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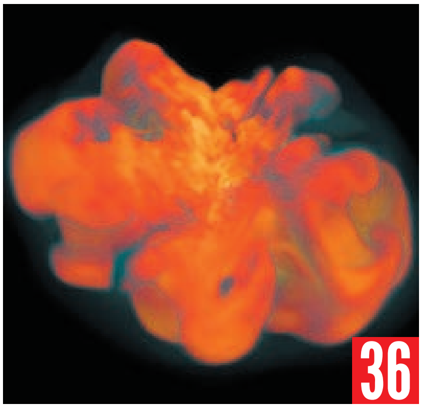

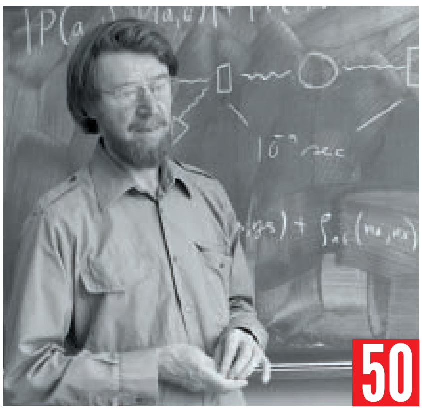

FEATURES

Reviews of Modern Physics at 90

ON THE COVER: In 1928 John Tate wrote to 48 of his fellow physicists to ask whether the American Physical Society should establish a review journal. The positive response he received sparked the launch a year later of *Reviews of Modern Physics*. Starting on **page 32** you'll find a series of short articles produced in celebration of the influential journal's 90th birthday. The cover illustration, a detail from *Composition 1923* by American cubist Patrick Henry Bruce (1881–1936), also comes from the 1920s, which saw great changes not just in physics but also in art, literature, and music. (Peter Horree/Alamy stock photo.)

Recently on PHYSICS TODAY ONLINE

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NATIONAL SCIENCE BOARD

▶ US science advisers

Last month the Senate confirmed Kelvin Droegemeier as director of the White House Office of Science and Technology Policy and presidential science adviser. David Kramer looks back at some of Droegemeier's predecessors, who experienced varying amounts of success in the challenging position.
physicstoday.org/Feb2019a

SKA SOUTH AFRICA

▶ Powering SKA

When completed, the Square Kilometre Array (SKA) will be the world's largest telescope configuration. The problem: how to power the project's radio dishes and antennas, many of which will be spaced far apart in remote areas. Sarah Wild explores SKA scientists' high-stakes energy strategy and how it has changed in recent years.
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ROYAL OBSERVATORY, EDINBURGH

▶ Bell Burnell Q&A

In 2018, a half century after her first publication on radio pulsars, Jocelyn Bell Burnell was awarded the $3 million Special Breakthrough Prize in Fundamental Physics. In an extensive interview, Bell Burnell discusses her discovery, her Nobel snub, and her decision to donate all of the prize money.
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Physics Today (ISSN 0031-9228, coden PHTOAD) volume 72, number 2. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to Physics Today, American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Views expressed in Physics Today and on its website are those of the authors and not necessarily those of AIP or any of its member societies.

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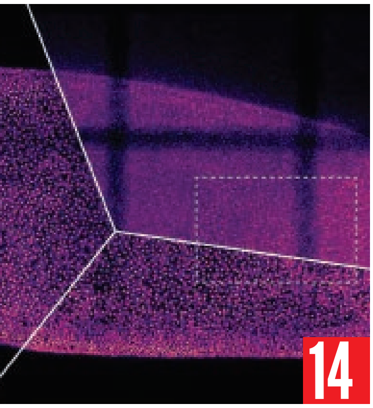

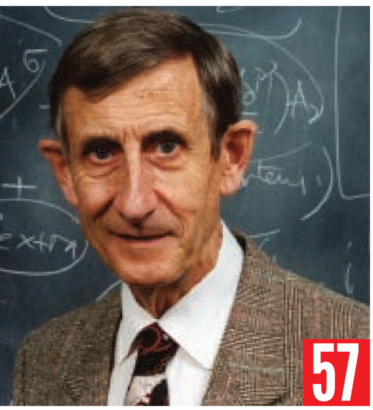

DEPARTMENTS

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Happy birthday, *Reviews of Modern Physics*!

Charles Day

This year the American Physical Society (APS) is celebrating the 90th anniversary of its journal *Reviews of Modern Physics* (*RMP*). This issue of PHYSICS TODAY joins the celebration. Starting on page 32, you'll find a brief history of the journal followed by 11 two-page articles that look back on how papers in *RMP* have tracked and recorded physicists' increasing understanding of superconductivity, critical phenomena, nucleosynthesis, and other topics.

In his introduction to the special issue, *RMP*'s current lead editor, Randy Kamien, speculates that many PHYSICS TODAY readers have, like him, photocopied and kept review articles for so long that they have become decorated with annotations and food stains. When I left the UK in 1988 to start a postdoc at Japan's Institute of Space and Astronautical Science, I took several photocopied reviews with me. I can't remember them all, but they included "Accretion powered x-ray pulsars" in *Astrophysical Journal*,[1] "Accretion discs in astrophysics" in *Annual Review of Astronomy and Astrophysics*,[2] and "X-ray emission from clusters of galaxies" in *RMP*.[3]

One way to gauge the usefulness of review articles is to count how many times they have been cited. In 2004 Sankar Das Sarma and two of his postdocs at the time, Igor Žutić and Jaroslav Fabian, surveyed the theory and applications of spintronics in *RMP*.[4] According to Google Scholar, the article has been cited 9000 times!

Another way to gauge a review's usefulness—or, more precisely, the temporal and disciplinary scope of its subject—is to look at its list of references. Žutić, Fabian, and Das Sarma's list runs for 24 pages and cites more than 900 papers. That huge corpus raises a question that Samuel Goudsmit tackled in a feature-length commentary on page 52 of the September 1966 issue of PHYSICS TODAY. At that time, Goudsmit was the managing editor of APS and editor of *Physical Review Letters*. He and others fretted about the booming proliferation of scientific literature. Goudsmit's solution started with the recognition that most original papers don't need to be cited or even read at all. (For a contrary view, see Ray Goldstein's article, "Coffee stains, cell receptors, and time crystals: Lessons from the old literature," PHYSICS TODAY, September 2018, page 32.) Experimental results were best presented in tables and other compendia. As for theory, he wrote, "The rate at which theoretical papers are published has increased enormously, and with a few brilliant exceptions, most of them contain very little advancement. Many are obsolete in a short time, and there is sharp competition among authors and strong pressure for rapid publishing."

To cope with the plethora of theory papers, Goudsmit advocated review articles and specialized books. His paragon was Arnold Sommerfeld's book *Atomic Structure and Spectral Lines*, which was published in the original German in 1919 and in English four years later: "It summarized in a clear and concise way all that was worth knowing up to the time of its publication."

Having praised review articles and specialized books, Goudsmit went on to consider how to produce them. Paying for them didn't work. He recounted an NSF-funded trial that *RMP* conducted in the early 1960s. Authors were offered $3000 to write one of four articles. The fee had about the same buying power as $24 000 does today. Despite that alluring bounty, *RMP*'s editor at the time, Edward Condon, struggled to find authors willing to give up their research time to write.

A better approach, Goudsmit argued, was to establish centers, whose permanent staff of generalist writers would gather and prepare material under the guidance of a subject-matter expert, who did not have to belong to the center. He looked to the American Institute of Physics (which publishes PHYSICS TODAY) to take the lead in running the centers.

I'm not sure why Goudsmit's idea did not catch on, but I can see a problem with it. Although his proposed centers would yield reviews—possibly more promptly than the current system of expert volunteers—the reviews themselves would unlikely be as good. That's because of the personal nature of a review. The best ones reflect how a small group of experts has surveyed and made sense of a field of research. A different group of experts reviewing the same field could well organize their review differently. That doesn't matter. There's no one true narrative path. What matters is the authors' journey of understanding, which you, the reader, can follow.

APOLOGY TO READERS. Due to a mistake on my part, an article on nuclear physics did not make it into this issue. Look out for it in the next issue.

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Commentary

Multimessenger solar astrophysics

The term "multimessenger astronomy"—combining different signals, or messengers, from the same astrophysical event to obtain a deeper understanding of it—is in the air nowadays, largely because of the remarkable success of the Laser Interferometer Gravitational-Wave Observatory (LIGO) in detecting gravitational waves[1] (see PHYSICS TODAY, December 2017, page 19). Four messengers reach us from beyond the solar system: photons, neutrinos, cosmic rays, and now gravitational waves. Lost amid the current buzz, though, is that the Sun produces many other messengers. What's more, multimessenger solar astrophysics began as long ago as 1722, when London clockmaker George Graham noted a new solar messenger: diurnal variations in Earth's magnetic field.

Multimessenger information routinely forms a major part of current research in solar and heliospheric physics. One such example, shown in the figure, is a "snowstorm" of solar cosmic rays directly detected by a space-borne extreme-UV imager. Scott Forbush identified similar signals detected at ground-based cosmic-ray stations in 1942 and 1946 as being due to energetic solar protons.[2] Such dangerous ionizing particles are a messenger no spacecraft or space traveler can afford to ignore.

The first recognized messengers of unusual solar activity were sunspots. The arrival in the 17th century of visual evidence of solar structure and rotation possibly caused as much scientific excitement then as the new gravitational-wave messenger has today. As additional messengers from the Sun arrived over the centuries, they were not always recognized as such because the physics had not yet been understood. Graham's diurnal geomagnetic variations, for example, are now known to be a signature of ionization that is produced by solar EUV radiation and dragged across Earth's magnetic field by high-altitude thermal winds. That message has now been translated, and we have most of the physical and phenomenological basis (far in the future in 1722) for interpreting it: Maxwell's equations and the independent characterization of the ionosphere and solar wind.

