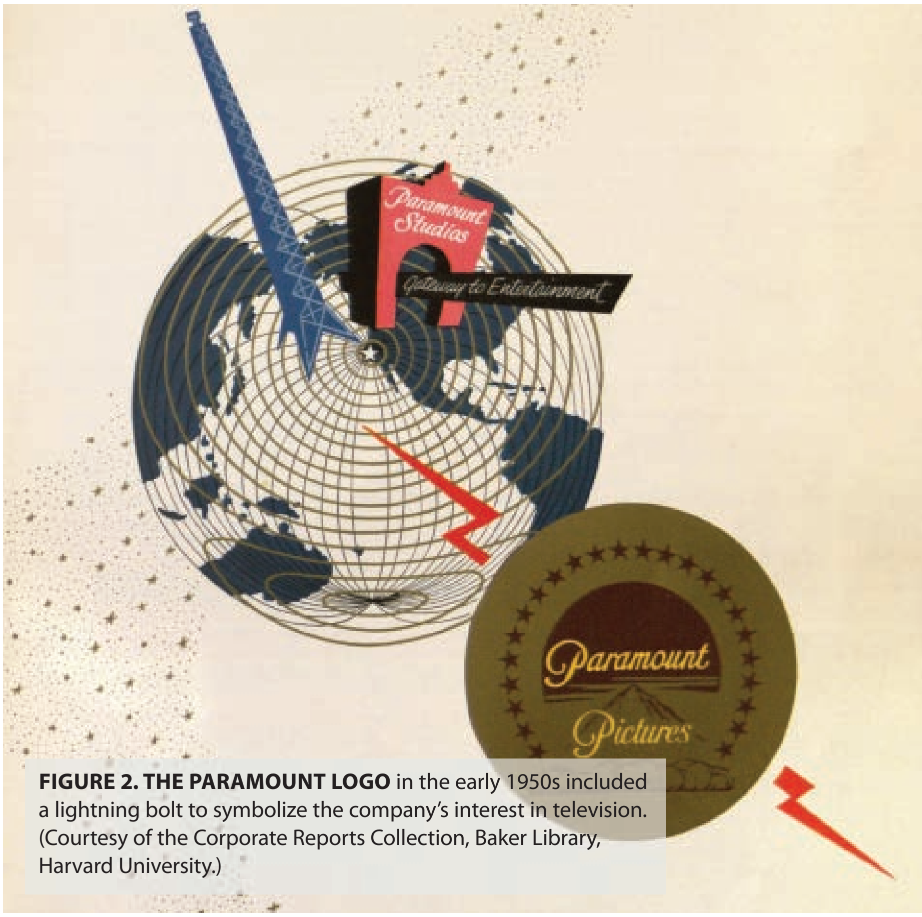


FIGURE 2. THE PARAMOUNT LOGO in the early 1950s included a lightning bolt to symbolize the company's interest in television. (Courtesy of the Corporate Reports Collection, Baker Library, Harvard University.)

Near the end of that summer, the Soviet Union detonated an atomic bomb. Three days later, the FCC hearings on color television proceeded at the urging of Johnson, who would also advise President Harry S. Truman on a super bomb. Lawrence and Alvarez brooded over hydrogen bombs while fretting over color television. In October they flew to Washington, DC, and lobbied the Atomic Energy Commission (AEC) to construct an enormous linear accelerator that could make uranium isotopes and tritium for bombs. Lawrence and Alvarez returned to Berkeley without any support, but they proceeded with their plans anyway.[2]

That fall, Lawrence purchased a third house, in Diablo, California. His family did not like its isolation, so Lawrence invited his colleagues over. They futzed around on color televisions and talked about super bombs inside the two-car garage.

On 28 October 1949, the FCC postponed its decision on a color standard until the coming year. But it stipulated that every color set should display black-and-white signals too. That same day scientists convened in Washington, DC, to advise the AEC about a hydrogen bomb. Alvarez was in the city consulting at the FCC television hearings, and he also showed up to lobby J. Robert Oppenheimer, chair of the AEC's General Advisory Committee, for the linear accelerator.

In business

In January 1950 Lawrence requested $7 million from the AEC to build a prototype for his giant Materials Testing Accelerator, also called the Mark I, on a former military base in Livermore. Two days later he struck a deal with the two young men refining his television. On the counsel of lawyer and businessman Rowan Gaither, Mack and Aiken should receive a third of all profits from Lawrence's color tube.

During the war Gaither had acted as a liaison between the physicists who designed radars and the companies that produced them. He was assuming that role again. In January 1950 Gaither and Lawrence established Gaither & Company, which invested the counselor's money in the physicist's devices. As the hearings on color television resumed in Washington, DC, a month later, the two men founded a second company, Telecolor.

Lawrence's color television prototype was still crude, but so were all the others. RCA's system had fragile mirrors. CBS's mechanical wheel was incompatible with black-and-white signals. Sleeper's set flickered so much that it was impossible to watch. Lawrence knew he could compete. So as the FCC hearings progressed, he renegotiated with his associates. He now agreed to pay them half of any future profits, but only up to $20 000 (roughly $200 000 today). Lawrence already knew that his idea was worth much more. Less than a week later, he filed for patents on a color television that displayed broadcasts from any other system—with phosphors deposited on metal strips, like venetian blinds, behind the screen.

The day after the filing, Gaither advised Richard Hodgson, the director of television development at Paramount Pictures, that he should meet Lawrence. The protracted struggle between cinema and television had only just begun. In 1948, the Supreme Court ended the studio monopoly in Hollywood and ordered Paramount to divest itself of theaters. So Paramount had invested in its competing technologies and became a media conglomerate. Now, it might invest in Lawrence. He and Hodgson even had something in common: Before Hodgson began developing televisions for a movie studio, he had worked on radar and managed physicists at Brookhaven National Laboratory.

Lawrence and Paramount struck a deal. Barney Balaban, Paramount's president, bought a half stake in Telecolor for $1 million and changed the name to Chromatic Television Laboratories. Hodgson became the president. Lawrence and Gaither joined the board. Alvarez, McMillan, and other physicists became consultants. Paramount even added a flash of lightning to its logo to represent its interest in electronics and Chromatic (see figure 2).

Lawrence immediately spent Paramount's money to equip his garage in Diablo. The location was convenient to his other responsibilities; Diablo was halfway between Berkeley and Livermore, where his accelerators were under construction. Lawrence even made labels to distinguish the instruments owned by Paramount from those he brought from his other labs. He then bought a Ping-Pong table and a fridge, which he stocked with beer, so everyone could have some fun at their third jobs.

Innovation and regulation

During the summer of 1950, the Korean War imposed on their plans. Lawrence and his colleagues were already busy constructing two accelerators with public funds, but they still wanted to compete with private television companies during wartime. Chromatic issued a press release asking the FCC to delay the color standard.

The FCC did not. That fall the regulator established CBS's mechanical system as the national standard. The FCC had ignored Condon's report, which praised Lawrence's idea, and voted against its own stipulation to preserve black-and-white broadcasts. After the decision, however, a federal court issued a stay on manufacturing color televisions, so as not to divert material from the war. RCA then sued for a better standard. The company had just developed a tube in which three beams passed through tiny holes in a metal plate called a shadow mask, resulting in a sharper image. RCA maintained that the federal regulator had backed a mechanical system unbefitting the electronic age.

FIGURE 3. ERNEST LAWRENCE, EDWIN MCMILLAN, AND LUIS ALVAREZ (left to right) admire a finished Chromatron. (Ernest O. Lawrence papers, BANC MSS 2005/200c, oversize box 3. Courtesy of the Bancroft Library, University of California, Berkeley.)

On the day the FCC announced its standard, Gaither informed Alvarez that "the latest model of the pump-connected tube has just arrived at Chromatic. If it performs well, we may issue a press release tonight or tomorrow."[3] Lawrence was so optimistic that he was already seeking manufacturers to license the tube. But it failed so decisively that Alvarez designed a mechanical set to comply with the seemingly inevitable standard.

Within a week, however, Lawrence told Hodgson that he had a new idea, a metal grid that Alvarez and McMillan thought was promising. He was going to try it out in his garage at Diablo.[4] When Alvarez had struggled to focus the beam inside his linear accelerator, he inserted a grid of wires. Lawrence and his technician, James Vale, fashioned a comb of charged wires that similarly focused electrons and then accelerated them. RCA's shadow mask focused its beams, but it absorbed so many electrons that the picture was dull. And RCA's tube had three electron guns; Lawrence's contained one.

From the point of view of physicists, Lawrence's design was elegant. Years later, McMillan even testified that the principles behind it and his accelerator were the same. McMillan built only one synchrotron, however; Chromatic wanted to make millions of television sets.

Lawrence's innovation—bands of wires that acted as a lens and a prod for electrons—was nearly impossible to mass-produce. It had to be woven by hand like fine cloth and its specifications were beyond the capabilities of any manufacturers. Still, Balaban fibbed to the stockholders of Paramount, "I can now report that Chromatic has produced practical color television tubes. These tubes also appear to have considerable value for military purposes."[5]

The Supreme Court upheld the FCC's mechanical standard in 1951, and color broadcasts were scheduled to start that June. But CBS could not make a screen larger than 12 inches, and its picture was still jerky. No one would buy one, so CBS executives tried to purchase the rights to Lawrence's tube. Chromatic instead joined RCA to compel the FCC to adopt an electronic standard.

Lawrence and his colleagues continued tinkering with their tube. After months of frustration and broken glass, they silk-screened phosphors onto a Lucite window and bolted it to a metal set. A loud vacuum pump ran continuously to clear the air inside. Nothing was audible over the pump, and the screen was plastic, but Lawrence and his colleagues had a viable prototype.

On 19 September 1951, Lawrence demonstrated his television and its hand-woven grid at Paramount's headquarters in New York City. Journalist William Laurence glowingly reported in the *New York Times* that the tube "reproduces colors with a lifelike fidelity without any apparent fuzziness." Lawrence primarily touted its application to national defense, as he did his accelerators.

Within weeks, Lawrence had patented an improved grid with steel wires threaded through holes in a supporting frame.

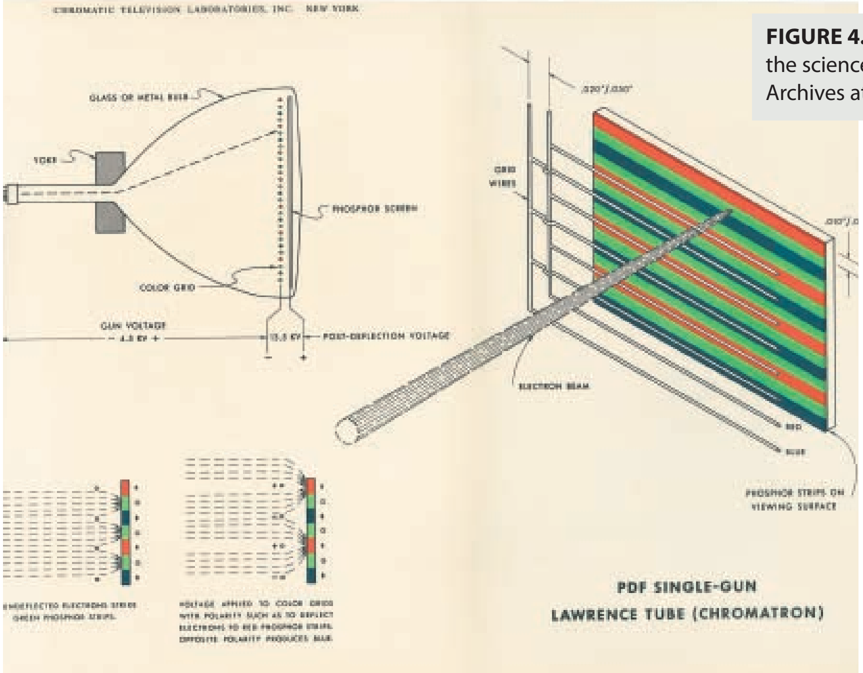


FIGURE 4. A BROCHURE FOR THE CHROMATRON emphasized the science behind the television. (Courtesy of the National Archives at San Francisco.)

Vale wove a ceramic thread perpendicular to those wires to dampen vibrations that defocused the beam. Chromatic purchased a building in Oakland to be its West Coast development lab, and trucks carrying steel and glass arrived daily. Lawrence and his associates felt the pressure of Paramount's investment. Don Gow, one of Lawrence's technicians, later said that Chromatic had underestimated the costs. The employees were used to working in a federally funded lab, not running a business.[6]

Chromatic and its competitors had even bigger problems. In October 1951, the National Production Authority ordered companies to cease producing color televisions again to prevent engineers and scarce materials from being diverted from military priorities. Companies were allowed to continue R&D, as long as federal contracts were not delayed.

Lawrence did not let regulation interfere with business. He had already postponed the Bevatron to complete the Mark I, which was also delayed and over budget, yet Lawrence designed color televisions unabated. That fall, McMillan received the Nobel Prize in Chemistry. Chromatic became the first company in the US, and the second in the world, to employ two Nobel laureates. Chromatic exploited its prestige and Lawrence's connections to promote an electronic standard.

In 1952 the *Wall Street Journal* reported that "Chromatic has made a vigorous assault on the ban." During meetings that Chromatic facilitated between regulators and television companies, CBS, RCA, and Chromatic argued for rescinding the halt order. CBS even decided that its mechanical system was inadequate, and the company announced that it too would support abandoning the mechanical standard for an electronic one.

That summer Lawrence sold his house in Diablo and moved his business out of the garage. From Oakland, he and his colleagues continued to string grids, now using nuts and saddles like those in a guitar. Paramount demonstrated Lawrence's latest tube, which had a 22-inch screen. "About the only criticism was that the colors tended to be too 'deep'," the *Wall Street Journal* reported on 23 December. Lawrence named his tube the Chromatron, in remembrance of his beloved cyclotron (see figure 3).

Fade to color

In January 1953, Lawrence traveled around the world with his family and met film stars on location. While he was away, Representative Charles Wolverton (R-NJ) scheduled hearings to determine the status of color television. "When," the representative asked, "will color television become a reality in the homes of the American people?"[7]

Lawrence sent his regrets from the Mediterranean, so Hodgson read a statement. Chromatic was producing dozens of tubes every day that could display any broadcast. "We are not talking about a gleam in some scientist's eye, or a blueprint design, or just a laboratory model," he testified. "We are referring to fully developed picture tubes that have been demonstrated successfully."[8] To prove the claim, Chromatic broadcast the coronation of Queen Elizabeth II to sick children in a London hospital that June.

The FCC agreed to reconsider its standard. RCA submitted a 700-page petition for an electronic system that it had spent $40 million to design. Paramount Pictures had its own financial worries. The company had just introduced widescreen and 3D films, and it had purchased the Warner Brothers lot on Sunset Boulevard in Los Angeles for its investments in electronics. Paramount wanted a return.

Chromatic produced a full-color brochure that included biographies of its physicists to sell television tubes based on their reputations (see figure 4). That November Crosley Radio and Television became the first company to license the Chromatron. Although retailers had begged the FCC not to announce a new color standard before the holidays, on 18 December 1953, the regulator approved RCA's electronic system. The era of color television officially began.[9]

Lawrence and his colleagues pressed to ready their tube in Oakland. They filed patents for different crosshatches of wires and leased a production plant in nearby Emeryville. They met there every Saturday to review their progress. Alvarez said, "This operation, which spent money extravagantly, resembled a downtown branch of the Radiation Laboratory."[10] That winter Chromatic signed its first production contract, to deliver green-and-orange radar screens to the US Navy.

For much of 1954, newspapers reported on the competition for television primacy among RCA, CBS, and Chromatic. The last claimed that its color sets would have the largest screens and retail for $500. RCA lowered its price and claimed that Chromatrons emitted radiation, so consumers might fear its science rather than buy it.

Yet Chromatic and its licensees still struggled to manufacture their accelerating grid. And as Hodgson admitted, "One out of twenty [tubes] might be satisfactory and the others would implode.”[11] Even still, RCA manufactured only 50 000 color televisions before 1955, a quarter of the company’s goal. Its sets also had to be wired by hand, and its phosphors were uniquely aligned with each shadow mask.

Exodus

In 1954, while Alvarez was the vice president of Chromatic, he asked his young colleagues at the Radiation Lab to build a tiny bubble chamber filled with liquid hydrogen to record the scattering of charged particles. He then proposed building one that was six feet wide. He wanted to make a large detector for the Bevatron rather than mass-produce small ones for others. In designing the bubble chamber, however, Alvarez realized it would capture too much data. Physicists would have to scan thousands of images or automate their discoveries. Lawrence helped Alvarez secure $1 million to develop the hardware and software to identify particles on screens. The computer revolution arrived in Berkeley before it emerged across the San Francisco Bay.

On 6 February 1956, a story on the front page of the *Wall Street Journal* called the Chromatron “tantalizing.” Meanwhile, Lawrence was still filling his ledger with ideas. On 4 March, he wrote in his notebook that the color and brightness of his latest prototype were so good that it might be even better than RCA’s set.[12]

Within weeks, however, Chromatic unraveled. Craig Nunan, the director of research, abruptly quit. He and three other engineers had been poached by Varian Associates, which was founded by physicists at Stanford University. Varian also produced vacuum tubes for televisions and accelerators, and it was the first company in Stanford Industrial Park. Hodgson, the president of Chromatic, then announced that he was leaving. A year later he wrote the check that founded Fairchild Semiconductor, which also moved into Stanford Industrial Park. That company produced the silicon chips that gave Silicon Valley its name.

Lawrence now sought a deal that would sever his ties to Chromatic.[6] On 1 January 1957, Litton Industries purchased Chromatic’s production plant in Oakland to manufacture radar screens. Alvarez wrote to a friend that Litton had also bought the company’s physicists as part of a package deal.[13] Alvarez resigned from Chromatic when he was appointed to the board of Hewlett Packard, which had also moved out of a garage and into Stanford Industrial Park.

In mid January, Paramount finally bought Lawrence and Gaither’s remaining interest for $160 000. Chromatic’s laboratory in the Paramount Building became the headquarters of a new subsidiary, Autometric, which developed “rapid automatic methods of handling masses of complex and conflicting information and reducing them to a decision.”[14] Autometric did for spies what Alvarez did for particle physicists.