Other variations of the geomagnetic field allow the detection of sunspots—and would do so even if terrestrial clouds never parted. Swiss sunspot-research patriarch Rudolf Wolf in 1859 famously wrote, "Wer hätte noch vor wenigen Jahren an die Möglichkeit gedacht, aus den Sonnenfleckenbeobachtungen ein terrestrisches Phänomen zu berechnen?"[3] ("Who would have thought just a few years ago, about the possibility of

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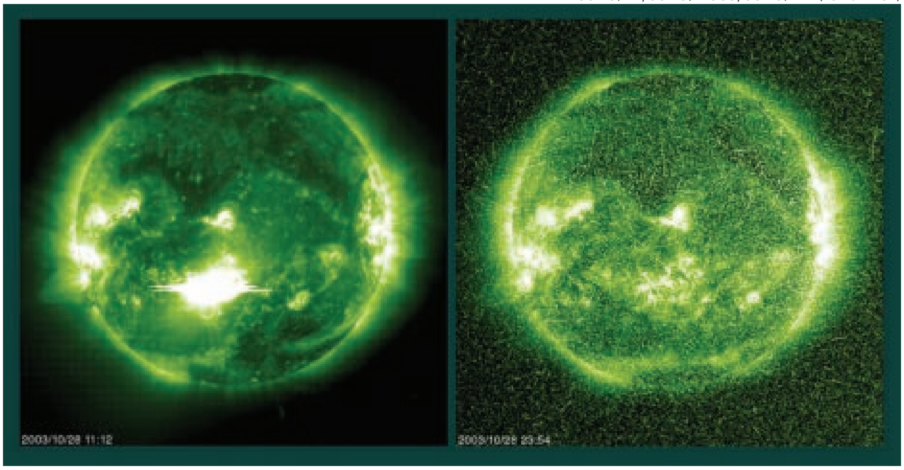

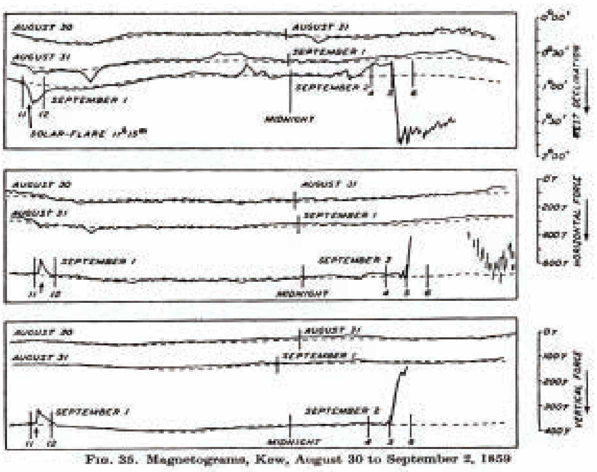

SOLAR MULTIMESSENGER EVENTS. Extreme-UV images of the Sun **(top)**, obtained by the *Solar and Heliospheric Observatory* spacecraft, recorded two messages from a solar flare: on the left, EUV photons that arrived 8 minutes after the flare happened (the horizontal "bleed" is due to CCD saturation), and on the right, the "snowstorm" of solar cosmic rays that arrived soon after and had filled the heliosphere within 12 hours later. **(bottom)** Magnetometers at London's Kew Observatory recorded several messages during the solar flare and geomagnetic storm on 1–2 September 1859. (Bottom panel from S. Chapman, J. Bartels, *Geomagnetism*, 2nd ed., Oxford U. Press, 1962, p. 333.)

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

computing a terrestrial phenomenon from observations of sunspots?")

Those early discoveries initiated multimessenger exploration of the quiet Sun. In addition to individual photons, leptons, and cosmic rays, we also receive organized plasma structures, such as the solar wind and various current systems in Earth's ionosphere, each of which transmits its own messages. The information they've delivered has allowed us to learn a great deal about the magnetic history of the Sun, including the behavior of the still poorly understood 22-year Hale cycle of global polarity changes in alternate 11-year sunspot cycles.

Other kinds of messengers debuted in conjunction with the first recognized solar flare.[4] As shown in the figure, magnetometers on 1 September 1859 recorded a short, sharp jump in Earth's field—a "geomagnetic crochet"—as solar x rays triggered enhanced currents in the ionosphere. Fourteen hours after those messages were received, there arrived a physical object now known as a coronal mass ejection (CME), well recognizable in the direct geomagnetic record (accomplished without electronics!). Rather appropriately, the CME announced itself directly in the telegraph system, not in Morse code but by actually setting instruments on fire! That type of messenger could never reach us from the distant cosmos; it is intrinsically local in the heliosphere.

A third new messenger in the 1859 flare was an interplanetary shock wave, analogous to those seen around supernovae, that preceded the CME and produced a distinct geomagnetic signature as it compressed Earth's magnetosphere. A fourth messenger produced by flare and CME disturbances was recognized only in 1942: Forbush's solar energetic particles.

As our knowledge of physics grew stronger over recent decades, the list of solar messengers expanded. It now includes neutrinos from the solar core; the solar gravity field, revealed in the precession of Mercury's perihelion, with implications for general relativity; and possibly axions. The axion messenger as yet is only hypothetical; many research programs are searching the possible parameter space, and its discovery would have far-reaching consequences in many fields of physics and astrophysics. For solar physics, the axion messenger would provide unique information not only about the solar interior but also about how the solar magnetic field penetrates the Sun's photosphere and eventually extends beyond Earth. Such information might help to explain the modulation at Earth of the cosmic-ray flux, which has been reconstructed[5] across the 9000 years of the Holocene epoch from yet another messenger: deposits of the cosmogenic radioisotopes carbon-14 and beryllium-10.

Also on the messenger list for flare and CME events are energetic neutral atoms and free neutrons. Because of the neutron's finite half-life, only those with sufficiently high energies will reach us. For the same reason, neutron messengers from any source outside the solar system cannot be detected.

Including the basic photons, neutrinos, and cosmic rays, we can count about a dozen distinct messengers from the Sun. We are highly unlikely to detect solar gravitational waves because of the minuscule masses involved, but then again, many physicists also doubted that LIGO would ever succeed!

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LETTERS

The inventor of puffed rice

As I read the July 2018 issue of PHYSICS TODAY, the Quick Study "Engineering puffed rice" by Tushar Gulati, Mayuri Ukidwe, and Ashim Datta (page 66) immediately caught my attention.

During the last 15 years of my career, I had the opportunity and privilege to teach physical science to students at the Tower View Alternative High School here in Red Wing, Minnesota. The school is housed on the campus of the Anderson Center for the Arts, the legacy of Alexander Pierce Anderson (1862–1943).

Anderson invented a process to make puffed rice. The invention led to a successful exhibit and demonstration of the process and the product at the 1904 World's Fair in St Louis, Missouri. The Quaker Oats Company eventually used Anderson's process to manufacture puffed rice for public consumption.

The Anderson Center staff always encourage teachers, students, and school personnel to utilize the center and to interact with visiting artists and writers as part of their daily experience. Anderson's inventiveness and spirit carry on today in the lives of those who are part of this vibrant family.

Thomas Wolters
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Red Wing, Minnesota

How to keep a scientist's mind

In his article "Who owns a scientist's mind?" (PHYSICS TODAY, July 2018, page 42), Douglas O'Reagan lays out all the concerns and fears of the competitive business leaders and scientists regarding the "ownership"—and loss thereof—of knowledge that resides in and travels with human beings. One might think of knowledge management as just another engineering problem, the solution to which is creating an environment for the knowledge bearers that provides meaningfulness to them. That is to say, a truly happy person may want to remain in the place that gives one's life meaning rather than run off for greener pastures. Greed at the top seems the bigger problem to solve.

William Greener
(Williamgreener9@gmail.com)
Ithaca, New York

Douglas O'Reagan's article "Who owns a scientist's mind?" (PHYSICS TODAY, July 2018, page 42) ought to make us grateful that at the times of their momentous discoveries, both Sadi Carnot and Lise Meitner were effectively unemployed.

James Bernard Lee
(cadwal@macforcego.com)
Portland, Oregon PT

Faculty positions in Institute for Advanced Study Soochow University, China

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About SUIAS

The Institute for Advanced Study of Soochow University (SUIAS) is a newly founded research center dedicated to fostering collaborative research between physicists, biologists, medical scientists, engineers, and material scientists. The 2016 Nobel Laureate in Physics, Prof. John Michael Kosterlitz, is the honorable director of the SUIAS and Prof. Xinsheng Sean Ling from Brown University serves as director. SUIAS plans to build two major research groups, a complex matter group working in the areas of nonequilibrium statistical mechanics and physical biology, and a quantum matter group working in the areas of exotic quantum properties of electrons in solids. The center has a total of 20 permanent faculty positions (tenured and tenure track faculty members, including 10 Principal Investigators) open for applications.

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Professor Zhi Hong Hang, Institute for Advanced Study (SUIAS), Soochow University. Suzhou, China. E-mails: zhhang@suda.edu.cn

An unexpected spin flip alters the course of a chemical reaction

Careful analysis of a bimolecular collision reveals that gas-phase chemistry still holds surprises.

The behavior of small molecules, alone and in reactions with one another, has been well studied. The basic physics is simple to describe: To a good approximation, it's just nonrelativistic quantum mechanics with Coulomb interactions. Exact solutions to the Schrödinger equation are not feasible for any but the simplest systems; as a result, many quantitative details—reaction rates, cross sections, energy barriers, and the like—remain to be measured or numerically determined. And there's plenty of room for innovative new computational and experimental techniques to illuminate those details (see, for example, PHYSICS TODAY, October 2013, page 15, and November 2013, page 15).

By and large, though, molecules' dynamics are consistent with the patterns established by generations of experiments and calculations that have come before. It's highly unusual for a pair of colliding molecules to behave in a way that's qualitatively new and unexpected. But in an experiment by the University of Missouri's Arthur Suits and colleagues, that's just what happened.[1]

Suits and company were studying the gas-phase reaction of atomic oxygen with dimethylamine (DMA, CH_3NHCH_3) to produce a pair of charge-neutral radicals, OH and CH_3NHCH_2. In at least 90% of the reactions, they observed an intersystem crossing, or radiationless spin flip, from an overall spin-triplet state to a spin-singlet state. So far, that's not so surprising: Intersystem crossings, facilitated by strong spin–orbit coupling, are common in molecular dynamics.

What makes the new result unusual is that the intersystem crossing occurred after the molecules had already reacted and the products were starting to move away from each other. That possibility had never before been observed or even considered. Intersystem crossings take time—typically between nanoseconds and milliseconds—and the products of a completed reaction can fly away from each other in just femtoseconds.

To help explain that so-called exit-channel intersystem crossing, Suits and his Missouri group called on Temple University theorist Spiridoula Matsika. Together they concluded that the explanation was twofold: The products separated more slowly than usual, and the system's electronic configuration was just right for the intersystem crossing to be atypically fast. Neither the slow separation nor the fast spin flip is by itself especially unusual, so exit-channel intersystem crossings may turn up in other systems as well.

Long-lived complex

The discovery was serendipitous: "We were not looking for this at all," says Suits. Rather, they were looking for suitable experiments to do with an O-atom source—a jet of gas-phase atoms introduced into a vacuum chamber—that postdoc Hongwei Li had just built. Li made the O atoms by breaking up sulfur dioxide molecules with a laser; that reaction has the advantage of producing O purely in its spin-triplet electronic ground state, with no contamination by the excited spin-singlet state. They chose DMA as the other reactant, also introduced into the chamber in a molecular beam, because they knew that the reaction products would be easy for them to detect.

As is typical for chemical dynamics experiments, the existence and timing of the intersystem crossing had to be inferred indirectly. The researchers didn't monitor the reaction progress or molecular spin state in real time. Instead, they measured the speeds and directions of the product radicals, and from that information they deduced what must have happened during the reaction.

The crucial and surprising observa-

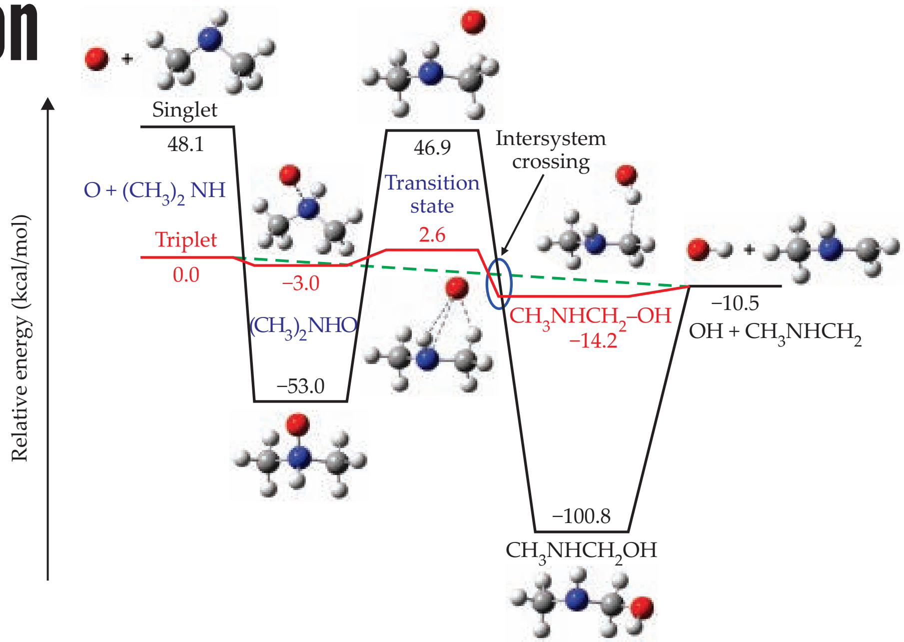

FIGURE 1. ENERGY LANDSCAPES of the singlet and triplet states of the reaction between atomic oxygen and dimethylamine. The triplet-state reaction can proceed in two ways—by either a barrierless direct mechanism (represented by the green line) or a more indirect mechanism (red line)—and undergoes an intersystem crossing to the singlet state late in the reaction process, as indicated by the blue oval. In the molecular structures, gray spheres represent carbon; blue, nitrogen; red, oxygen; and white, hydrogen. (Adapted from ref. 1.)

tion was that the reaction was almost perfectly isotropic: The product radicals were no more likely to emerge in one direction than any other. From that, the researchers inferred that the reactants had been bound to each other for tens to hundreds of picoseconds, long enough for the bound complex to tumble around many times before finally breaking up into products. Like the seeker in a game of blindman's bluff, the products emerge with little memory of their original directions.

But there's a problem: Such a long-lived complex must be energetically stable, and the triplet-state system doesn't have access to any such structure. Suits and colleagues considered two ways the triplet reaction can happen: The O atom could approach one of the methyl groups and extract a hydrogen atom directly, or it could initially approach the nitrogen atom in the middle of the molecule, then migrate to one of the ends to extract an H atom. The first pathway, represented in green in figure 1, has no discernable energy peaks or valleys at all; the second, represented in red, has a few, but they're not nearly deep enough to bind the complex for the requisite time.

In the singlet state, shown in black, the situation is different. Rather than gently rolling hills, the energy landscape features two deep wells with a mountain in between. Each well is sufficiently deep to trap the complex for long enough to produce the observed angular distribution, but it was easy for the researchers to deduce that only the second well would do. The O and DMA beams were introduced into the vacuum chamber at known speeds that correspond to a total kinetic energy of 7.8 kcal/mol. If the complex had crossed to the singlet state early in the reaction process, it wouldn't have had enough energy to surmount the 46.9 kcal/mol barrier to complete the reaction. It must, therefore, have undergone intersystem crossing late in the reaction and plunged into the second energy well, where it would have enough energy to get back out.

Spin–orbit coupling

Once Suits and his fellow experimenters had satisfied themselves that the reaction must involve an exit-channel intersystem crossing, they turned to Matsika to help them understand how it happens.

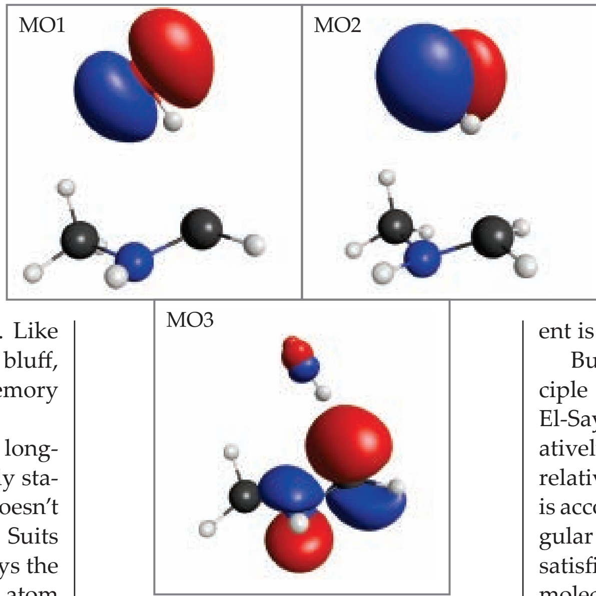

FIGURE 2. MOLECULAR ORBITALS participating in the intersystem crossing. Red and blue lobes represent, respectively, positive and negative regions of the single-electron wavefunctions. The CH_3NHCH_2–OH complex has two unpaired electrons: one localized on the OH fragment (in either MO1 or MO2) and the other mostly localized on the organic fragment (in MO3) but also present on the OH fragment. The OH electron can move between MO1 and MO2 in tandem with a spin flip; the accompanying change in orbital angular momentum is key to an ultrafast intersystem crossing. (Adapted from ref. 1.)

Unfortunately, a theoretical smoking gun—a simulation of the full reaction in sufficient quantum detail to show the change in electronic state—is far too computationally costly. So Matsika focused on the part of the reaction trajectory in which the intersystem crossing is most likely to occur because the singlet and triplet states have nearly the same energy. First, she analyzed the electronic configuration to estimate the speed of the possible spin flip. Then she determined how long the complex spends in the near-degenerate geometry.

Singlet–triplet near-degeneracy is achieved in geometries similar to the CH_3NHCH_2–OH structure in figure 1, and it's intuitively easy to see why. Each fragment, the OH and the CH_3NHCH_2, carries one unpaired electron. The farther apart the fragments get, the less it matters to the overall energetics whether the unpaired spins are in a singlet or triplet configuration.

Just because the singlet and triplet states have nearly the same energy, though, doesn't mean the system can easily move from one to the other. Spin–orbit coupling is a relativistic effect. It's strong in the presence of heavy atoms, such as bromine or iodine, whose electrons orbit at a significant fraction of the speed of light. When the heaviest element present is O, the coupling is much weaker.

But not always. According to a principle laid out 50 years ago by Mostafa El-Sayed, spin–orbit coupling can be relatively strong, and intersystem crossing relatively fast, when the change in spin is accompanied by a change in orbital angular momentum.[2] The O–DMA complex satisfies that criterion, as shown by the molecular orbitals in figure 2. The organic fragment's unpaired electron occupies MO3 (which has some amplitude on the OH fragment because the fragments are not yet completely separate). The OH fragment's unpaired electron can occupy either MO1 or MO2, which are nearly equal in energy but different in orientation. The electron can move from one orbital to the other in tandem with a spin flip.

Furthermore, the electron density hardly has to change at all: Both MO1 and MO2 are localized on the O atom. A similar situation—a large change in orbital angular momentum with a small change in electron density—has been observed in isomers of nitronaphthalene,[3] which undergo intersystem crossing in mere hundreds of femtoseconds. From Matsika's calculations, the researchers concluded that their system is likely to be similarly fast.

But even that's generally too slow for an exit-channel intersystem crossing. By the time the OH and organic fragments have separated enough for the singlet and triplet states to be degenerate, they should be well on their way to separating for good.

Roam if you want to

The second half of the explanation lay in another counterintuitive molecular phenomenon, the roaming pathway, first described in 2004 by Suits and collaborators.[4] In some chemical reactions, those researchers found, the products don't separate immediately but instead orbit each other for a while before parting.

To see how that happens, consider that a molecule or complex of *N* atoms has

$3N - 6$ internal degrees of freedom, most of which correspond to normal modes of vibration, and only one to the reaction coordinate (for example, the lengthening of the bond that ultimately breaks). In a highly vibrationally excited system, energy flows at random among the degrees of freedom, and only when enough energy builds up in a single bond does that bond break. "That's unlikely, and it takes time," says Suits. But it's less unlikely for the bond to accumulate enough energy to stretch to a long distance—two or three times its resting length—without breaking. As the bond stretches, it becomes floppier; the emerging molecular fragments remain quasibound but behave almost like independent roaming entities. "Molecules are sticky at long range," says Suits. "They are not billiard balls." (For more on the physics of roaming pathways, see the article by Joel Bowman and Arthur Suits, PHYSICS TODAY, November 2011, page 33.)

Sure enough, a detailed simulation of the triplet-state reaction showed that the product radicals roam around each other for more than half a picosecond before ultimately separating. With that observation, all the pieces fell into place: During roaming, the molecular complex undergoes an ultrafast intersystem crossing, falls into the singlet-state energy well where it remains for tens to hundreds of picoseconds, and then dissociates with an isotropic angular distribution.

None of the key ingredients in that process are terribly rare. The same configuration of molecular orbitals that enables the subpicosecond spin flip is present in many other reactions involving O and N atoms. And roaming pathways, first recognized in photoinduced decomposition of formaldehyde molecules,[4] have since been observed in various other systems. Now that researchers know to look for it, the exit-channel intersystem crossing may prove to be similarly general.

If fast intersystem crossings are so common, why haven't they been noticed before? Part of the reason is the indirect nature of the tools, both theoretical and experimental, that are used to probe chemical dynamics. To interpret their results, researchers often must already have a sophisticated understanding of how they expect a reaction to play out. If that understanding is wrong, the interpretation may be too, and if the difference is subtle enough, the error may go unnoticed. But Suits and colleagues happened upon a reaction in which the unexpected intersystem crossing, positioned on the precipice of a singlet-state energy well, completely changed the angular distribution of the reaction products. It was impossible to ignore.

"Our inner dialog is always how much we understand about things, rarely how much we don't understand," reflects Suits. "As our tools get sharper and we look more deeply, we see that extrapolation from simple models may overlook key features that force a change in our perspective. I am confident that many more surprises are in store."

Johanna Miller

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Machine learning improves image restoration

A neural network increases image quality when it knows what to look for.

Live imaging of cells is crucial for understanding microscopic cellular processes and dynamics. Frustratingly for biologists, taking high-resolution images can be challenging. Many cells have low contrast, and the boundaries of different cellular regions and the edges of cells themselves are often difficult or even impossible to discern.

Fluorescence imaging allows biologists to artificially add contrast to specific cellular components and observe them in more detail than with regular optical microscopy. Cell nuclei, microtubules, and other structures can be labeled with fluorescent dye molecules and then observed during dynamic processes such as cell division and organization.[1] (See, for example, the Quick Study by Abhishek Kumar, Daniel Colón-Ramos, and Hari Shroff, PHYSICS TODAY, July 2015, page 58.) Despite its strengths, fluorescence imaging is not a magic bullet: The laser light needed to excite the dye molecules can harm the cells, and the dye can absorb only a certain amount of light before it stops fluorescing. Imaging fluorescent samples always involves a tradeoff between how much light is used, the speed at which pictures are taken, and the spatial resolution of the resulting image.