In the summer of 1958, Lawrence was in Geneva to negotiate a nuclear-test-ban treaty when he became ill. Five days after President Eisenhower announced the moratorium, Lawrence died. Gaither delivered the eulogy for his partner. A year later he cofounded Draper, Gaither, and Anderson—the first venture capital firm in Silicon Valley.

Foreign success

In 1961 Masaru Ibuka and Akio Morita, the founders and chief executives of the Sony Corp, witnessed a demonstration of Lawrence’s tube at a trade show in New York.[15] The next day, Morita negotiated a license with Paramount; Japan was the only other country in the world with color programming, but there were only about 1000 RCA sets in the country. Senri Miyaoka, a physicist, traveled to New York to retrieve the Chromatron from Autometric.

Sony demonstrated its first color television in Tokyo in 1964. The company boasted that it had significantly improved an American technology, but it had as much trouble with mass production as the Berkeley physicists. The following year, Sony released its first Chromatron television, with three electron guns instead of one so it would not have to divide a single beam into three. The sets were priced at less than half the cost to make one so the company could compete with RCA. Sony would only sell 18 000 of them despite a lifetime guarantee. Morita announced that his company would not introduce the Chromatron to the US market anytime soon. One company tried; Fairchild Semiconductor licensed the tube from Paramount but failed in mass production too.

Sony was on the verge of bankruptcy after its investment in the Chromatron. But a Sony engineer, Susumu Yoshida, recommended using a single electron gun, as in Lawrence’s original design. He and Miyaoka fashioned a tube that divided the beam three times and focused it twice, through a large electronic lens and small prisms. The beams then accelerated through a grill rather than a grid. Miyaoka worked 13 hours a day, 6 days a week, until he and his colleagues had a tube that transmitted clear pictures. In 1967, Ibuka named their homespun

FIGURE 5. A SONY TRINITRON TELEVISION sold in the UK. (Courtesy of the Science Museum Group Collection, CC BY 4.0.)

tube the Trinitron, after its three convergent beams from a single source and its origin as the Chromatron.

The Trinitron system became the innards of the best-selling televisions in the world and the color screens that most Americans grew up with (see figure 5). By 1973 it accounted for 38% of the company's sales, and it was cited as a leading factor in the trade deficit between the US and Japan. IBM installed Trinitrons in its personal computers, and the Federal Aviation Administration used them exclusively in radars. Sony even bought its own movie studio, Columbia Pictures, and became the media conglomerate that Paramount had wanted to be.

Lawrence is barely remembered for his contribution to color television. But innovations are rarely the product of a single genius toiling in a garage. They don't even result from sound business decisions much of the time. The advent of color screens was not the product of either. No company has employed three Nobel laureates and failed as dramatically as Chromatic Television. Sony succeeded in refining its foreign technology, but only because of its stubborn persistence through near bankruptcy. The development of our ubiquitous color screens is thus a sordid tale at the intersection of government, science, academia, and business, as so many innovation stories are.

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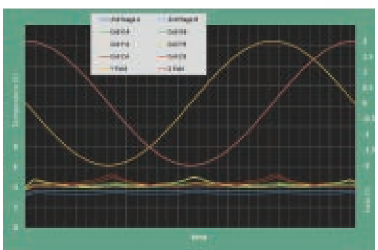

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Anne Matsuura is the director of quantum applications and architecture, **Sonika Johri** is a quantum algorithms research scientist, and **Justin Hogaboam** is a senior quantum systems architect at Intel Labs in Hillsboro, Oregon.

A systems perspective of QUANTUM COMPUTING

Anne Matsuura, Sonika Johri,
and Justin Hogaboam

Quantum architects, with knowledge of both physics and computer engineering, are key to developing scalable quantum computers.

Quantum computing research is coming of age. Recent engineering advances in quantum bit, or qubit, systems have led to a steady stream of successful physics experiments that demonstrate the computational capabilities of small numbers of qubits. Companies are tackling the difficult task of advancing beyond small, lab-scale, proof-of-principle devices to build scalable quantum computing systems that utilize those capabilities. The ultimate goal of a full quantum computing system of commercially relevant scale—thousands to millions of logical qubits—is to harness the power of quantum mechanics inside a technology capable of solving real-world problems that are intractable for classical computers.

Historically, quantum computing research has existed in the realm of physics and mathematics and has concentrated on two fundamental areas: qubits and quantum algorithms. Qubit research has focused on the creation, operation, and performance benchmarking of qubits in experimental devices. Those efforts have been guided by the DiVincenzo criteria, which list the operational conditions necessary to demonstrate quantum computing in a physical system.[1] Quantum algorithm research has focused on developing algorithms[2] that can be implemented on abstract ideal qubit systems and, more recently, on real qubit systems.[3] However, a quantum computing system will be composed of far more than algorithms and qubits, just as a classical computer is made of more than software programs and transistors.

How does one create a quantum computing system that takes a quantum algorithm as input and automatically performs a computation on qubits? Researchers have now begun to define the essential functionalities of the architectural layers[4,5] without specifying how to build the remaining components of a fully operating and reproducible quantum computing system. Examples of a few of those functionalities are illustrated in figure 1.

Opportunities are available for those willing to acquire the cross-disciplinary skills needed to help build a fully scalable quantum computer. Designers of such a system are asking thought-provoking questions that cross the boundaries between physics, engineering, and computer architecture.

Application-driven design

How does one program and run a quantum algorithm on real qubits? First it is decomposed into a quantum circuit (see box 1) comprising a series of logical operations, or gates. Designers find symmetries in the physics that simplify the circuits and enable the algorithms to run on the few physical qubits available today. However, quantum algorithms cannot be optimized completely by computers yet, and so those painstaking calculations must be done entirely by hand. Aided by software tools, the designer then estimates the number of qubits and gates required by analyzing how the accuracy of the result is affected by parameters such as coherence times, gate fidelities, and approximations in the algorithm. Optimization tools should be developed that eliminate the need to simplify algorithms by hand. For example, they should be able to quickly generate various circuits that achieve the same targeted unitary transformation and then allow the circuit designer to pick the best one.

Today a number of programming environments allow compilers to perform rudimentary optimization of algorithms and prepare them for resource analysis, simulation, or execution on a particular type of qubit. Basically, the compilers take a quantum circuit and translate it into a sequence of logical quantum instructions known as quantum assembly language (QASM). The text-format language represents the quantum circuit as a series of operations. The instruction sequence describes what needs to happen to each qubit in order to run the given algorithm.

From the algorithm designer's perspective, the QASM code sequence is now ready to execute on a real qubit system. Unfortunately, all QASM-defined quantum logic gates are not necessarily available on every type of qubit system. Qubits can be created out of many materials, and the choice determines which physical quantum gates are available. Such gates, called native gates, are specific to the underlying qubit system. The logical QASM operations must therefore be translated into the corresponding sets of native gates. However, in doing so, researchers need to consider factors that influence system design and architecture, such as whether the logical qubit operations used in the algorithm can run directly on the qubit system. If they can't, what equivalent gates or gate sequences can be run? What gates can be run in parallel? How many gates can be run in series within the fidelity, or error, budget?

After choosing the appropriate logical operations and type of qubit, the researcher applies the sequence of native gates to real physical qubits. From an algorithm designer's perspective, a two-qubit gate can be applied between any pair of available qubits. However, in many types of systems, those two qubits must be physically near one another to perform the operation. Thus the algorithm needs to be mapped to the parts of the qubit grid capable of executing operations and be sequenced into a schedule of operations that can be optimally implemented, sometimes in parallel, within the limitations of the quantum device.

Mapping and scheduling the algorithm operations onto the qubits is difficult because most qubit devices have limited, often nearest-neighbor, connectivity, which places constraints on where particular qubit operations can be implemented. Operations between more distant qubits may require shuttling or quantum teleportation, which rapidly depletes the quantum resources available to run the algorithm.[6] Mapping and scheduling protocols are made even more challenging because physical qubits are notoriously fragile and noisy, so protocols need to be created that can adapt to those imperfections.

Ensuring that a quantum computer is initialized to a state that is as similar as possible for all algorithmic runs is also important because quantum algorithms must be executed repeatedly to achieve a statistically meaningful result. The process must be performed in a rapid and accurate manner so that it does not introduce an additional source of error into potentially thousands of runs of the quantum circuit.

As in classical computing, error correction will be critical for the reliable functioning of a quantum machine, but classical

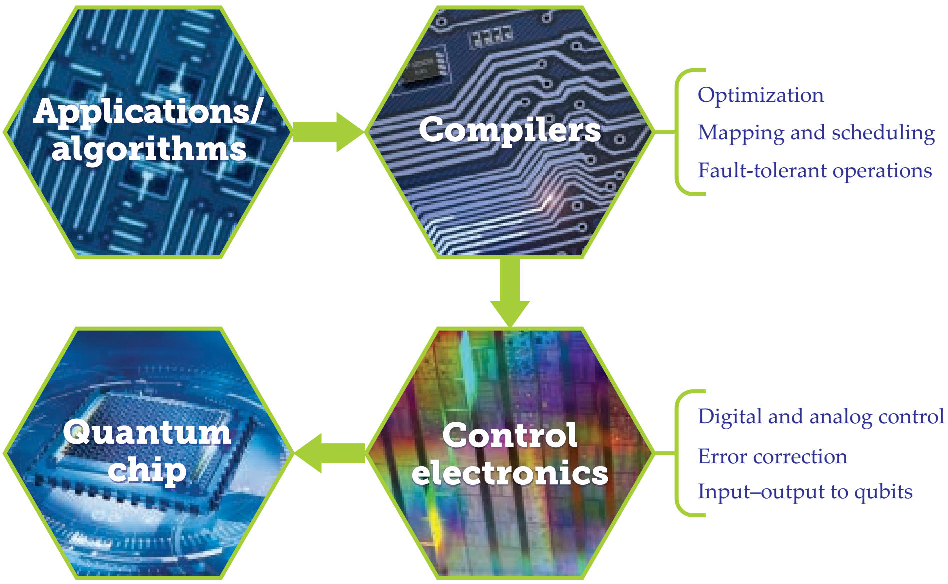


FIGURE 1. FUNCTIONALITIES NECESSARY FOR A QUANTUM COMPUTER are shown here. An application-driven design will help determine how to create a system that will accelerate algorithms from a particular application area. (Applications/algorithms: Jay M. Gambetta, Jerry M. Chow, and Matthias Steffen, CC BY 4.0; compilers: iStock.com/Bet_Noire; control electronics: Steve Jurvetson, CC BY 2.0; quantum chip: Yurchanka Siarhei/Shutterstock.com.)

error-correcting protocols do not work directly for quantum computing. Like bits in classical computers, the information encoded in individual qubits can be destroyed by environmental noise. However, quantum computing error sources are more numerous, and error rates are much higher. Quantum error correction involves encoding a logical qubit state in multiple physical qubits and using measurements and classical computing resources to detect errors quickly enough to correct them during computation. In today's Noisy Intermediate-Scale Quantum (NISQ) era,[7] the short qubit coherence times and low gate fidelities require a high ratio of physical to logical qubits. The lack of active feedback in most current qubit devices means that state-of-the-art ones still cannot apply a nondestructive error measurement to a series of qubits, identify the source of errors, determine a correction, and implement the correction within the lifetime of the physical qubits.

Since the number of physical qubits is currently limited, error-mitigation techniques, as opposed to full, rigorous error correction, need to be designed for the NISQ-era devices. One such technique is the removal of errors using additional or postselected measurements.[8] The hope is to eventually build a fully fault-tolerant quantum computer that is robust to physical errors. Such a computer requires qubits with long lifetimes, high-fidelity gates, and fast feedback—all challenges for the research field.

The first quantum computers probably will be coprocessors coupled with a classical central processing unit. In such a model, the quantum computer acts as an accelerator for a particular part of the algorithm. In the short term, when error correction is not available, the most promising algorithms are quantum–classical hybrids, which require an intimate coupling between the classical and quantum processors. Thus architectural design

BOX 1. CODESIGN: QUANTUM FOURIER TRANSFORM

In a quantum circuit, as shown on the left below, each line corresponds to a particular qubit. Each box represents an operation, and the chronological order proceeds from left to right. Quantum gates represent the unitary operations that need to be applied on the qubits and are denoted by specific symbols. Quantum gates are the building blocks of a quantum circuit, just as classical logic gates are the building blocks of digital circuits in classical computing. This particular diagram describes a quantum Fourier-transform (QFT) algorithm. Here *H* is the Hadamard gate, a one-qubit rotation that maps the qubit basis states |0> and |1> to two superposition states: |0> maps to |0>+|1> and |1> maps to |0>−|1>, where

$$H = 1/\sqrt{2}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}.$$

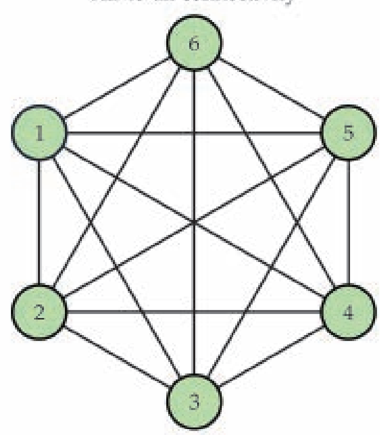
A controlled phase gate, $C\text{–}P_n$, acts on two qubits and applies a phase change when they are both in the |1> state:

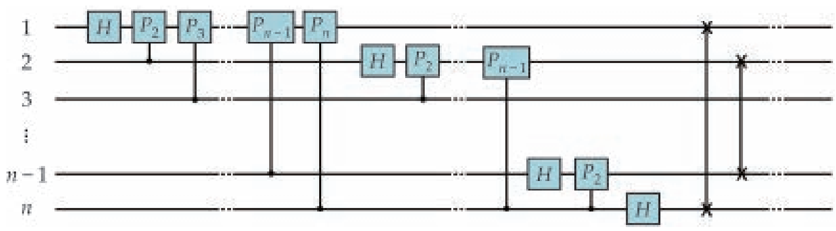
$$C\text{–}P_n\,|j\rangle \otimes |k\rangle = \exp\left(\frac{2\pi i(kj)}{2^n}\right)|j\rangle \otimes |k\rangle.$$

Each SWAP gate, denoted by a vertical line at the far right of the circuit, exchanges the quantum states of two qubits.

The quantum circuit is executed on *n* qubits, and the total number of gates scales as $O(n^2)$. The O notation classifies algorithms according to how their running time or space requirements grow with the input size. However, the circuit depth—the longest path between algorithm input to output—can be calculated as $O(n)$ in the optimal, theoretical case, when every qubit is connected to every other qubit, as shown on the right. The green circles represent individual qubits, and the black lines indicate where two-qubit gates are possible. It would be much easier to manufacture a linear array of qubits with nearest-neighbor connectivity as shown below on the left. A surprising result is that the QFT can be scheduled to run even on a linear array of qubits with a circuit depth that also has $O(n)$ scaling and only a small constant-factor overhead of 1.25. (For details, see A. Holmes et al., https://arxiv.org/abs/1811.02125.) The pseudocode for the algorithm at the bottom right has an outer loop that executes *n* times. Within the outer loop are two loops that can each be executed in parallel, which implies O(1) time steps. That algorithm construction also eliminates the need in the end for an extra time step with SWAP gates.

All-to-all connectivity

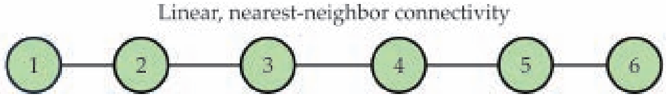




Algorithm 1 Linear Quantum Fourier Transform

```
logical qubit x_i mapped to physical qubit q_i
H (q_1)
for i in {2, 3, 4, ..., n − 1, n, n − 1, ..., 2} do
    j ← i
    while j ≥ 2 do Parallel
        CP_j (q_j, q_{j−1})
        j ← j − 2
        if j == 1 then
            H (q_1)
        end if
    end while
    j ← i
    while j ≥ 2 do Parallel
        SWAP (q_j, q_{j−1})
        j ← j − 2
    end while
end for
H (q_1)
```

Linear, nearest-neighbor connectivity



features throughout the computing system will likely be a mix of classical and quantum pieces. In the design of the instruction sequence, for instance, some researchers advocate for a hybrid of quantum and classical instructions,[9,10] while others propose that the instruction sequence should be purely quantum.[11] Whereas the efficient use of coprocessors in computer architecture is a well understood benefit of modern design, how to implement hybrid architecture for quantum computing remains an open research question.

Classical electronics for controlling qubits will be an integral part of any quantum computing system. Currently, even small qubit systems require racks of laboratory electronics and numerous wires for controlling and operating qubits in a cryogenic refrigerator or ultrahigh vacuum chamber. As the number of qubits scales up, the increase in on-chip and input–output wiring interconnects will introduce more heat and noise to the qubit system. Noise is also easily added during the often long delay times necessary to send electrical signals to the qubits in the chamber. Current qubit hardware uses between five and seven input–output cables for each qubit. However, that arrangement does not scale beyond a few tens of qubits before manufacturers would need to build larger, custom dilution refrigerators. The problem of interconnect scalability for qubit control will be critical to any quantum computing system of useful size.

Different qubit connectivity layouts and engineering constraints, such as the number of control lines relative to the number of qubits and the parallelization and selectivity for qubit control operations, introduce further restrictions. However, such restrictions offer opportunities for optimization. At Intel Labs, for example, research has shown that the quantum Fourier-transform algorithm can be scheduled to execute on a linear array of qubits with nearest-neighbor connectivity almost as efficiently as a fully connected qubit system, as shown in box 1.

The key to designing a quantum computing system is to develop a library of algorithms that are small building blocks of larger, real-world applications in areas such as quantum chemistry and condensed-matter physics. Those algorithms may then be used to drive the design of the full quantum computer system down to the physical qubits. Such an approach will help researchers understand the appropriate layers of functionality required to run the algorithm on real qubits and to design a scalable quantum computing system that incorporates those layers. Even with system noise, the knowledge gained by running small algorithmic building blocks can help researchers improve the system organization and architecture, including the optimal connectivity of the qubits and the appropriate qubit grid organization. By keeping the number of gates low, researchers can run small algorithms on as few as five to seven qubits[12,13] without using quantum error correction. If all the commonly used components of algorithms from a particular application area can be run separately, the hope is that full-scale quantum algorithms can be run on the larger-scale qubit system as the number of qubits and executable circuit depth are scaled up. An application-driven design will thus result in a system architecture that will serve as an accelerator for the particular application area. Although difficulties will arise as successively larger qubit systems are created, running algorithms on each generation of quantum hardware will allow researchers to learn from each new system and solve scaling problems in a systematic manner.