Sometimes image quality has to be sacrificed for sample health or imaging speed. However, the images can still carry information that is not visible to the naked eye. Researchers then turn to postprocessing techniques—typically deconvolution and denoising algorithms that try to model and undo distortion from imaging—to improve the image quality.

In an effort to extend the limits of postprocessing techniques, Martin Weigert, Florian Jug, Loïc Royer, Eugene Myers, and coworkers at the Max Planck Institute of Molecular Cell Biology and Genetics in Dresden, Germany, have successfully demonstrated a new method based on an artificial neural network.[2] They trained their content-aware image restoration (CARE) networks to decipher low-resolution fluorescent images and create accurate, high-resolution reconstructions. To achieve the best possible results, the networks are trained to incorporate information from high-resolution images of the same biological system.

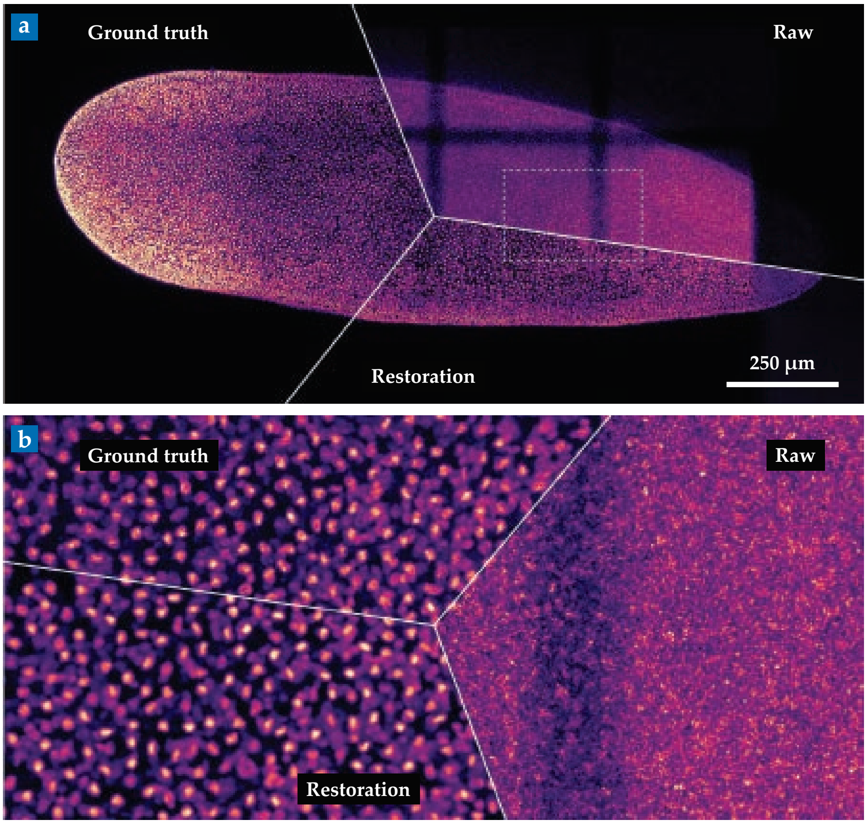

FIGURE 1. IMAGE RESTORATION. (a) A trained deep-learning network can turn a raw, low-signal-to-noise image of flatworm cells into a restoration that has a high signal-to-noise ratio and is of the same quality as a real high-resolution, or ground-truth, image. **(b)** Zooming in on the inset in panel a shows that nuclei cannot be distinguished in the raw image, whereas they are clearly identifiable in the restored image. (Adapted from ref. 2.)

The researchers found that information could be gleaned from previously unusable images, which were taken with 1/60 of the light required for a high-resolution image, after they were restored using CARE. The networks also fixed apparent stretching in three-dimensional data and identified features below the diffraction limit as effectively as a state-of-the-art superresolution imaging technique, but in a fraction of the time.

Informed images

A CARE network uses deep learning to restore fluorescent images. Its input nodes are the pixels of the raw image; its output nodes are the pixels of the restored image. Unlike conventional machine learning, which requires the user to specify how a network should classify features, a deep-learning network identifies patterns itself directly from raw images.[3] The trained network performs a series of operations on the input pixel values to highlight such important features as edge locations while suppressing unimportant variations in intensity.

Each operation a network performs has adjustable parameters that have to be optimized through training before the network can be used. That entails giving the network pairs of images—one low resolution and one high resolution—of the same area in a sample. The network processes the low-resolution image and outputs a restoration that is then compared with the high-resolution image. The

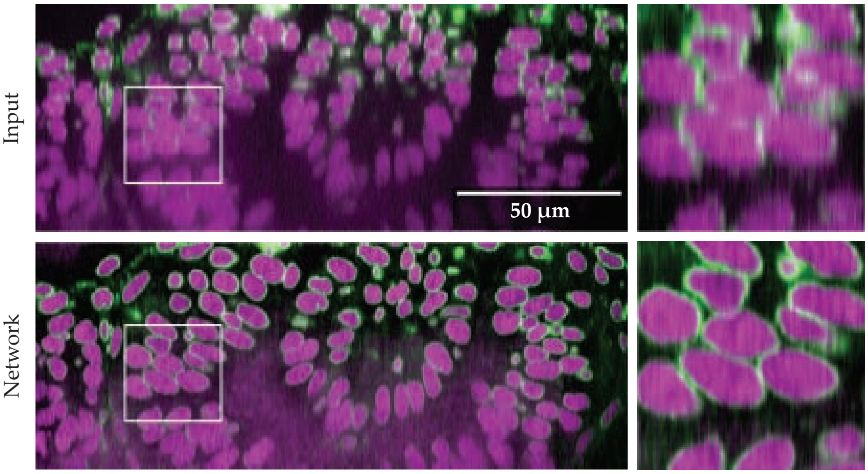

FIGURE 2. AXIAL ELONGATION. Three-dimensional images appear elongated along the optical axis because microscopes have lower resolution in that direction. A deep-learning network can be trained to turn a stretched axial slice of a developing zebrafish eye (top row) into a restored image with isotropic resolution (bottom row). (Adapted from ref. 2.)

network's goal is for the restoration and high-resolution images to be the same. It adjusts its parameters to minimize their differences, which encodes into the network specific information about what the sample looks like. That information can then be used to better restore images.

The lack of training data has previously been a roadblock for applying machine learning to image-restoration tasks. Weigert and coworkers used two strategies to solve the problem. First, they chose a network structure that was developed for analyzing biomedical images and is known to require less training data than other networks.[4] They then generated training data by imaging fixed, or nonliving, samples of biological systems. Fixed samples can be imaged at higher light intensities and lower frame rates than living samples can, so the researchers recorded pairs of high-resolution "ground-truth" images and low-resolution images of the same areas taken at conditions suitable for living organisms.

Once a CARE network has been trained on pairs of images, it can be applied to images of live samples for which there is no ground truth. Despite the name, restoration does not mean an image is returned to its previous condition. "There is an ideal image that is unfortunately not observable with the technology that we have, and we can only perceive something worse than that," says Royer. "But that image exists in theory," and that is what a CARE network aims to recover.

Figure 1 shows the result of applying CARE to images of the flatworm *Schmidtea mediterranea*, which is a model organism for studying tissue regeneration. Under even moderate amounts of laser light the worm flinches its muscles, and raw images taken at tolerable intensities have such a low signal-to-noise ratio that they could not previously be interpreted. The undetectable fluorescently labeled cell nuclei became easily discernible after the raw image was restored with CARE, and the improved image quality rivals that of the ground-truth image. The benefits of CARE can also be quantitative: When a CARE network was used to restore images of a red flour beetle embryo, the accuracy with which individual nuclei could be identified increased from 47% to 65%.

Extending CARE

CARE networks can be applied to a range of biological systems because the information they use to restore images comes from training data. The researchers demonstrated that versatility using images from eight systems, including fruit fly wings, zebrafish eyes, and rat secretory granules. Once the researchers realized how well the networks addressed the problem of low illumination, they wondered whether the networks could

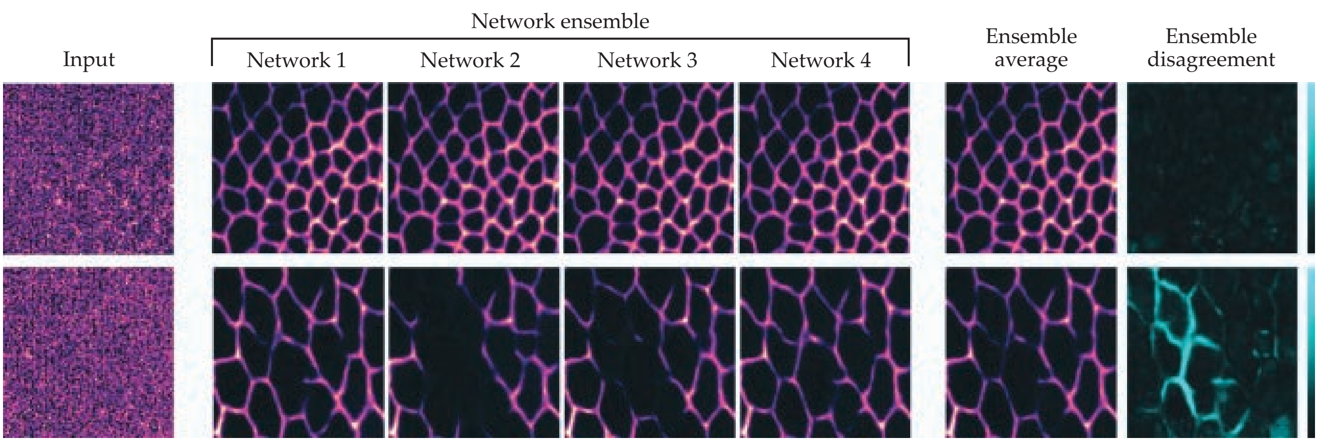

FIGURE 3. ASSESSING ACCURACY. The faithfulness of a restored image can be assessed by comparing restorations from an ensemble of networks. In each row, a raw image is used as the input for an ensemble of four trained CARE networks. The ensemble disagreement indicates how reliable the restoration is in a particular area, with brighter blue indicating a higher level of disagreement. The top row shows an area where the networks largely agreed on the restoration; the bottom row reveals a region with higher disagreement, which indicates that the restoration may not be accurate. (Adapted from ref. 2.)

also solve other problems in fluorescence microscopy.

It is often useful for biologists to capture 3D pictures of their samples by taking 2D images at different depths and then stacking them to re-create the entire volume. However, a microscope's resolution is always worse along the optical axis than in the imaging plane, so the axial images—2D images in which one dimension is in the imaging plane and the other is along the optical axis—appear elongated in that direction. "This is a fundamental problem in microscopy," notes Royer. "You get beautiful 3D data sets, but when you rotate them, you realize that one dimension is very poor."

Weigert and coworkers addressed that problem by applying CARE networks to volumetric data with poor axial resolution. Unlike with 2D image restoration, they couldn't directly acquire high-resolution ground-truth axial images to train the networks because the poor resolution is inherent to the optical system. Instead, they generated training data by computationally modifying well-resolved lateral images to resemble the poorly resolved axial images. A CARE network trained on the modified data was able to restore nearly isotropic resolution and remove the apparent stretching in the axial slices, as shown in figure 2.

Imaging nanometer-scale features is another challenge in microscopy. Superresolution techniques are needed to resolve objects that are smaller than the diffraction limit (see PHYSICS TODAY, May 2015, page 14), but they usually entail low image-acquisition rates as many images are needed to generate one superresolution image. As a result, superresolution techniques cannot image fast-moving live samples. Weigert and coworkers saw the potential of applying CARE networks to the task: If the networks could restore structures below the diffraction limit, they could greatly increase the speed of superresolution imaging.

Such small objects, though, cannot be imaged directly to generate training data, so the researchers used simulation-generated images. That introduces a complication because it does not guarantee that the training data accurately represent the physics of the system: "If you get the training data wrong, you're going to have some artifacts," cautions Royer.

The researchers applied their superresolution technique to two types of structures: rat secretory granules, which are more or less spherical, and meshes of microtubules. In both cases the CARE network revealed substructures that had remained imperceptible after they were enhanced with a traditional deconvolution method of image restoration. For the microtubule sample, the CARE network resolved structures as effectively as a state-of-the-art superresolution technique but did the job 20 times as fast because it required fewer images.

Verifying the results

Although their performance is impressive, CARE networks are only useful to the extent that their output is reliable. "For the scientific utility of the network, it is very important to know not only what is predicted but how accurate it is," says Royer. To that end, the researchers changed the last step of the CARE network so that instead of just reporting a pixel value, it gave a probability distribution for each pixel whose mean was the predicted pixel value and whose width indicated the uncertainty in that prediction.

The consistency of the CARE networks also factored into their reliability measure. Instead of relying on a single network, the researchers trained an ensemble of networks; based on the restorations produced by each network, they calculated an ensemble disagreement value that quantified the networks' confidence in the predicted pixel value, as shown in figure 3. The networks often—but not always—agreed on pixel values and had a low ensemble disagreement. The ability to identify areas of disagreement is crucial to CARE's utility because those areas alert researchers to places where an image restoration may not be reliable.

CARE networks have thus far outperformed other currently available image restoration methods for all tasks to which they have been applied. But Royer acknowledges that there is still room for progress: "There are scenarios where more research is needed to get a really secure, really robust estimate of where and when to trust the networks."

Christine Middleton

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Satellites glimpse the microphysics of magnetic reconnection

In situ measurements capture a nonturbulent, efficient reconnection event on Earth's nightside.

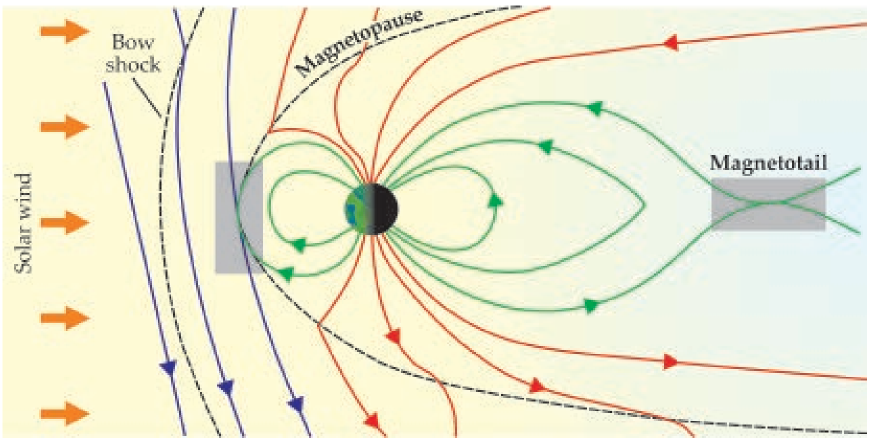

FIGURE 1. MAGNETIC RECONNECTION can occur in two parts (gray boxes) of Earth's magnetosphere. In the magnetopause, the Sun's magnetic field (blue) points southward and reconnects with Earth's closed field (green). In the magnetotail, reconnection occurs when Earth's open field (red) is squeezed together. (Adapted from ref. 2.)

Because of Earth's magnetic field, the stream of electrons and ions that constantly blows from the Sun gets diverted around the planet. The particles mostly travel with the solar-wind magnetic field lines on their way past Earth, but sometimes they breach the magnetosphere, the region of space where the dominant magnetic field is that of Earth. Such breaches eventually manifest themselves as auroras and geomagnetic storms. Driving the large-scale bursts of energy released in those space weather events are electron interactions that may be an important mechanism for energy conversion throughout the solar system.

When oppositely directed magnetic field lines approach each other in astrophysical plasmas, they can break and reconnect in a lower-energy configuration (see the article by Forrest Mozer and Philip Pritchett, PHYSICS TODAY, June 2010, page 34). Bent tightly at first, the field lines abruptly straighten, which sends charged particles streaming away from the reconnection locus. So far, only with laboratory experiments and computer simulations have researchers been able to probe the details of the process at such scales that they can determine how efficiently energy is converted from magnetic to kinetic. However, reconnection in laboratory plasmas proceeds much too slowly, so researchers have not been able to explain geomagnetic storms and other explosive phenomena observed in space.

Now a new observational window has opened. The four formation-flying spacecraft of NASA's Magnetospheric Multiscale (MMS) mission have witnessed the electron interactions that drive reconnection events in Earth's magnetosphere.[1]

The magnetosphere offers a local, natural laboratory in which to study two regions that host frequent reconnection events.[2] On Earth's dayside, the solar wind abuts Earth's magnetic field at a region called the magnetopause. On the nightside, Earth's field lines sweep out into a trailing magnetotail. Both regions are shown in figure 1. The MMS was launched in 2015 to make the first high-resolution *in situ* measurements of plasma and fields and to map reconnection events on both sides of Earth.

Reconnection reconnaissance

In a plasma in a strong magnetic field, the field lines act like wires: Charged particles tightly orbit the field lines, and the net electric current is guided on fixed paths through the plasma. Since the 1970s plasma physicists have understood that for reconnection to occur, the magnetic field must first become "unfrozen" from the plasma's electrons and ions in a process called demagnetization.

As magnetized plasmas flow toward each other, field lines get squeezed together from above and below the midplane toward a notional central locus called the X-line, as illustrated in figure 2. When the radius of curvature of the field lines becomes comparable to the radius of gyration of charged particles' spirals about the field lines, the particles resist that squeezing and break away. Positive ions, with their larger radius of gyration, leave their field lines while electrons stay tied to the magnetic field lines and continue to stream into a confined region, typically just tens of kilometers across, known as the electron diffusion region. There the electrons finally leave their field lines and set off the reconnection process. As the tightly bent magnetic field lines straighten, the electrons are flung outward in two oppositely directed jets.

Reconnection had never before been observed directly and completely. In 1999 NASA's *Wind* spacecraft filled in part of the picture, when it detected magnetic fields and electron currents established by inflowing electrons during reconnection (see PHYSICS TODAY, October 2001, page 16). Now the MMS is peering inside the electron diffusion region to investigate the processes that unfreeze those electrons and drive reconnection. The mission's four identical satellites each carry eight electron sensors and travel in an adjustable 10-km-scale tetrahedron to measure the three-dimensional electron distribution and the electric and magnetic fields when the spacecraft fly through the epicenter of a reconnection event.

Efficient reconnection

The MMS spent the first part of its mission observing Earth's dayside where unequal magnetic fields, that of the solar wind and that of Earth, reconnect in an asymmetric fashion. Since 2017, the satellites have been observing the nightside. On 11 July 2017, the MMS detected jets of ions and electrons streaming toward and away from Earth, providing evidence of an electron diffusion region.

The four spacecraft travelled in a pyramid formation; they were 17 km apart and stayed within 50 km of the most probable region for a reconnection event to occur. During a 10-minute period, the spacecraft moved together from south to north across the magnetotail midplane, 22 Earth radii from Earth. For six seconds, the satellites straddled the electron diffusion region of a reconnection event. Those seconds marked the first *in situ* observation of terrestrial magnetic field lines reconnecting with themselves in a symmetric fashion.

When Roy Torbert (University of New Hampshire) and colleagues looked at the 2017 data, they found an electron velocity that exceeded 15 000 km/s. The high-speed jets carried a strong current away from the X-line, at speeds near the theoretical limits expected for highly efficient conversion of magnetic to kinetic

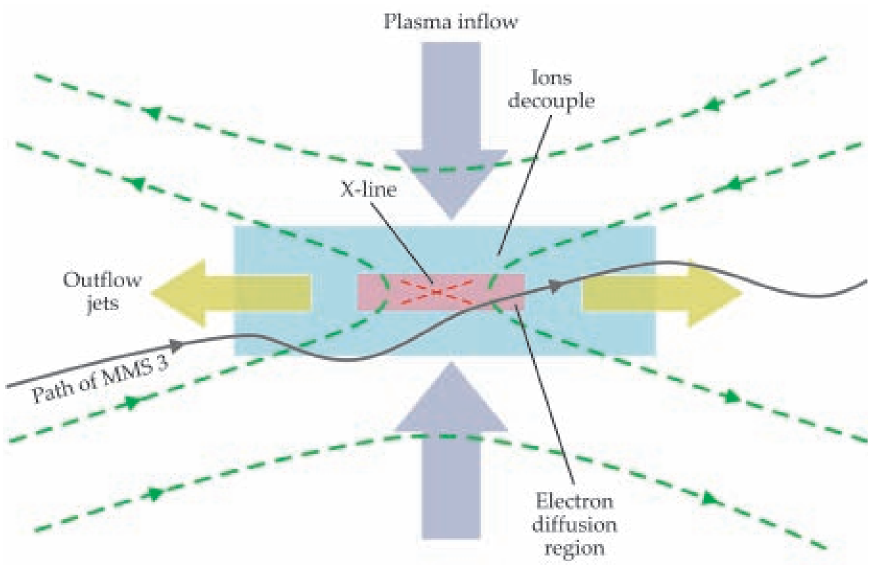

FIGURE 2. THE FOUR SATELLITES IN NASA'S MAGNETOSPHERIC MULTISCALE (MMS) mission flew through the electron diffusion region of a reconnection event in Earth's magnetotail. Here, magnetic field lines (dashed green lines) are compressed from above and below the conceptual X-line, indicated by dashed red lines. Positive ions decouple from the bent field lines, followed by electrons. During reconnection, magnetic energy is sent to oppositely directed particle jets (yellow). The path of one of the satellites, MMS 3, is traced in gray. (Adapted from ref. 1.)

and thermal energy. Figure 3a shows observations from the MMS magnetotail encounter.[1]

One of the MMS's goals was to determine the reconnection rate in the electron diffusion region or, as Torbert's coauthor James Burch (Southwest Research Institute) says, "what fraction of the lines reconnect when the plasmas are squished together." The aspect ratio of the electron diffusion region represents the ratio of plasma outflow to inflow and is considered an indicator of the reconnection rate. If the sides and the ends of the diffusion region were of equal length, then the outflow rate would equal the inflow rate. Since all the plasma flowing in to the diffusion region must flow out the ends, the outflow region acts like a pair of nozzles that regulate the inflow rate. Measurements taken as the MMS probes transited revealed an aspect ratio of 0.1 to 0.2, which is consistent with simulations of fast reconnection.[3]

Curious crescents

In the 1990s Michael Hesse and colleagues at NASA's Goddard Space Flight Center had proposed a laminar mechanism for dissipating magnetic energy, in which thermally mobile electrons rapidly transit through and carry energy away from the electron diffusion region. From their dayside work three years ago, Burch, Torbert, and colleagues reported MMS observations of electron demagnetization and acceleration.[4] The results included identification of a crescent-shaped feature in the velocity distributions of electrons at the reconnection site, such as the ones shown in figure 3b. The crescent feature was predicted to be a result of electrons whose orbits meander across a boundary between oppositely directed magnetic fields. The meandering is part of the demagnetization of electrons.[5]

Torbert and colleagues now report multiple discrete structures in electron velocity distributions during reconnection in the magnetotail. As shown in figure 3b, the structures appear crescent shaped in a 2D plot of two velocity components. The velocity distributions from the MMS vindicated predictions that laminar flow, rather than turbulence, dominates the electron dynamics during reconnection.