System versus qubit performance

Traditionally, quantum computing performance has been primarily focused only on qubits. The most important quantification metrics have been the physical characteristics of the qubit technologies themselves, such as whether they satisfy the DiVincenzo criteria by concentrating on longer qubit coherence times and on qubit gate performance as measured by gate error rates, gate execution speed, and interconnectivity. However, for quantum computing to move beyond physics research to a computer technology, researchers need to start thinking in terms of overall system performance, which is ultimately what end users will care about most.

Research that compares the hardware architectures of two systems built from different qubit technologies[14] illustrates issues from a hardware perspective. However, that perspective leaves out many components that are critical to a complete quantum computing system beyond individual qubit performance. The field is beginning to move toward approaches such as IBM's quantum volume metric that defines a family of quan-

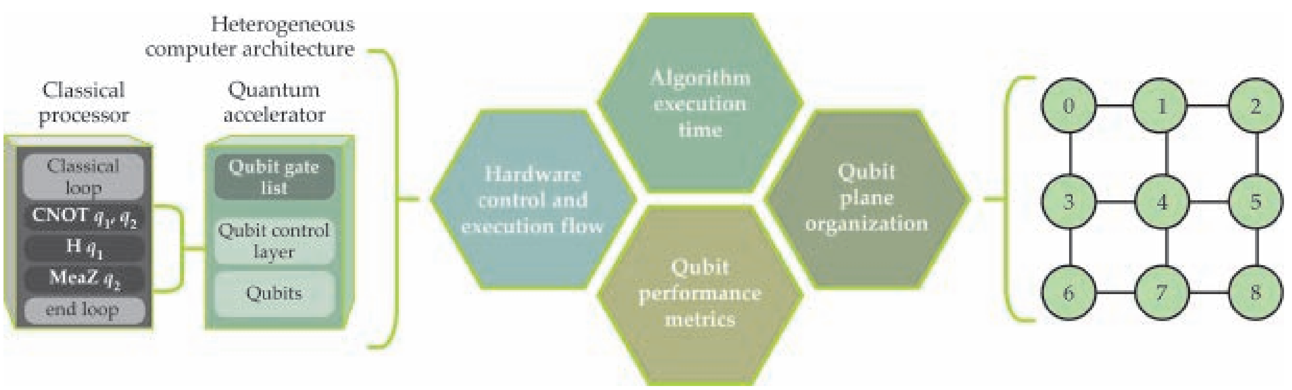
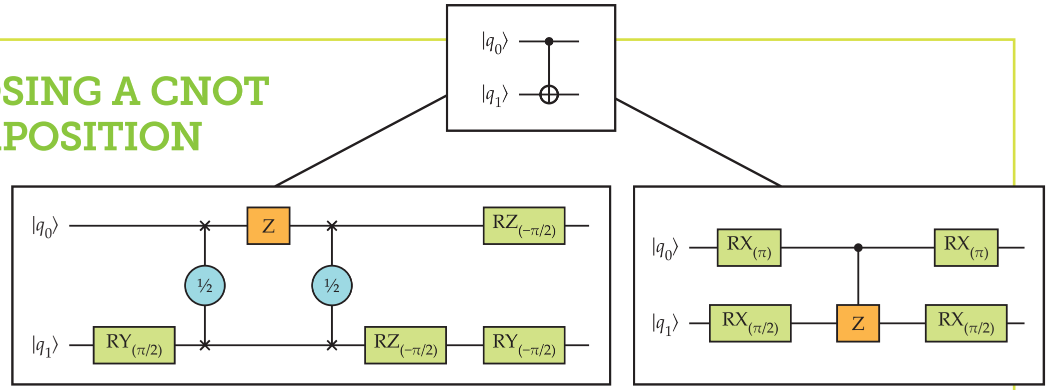


FIGURE 2. RESEARCHERS CONSIDER FOUR INTERACTING CATEGORIES OF FUNCTIONALITIES when designing a system capable of running a quantum algorithm automatically on real qubit devices. For example, the connectivity of the qubits, as shown on the right, may influence the number of control lines that connect to the qubits in the cryogenic refrigerator. The left side shows how the quantum coprocessor may interact with the classical processor.

BOX 2. CHOOSING A CNOT GATE DECOMPOSITION



A logical controlled-NOT, or CNOT, gate is an entangling operation that flips the target qubit between 1 and 0 if the control qubit is in the 1 state. It must be decomposed into a sequence of native quantum gates for the qubit technology to perform the gate operation on the specific qubit system. Two possible decompositions are shown, where RX, RY, and RZ denote rotations around the *x*-, *y*- and *z*-axes, respectively. A system performance simulation could provide metrics to help choose which CNOT to incorporate into the specific design.

Depending on the fidelity of the single- and two-qubit gates in the circuits and on their speed, researchers may want to choose only one to implement the logical CNOT in the system. Depending on the performance of the qubits available at a particular point in the execution of the algorithm, it is also possible to choose a different logical CNOT sequence.

tum circuits for measuring system performance.[15] Challenges in the field remain, such as defining a set of broader system performance metrics appropriate for a larger-scale computing technology and building on the lessons learned from running realistic algorithms for useful application areas on small qubit systems.

As quantum computing systems scale beyond small numbers of qubits running small algorithms, researchers may be able to leverage well-established engineering techniques from classical computing to learn how to design and scale quantum computers to sizes that are useful for more complex quantum algorithms. A few of the trade-offs architects consider when designing a quantum computing system are shown in figure 2. **Algorithm execution time** refers to the amount of resources that must be devoted to compiling and scheduling a sequence of quantum gates to run on the specific qubit device technology and qubit plane organization provided by the hardware. **Hardware control and execution flow** consist of the set of available quantum gates and the parallelism and degree of individual qubit control afforded by classical control electronics that will be key to determining how a system performs. **Qubit performance metrics**, such as one- and two-qubit gate fidelity, state-preparation and measurement errors, and coherence times, influence the maximal executable circuit depth, fault tolerance approach, and other system performance characteristics. **Qubit plane organization** considers how connected the physical qubits are to each other. If the qubit plane provides nearest-neighbor, two-dimensional planar connectivity between qubits, it will be possible to implement topological error-correction codes. If that degree of connectivity cannot be provided, then a repetition code or another error-correcting approach must be taken, which will affect the amount of fault tolerance that the system can provide.

The new multidisciplinary field of quantum architecture

In classical computing, software tools are used to model and simulate the functioning of all the components in the system, with its limitations and constraints, to enable better hardware design. Numerous alternate designs are first modeled in a system performance simulator before any hardware is built. In the case of quantum computing, creating a system performance simulator is a more computationally expensive task because of the superposition of states and the entanglement of qubits. In addition, the physics of the qubits themselves affects the functioning of the quantum computing system. The challenge is to construct a simplified Hamiltonian for a grid of qubits that when incorporated into the system performance simulator provides predictive insights for system design decisions without exceeding the running time and memory constraints of the simulation.

A system performance simulator for quantum computing involves two simulator classes. The first, a system simulator, models the software architecture, hardware architecture, and control electronics from the compiler down to the classical control pulses and interacts with the second, a quantum device simulator that mimics the Hamiltonians of few-qubit systems and the interface with classical control.

The first kind of simulator captures basically everything not quantum about the quantum computer, such as programming languages, the compiler, control schemes, and qubit connectivity. Such a simulator may help address quantum architecture questions such as the following: How many qubits are needed to enable useful applications? What number of qubits should the quantum architecture be able to handle in the next 10–20 years? Where should the division between room temperature and cryogenic control be? Should different elements of the architecture be constructed of different qubit types?

The second kind of simulator will consist of the Hamiltonian of a small number of qubits. It takes as inputs device-level metrics, such as the coherence times, one- and two-qubit gate fidelities, electromagnetic cross talk between qubits, qubit connectivity, and the electronics that are used to control the gates. Since a qubit is often an approximation for a multilevel quantum system, a low-level simulator may involve extra levels that have perturbative but nonvanishing effects on the system. The simulator may also incorporate noise such as charge-trapping defects for semiconductor dots and will allow researchers to perform functions like optimizing the implementation of common quantum computing algorithms, pinpointing the most damaging sources of noise, and debugging quantum hardware.

It would be more powerful to combine the two simulator approaches into one overall quantum computer system performance simulator. The joint simulator could run small algorithms on a model with, for instance, a specific compiler, qubit control system, type of qubit, and qubit connectivity. It could also analyze modifications to any of those components and reveal how the changes would affect overall computation. Computer architects then could make better design choices at both classical and quantum levels of the quantum computing system. Furthermore, experimentalists and qubit designers could analyze the impact of their choices regarding qubit type, connectivity, and control constraints and better understand how their qubits might be used in a full system environment.

Box 2 details a particular system-level design choice that could be facilitated by a system performance simulation. It shows two ways to decompose a common logical operation, the CNOT gate—a two-qubit gate that performs a NOT operation on the second qubit only when the first qubit is in state $|1\rangle$—into physical qubit operations and rotations. For a specific quantum system, the best choice for the physical gate decomposition will depend on many factors, such as qubit coherence times, gate fidelity, the execution time of the gate operation, and qubit connectivity. A simulator that models the entire quantum computing system will help with those design decisions.

The classical–quantum design choices that need to be made throughout the quantum computing system require researchers with knowledge of both physics and computer architecture design. The new field of quantum architecture stands poised to be an exciting career choice for a new generation of physicists. It bridges the boundary between quantum and classical computing and will be key to building truly useful quantum computers in the future.

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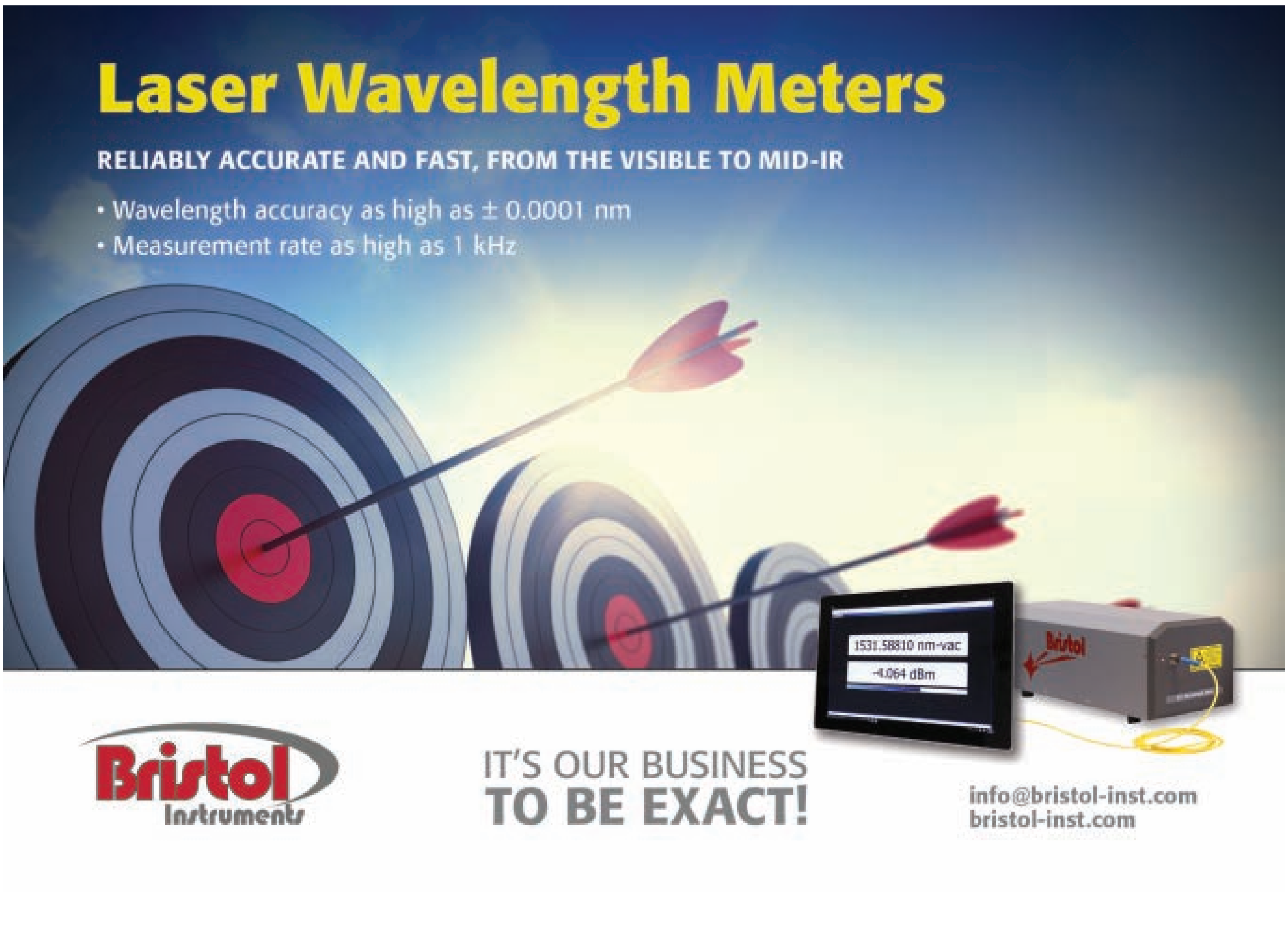

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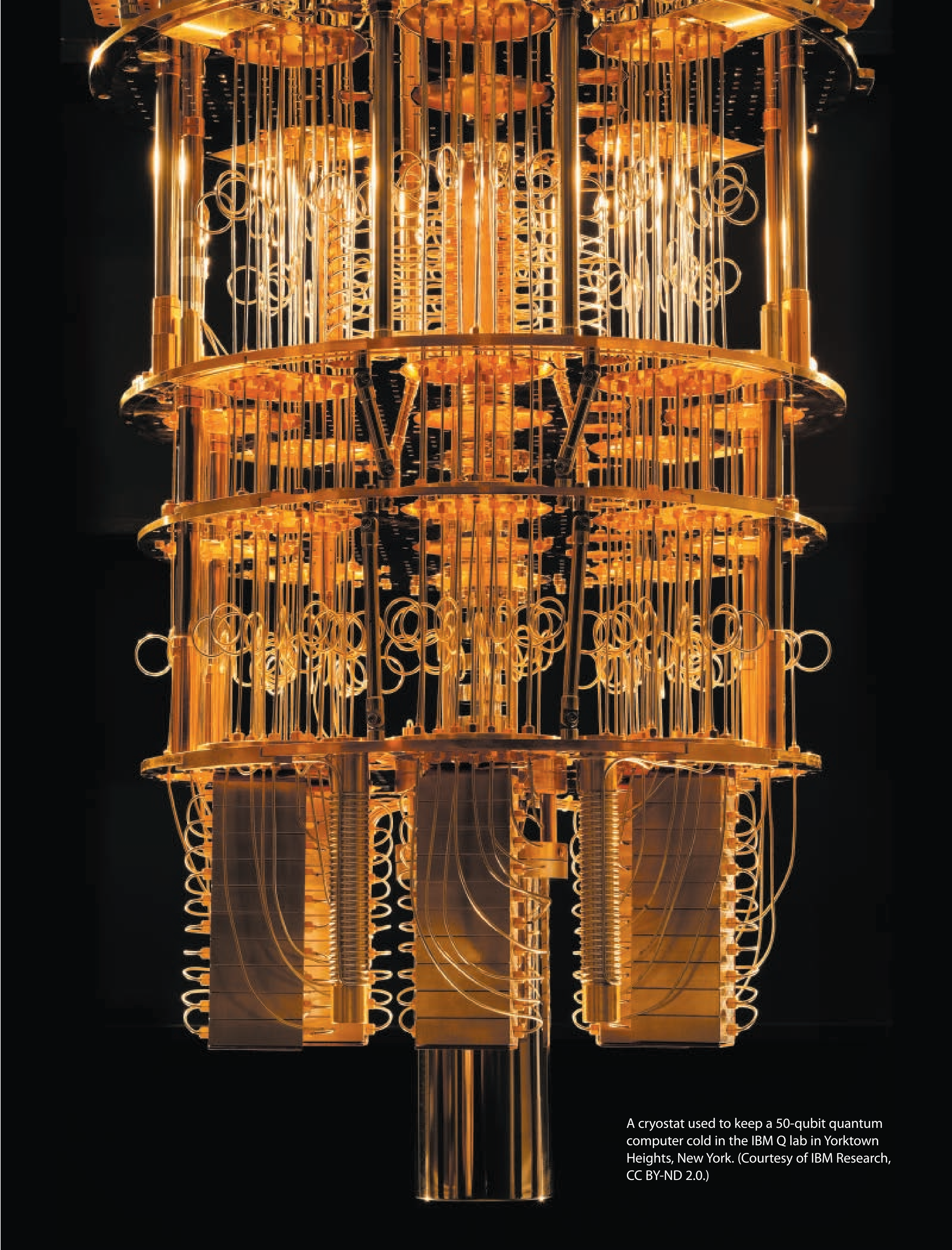
MACHINE LEARNING *meets* QUANTUM PHYSICS

Sankar Das Sarma, Dong-Ling Deng, and Lu-Ming Duan

The marriage of the two fields may give birth to a new research frontier that could transform them both.

Machine learning is a field of computer science that seeks to build computers capable of discovering meaningful information and making predictions about data. It is the core of artificial intelligence (AI) and has powered many aspects of modern technologies, from face recognition and natural language processing to automated self-driving cars.

The field is rapidly growing, and its applications have become ubiquitous.[1] Google Translate's online service uses machine learning to convert Chinese characters into English text with no human intervention. Machine-learning techniques were recently used to build AlphaGo,[2] a robot that has defeated the world's best players in Go, an ancient board game; developers have considered mastering the game as the highest AI achievement. Until AlphaGo demonstrated its prowess, the game was widely thought to be too intricate for machines to excel at because of the huge number of possible moves.