The crescent structures remained unperturbed during rapid fluctuations in the electromagnetic fields during reconnection. That stability implies that turbulent effects, which would scatter electrons and hence eliminate distinct features like crescents, do not dominate the particle dynamics in the electron diffusion region during reconnection. Rather, the recon-

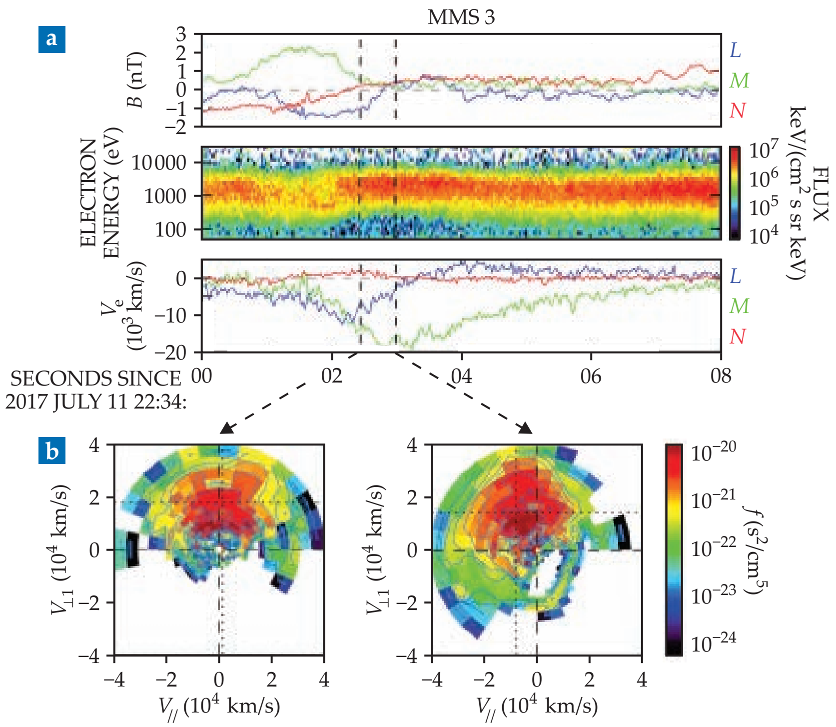

FIGURE 3. A CAPTURED RECONNECTION EVENT. Observations by the Magnetospheric Multiscale mission include **(a)** the magnetic field *B* (top), electron spectrogram (middle), and electron velocity V_e (bottom) in the electron diffusion region of a magnetic reconnection event on 11 July 2017. Velocity and field vectors are separated into orthogonal components *L*, *M*, and *N*. During reconnection, the magnetic field vanished and the electron bulk velocity peaked at 15 000 km/s. **(b)** Crescent-shaped structures persisted in the electron velocity distribution during reconnection. The plots show phase-space density *f* as a function of velocity components $V_{\perp 1}$, in the direction perpendicular to the magnetic field, and $V_{//}$, parallel to the magnetic field. (Adapted from ref. 1.)

necting field can continuously accelerate the electrons and drive them into high-speed jets, possibly as a consequence of confinement in the symmetric magnetic structure.

Surprises and predictions

The observations provide the first evidence of how reconnection works at the electron scale, and they confirm that reconnection releases magnetic energy efficiently. MMS scientists hope that more data from Earth's magnetosphere will help explain just how much energy is dissipated by magnetic reconnection throughout the universe and what conditions determine when reconnection begins and ceases.

Torbert's colleague Tai Phan (University of California, Berkeley) has already found one surprise in data transmitted from the MMS while it transited Earth's turbulent magnetosheath, the region between the magnetosphere and the bow shock produced when the solar wind speed decreases as it approaches the magnetopause (see figure 1). There, diverging electron jets provided the telltale sign of reconnection. But in contrast to standard reconnection, ions were bystanders. Phan concluded that reconnection driven by electron interactions alone can facilitate energy transfer in a turbulent plasma.[6]

By studying reconnection on both sides of Earth, the MMS also helps astronomers understand reconnection elsewhere, such as in the atmospheres of stars, near black holes and neutron stars, and at the boundary between our solar system's heliosphere and interstellar space.

Rachel Berkowitz

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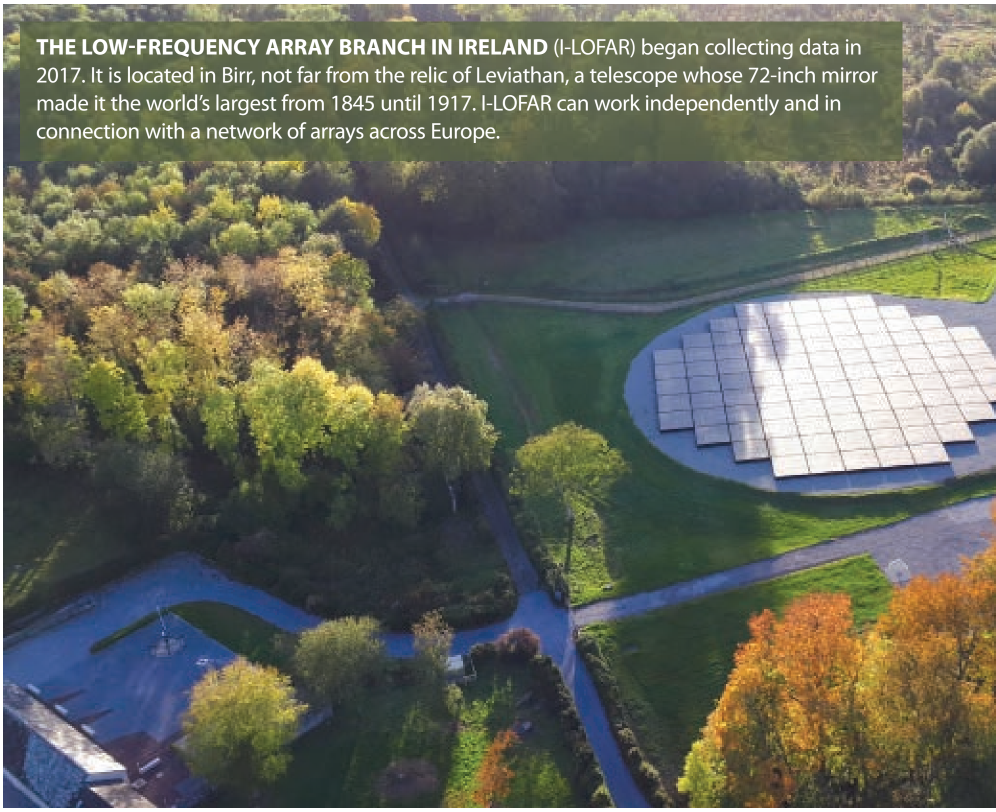
Ireland's scientists seek a shift in support toward basic research



THE LOW-FREQUENCY ARRAY BRANCH IN IRELAND (I-LOFAR) began collecting data in 2017. It is located in Birr, not far from the relic of Leviathan, a telescope whose 72-inch mirror made it the world's largest from 1845 until 1917. I-LOFAR can work independently and in connection with a network of arrays across Europe.

Their wish list: Support creativity and theoretical disciplines, maintain links with UK colleagues amid the uncertainty of Brexit, and continue the strong ties with industry that helped the country recover from deep recession.

With the establishment in 2000 of Science Foundation Ireland (SFI), the country rose rapidly from a scientific backwater to a full-fledged international player. Then the global financial downturn triggered a deep national recession that lasted roughly from 2008 to 2014. Although the government maintained SFI's budget, the foundation narrowed its funding portfolio to focus almost exclusively on applied and industry-oriented projects. Now that Ireland's economy is largely recovered, researchers say the government should invest more in science and education and rebalance how it divvies up support between fundamental research and research with short-term commercial goals.

Ireland's scientific community is "struggling to get back to where we were 10 years ago, when there was a sense that anything was possible," says physicist John McInerney of University College Cork and the Tyndall National Institute, which focuses on photonics and electronics. "We are trying to get that mojo back. You have to keep the innovation pipeline loaded. [The funders] took out the cool stuff, the emerging stuff."

Recent signs point toward a revival in basic research that the country's scientists deem critical. The Irish Research Council, the main national source of funding after SFI, last year introduced a new grant line, and this year SFI will call for proposals from individual investigators after a two-year hiatus. In October Ireland joined the European Southern Observatory (ESO), which gives the country's astronomers access to telescopes (and its companies the opportunity to bid for tenders). In 2017 a radio telescope—the westernmost site in the Low-Frequency Array that stretches to Poland—started collecting data in Birr, in Ireland's center.

More industry, less creativity

In 2002 chemist John Boland returned to Ireland to work at Trinity College Dublin after 23 years in the US, in large part because of SFI. "It was the first time in Ireland's history that we invested in science. That attracted me and many others back to Ireland."

From the get-go, SFI focused on biotechnology and on information and communications technology. Ireland is a small country, and the idea was to focus, not to try to do it all, says William Harris, SFI founding director, who had earlier served as assistant director for mathematical and physical sciences at the US's NSF. For a country that was famous for poets, writers, and education, not for huge investments in research, he says, "the government's decision to fund SFI was bold and significant." It helped Ireland strengthen university research and attract tech companies. About 10% of SFI's budget went to frontier research in any field, he adds.

But in the late 2000s, says Lorraine Hanlon, a high-energy astrophysicist at University College Dublin, SFI let it be known that it would no longer fund astronomy or particle physics. The recession accelerated the agency's shift toward research with identifiable economic outcomes.

As part of its growing emphasis on industry-facing research, SFI began concentrating its grants on large multi-institution centers over individuals. It now funds 17 centers around Ireland, in research areas that fit with strategic national priorities, such as green energy, big data, and medical devices. Centers each get between €2 million ($2.3 million) and €4.5 million annually for six years. SFI's total budget this year is €189 million.

ALISON DELANEY, EDUCATION OFFICER AT BIRR CASTLE

The SFI money makes up about a third of a center's budget, with the centers required to raise the rest equally from industry and other sources. "A third from industry is a big ask," says Michael Coey, who works in spintronics and magnetism at the Advanced Materials and Bioengineering Research (AMBER) center at Trinity. "The danger is, the more of their money you take, the more you focus on their short-term projects."

In the early years, SFI put 80% of its budget toward grants for individual investigators, and the rest toward a few centers. The agency says the split is now 50-50. But researchers both with and without center affiliation say the portion that goes to centers is higher, largely because calls for proposals typically emphasize contributions to society and the economy, a requirement that matches the capabilities at centers. "The centers are hoovering up too much of the budget," says Hanlon. The focus on centers and on industry-oriented research is "deeply flawed," she says. "It excludes a lot of capable people and hollows out the base."

Following the money

With SFI's change in funding priorities, researchers have mostly realigned their work or turned to European and other external funding sources. Some have left the country or watched their research programs dry up. Researchers who could shift their work to collaborate with industry have done well, says Trinity's Jonathan Coleman, who developed a scalable method to produce graphene. "If you weren't able to do that, you were screwed."

After joining the faculty at Trinity in 2009, Matthias Möbius turned from basic research to applications related to foams, emulsions, and complex fluids. One of his projects involves replacing water with foam in paper production. Another involves nanosuspensions for ink-jet printers. "The money was the motivation for changing my research," he says, "but the questions are still interesting to me."

Peter Gallagher, an astronomer at the Dublin Institute for Advanced Studies, also followed the money: "I became more industry focused [but still] tried to keep my research program balanced." Power-grid operators and insurance companies support his research on solar flares.

"It depends where you start from and how far you are willing to realign your research interests," says theoretical particle physicist Sinéad Ryan of Trinity. For many in string theory, particle physics, and mathematics, it's quite difficult to fit into the priority themes and short-term applications. "It has been very difficult to sustain vibrant research programs," she says.

Among theoretical physicists and pure mathematicians, says Ryan, "we are 'out,' so there is a sense of collegiality." But the funding disparities across the broader field can create tensions. For example, promotion and recruitment may become difficult. "If you have two people from the physics department, and one has three grants and the other has none—because they do fundamental research—you can imagine it requires dexterity to see beyond this simple metric and also

NAOISE CULHANE

STEFANO SANVITO (RIGHT) AND MUNUSWAMY VENKATESAN of Trinity College Dublin melt metallic powders to create new magnetic compounds. Sanvito's team uses computer simulations to design magnetic materials and has created many of them.

promote the person with no grants or fewer publications."

"We won't get interest from SFI if we talk about gamma rays or an unbelievable breakthrough in astrophysics," says Hanlon. "But if we hide the astrophysics and talk about a new technology, we may get funding. It's a weird dynamic." Around when SFI stopped supporting her work, funding came through from the European Space Agency. She and her group are working on a miniaturized gamma-ray detector that will be one of three experimental payloads to fly on Ireland's first satellite, *EIRSAT-1*, which is slated to launch in 2020.

Some researchers relocated, but for many, "leaving in a time of crisis is impossible," says Gerard O'Connor, head of physics at the National University of Ireland, Galway. "They've taken a mortgage and have negative equity. It's a trap. Generally, people have had to reinvent themselves." In his department, he says, people struggled most to get funding for astronomy; the SFI priorities were easy fits for researchers in climate change, atmospheric physics, and biomedicine. The western part of Ireland is known for producing disposable medical equipment, he notes, with about a third of the world's contact lenses and nearly 80% of stents sold worldwide made there.

Reverberations

The effects of the recession on scientists are wider than SFI's sharpened focus on research impact and centers. For example, all public employees took repeated pay cuts. For university faculty, those cuts were as high as 20%. College enrollments swelled, while over the past decade government funding per undergraduate has shrunk by 50%, according to Ireland's Higher Education Authority. In some cases, teaching loads grew to the point that scientists didn't have time for research, says O'Connor. With more students and less money, university international rankings dropped. "The universities have worked hard to hold the show together with continually decreasing budgets," says Coleman. "But you only do more for less for so long before the house of cards collapses."

Degradation of scientific equipment is widespread. In a survey last year by the Royal Irish Academy, 90% of respondents in science, technology, engineering, and mathematics reported gaps in the availability of infrastructure in their discipline; 35% said they are not generally able to access the research infrastructure they need; and 77% said the infrastructure that is available is not adequately funded or maintained.

Stefano Sanvito, a condensed-matter theorist who heads the Centre for Research on Adaptive Nanostructures and

STEVEN BURKE AND MATTHIAS MÖBIUS

A CT SCAN of a cellulose fiber structure (9 mm to a side) made by Matthias Möbius of Trinity College Dublin and colleagues helps them study how the fiber's structure affects its mechanical properties. Like many scientists in Ireland, Möbius has aligned his research to work on problems that are interesting to, and generate funding from, companies.

Nanodevices at Trinity and is a member of AMBER, notes that workhorse instruments like NMR machines are aging. "We haven't been able to replace them. There are many things at this level. The bread and butter of the university has been undermined."

Travel money can also be hard to come by. James Gleeson, a mathematical physicist at the University of Limerick and a member of two SFI centers, works on modeling of information spread relevant for studying epidemics and online social networks. He says that graduate students can sometimes attend conferences using fellowships from the Irish Research Council, but their advisers often can't muster the money to join them. That slowing of international scientific exchange makes collaborations harder to sustain and is "a disincentive to bring researchers here to join our intellectual ecosystem."

Looking ahead

Despite some complaints, researchers acknowledge that SFI's strategy contributed to the country's economic recovery. And they point to many scientific achievements and their community's quick rise in the international arena. "No country on the planet has outputs like we do," says Boland, a member of AMBER. "With just 1.2% of our GDP going to R&D, half the OECD [Organisation for Economic Co-operation and Development] average, our centers compare with the best in the world."

Ireland continues to attract multinationals, the economy is strong, and, says Gleeson, "engagement between universities and industry is far improved. Now it's the norm, and you can credit the SFI funding model." Says Boland, "We need the centers. They provide scale—industry doesn't want to work with single investigators. They need the right collection of people. The center provides an interface."

The presence of multinational companies speaks to Ireland's education

Sundry Stats

▶ In 2016, nearly 1.8% of Ireland's workforce was employed in R&D, the fifth-highest of the 36 countries in the Organisation for Economic Co-operation and Development (OECD). Denmark, Finland, Israel, and Sweden lead the list.*

▶ In 2016, 1.18% of GDP was invested in R&D; the average for the 28 European Union countries was 1.93%.*

▶ Ireland is ranked 11th worldwide in overall quality of scientific research, after Singapore and before Germany. Switzerland tops the list. The US takes the 6th spot.†

▶ Of awards to individual investigator groups by Science Foundation Ireland (SFI) in 2001–17, women made up 23% of lead applicants, were awarded 20% of grants, and received 13% of the total funding.‡

▶ In 2017, SFI award holders reported 2443 collaborations with counterparts in 66 countries. The largest number was with the UK (563, of which 89 were with Northern Ireland), followed by the US (447), Germany (201), France (145), Italy (137), Spain (116), and China (87).§

* OECD.
† InCites Essential Science Indicators, April 2018.
‡ SFI data, analyzed by Derek O'Callaghan.
§ SFI, 2017 annual report.

system and the high quality of college graduates it produces, says Alexander Chamorovskiy, senior researcher at Superlum, a company in County Cork that produces broadband semiconductor light sources. "It's getting hard for small companies to hire Irish students," he says. "We can't compete with big multinationals, which offer much higher salaries."

And it's not just scientists with the SFI centers who support a rebalancing of funding, with more going to fundamental research; the scientists who struggle for national funding say that the centers should continue. "I would not argue that the centers should get less funding," says Ryan. "Funding needs to be increased across the board and diversified to support excellence in all disciplines." She also wants to see Ireland join CERN.

Ciarán Seoighe, SFI deputy director general, notes that the agency's responsibility has always been for "oriented basic, with applied research added in 2013." Over several months in late 2018, he met with 1000 or so researchers to take the pulse of the community for a new five-year strategy, which SFI aims to set by year's end. "We are looking at the whole ecosystem and looking for gaps," he says. "We may come out of this quite a different organization. Our core objectives may change."

Meanwhile, not far from anyone's mind is Brexit, the impending departure of the UK from the European Union. (See PHYSICS TODAY, March 2017, page 24.) As Britain's close neighbor, Ireland will undoubtedly be strongly affected by Brexit. But what it means for science is still anyone's guess. Séamus Davis, who works in experimental quantum matter and in January moved to University College Cork and Oxford University after decades in the US, says the long-standing ties between Ireland and the UK will survive the change whatever form it takes. Seoighe points to Davis's new split position as part of the glue to keep the ties strong and says the science communities in both countries are looking for new ways to partner.

In Ireland as elsewhere in the European Union, researchers are backing away from UK partnerships in anticipation of funding difficulties. Irish universities are seeing an uptick in inquiries about faculty jobs. And in the wake of Brexit, Ireland could become more attractive for scientific partnerships by virtue of being the main English-speaking country in the European Union.

"Everybody is waiting to see what will happen," says Eucharia Meehan, head of the Dublin Institute for Advanced Studies and former director of the Irish Research Council. "But a lot of people are thinking creatively about how to keep the UK as part of the European scientific landscape."

Toni Feder

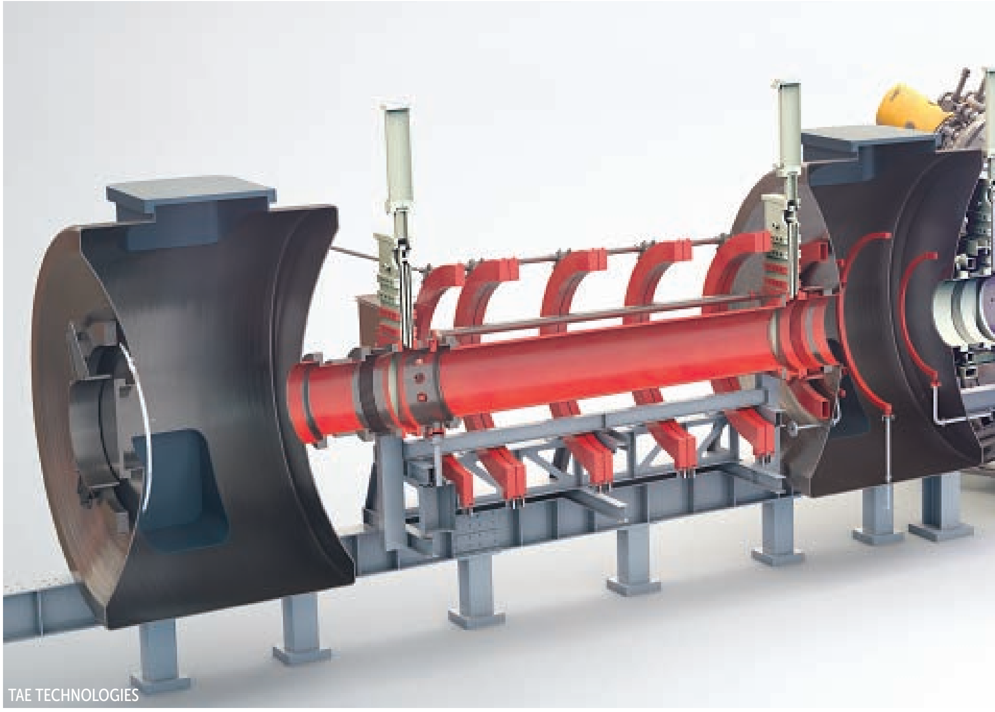
Side trips on the road to fusion

A private company pursuing an alternative path to fusion energy is banking on revenues from inventions it makes along the way.