A cryostat used to keep a 50-qubit quantum computer cold in the IBM Q lab in Yorktown Heights, New York. (Courtesy of IBM Research, CC BY-ND 2.0.)

One of the biggest problems facing machine learning is the so-called curse of dimensionality—in general the number of training data sets required for the machine to learn the desired information is exponential in the dimension *d*. If a data set lies in a high-dimensional space, then it quickly becomes computationally unmanageable. That complexity is similar to quantum mechanics, for which an exponential amount of information is generally also required to fully describe a quantum many-body state.

Despite its intricacies, quantum theory is arguably the most successful quantitative theory of nature. It not only provides the basis for understanding physics on all length scales, from elementary particles like electrons and quarks to gigantic objects like stars and galaxies, but also lays the foundation for modern technologies ranging from lasers and transistors to nuclear magnetic resonators and even quantum computers.[3] Given the great successes of both machine learning and quantum physics, one may ask: Can these two seemingly unrelated but intimately connected fields merge in a seamless, synergistic manner?

It sounds like science fiction, but that fusion is happening right now and may lead to presently unimaginable breakthroughs in both fields. Machine learning has progressed dramatically over the past two decades, and many problems that were extremely challenging or even inaccessible to automated learning have now been solved. Those successes raise new possibilities for machine learning to solve open problems in quantum physics.

Meanwhile, the idea of quantum information processing has revolutionized theories and implementations of computation. New quantum algorithms may offer tantalizing prospects to enhance machine learning itself. The interaction between machine learning and quantum physics will undoubtedly benefit both fields.

Uncovering phases of matter

When applying machine learning to physics problems, a straightforward strategy is to use supervised learning, in which an algorithm is trained with data that are labeled beforehand; the algorithm's goal is to take that information and establish a general rule for assigning labels to data outside the training set. For example, in identifying pictures of dogs and cats, a supervised learning algorithm will take thousands of images labeled either "dog" or "cat" and determine a relationship between the images' pixel values and their labels. It then assigns those labels to images that it has not seen before.

The same supervised learning technique can be used for identifying distinct phases of matter and the transitions between them, one of the central problems in condensed-matter physics. Juan Carrasquilla and Roger Melko were the first to explore that idea in their study of the ferromagnetic Ising model, which features discrete atomic spins arranged on a lattice.[4] The spins display a disordered paramagnetic phase at high temperatures and an ordered ferromagnetic phase at low temperatures, and a phase transition occurs between the two at some critical temperature T_c.

Instead of sorting dogs and cats, Carrasquilla and Melko used equilibrium spin configurations sampled from Monte Carlo simulations to train the algorithm to identify paramagnetic and ferromagnetic states. They demonstrated that after training with those labeled samples, the algorithm could correctly assign the labels to new samples. Moreover, by scanning a range of temperatures, it located T_c and found the critical exponents that are crucial to the study of phase transitions.

Supervised learning requires that users know *a priori* how their data should be categorized. Alternatively, unsupervised learning uses unlabeled training data and allows the network to find meaningful patterns and structures in them. A common example of unsupervised learning is clustering, in which training data are divided into several groups based on identified similarities and those groups are used to categorize new, previously unseen data. In 2016 Lei Wang applied clustering to the Ising model and successfully identified the paramagnetic and ferromagnetic phases and the transition between them, despite not giving the algorithm explicit sorting criteria.[5] Around the same time, Evert van Nieuwenburg and coworkers proposed a confusion scheme that combined both supervised and unsupervised learning.[6] They tested their approach on several

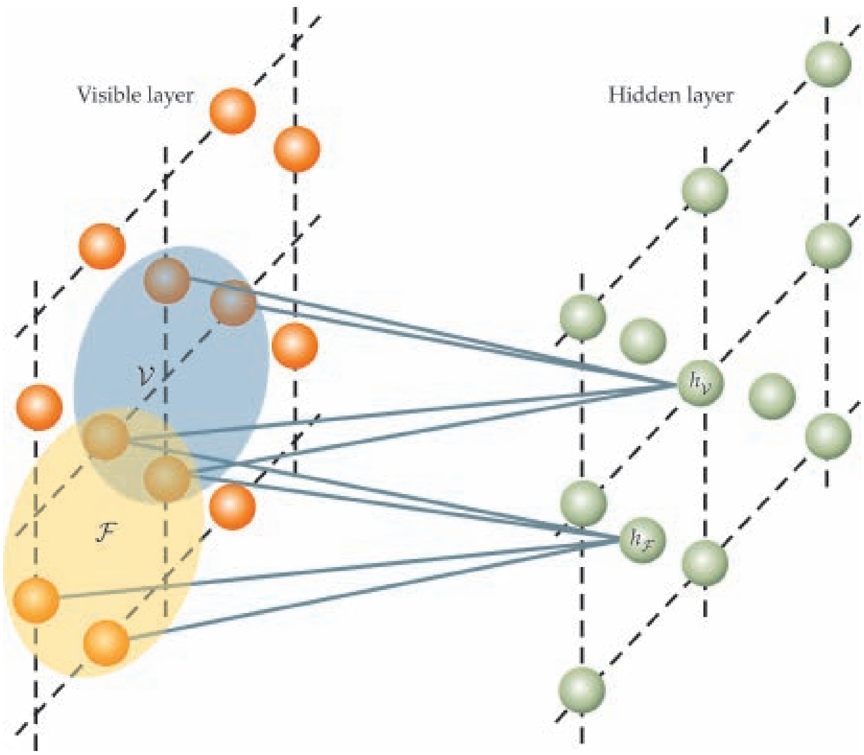


FIGURE 1. THE RESTRICTED-BOLTZMANN-MACHINE REPRESENTATION of the toric-code state with intrinsic topological order. Each vertex $\mathcal{V}$ or face $\mathcal{F}$ has four visible neurons that are connected to one hidden neuron $h_\mathcal{V}$ or $h_\mathcal{F}$. The representation is efficient because each connection corresponds to one parameter in the neural network, so the number of parameters scales linearly instead of exponentially with the system size.

TWO REPRESENTATIONS

A quantum state of a system with N qubits has the general form $|\Psi\rangle = \sum_{\Xi}\Phi(\Xi)|\Xi\rangle$ where $|\Xi\rangle = (\sigma_1, \sigma_2, \ldots, \sigma_N)$ denotes a possible many-body qubit configuration, and $\Phi(\Xi)$ is a complex function that specifies the amplitude and phase of the state. One can interpret the quantum state as a computational black box that for a given $|\Xi\rangle$ returns a complex number $\Phi(\Xi)$, which is the coefficient for the $|\Xi\rangle$ component of the state.

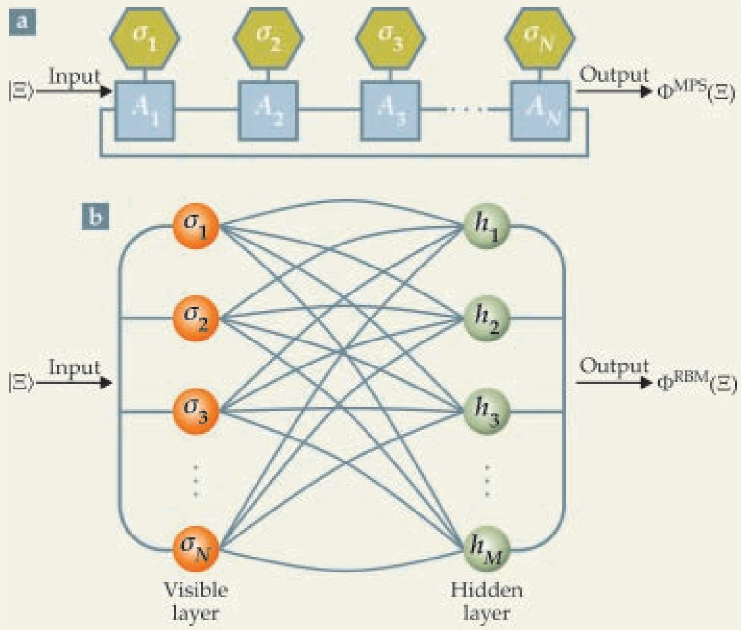
The tensor-network representation uses tensors to represent quantum states. A tensor's rank indicates its dimensionality, or the number of indices it has, so rank-1 tensors are vectors, rank-2 tensors are matrices, and so on. For simplicity, consider a one-dimensional system with N qubits, shown in panel a, known as the matrix product states (MPS) representation. Each qubit has an associated rank-3 tensor $\mathbf{A}_{ijk}$. The tensors form a network in which the connections represent the indices of the tensors. If two tensors are connected, then their shared index is contracted by summing over all possible values of the repeated index. In the 1D case, two of the indices of each tensor are connected to neighboring tensors and contracted, leaving a rank-1 tensor σ_i that represents the physical degrees of freedom. The resulting quantum state is then given by

$$\Phi^{\mathrm{MPS}}(\Xi) = \mathrm{Tr}[A_1 A_2 \ldots A_N].$$

A restricted Boltzmann machine (RBM) representation is a neural network with two layers—one visible layer with N visible neurons corresponding to the physical qubits and another layer with M hidden neurons, as shown in panel b. The visible neurons are connected to the hidden neurons, but neurons in the same layer are not connected. The quantum state is given by

$$\Phi^{\mathrm{RBM}}(\Xi) = \sum_{\{\mathbf{h}\}} e^{\sum a_j \sigma_j + \sum b_k h_k + \sum W_{jk} h_k \sigma_j}$$

where $\{\mathbf{h}\}$ denotes the possible configurations $h_1, h_2, \ldots, h_M$ of the hidden neurons, W_{jk} is the coupling strength between the visible and hidden neurons, and a_j and b_k are their bias parameters.



models, the Ising model included, and demonstrated that it could identify various phases and the transitions between them.

Neural-network representation

In parallel with the fast development of machine-learning algorithms for identifying phases of matter, exciting progress has been made in using artificial neural networks to represent quantum states and solve related quantum many-body problems.

In quantum mechanics, fully describing an arbitrary many-body state requires an exponential amount of information. Consider a system with N qubits, or quantum bits. Each qubit has two possible independent configurations, either 0 or 1; thus there are 2^N possible configurations in total. Computationally, that means fully describing the corresponding quantum state requires 2^N complex numbers.

The exponential complexity poses an enormous challenge for numerical simulations of quantum many-body systems performed on a classical computer—describing even few qubits requires an extremely large memory. For example, simulating a quantum system with 30 qubits requires tens of gigabytes, about the largest memory for a personal desktop; simulating 50 qubits requires tens of petabytes, more than the memory for the largest supercomputer in the world to date; and simulating 300 qubits requires more bytes than the number of atoms in the observable universe.

Fortunately, most physical states of interest, such as the ground states of many-body Hamiltonians, typically access only a small corner of the entire Hilbert space of quantum states and can therefore be described with a reduced amount of information. Thus designing compact representations of those states in a way that retains their essential physical features is necessary for tackling quantum many-body problems with classical computers.

A renowned description for such states is the tensor-network representation,[7] in which a tensor is assigned to each qubit, and together those tensors describe the many-body quantum state. Such a construction can represent most physical states efficiently in the sense that the amount of information required scales only polynomially, rather than exponentially, with the system size.

Artificial neural networks—highly abstracted and simplified models of the human brain—can also be used to construct compact representations of quantum states. Giuseppe Carleo and Matthias Troyer first explored the idea when they introduced a new representation based on the restricted Boltzmann machine (RBM),[8] a special neural network broadly used in the machine-learning community. (The tensor-network and RBM representations are compared in greater detail in the box above.) An RBM is arranged as two layers of neurons, a visible and a hidden layer, as illustrated in figure 1. The visible neurons represent the physical qubits, and the hidden neurons describe auxiliary degrees of freedom that are eventually eliminated by a summation to produce the network's output, a complex number that serves as the coefficient for the corresponding qubit configuration.

What kinds of quantum many-body states can be efficiently described by RBMs? Certain exotic states, such as topological states, are well represented by RBMs.[9] Figure 1 is a sketch of the RBM representation for the ground state of the toric-code Hamiltonian, a topological state introduced by Alexei Kitaev in the context of topological quantum computation (see the article by one of us [Das Sarma], Michael Freedman, and Chetan Nayak, PHYSICS TODAY, July 2006, page 32). To represent the toric-code state, each hidden neuron of the RBM connects only to its nearest four visible neurons. Each connection is described by one network parameter, so the total number of parameters is roughly four times the number of qubits, which scales linearly, rather than exponentially, with the system size. The strikingly compact representation of the toric-code state can carry over to the excited states as well.

There also exist quantum states with physical interest that carry no efficient RBM description.[10] However, the RBM's applicability increases if it includes an additional hidden layer. The resulting neural network, known as the deep Boltzmann machine, can represent almost all physical quantum states efficiently, with the required number of parameters scaling at most polynomially with the system size.

Entanglement in neural-network states

What, then, limits neural networks in efficiently representing quantum many-body states? For the conventional tensor-network representation, quantum entanglement is the key. Is it also a critical factor for the neural-network representation?

Quantum entanglement is a physical phenomenon in which measurements on one particle will instantaneously influence the state of another, even when the particles are spatially separated by a large distance—a phenomenon Albert Einstein called "spooky action at a distance." Entanglement is also at the heart of the famous Schrödinger's cat paradox. Both Einstein and Erwin Schrödinger were deeply bothered by quantum entanglement.

Imagine dividing a pure quantum many-body state into two subsystems, *A* and *B*, as shown in figure 2. Just as classical many-body systems can be characterized by their entropy, quantum many-body systems can be characterized by their entanglement entropy. Many natural quantum systems satisfy the entanglement area law, which says that the entanglement entropy of a subsystem scales as at most the surface area or the boundary of the subsystem rather than as its volume. That is the case for the Bekenstein–Hawking entropy of a black hole, which scales as the area of its event horizon. In fact, the origin of the black hole entropy is widely believed to be the quantum entanglement between the inside and outside of the black hole. In quantum many-body physics, the ground states of many typical local Hamiltonians also satisfy the entanglement area law, although a rigorous proof of that is notoriously challenging and remains unknown.

The entanglement area law is crucial in the tensor-network representation of quantum many-body states and forms the backbone of numerous tensor-network-based algorithms. In general, the number of parameters that a tensor network needs to describe a quantum state that satisfies the entanglement area law scales only polynomially with the system size. Thus such quantum states typically bear an efficient tensor-network representation. However, for quantum states with massive entanglement, such as highly excited states of quantum Hamiltonians that have volume-law entanglement, the traditional tensor-network representation is not efficient—the number of parameters required scales exponentially with the system size.

All RBM neural-network states with short-range connectivity obey the entanglement area law, independent of their dimensionality and subsystem geometric details.[11] The toric-code states, in which each neuron connects only to its four closest vertices, must then obey the area law, a conclusion that has also been confirmed via other sophisticated mathematical techniques.

Without the short-range condition, general RBM states satisfy an entanglement volume law. In fact, one can analytically construct families of RBM states with maximal entanglement. A sketch of such a construction is shown in figure 2, from which a striking conclusion immediately follows: The RBM description of heavily entangled states is remarkably efficient. Each visible neuron connects to at most three hidden neurons, so the number of parameters scales only linearly with the system size; that scaling demonstrates the unparalleled power of neural networks in describing quantum many-body states with large entanglement. The RBM scaling is in sharp contrast with the

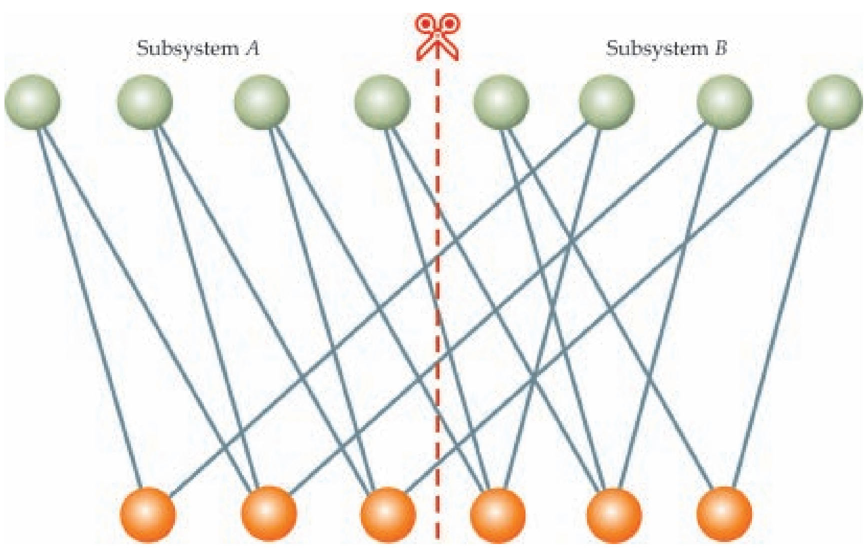


FIGURE 2. A NEURAL-NETWORK REPRESENTATION of a one-dimensional quantum state that has maximal volume-law entanglement: If the system is divided into two subsystems, *A* and *B*, the entropy of each subsystem is proportional to its volume. Each visible neuron connects to at most three hidden ones, so the number of parameters needed to describe the subsystem scales linearly with the system size rather than exponentially, as in a conventional tensor-network representation.

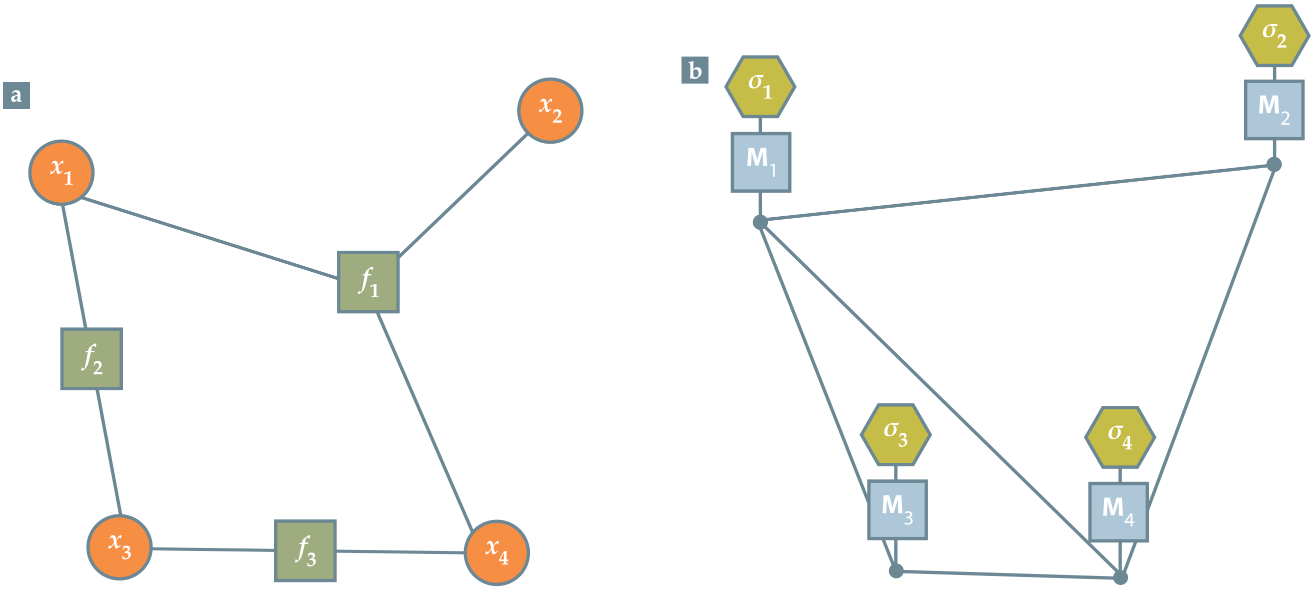


FIGURE 3. CLASSICAL AND QUANTUM GENERATIVE MODELS are widely used in both supervised and unsupervised machine learning. **(a)** This illustration of a classical generative model, or factor graph, models the joint probability distribution of the observables x_i as a product of factor functions: $P(x_1, x_2, x_3, x_4) = f_1(x_1, x_2, x_4)\, f_2(x_1, x_3)\, f_3(x_3, x_4)$. A classical generative learning task is then reduced to optimizing the adjustable parameters in the factor functions f_i. **(b)** This sketch shows a quantum generative model with four qubits σ_i. The figure represents a special quantum state that is constructed by acting the two-by-two invertible matrices $\mathbf{M}_i$ on a tensor network state. The probability distribution can then be obtained from projective measurements on the resulting state. A quantum generative learning task is then reduced to optimizing the adjustable parameters in the matrices $\mathbf{M}_i$.

traditional tensor-network representation, which requires an exponentially large number of parameters to describe highly entangled states. Clearly, entanglement is not the limiting factor for the efficiency of the neural-network representation.

Quantum many-body problems

Solving quantum many-body problems usually entails finding either the system's ground state or the dynamics of the system's time evolution. That can be achieved through an RBM-based variational learning algorithm adopted by Carleo and Troyer in the same paper in which they introduced the RBM representation.[8] They tested the approach on two prototypical quantum spin models—the Ising model in a transverse magnetic field and the antiferromagnetic Heisenberg model—and found that the RBM approach faithfully captured the ground state and the time evolution for each one.

The exceptional ability of neural networks to represent massively entangled states offers a new way to solve intricate many-body problems that involve large entanglement; such problems are challenging or even unsolvable with conventional methods. When applied to a model Hamiltonian with long-range interactions, the RBM-based variational learning algorithm found the system's ground state, which has been numerically shown to hold power-law entanglement.[11] Moreover, the RBM technique has also been used in quantum state tomography—a process of reconstructing the quantum state from the outputs of quantum measurements—for highly entangled states.[12]

Nonlocality, which is closely related to entanglement, is another enigmatic feature of quantum mechanics. As resoundingly established by John Bell, quantum nonlocality precludes any local realistic description of our world and represents the most profound departure of the quantum world from the classical. In practical applications, nonlocality is an indispensable resource for various device-independent quantum technologies, such as secure cryptographic key distribution and certifiable random-number generation. The complete characterization of quantum nonlocality for a generic many-body system is extremely challenging; nevertheless, machine learning, especially RBM-based variational learning, is a promising technique for at least partially solving that problem.[13]

Quantum-enhanced machine learning

The above examples have clearly uncovered the unparalleled power of machine-learning techniques in solving various challenging quantum problems. Strikingly, unlike in the traditional tensor-network approach, entanglement is not the limiting factor for the efficiency of the neural-network representation and for the related algorithms to learn such a representation. In addition, the neural-network approach works for high-dimensional systems because of the huge flexibility of neural-network structures.

The opposite also holds true: Quantum technologies, especially quantum computing, have the potential to provide a huge boost to machine learning. For one thing, machine learning often deals with large amounts of data, and one common data-analysis technique is the fast Fourier transform (FFT). With quantum computers, there is a quantum version of FFT that is exponentially faster than the classical version.[3] For another, machine-learning algorithms often require solving a huge number of linear problems that amount to doing many matrix multiplications. Quantum computers have intrinsic advantages in executing those operations since quantum mechanics is naturally described by linear algebra—in fact, an early formulation of quantum mechanics by Werner Heisenberg, Max Born, and Pascual Jordan was called matrix mechanics. Thus many conceptual connections exist between machine learning and quantum computing.

Quantum computers aren't expected to speed up every machine-learning algorithm. However, scientists have found a number of quantum algorithms that promise exponential speed increases for certain important tasks.[14] One algorithm that is foundational to the current quantum machine-learning minirevolution is called the HHL algorithm, after its inventors Aram Harrow, Avinatan Hassidim, and Seth Lloyd.[15] Many other quantum learning algorithms either extend HHL or use it as a subroutine. The algorithm seeks to solve a system of linear equations: Given an $N \times N$ matrix $\mathbf{A}$ and a vector $\mathbf{b}$, the aim of HHL is essentially to solve $\mathbf{Ax} = \mathbf{b}$ for $\mathbf{x}$. For many matrices of physical interest, the HHL algorithm takes on the order of $\log^2 N$ quantum steps to output a quantum state, whereas the best-known classical algorithm requires on the order of $N \log N$ steps.

Several caveats to the HHL algorithm and its variants may nullify its potential benefits.[14] For instance, to map a classical vector to a quantum state the algorithm requires quantum RAM, or qRAM, which could be exponentially expensive. Xun Gao, Zhengyu Zhang, and one of us (Duan) recently introduced a quantum generative model that relaxed the qRAM requirement and thus circumvented the problem of exponential overhead in the initial step of transferring classical data to quantum states.[16]

Compared with more familiar discriminative models, generative models take a different approach to solving problems through machine learning. To understand the difference between the two, consider the earlier example with images of dogs and cats. A discriminative model aims to learn the characteristics that distinguish images of the animals to differentiate between them. The goal of generative models is to be able to produce new images of dogs and cats. In practice, the generative approach is to figure out an underlying probability distribution from a set of training data. In the classical scenario, the probability distribution can be represented by a factor graph. However, for the quantum generative model, the probability distribution is described by a quantum state. Sketches of both the classical and quantum generative models are shown in figure 3.

The quantum generative model has exponential advantages over its classical counterpart in three significant aspects. Not only can it efficiently represent more probability distributions, but the quantum algorithm is also exponentially faster than the classical one both at learning certain probability distributions and at generating new data. The quantum generative model opens a fresh way to explore the power of quantum computing in solving challenging machine-learning problems, and it should thus have important applications in the future.

The above examples are just a glimpse into an increasing zoo of quantum algorithms that may significantly boost machine learning and, more generally, AI tasks.[14] Other intriguing algorithms, such as quantum principal component analysis and quantum support-vector machine, also show great speed-up potentials. In addition, a recently proposed quantum-inspired tensor-network algorithm for machine learning is beginning to show intriguing merits.[17]

Future partnership

The interdisciplinary field of combining machine learning and quantum physics is growing rapidly, and exciting progress is being made. The above discussions are only the tip of the iceberg.

Applying machine learning to quantum physics requires answers to two crucial questions: What is the killer application for machine learning in solving quantum problems? And can machine learning help discover new physics in quantum systems? An ambitious project that could answer both questions at once is a learning algorithm that specializes in identifying high-T_c superconductors. After training on the huge collection of available experimental data, it should be able to predict new high-T_c superconducting materials and provide new insights into the theory of superconductivity.

For quantum-enhanced machine learning, a unified quantum learning theory has not been developed, and many fundamental questions remain open: What is the general criterion for determining if a machine-learning task can be significantly expedited by a quantum computer? What learning problems can be efficiently solved by a quantum computer but not by a classical one? And how can a quantum computer efficiently analyze large quantum data sets that may eventually be available?

For classical machine learning, there is an exact map between the variational renormalization-group method in physics—an iterative coarse-graining scheme that extracts relevant features for a physical system at different length scales—and deep learning,[18] and that map gives valuable insight on why deep learning is powerful. Is it possible to construct such a map for the case of quantum deep learning? Moreover, a smoking-gun experimental demonstration of quantum speed-ups in a practical machine-learning task would be an important milestone.

It is hard to foresee when the first practical quantum computer will be available and harder still to predict what the quantum future will look like. Yet one thing is certain: The marriage of machine learning and quantum physics is a symbiotic relationship that could transform them both.

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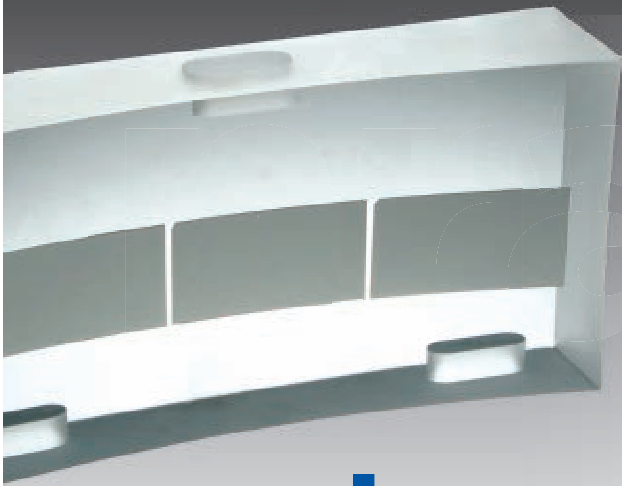

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Nuclear physics in *Reviews of Modern Physics*

Throughout its 90-year history, the journal has elucidated all the major advances in the science of the densest phases of matter.

George Bertsch, Witold Nazarewicz, and Achim Richter

In 1932, shortly after the founding of *Reviews of Modern Physics* (*RMP*), nuclear physics became a scientific discipline with the discovery of the neutron. In the ensuing five years, the field had grown to an extent that justified the 450-page, monumental three-part review in *RMP* by Hans Bethe and his collaborators.[1] Nicknamed Bethe's Bible, it covered not only the new phenomena revealed by nuclear reactions and beta decay, but also a theory of nuclear forces, which would later explain nuclear shells, and various experimental findings.

Compared with that early review, the scope of nuclear physics today is enormous. The field deals with the structure of hadrons and nuclei, nuclear matter at extreme densities, nuclear astrophysics, and symmetry tests involving all the fundamental forces of nature.[2] As illustrated by selected examples below, articles in *RMP* have played a uniquely important role in shaping the agenda of nuclear physics research and in seeding new topics.

The biggest breakthrough in nuclear physics after World War II and the Manhattan Project was the recognition of nuclear shells in 1949. The shell model not only explained the distinctive properties of nuclei with the closed-shell magic numbers; its wavefunctions also made it possible to describe nuclear structure in detail. For example, in their 1963 *RMP* article, Leonard Kisslinger and Raymond Sorensen showed how a simplified interaction between shell orbitals could quantitatively account for many features of nuclear spectra.[3] A crucial component of the model is an attractive interaction between like particles that produces a pairing condensate. The pairing has consequences that are qualitatively similar to those seen in superconductivity. Today, as Mark Alford and his coauthors pointed out in their 2008 *RMP* article, superconductivity is a ubiquitous nuclear phenomenon that arises not only in nuclei and nuclear matter but also in dense quark matter.[4]

The development of nuclear reaction theory beyond its prewar state has several important milestones recorded in *RMP*. Electron scattering, a basic experimental tool of nuclear physics since the early 1950s, was reviewed in 1956 by Robert Hofstadter.[5] When hadronic probes are used, reaction theory requires joining together two differ-

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ent kinds of wavefunctions, namely the continuum wave functions of the scattering particles and the discrete wavefunctions of the resonances and internal states of the nuclei formed. That difficult challenge can be handled by R-matrix theory, which Anthony Lane and Robert Thomas reviewed[6] in 1958.

Another important reaction for studying nuclear structure and the response of nuclei to external probes is Coulomb excitation by a heavy ion passing nearby. In their 1956 *RMP* article, Kurt Alder and his coauthors reviewed the required theory and the early results it yielded.[7] Another process, particle transfer from one nucleus to another, is also invaluable for elucidating the shell structure of nuclei, as Malcolm Macfarlane and Bruce French laid out in their 1960 *RMP* article.[8] Today, all those tools and their sophisticated variations are used to study nuclei and hadrons at modern low- and medium-energy nuclear facilities.

Nuclear fission is a complex process whose elucidation in *RMP* has brought many threads together. The explanation, presented in the ground-breaking 1972 paper by Matthias Brack and his coauthors,[9] arose from the same theory that describes nuclear shells and shape deformations. The paper showed that the path to fission has hills and valleys in the total energy surface that can trap the system before it gets to the point at which the nucleus breaks into fragments. That work was followed by Sven Bjørnholm and J. Eric Lynn's 1980 review of fission data.[10] Since the 1990s a microscopic description of fission has been given by nuclear density functional theory, which, as Michael Bender, Paul-Henri Heenen, and Paul-Gerhard Reinhard reviewed[11] in 2003, explains the presence of nuclear deformations in terms of symmetry-violating intrinsic states.

In more recent years, the domain of nuclear physics has expanded to include high energy densities and small length scales that are best understood within the framework of the standard model of particle physics with quantum chromodynamics (QCD). High energy densities can be produced in the laboratory only by smashing large nuclei together. A seminal review of the properties of highly excited hadronic matter, interpreted as a quark–gluon plasma, was published in *RMP* in 1981 by David Gross, Robert Pisarski, and Laurence Yaffe.[12] In QCD the underlying interactions mediated by gluons are largely hidden from experimental view. Instead, the observable dynamics are likely manifested by effective interactions—in particular, those characterized by the so-called instanton solutions to equations of motion. The 1981 review has guided the interpretation of experimental findings from relativistic heavy ion collisions. In their 1998 *RMP* paper, Thomas Schäfer and Edward Shuryak showed that the instanton could also be applied to a qualitative understanding of meson masses and other hadronic properties.[13] One of the main research directions in nuclear structure is to anchor the nuclear force, which binds protons and neutrons into nuclei, in QCD, as reviewed 10 years ago by Evgeny Epelbaum, Hans-Werner Hammer, and Ulf-G. Meißner.[14]

In this brief overview, we inevitably left out many topics in nuclear physics and its intersections having an impact on other branches of physics. Examples are the statistical theory of spectra in strongly interacting systems, as reviewed in 1981 by Tomás Brody and his coauthors;[15] solar fusion, as reviewed in 1998 by Eric Adelberger and his coauthors;[16] and double beta decay, as reviewed in 2008 by Frank Avignone, Steven Elliott, and Jonathan Engel.[17]

In 2013, one century after Ernest Rutherford discovered the atomic nucleus, the National Academy of Sciences published its fourth and most recent decadal survey of nuclear physics.[2] The survey's authors identified four overarching questions that are being addressed by nuclear physics: How did visible matter come into being and evolve? How does subatomic matter organize itself? Are the fundamental interactions that are basic to the structure of matter fully understood? How can the knowledge and technological progress provided by nuclear physics best be used to benefit society? Given that the questions remain open, we foresee a continuing presence of forefront nuclear reviews in the pages of *RMP*.

This article should have appeared in February's special issue, which celebrates the 90th anniversary of RMP. *Physics Today apologizes to the authors and to readers for the error.*

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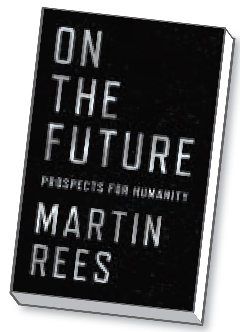
The perils of not thinking ahead

On the Future
Prospects for Humanity
Martin Rees
Princeton U. Press, 2018. $18.95



Despite the title, Martin Rees's new book *On the Future: Prospects for Humanity* is not really about predicting the future. Instead, it is about getting us to pay attention to and build our priorities around what is down the road. Much of the book is an ode to how bad we are, as a species and a civilization, at thinking ahead. Rees, the UK's Astronomer Royal, argues that there is now an "explosive disjunction" between the time scales of human social and technological development and natural processes. And Rees is surely onto something—his earlier book *Our Final Century? Will the Human Race Survive the Twenty-First Century?* (2003) was for its American edition renamed *Our Final Hour: A Scientist's Warning: How Terror, Error, and Environmental Disaster Threaten Humankind's Future in This Century—On Earth and Beyond*, presumably to make the time scale seem pressing to present-minded readers.

On the Future does spend some time prognosticating, although Rees warns that he is writing as much as a worried citizen as a scientist. He doesn't include many predictions from his own fields of astronomy and physics—he says don't stress about asteroid impacts, and he would like particle physicists to lay off experiments that might destroy the planet—though he does present rich images of a time when humans and their machines will fill the vastness of space.

Most of the predictions he discusses are of the eco-threat variety. Our actions in the next century, he writes, will determine the course of the planet for thousands of years. He is actually fairly optimistic that science and technology can create a future that is benign rather than catastrophic. The problems, he contends, are essentially political, not technical, and thus his expertise as a scientist is of limited value for predicting our actual future. Unfortunately, the Schrödinger equation is of little help in foreseeing what the US Senate will do next.

Rees is remarkable in his modesty. Books of this sort tend to be exercises in deploying the author's specific expertise as strongly and widely as possible. Not here. The final section of *On the Future* is the author reflecting on the limits of science and how those limits should shape the way scientists think about their social role. Drawing from his long and storied career, Rees slays a number of sacred cows. He rejects the idea that scientific reasoning is particularly elite. He denies that the scientific community is monolithic and unified. He trounces reductionism. He calls for peaceful coexistence of science and religion. He accepts the possibility that there are some things about the universe that scientists will never know.

All of those arguments are small steps toward his conclusions about how scientists should function in society. Rees does not want an elitist model in which scientists make decisions and everyone else simply accepts them. Rather, he wants decisions to come from public debate. For that to happen, though, the public needs a "feel" for the key ideas of science so they won't be "bamboozled." He says that scientists need to engage with the public in a substantial way and that they should not be afraid to take strong positions on issues—his models are Hans Bethe, Rachel Carson, and Carl Sagan.

Rees argues that at the end of the day, the goal should be to get politicians to create good policy, though he doesn't think much of scientists being formal advisers to leaders. Instead, he suggests that addressing the public is a more powerful tool for influencing politicians. Rees believes that we can build a good future in which science and technology will be essential, but that future cannot be created by scientists alone. They need to be guided by ethics that science itself cannot provide.

On the Future is a short, lively book that summarizes many of the positions that the Astronomer Royal has taken over the years. It is written in a compelling style and has little jargon. Its brevity, though, means it does not go into detail on many of the scientific issues, so it will perhaps be more appreciated by those with some previous knowledge of, say, climate change.

The book's great contribution is placing those scientific issues in the context of modern society's difficulty with thinking beyond today. Intergenerational justice—how much we are willing to let our grandchildren suffer for our own benefit—is not a subject in which scientists are typically trained. But Rees says it should be. He wants everyone in the lab to think about the implications of their work and to try and guide that work to beneficial goals. If our civilization ends in catastrophe, he writes, it will not be the fault of science. It will be the fault of how we think about science: Can we ponder its implications over centuries, or are we stuck in the next hour? Rees's book is a warning that we are at a crossroads. Which path we take depends on whether we choose to think long-term.

Matthew Stanley
New York University
New York City

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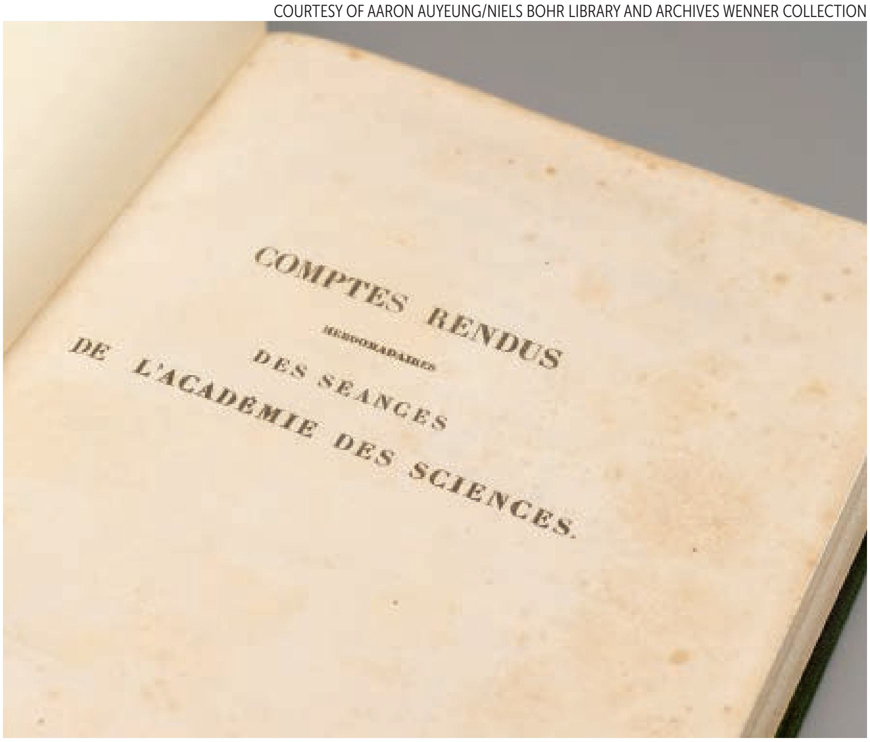

Writing the record of scientific knowledge

The Scientific Journal
Authorship and the Politics of Knowledge in the Nineteenth Century

Alex Csiszar
U. Chicago Press, 2018. $45.00

The Wikipedia entry for PHYSICS TODAY states that the esteemed publication you are currently reading is "scientifically rigorous and up to date." However, the entry explains, the magazine "is not a true scholarly journal in the sense of being a primary vehicle for communicating new results."

The careful inclusion of that distinction points to some important assumptions about what constitutes a "true" scientific journal. As historian of science Alex Csiszar observes in the introduction to his book *The Scientific Journal: Authorship and the Politics of Knowledge in the Nineteenth Century*, readers expect a great deal of those periodicals. They are "both permanent archive and breaking news, both a public repository and the exclusive dominion of experts, both a complete record and a painstakingly vetted selection." Csiszar's book explores how the scientific journal came to embody those apparent contradictions and demonstrates why we have made that particular medium the preeminent mode of communicating claims to knowledge.

Tempting as it is to draw a direct line between the establishment of the *Philosophical Transactions of the Royal Society of London* in 1665 and the 21st-century peer-reviewed scientific journal, recent historical scholarship has increasingly shown that the narrative is far more complicated. The rise of the scientific journal was the result of the interplay of political and commercial forces in post-Enlightenment Europe. Csiszar meticulously traces the development of journals in Britain and France during the 19th century, and he shows that shifting and competing ideas about scientific audiences and authors led to significant changes in the way scientific researchers engaged with print.

At the beginning of the 19th century, academies and learned societies were the most influential arbiters of scientific authority. Publication was not considered necessary for the establishment of a scientific reputation; in fact, the idea of putting scientific work in print could be viewed with deep suspicion, if not outright hostility. Journalism carried the taint of commercial opportunism, a problem when the ideal scientific practitioner was supposed to be disinterested in compensation.

But as publications dedicated to scientific subjects, produced mostly by entrepreneurial publishers, began to proliferate in the wake of the French Revolution, learned societies and academies sought to maintain their sway over scientific legitimacy by going into print themselves. The scientific journal as we would now recognize it took shape in the course of debates over questions of who could write about science, who could claim intellectual property rights, and who should be able to access scientific writings.

The great strength of Csiszar's book is how it challenges both historians and scientists to confront the ways in which formats and genres of communication shape modes of inquiry. Our understanding of the history of scientific priority is considerably enriched when we pay close attention to the media through which claims to "discovery" were made. Similarly, modern scientific careers are shaped by the pressure to publish in certain journals, and that pressure influences the kinds of research scientists undertake. Csiszar asks us to imagine a world in which scientists were expected to write "a longer book that synthesized a field of information based on their own and others' research," an intriguing counterfactual that invites speculation as to how different the academic landscape would be.

The book's comparison between France and Britain is particularly instructive and sets *The Scientific Journal* apart from much of the existing scholarship on 19th-century scientific periodicals, which has tended to be Anglocentric. Highlighting the differences between the two countries during that period shows us that the journal's development and current form were far from inevitable. For example, referee systems in Britain and the US were initially exceptions rather than the rule. Meanwhile, the dominant journal in France, *Comptes rendus de l'Académie des Sciences*, employed no such system. Not until the second half of the 20th century did peer review become an internationally widespread method of judging potential publications.

The book concludes with a brief coda reflecting on the present, in which alternative formats made possible by the internet are challenging the apparent dominance of the scientific journal. However, Csiszar insists that those new platforms are subject to the same entanglement of scientific, political, and economic considerations as the supposedly antiquated print media they are purported to supersede. Technology alone cannot render knowledge "free" or "transparent," he argues, and in order to chart a new future for the scientific journal, it will be important to understand its history. Csiszar's book is an excellent example of how that history should be done.

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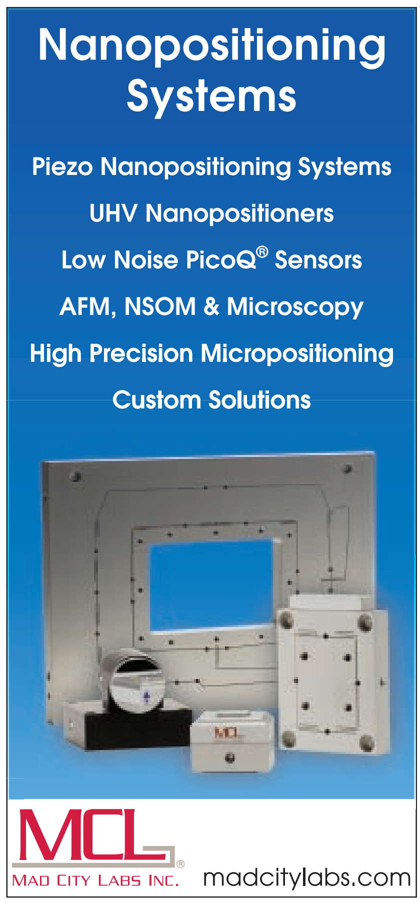

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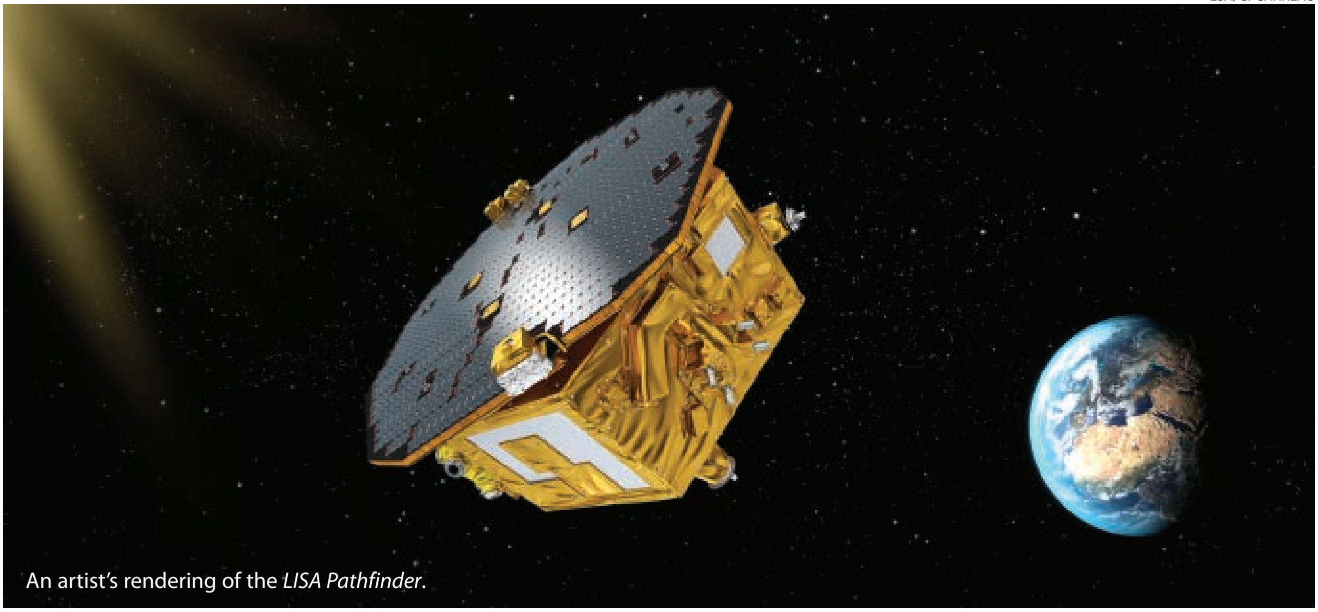
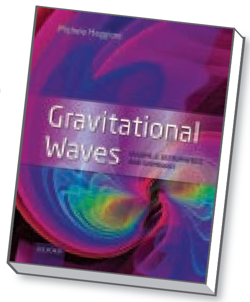


An artist's rendering of the *LISA Pathfinder*.

A bird's-eye overview of gravitational-wave astronomy

Gravitational Waves, Volume 2
Astrophysics and Cosmology
Michele Maggiore
Oxford U. Press, 2018. $81.00



Gravitational-wave astronomy has undergone a revolution since 2008, when Michele Maggiore's *Gravitational Waves, Volume 1: Theory and Experiments* was published. In 2015 the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected gravitational waves from a black hole binary merger, and *LISA Pathfinder* was launched, paving the way for future gravitational-wave observations in space. Since then the LIGO/Virgo collaboration has detected a total of 10 black hole binary mergers and a neutron star merger, an event that marked the birth of multimessenger astronomy. An international network of pulsar timing arrays is expected to lead to more detections within the next few years. In short, gravitational-wave astronomy is in full bloom.

When Maggiore's first volume went to press, the publisher could claim that it was the "only existing book on gravitational waves." That is no longer true. Jolien Creighton and Warren Anderson's *Gravitational-Wave Physics and Astronomy: An Introduction to Theory, Experiment and Data Analysis*, published in 2011, contains an excellent introduction to interferometric detectors and gravitational-wave data analysis. In 2014 Eric Poisson and Clifford Will published the superb *Gravity: Newtonian, Post-Newtonian, Relativistic*, which deals with the motion of self-gravitating bodies, the physics of gravitational waves, and experimental tests of general relativity. A revised edition of Peter Saulson's 1994 *Fundamentals of Interferometric Gravitational Wave Detectors* was released in 2017.

How does Maggiore's two-volume opus, now completed by *Gravitational Waves, Volume 2: Astrophysics and Cosmology*, compare with those more specialized references? Volume 1 was not reviewed in Physics Today, but Poisson reviewed it for *Classical and Quantum Gravity*. Despite some minor criticisms, he called it a "truly remarkable achievement," an assessment with which I agree. Maggiore's first book covers the basics of gravitational-wave physics, including the theory of gravitational-wave generation and propagation and data-analysis techniques. A few chapters, such as the ones on resonant mass detectors and interferometric detectors, are now of mostly historical interest, as the technology has advanced significantly since 2008.

Volume 2, which builds on and draws from the material in volume 1, is a pedagogical introduction to astrophysical and cosmological sources of gravitational waves. The chapter numbering picks up where volume 1 left off. The opening chapter 10, on stellar collapse, contains topics that are not often covered in textbooks, such as gravitational waves from neutrino emission. However, its coverage of numerical relativity simulations is already slightly outdated. Chapter 11 focuses on neutron stars and reviews current observations and various mechanisms for gravitational-wave emission, including stellar oscillations, instabilities, and postmerger radiation. Chapter 12 is an excellent introduction to black hole perturbation theory. Maggiore covers the basics of linearized perturbations of nonrotating black holes. He also presents some advanced topics, such as gauge transformations, the radiation from infalling point particles, and a rigorous definition in terms of Laplace transforms of both black hole quasinormal modes and late-time power-law tails.

The book moves into more mathematical territory in chapter 13, which discusses the 3 + 1 formulation of Einstein's equations, conserved quantities in general relativity, and the Newman–Penrose formalism. Chapter 14 covers the modeling of binary mergers of compact objects, including the effective-one-body formalism developed by Alessandra Buonanno, Thibault Damour, and their collaborators; chapter 15 offers a summary of the LIGO/Virgo discoveries. Chapter 16 discusses massive black hole binaries, including estimates of the stochastic background that they produce and of their detectability by space-based detectors and pulsar timing arrays.

The final seven chapters focus on cosmology. After a compact and clear introduction to the basics of Friedmann-Robertson-Walker cosmology in chapter 17, Maggiore turns to the helicity decomposition of metric perturbations in flat and curved spacetime in chapter 18. Chapter 19 describes the evolution of cosmological scalar and tensor perturbations; it also introduces binary mergers as "standard sirens" to probe dark energy and modified gravity. Subsequent chapters describe the imprint of primordial gravitational waves on the cosmic microwave background, inflationary cosmology, and stochastic backgrounds of cosmological origin. Finally, chapter 23 revisits Steven Detweiler's original calculation of the effect of gravitational waves on the timing of a single pulsar, describes the response of pulsar timing arrays to continuous and stochastic signals, and concludes with a description of modern data-analysis techniques and the status of current gravitational-wave searches.

Maggiore is a high-energy theorist and cosmologist by training, and his approach to his subject reflects that expertise. I admire his effort to cover all aspects of gravitational-wave research, although the result is, perhaps inevitably, uneven in depth and scope. Important omissions include comprehensive treatments of modified theories of gravity and the timing of binary pulsars. In my opinion—which, of course, reflects my own bias and expertise—the book shines in its treatment of cosmological gravitational waves. Some of the material on astrophysical sources, however, is more descriptive than didactic. Readers interested in perturbations of rotating black holes, core collapse, compact binary formation, or astrophysical stochastic backgrounds are still best served by research articles and specialized reviews. I also have a minor quibble with the excessive use of margin notes, which can be distracting.

In summary, the book covers a staggering breadth of material and is extremely useful as a bird's-eye overview of the field. When I was a student, the bible for newcomers to gravitational-wave astronomy was Kip Thorne's outstanding 1987 review in Stephen Hawking and Werner Israel's *Three Hundred Years of Gravitation*, which has been steadily updated by Thorne's students and collaborators over the years. More recently I have referred students to a handful of newer review articles. Maggiore's book is more comprehensive and pedagogical than those articles, and from now on I will recommend it as the best entry point for students who want to join this blooming research field.

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KOREA INSTITUTE FOR ADVANCED STUDY (KIAS)
Assistant Professor & Research Fellow in Theoretical Physics at KIAS

The School of Physics at Korea Institute for Advanced Study (KIAS) invites applicants for the positions at the level of KIAS assistant professor and postdoctoral research fellow in theoretical physics. Applicants are expected to have demonstrated exceptional research potential, including major contributions beyond or through the doctoral dissertation.

The annual salary starts from 50,500,000 Korean Won (approximately US$45,500 at current exchange rate) for Research Fellows, and 57,500,000 Korean Won for KIAS Assistant Professors, respectively. In addition, individual research funds of 10,000,000 Korean Won for research fellows and 13,000,000 Korean Won for KIAS Assistant Professors are available per year. The initial appointment for the position is for two years and is renewable once for up to two additional years, depending on research performance and the needs of the research program at KIAS.

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Where did the "New Books" go?

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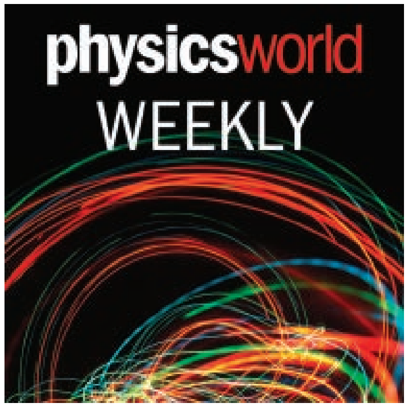
NEW BOOKS & MEDIA

Physics World Weekly Podcast



Physics World, 2018–present

If you've been looking for a podcast on the latest and most interesting news from the physics community, this offering from the British magazine *Physics World* is for you. In nicely bite-sized episodes of 40 minutes or less, *Physics World* journalists talk about stories they're working on, scientific papers they're excited about, and predictions for where physics is going. Some of the most interesting episodes feature interviews with physicists like Melanie Windridge, who talks about how physics has changed the climb up Mount Everest, and Lincoln Carr, a professor at the Colorado School of Mines and former actor. New episodes post on Thursdays and are available for download from iTunes. —MB

Eco Kids Self-Sufficiency Handbook

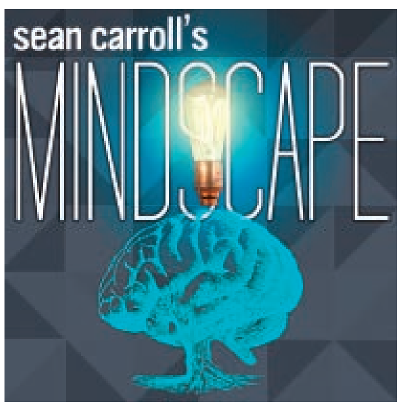
STEAM Projects to Help Kids Make a Difference

Alan Bridgewater and Gill Bridgewater
Happy Fox Books, 2019. $14.99 (paper)

Emphasizing science, technology, engineering, arts, and math (STEAM), this colorfully illustrated guide walks young readers through DIY projects that range from building their own backyard cabin to growing their own food. With a little help from parents or other adults, say authors Alan Bridgewater and Gill Bridgewater, children aged 7 to 14 years can begin to build a self-sufficient "world in miniature." The goal is for kids to learn how things work, how to use common tools, and how to reduce their carbon footprint by recycling materials and taking advantage of greener forms of energy, like wind and solar. —CC

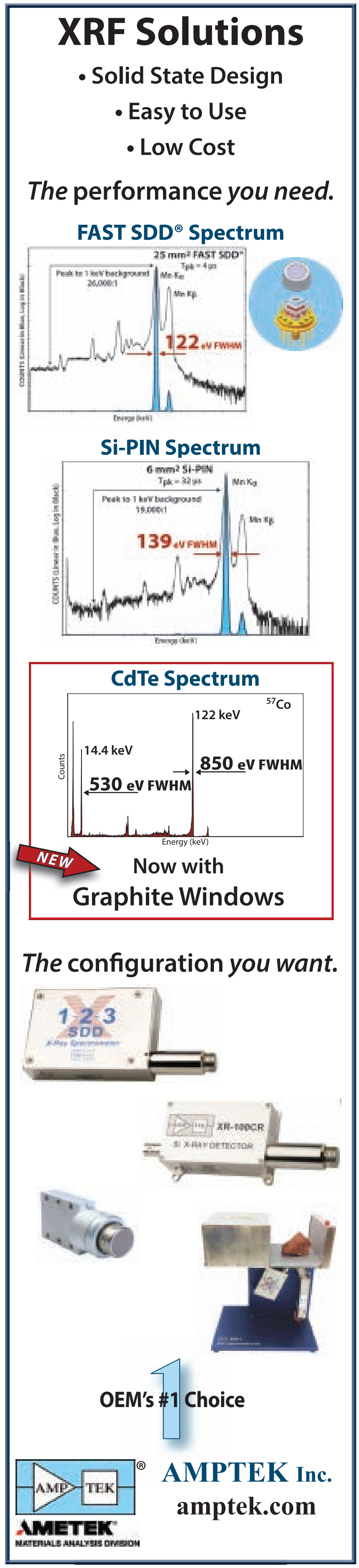
Sean Carroll's Mindscape

Science, Society, Philosophy, Culture, Arts, and Ideas



Sean Carroll, 2018–present

Caltech theoretical physicist Sean Carroll hosts and produces this weekly podcast, which features in-depth interviews with scientists, artists, humanists, and other interesting figures. Guests so far have included physicist Roger Penrose, chemist Raychelle Burks, religion scholar Anthony Pinn, and professional poker player Liv Boeree. Carroll is an engaging interviewer and chooses his topics and guests with care; although many episodes are 90 minutes or longer, the discussions are deep enough to sustain that length. New episodes post on Mondays and are available for download from iTunes, Google Play, and other podcast platforms. —MB PT



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FACULTY POSITION

School of Natural Sciences
Institute for Advanced Study
Princeton, New Jersey

The Institute for Advanced Study intends to make a new professorial appointment in physics in the School of Natural Sciences. Only candidates with distinguished scholarly accomplishments in this field will be considered.

We invite applications and nominations for this position. These should contain a curriculum vitae and bibliography, and be sent by June 30, 2019 to Michelle Sage, Administrative Officer, School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, New Jersey 08540, USA. Email: michelle@ias.edu. All communications will be held in strict confidence. The Institute for Advanced Study is an equal opportunity institution, and we especially welcome applications or nominations from underrepresented groups.

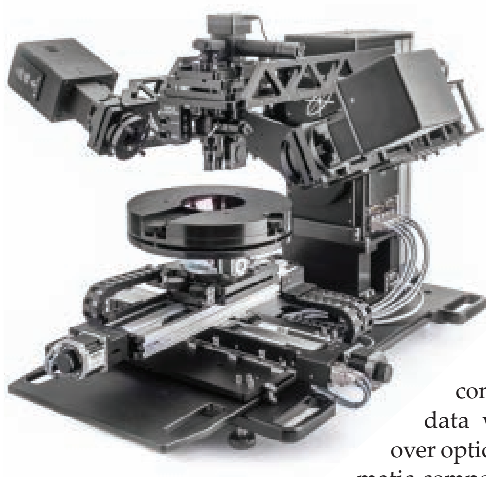
Focus on test, measurement, and data acquisition

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

Andreas Mandelis

Programmable DC power platforms

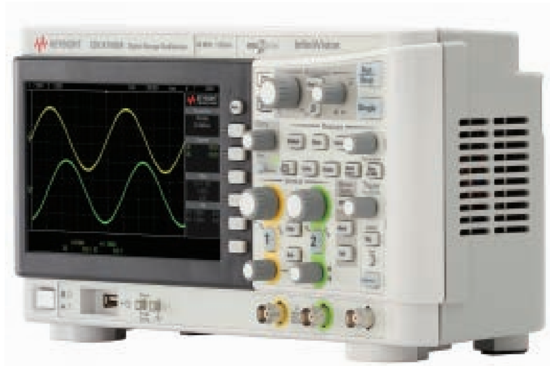
Ametek Programmable Power's Asterion power-supply platform line now includes programmable DC supplies with high power density and either fixed or auto-ranging output. The compact DC-series supplies offer rated outputs of 40 V and 60 V for 1.7 kW, 3.4 kW, and 5.0 kW power levels. The fixed-range units are economical, traditional rectangular-wave output-power supplies; the auto-ranging supplies offer expanded current and voltage range at the full output-power level, so users can fulfill wider testing needs without purchasing additional models. An auto-paralleling capability supports operating multiple units in parallel to increase the total output-power level. Applications include electronics test, DC power simulation, R&D, and a wide range of automatic test equipment. ***Ametek Programmable Power Inc**, 9250 Brown Deer Rd, San Diego, CA 92121, www.powerandtest.com*



Spectroscopic ellipsometer

The RC2 spectroscopic ellipsometer from J. A. Woollam combines the best features of previous models with innovative new technology. Dual rotating compensators provide complete Mueller-matrix measurements to characterize advanced samples and nanostructures. Synchronous operation of both compensators delivers highly accurate data without waiting to "zone-average" over optical elements. A patent-pending achromatic compensator design yields optimized performance over a wide spectral range. According to the company, the RC2 is the first commercial ellipsometer to use the latest thermoelectrically cooled, strained indium gallium arsenide array to collect hundreds of wavelengths in the IR out to 2500 nm. An advanced dual light source includes computer-controlled beam intensity to optimize the signal on low- or high-reflection samples. ***J. A. Woollam Co Inc**, 645 M Street, Ste 102, Lincoln, NE 68508, www.jawoollam.com*

Entry-level oscilloscopes



Keysight Technologies designed its 200 MHz, four-channel InfiniiVision 1000 X-Series oscilloscopes to provide professional-level measurements and capabilities at lower cost. They feature the same user interface and measurement technology as the company's higher-performance InfiniiVision oscilloscopes, and are bandwidth-upgradable via software license as designs evolve. The InfiniiVision 1000 X-Series oscilloscopes are available at 70, 100, and 200 MHz bandwidth. Custom Keysight MegaZoom IV application-specific integrated-circuit technology delivers an update rate of 50 000 waveforms/s and sample rate of 2 GSa/s, which allow visualization of random, infrequent glitches and anomalies that similarly priced oscilloscopes might miss. ***Keysight Technologies Inc****, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Hall effect measurement controller

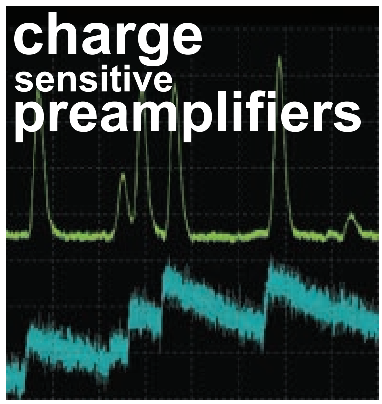
The MeasureReady M91 measurement controller from Lake Shore Cryotronics features the company's patented FastHall technique, which allows for fast, accurate, and convenient measurements of electronic materials, especially when using high-field superconducting magnets and when measuring very-low-mobility materials. By eliminating the need to switch the polarity of the applied magnetic field during the measurement, the M91 fundamentally changes the way the Hall effect is generated and measured. It combines all the necessary Hall-effect measurement functions into a single instrument, automates and optimizes the measurement process, and directly reports the relevant parameters. The M91 performs Hall analysis, including calculation of derived parameters for van der Pauw and Hall bar samples. ***Lake Shore Cryotronics Inc****, 575 McCorkle Blvd, Westerville, OH 43082, www.lakeshore.com*

High-speed semiconductor test pulser

The AVRQ series of semiconductor test pulsers from Avtech Electrosystems is suitable for generating the high-speed, high-voltage waveforms needed for transient immunity testing of optocouplers and other semiconductor devices. The instruments can also be used for applications that require a high-voltage "sweep" waveform, such as sweep-control of particle-beam systems. The company's latest common-mode transient immunity tester, model AVRQ-5-B, provides 1.5 kV pulses with linear leading edges, followed by a slower exponential decay back to zero. The transition time (10–90%) of the leading edge is less than 10 ns into a non-capacitive load, which provides transition rates of up to 120 kV/μs. The transition time may be increased up to 50 ns by adding capacitance across the load. ***Avtech Electrosystems Ltd****, PO Box 265, Ogdensburg, NY 13669-0265, www.avtechpulse.com*

Fast time-domain terahertz system

According to Toptica Photonics, its TeraFlash smart time-domain terahertz (TD-THz) platform sets new standards for measurement speed. Using the company's proprietary technique called electronically controlled optical sampling or "ECOPS," the system replaces the mechanical delay of conventional TD-THz systems with two synchronized femtosecond lasers and an electronic scanning scheme. The new platform attains scanning speeds up to 1600 pulse traces per second. It is suitable for measurements on rapidly moving samples such as extrusion lines, particularly if high spatial resolution is required. Other potential applications include measurements under rapidly changing environmental conditions and studies of the properties of samples in pulsed magnetic fields. Both transmission and reflection measurements can be made. ***Toptica Photonics Inc****, 5847 County Rd 41, Farmington, NY 14425, www.toptica.com* PT



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Cremat Inc. West Newton, MA USA

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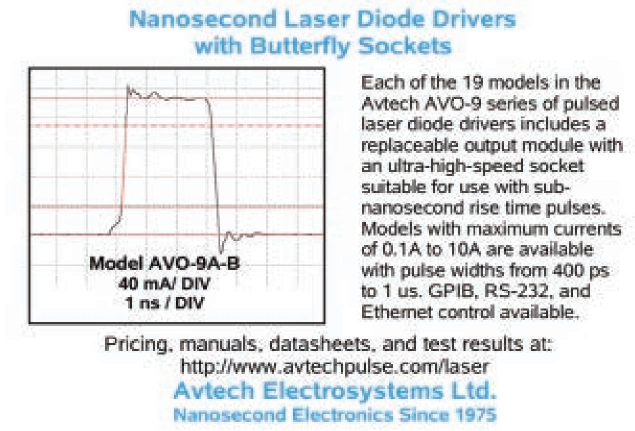

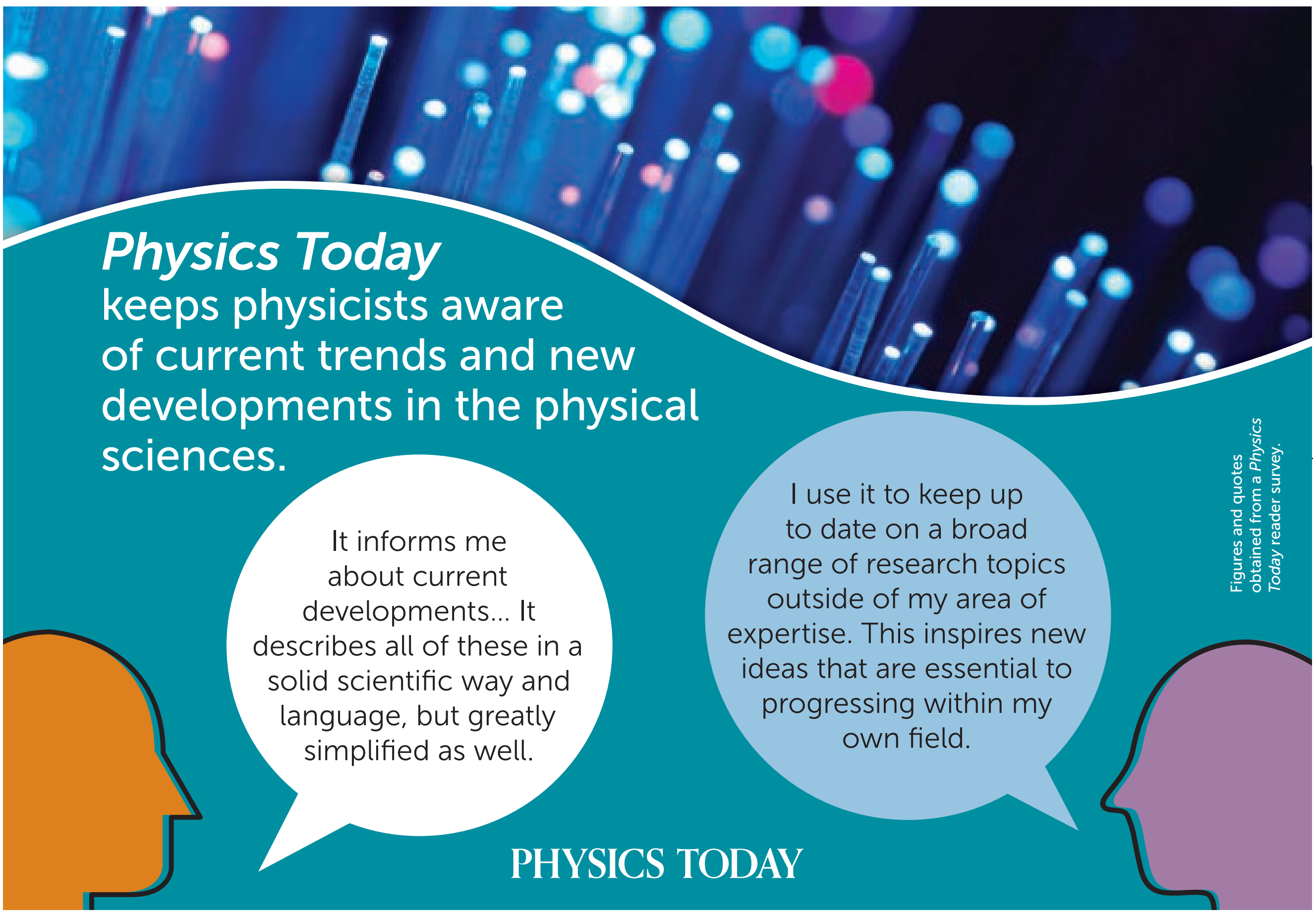

Peter George Oliver Freund

On 6 March 2018, Peter George Oliver Freund—prominent theoretical physicist, fiction writer, lover of the arts, and raconteur—died in Chicago at age 81.

Peter was born on 7 September 1936 in Timișoara, Romania, into a well-off and cultured Jewish family. His father was a doctor and his mother an opera singer. His early life was disrupted first by the Nazis and then by Soviet rule. His family fled Romania for Israel in 1959. After a last-minute dramatic visa appeal, Peter was able to enter the doctoral program at the University of Vienna, where he received his PhD in particle physics in 1960 under the supervision of Walter Thirring.

The early 1960s were a busy time for Peter. In 1961 he was appointed as a research associate for theoretical physics at the University of Vienna. Later that year he received an appointment as *chef de travaux* at the University of Geneva's Institute of Theoretical Physics. He moved to the University of Chicago as a research associate in the fall of 1962 and was appointed to the Chicago faculty in 1965.

Peter entered particle physics during the early days of Regge-pole phenomenology. He wrote numerous papers that helped develop both the formalism of finite-energy sum rules and the ideas of dual-resonance models that were the precursors of string theory. His studies on magnetic monopoles, the topology of gauge fields, and the function of the axial anomaly in gravitational theories were critical to understanding the role of topology in particle physics. Peter loved novel mathematical structures and early on appreciated the possible role of supersymmetry in particle physics; not long after the discovery of spacetime supersymmetry, he and Irving Kaplansky wrote a paper on the classification of graded Lie algebras.

Peter's most cited paper, written with Mark Rubin in 1980, is on the dynamics of dimensional reduction in higher-dimension theories in which gravity interacts with antisymmetric tensor gauge fields. That situation arises in many supergravity theories and has been critical in the anti–de Sitter/conformal field theory correspondence. In the 1980s Peter wrote a series of papers with Lee Brekke, Mark Olson, and Edward Witten on the possibility of using *p*-adic numbers to define a new kind of string theory. It seems fair to say that their work led to striking results that, if they are to be fully incorporated into the theory's structure, will require new ideas. Following the work of Michael Green and John Schwarz on anomaly cancellation, Peter wrote a note that anticipated some of the structure of the heterotic string.

Many physicists know Peter not only for his research but for his remarkable storytelling ability. He viewed physics as a very human enterprise, embedded in the culture of the times, with ties to the arts and influenced by the prevailing intellectual winds. He told rich and elaborate stories, continually adding to them and perfecting his delivery. Those stories included the many colorful adventures


Peter George Oliver Freund

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of his family and of the numerous physicists and mathematicians he admired. Several of his tales are collected in his book *A Passion for Discovery* (reviewed in PHYSICS TODAY, August 2008, page 56).

His passion for physics and storytelling made Peter a compelling teacher who motivated many generations of students at the University of Chicago. In his Nobel Prize acceptance speech, Frank Wilczek said, "I'd especially like to mention the inspiring influence of Peter Freund, whose tremendous enthusiasm and clarity in teaching a course on group theory in physics was a major influence in nudging me from pure mathematics toward physics."

Peter was a romantic at heart, with an aristocratic bearing, a booming baritone voice, and a highly developed aesthetic sense. He had a lifelong love of opera and sang in an amateur opera company in Chicago. With his passing, we have lost a stimulating colleague, an engaging teacher, and a dear friend.

Jeffrey A. Harvey
Emil J. Martinec
Enrico Fermi Institute
Chicago, Illinois PT

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Mike Brown is a professor of planetary astronomy at Caltech in Pasadena, California.

The Planet Nine hypothesis

Michael E. Brown

The putative planet accounts for similarities in the orbits of a collection of objects in the distant Kuiper belt.

In 1820 Alexis Bouvard, the director of the Paris Observatory, made what could have been a huge discovery. The planet Uranus, whose position he had tracked back 130 years in old star catalogs, didn't quite go around the Sun the way that he predicted it should. It traveled along its elliptical orbit as expected, but sometimes the old observations suggested it was a little ahead of its predicted position and sometimes a little behind. Bouvard might have realized that there was something beyond Uranus, but instead he was convinced the old star catalogs were simply wrong.

Twenty more years of careful observation showed that Uranus still deviated from its predicted orbit. By 1840 it became widely accepted that the likely reason for the discrepancy was that a more distant planet was perturbing Uranus's orbit—sometimes pulling it a little faster, sometimes holding it back. Within the next five years, French mathematician Urbain Leverrier used Bouvard's data to work out the orbital mechanics. In a single night of searching in 1846, astronomer Johann Galle discovered Neptune—within a single degree of its predicted position. (See the article by Deborah Kent, Physics Today, December 2011, page 46.)

That story of prediction, discrepancy, new theory, and triumphant confirmation is classic, and Leverrier became famous for it; his statue still stares up the Avenue de l'Observatoire in Paris today. Almost immediately people tried predicting even more planets. In the past 173 years, dozens of scientists have used some sort of alleged orbital discrepancy to motivate the effort. Their predictions have invariably been wrong. The most famous of them came in the early years of the 20th century from businessman, mathematician, and astronomer Percival Lowell, who called the planet he thought was perturbing the orbits of Uranus and Neptune Planet X.

When Pluto was discovered at the Lowell Observatory in 1930, it was thought to be Planet X. Astronomers now know that Pluto is about 0.03% as massive as the predicted Planet X. After the *Voyager 2* flyby of Neptune in 1989, new calculations revealed that the giant planets were where they should be. There is no Planet X after all.

Just as that hypothetical planet was disappearing from the picture, though, astronomers started noticing that the outer solar system is far from empty. Thousands of tiny icy bodies orbit the Sun just beyond the known planets. Most of the objects in that region, now known as the Kuiper belt, have mildly eccentric orbits. They are constantly pushed and pulled by the planets' gravity, which produces intricate resonances, vast unstable regions, and violent gravitational scattering. A combination of analytic celestial mechanics and powerful computer simulations has traced the influences of planets throughout the Kuiper belt and placed the thousands of known objects in the context of the rest of the solar system. (See my article, Physics Today, April 2004, page 49.)

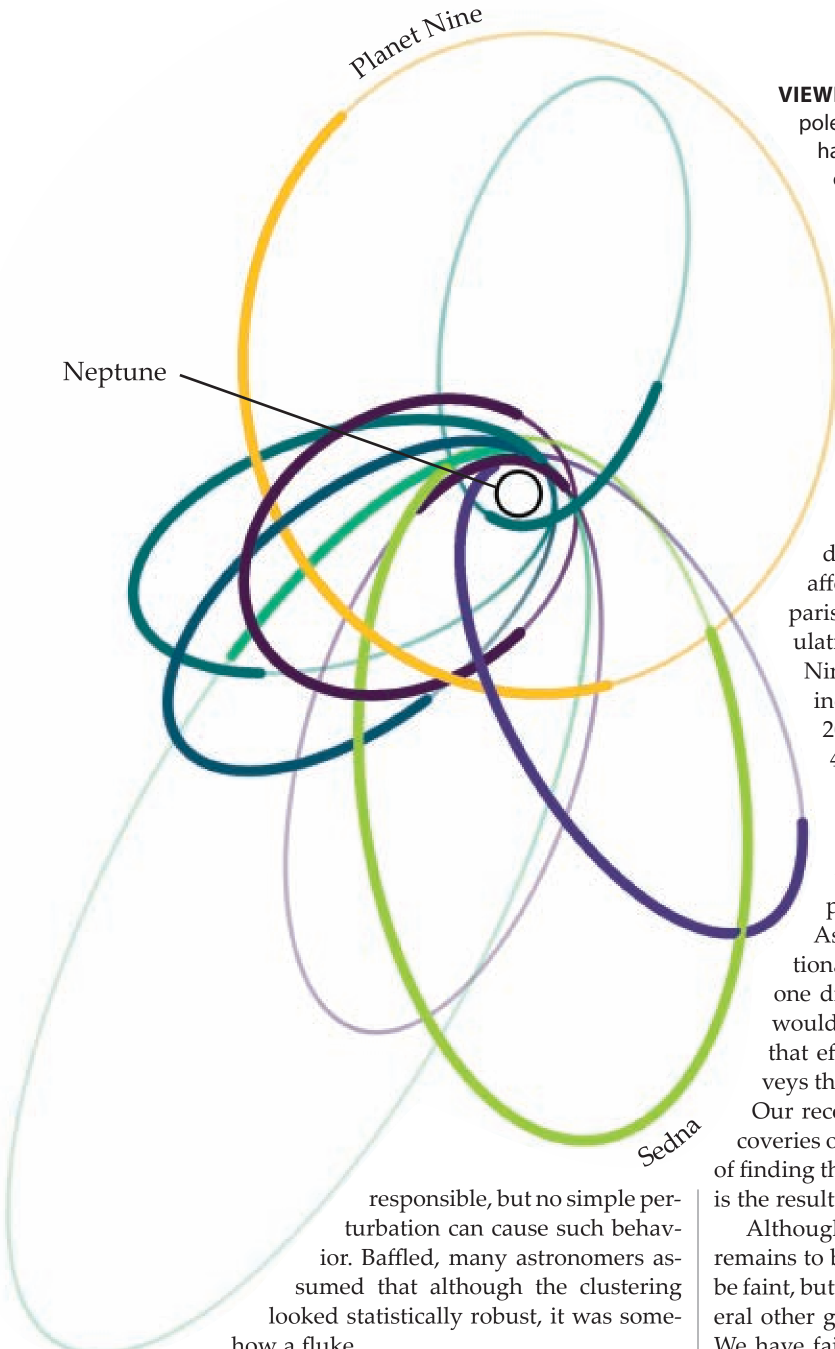
Everything is where it is supposed to be. Almost.

The discovery of Sedna

In 2002 I led a survey that uncovered an object now known as Sedna (see Physics Today, June 2004, page 23). It has a hugely elongated orbit that takes 10 000 Earth years to complete. The extreme eccentricity is unusual but not unprecedented. A modest number of Kuiper belt objects have strayed too close to Neptune and been flung deep into the outer solar system. If not ejected, they return and will probably have to deal with Neptune again in the future. The surprising aspect of Sedna's orbit, however, is that it never comes close to Neptune. At its closest approach to the Sun, Sedna is two and a half times as far away as Neptune ever is. Its strange orbit can't be the fault of Neptune; something else must be responsible.

At the time of Sedna's discovery, Chadwick Trujillo (then at the Gemini Observatory), David Rabinowitz (Yale University), and I suggested that Sedna's orbit was likely modified by a passing star early in the history of the solar system, when the Sun would still have been part of the cluster of stars in which it was born. The close proximity of potentially thousands of stars could have given Sedna enough of a nudge to move its orbit away from that of Neptune. When the cluster of stars dispersed, Sedna would have been left as a fossil record of the distant past. But in 2012 Brazilian astronomer Rodney Gomes pointed out that Sedna and others like it could instead be the natural consequence of a distant massive planet.

Another odd property of such distant objects was pointed out by Trujillo and Scott Sheppard (Carnegie Institution for Science) in 2015. They noted that when objects with extremely elongated orbits are at points closest to the Sun, they preferentially move from below the plane of the solar system to above it. They speculated that a distant planet may somehow be



VIEWED FROM THE DIRECTION of the solar system's north pole, almost all the stable objects in the outer solar system have orbits that cluster strongly in one direction. Those orbits are also tilted in the same direction, which is evident from the thickness of the lines; the thinner, fainter lines denote when the orbits are below the plane of the solar system. The yellow ellipse is our best estimate of the current orbit of Planet Nine. A massive body on an eccentric orbit will force a population of distant orbits to be mostly anti-aligned to its direction.

responsible, but no simple perturbation can cause such behavior. Baffled, many astronomers assumed that although the clustering looked statistically robust, it was somehow a fluke.

The pieces of that puzzle fell into place in 2016, when Konstantin Batygin and I realized that when viewed correctly, all of the most elongated objects point in the same direction and are tilted in the same direction. In terms of orbital elements, they are clustered in the longitude of perihelion and in pole position. Such a clustering shouldn't persist; with nothing holding the orbits in place, differential precession would randomize their longitudes and pole positions in a scant 100 million years.

Batygin and I further realized that a massive, distant, eccentric, and inclined planet would produce exactly that result. It also explains the confusing clustering. Finally, we had found an effect in the distant Kuiper belt that could be caused by perturbations from a distant, giant planet. The Planet Nine hypothesis was born. (See PHYSICS TODAY, April 2016, page 23.)

In the three years since the original publication of the hypothesis, we have come to a much more detailed understanding of how Planet Nine might affect the outer solar system. In a sophisticated comparison of solar-system observations to numerical simulations, we find a best match to be a putative Planet Nine that is approximately six times the mass of Earth, inclined with respect to the ecliptic by a little less than 20 degrees, and in a moderately eccentric orbit about 400 times as distant from the Sun as Earth. (See the figure.)

Shockingly, no alternative hypothesis has come forward to explain the observations of orbital clustering. If the observations are trustworthy, it appears that Planet Nine is probably real. But are they?

Astronomers are always concerned with observational bias. For example, if an observer looked in only one direction in the sky, all distant objects found there would appear to be tilted in that direction. Correcting that effect has proven challenging for the scores of surveys that have been done. But we finally have the answer. Our recently published meta-analysis of all previous discoveries of Kuiper belt objects shows only a 0.2% probability of finding that the extreme clustering in the distant Kuiper belt is the result of bias and chance.

Although the statistical analysis is convincing, the planet remains to be found. At its extreme distance, Planet Nine will be faint, but not too faint for our largest telescopes. We and several other groups are using our predictions to track it down. We have failed to match the record of a one-night discovery of a planet by Leverrier and Galle, but we have confidence that within a few years an astronomer somewhere will find a faint, slow-moving point of light in the night sky and triumphantly announce the discovery of another new planet in our solar system.

Additional resources

▶ C. A. Trujillo, S. S. Sheppard, "A Sedna-like body with a perihelion of 80 astronomical units," *Nature* **507**, 471 (2014).
▶ K. Batygin, M. E. Brown, "Evidence for a distant giant planet in the solar system," *Astron. J.* **151**, 22 (2016).
▶ M. E. Brown, K. Batygin, "Orbital clustering in the distant solar system," *Astron. J.* **157**, 62 (2019).

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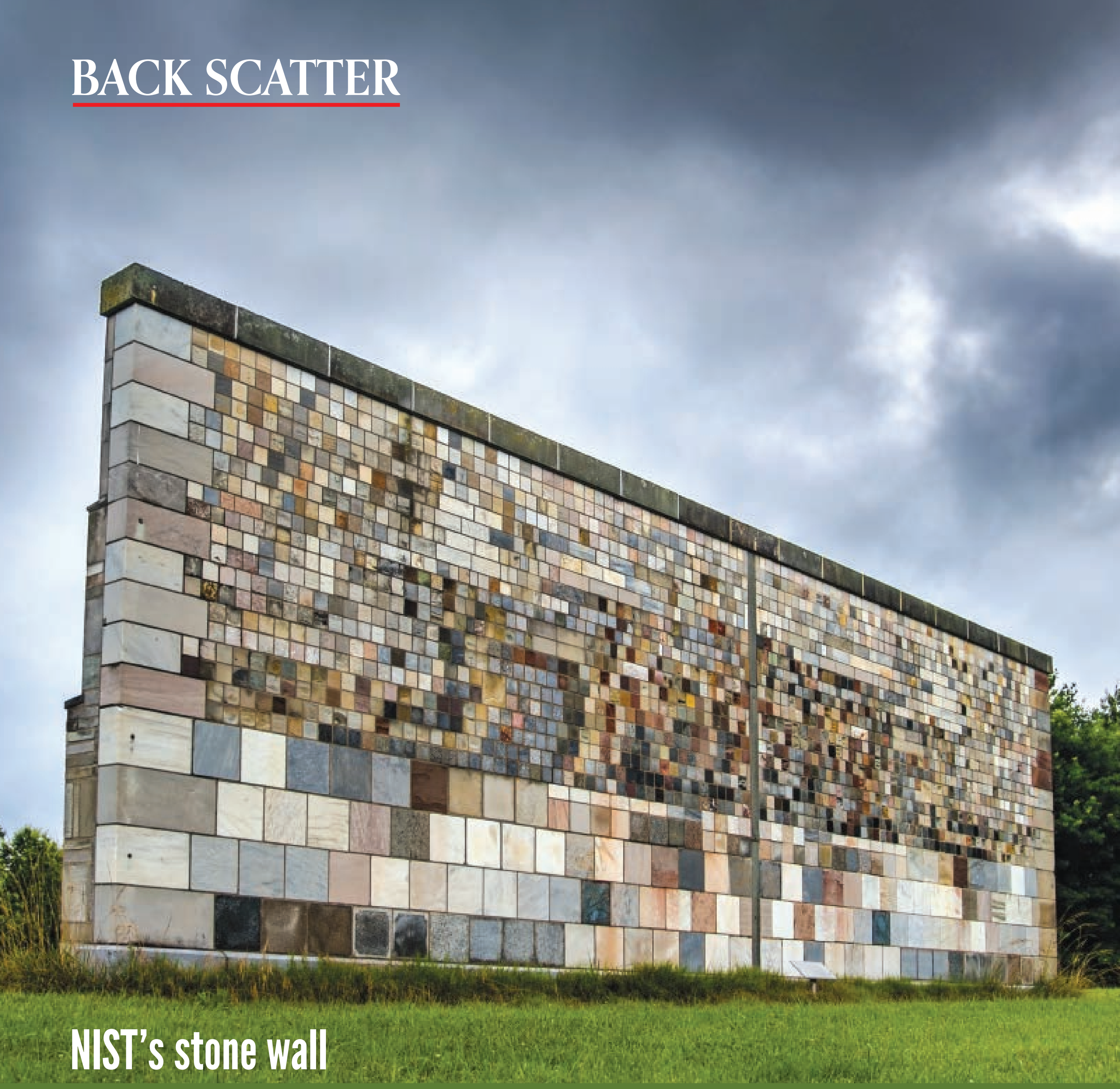

NIST's stone wall

Standing in the southwest corner of NIST's campus in Gaithersburg, Maryland, is a 70-year-old experiment: studying the effect of weathering on various types of stone. NIST's stone test wall, nearly 12 meters long and 4 meters high, contains 2352 individual stone samples, quarried from 47 states and 16 foreign countries. The stones on the left half are set in high-calcium lime mortar; on the right half, in a mortar made from Portland cement. The arrangement exposes the many stones and the two mortars to the same climatic conditions. As their texture changes, their durability and performance can then be correlated with mineralogical and microstructural properties. The wall also allows rapid-weathering tests to be validated against real-world observations.

The wall's origins date back to the 1876 Centennial Exposition in Philadelphia and to the 1880 US census, which surveyed the nation's quarries and systematically collected reference specimens. Originally on display at the National Museum (which became the Smithsonian Institution's Arts and Industries Building), the stones were assembled into a wall in 1948 on the grounds of NIST's precursor, the National Bureau of Standards, in Washington, DC. Following the bureau's relocation in the 1960s to Gaithersburg, the wall was moved intact to its present site in 1977. For more on the wall, see https://stonewall.nist.gov. (Photo by J. Stoughton/NIST.) —RJF

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Looking beyond our solar system with ray tracing simulation...

Visualization of ray trajectories in a white pupil échelle spectrograph.

Astronomers detected an Earth-like planet 11 light-years away from our solar system. How? Through data from an échelle spectrograph called HARPS, which finds exoplanets by detecting tiny wobbles in the motion of stars. Engineers looking to further the search for Earth-mass exoplanets can use ray tracing simulation to improve the sensitivity of échelle spectrographs.

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