A California startup has a multipronged approach to help pay for its decade-long quest to demonstrate fusion at a commercial scale. The approach includes a novel concept to become a part-time scientific user facility funded by the Department of Energy. TAE Technologies also is soliciting tax breaks and other financial inducements from state and local governments as it decides on a site for a new $500 million test reactor. The company is reporting initial success in commercializing several technologies it has developed as it has built its experimental devices.

Based in Orange County, the 160-employee TAE is the largest of a handful of privately held startups that are pursuing alternative approaches to controlled fusion. Others include General Fusion in British Columbia, Canada; Commonwealth Fusion Systems in Cambridge, Massachusetts; and Tokamak Energy, near Oxford, UK.

TAE remains focused on demonstrating commercially viable grid-scale fusion by the late 2020s, says CEO Michl Binderbauer. In the meantime, it is looking for revenue sources to offset some of the company's $50 million annual operating expenses and attract additional investors. Spin-off technologies, in particular, "create the opportunity for investors to feel we are more than a one-


TAE TECHNOLOGIES

trick pony, that there are hedging opportunities that can happen independent of the cadence in fusion."

To date, TAE has attracted more than $600 million in equity from investors, including financiers Arthur Samberg, who chairs its board; Charles Schwab; and former Morgan Stanley CEO John Mack. It has backing from venture capital firms New Enterprise Associates and Venrock, the UK's Wellcome Trust, and several sovereign funds. Shareholder Google also is a technical partner, says Binderbauer.

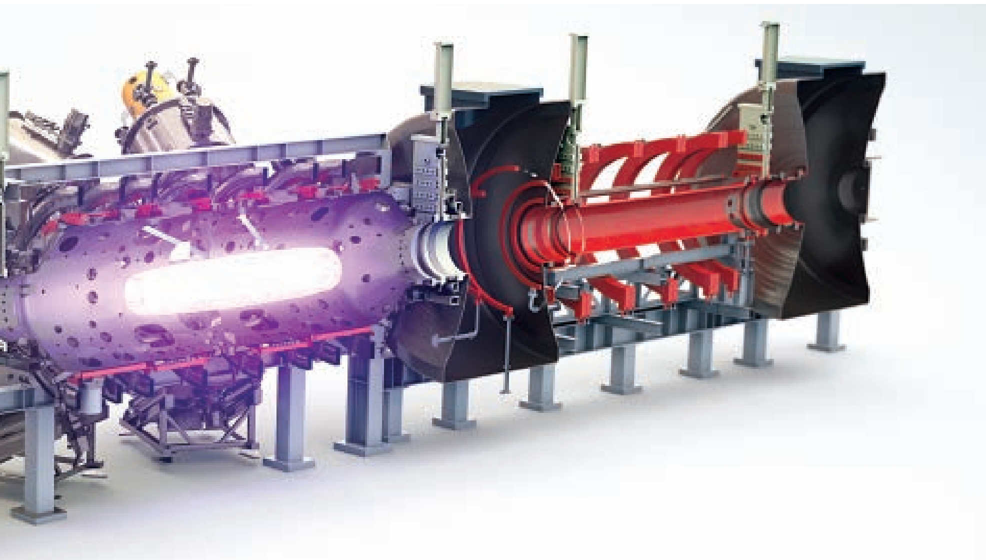
Departing from the mainstream

Rather than bottling a plasma in magnetic fields in a toroidal-shaped reactor—the mainstream tokamak approach that's being pursued at ITER in France, DOE's DIII-D device in California, and the Joint European Torus in the UK, among others—TAE's linear device uses a magnetic framework, known as a field-reversed configuration, to confine plasmas (see PHYSICS TODAY, October 2015, page 25). Plasmas formed at opposite ends of the machine are accelerated magnetically to collide at the center and create a larger, more energetic plasma that is sustained by particle-beam injectors.

TAE further departs from the fusion mainstream in aspiring to fuse protons and boron-11. That reaction will yield three alpha particles and few or no neutrons, thereby avoiding the neutron-induced damage and safety issues inherent in the conventional deuterium–tritium reaction. But p–^{11}B fusion requires a plasma temperature of about 3 billion kelvin, compared with the 100 million to 300 million kelvin needed for D–T. And p–^{11}B produces about half the energy of the D–T reaction.

In its current device, called Norman, TAE hopes to achieve plasmas of around 35 million kelvin for 30 milliseconds by midyear. Its next-generation experiment, Copernicus, is expected to produce plasmas more than three times as hot but still at least two orders of magnitude below the eventual goal. The plasmas in Copernicus will be formed from ordinary hydrogen, and results can be extrapolated to a D–T regime by other developers who may want to pursue that approach, Binderbauer says. Copernicus will "give us the confidence to build a machine that can burn p–^{11}B in the later part of the 2020s," he says.

TAE expects to choose a site for Copernicus by midyear and is weighing bids from local governments in at least two states that Binderbauer declined to identify. In addition to financial incentives, factors in the selection will include the availability of adequate power; the device will have a peak demand of 300 megawatts, which is more than the electricity infrastructure can accommodate at TAE's Southern California location.



A DIAGRAM OF TAE TECHNOLOGIES' EXPERIMENTAL DEVICE, NORMAN. Plasmas are created at opposite ends and accelerated to the center, where they collide and form a larger, hotter plasma. Eight beam injectors supply angular momentum to stabilize the football-shaped plasma.

Construction should get under way in 2020, with experiments commencing in late 2023 or early 2024.

Binderbauer says DOE officials have expressed "considerable interest" in his user-facility concept, and he plans to submit a more concrete proposal to the department later this year. Paul Dabbar, DOE undersecretary for science, says TAE's concept hasn't been discussed within the agency, but, he adds, "I'm not saying we wouldn't do something like that in the future. I'm very open to ideas, and I'm a big supporter of the private-sector fusion effort and engagement [with it]." Dabbar and Energy secretary Rick Perry both toured the TAE facilities last year.

Norman, named for the late TAE cofounder and noted fusion researcher Norman Rostoker (see PHYSICS TODAY, August 2015, page 64), is well suited to explore astrophysical phenomena having a high-pressure component, Binderbauer explains. Examples include differentially rotating plasmas, such as those found in accretion disks, and high-pressure, high-temperature collisionless plasmas to study conditions found in the solar corona, solar mass ejections, and stellar superflares.

E. Michael Campbell, director of the Laboratory for Laser Energetics at the University of Rochester, says astrophysics experiments of the type Binderbauer describes can be performed at his lab's Omega laser and at the National Ignition Facility. But Norman's time and space scales would be much larger than those achieved with the lasers, so the device would offer more opportunities for data gathering.

TAE's user-facility proposal is unrelated to a program now being finalized to improve access by the private sector to DOE's fusion facilities, national laboratories, and scientific computing assets, Dabbar says. That program will be patterned after an existing program at DOE's Office of Nuclear Energy (see PHYSICS TODAY, December 2018, page 26).

Cancer and electric vehicles

Last year the company spun off TAE Life Sciences to commercialize the accelerator technology developed for Norman. The low-energy neutrons the technology produces are well suited for the cancer treatment method known as boron–neutron capture therapy (BNCT). The first unit will be delivered to a Chinese company, NeuBoron Medtech, which is scheduled to begin treating patients with laryngeal and neck cancers in the fall. There is a particularly high rate of such cancers in southeast China.

In BNCT, a patient is injected with a drug that contains boron and is preferentially concentrated in cancerous tissue. When irradiated with neutrons, the ^{10}B fissions into lithium-7 and high-energy alpha particles. The alphas destroy DNA in the surrounding tumor, with minimal damage to healthy tissue. BNCT has not been approved for treatment in the US by the Food and Drug Administration. Binderbauer says the company is at the "advanced stage" of selling compact accelerators to medical centers in Italy, in the UK, and on the US West Coast for use in BNCT clinical trials. He declined to identify the customers.

To date, research reactors have been the source of neutrons used for nearly all BNCT studies, which have also been conducted on patients with glioblastomas, particularly lethal brain tumors. Neutron Therapeutics of Danvers, Massachusetts, last year delivered the first BNCT neutron-source accelerator to Helsinki University Central Hospital in Finland. It's now being commissioned for use in clinical trials, says Noah Smick, the company's vice president of business development. The company hasn't yet received another order, but Smick estimates the market for BNCT accelerators could reach $10 billion.

TAE is currently shopping around to electric vehicle (EV) equipment manufacturers a second spin-off technology: a vastly scaled-down version of software and electronics that it developed on Norman to control the power flows, which peak at about 750 megawatts. Binderbauer says laboratory experiments with full-scale EV components show TAE's technology could extend EV range by 30% or more, in part by reducing heat buildup. TAE is in "exploratory discussions" with a Chinese company he wouldn't name to license the technology for a new two-seat EV. In China, General Motors, Renault-Nissan, and domestic firms have been manufacturing such vehicles.

TAE is working with "joint ventures in the Barcelona and Paris areas" to apply power-management systems to electric buses and service vehicles such as garbage trucks, Binderbauer says. Citing nondisclosure agreements, he declined to identify the partnering organizations.

David Kramer PT

Reviews of Modern Physics at 90

PEINTURE/NATURE MORTE, 1928 (OIL AND PENCIL ON CANVAS), PATRICK HENRY BRUCE (1881–1936)/PRIVATE COLLECTION/BRIDGEMAN IMAGES

Randall D. Kamien

In 1597 the English philosopher Francis Bacon wrote, "*ipsa scientia potestas est* (knowledge itself is power)." Today we are inundated with knowledge and information. There exist nearly a billion websites, more than a million articles on the arXiv eprint server, and now, more than 100 physics journals. What makes one site stand out over another? Is it one particular posted article? Is it one particular journal? The quality of its content? Its breadth of use and appeal?

Over its 90-year history, *Reviews of Modern Physics* (*RMP*) has served the whole physics community. The journal has reported on current trends through colloquia and reprinted prize lectures (Nobel and now the American Physical Society's Medal for Exceptional Achievement in Research). It has published values of fundamental constants and particle data, reviewed mature topics, and, perhaps uniquely among the journals of the American Physical Society (APS), it, has offered refereed, pedagogical lectures.

What drives *RMP*? In a word, impact. It's not a metric that can easily be used by tenure committees or review panels. Rather, the impact that *RMP* strives to make is to unify ideas across physics, to introduce readers to new paradigms, and to publish foundational, essential articles that are read over and over again. If a colleague years ago had to stand over a photocopier to obtain a personal version of an *RMP* paper, it is likely they still have it. If that colleague is like me and my graduate school classmates, the much-loved copy is well worn, extensively annotated, and dotted with coffee and food stains.

For this special issue of PHYSICS TODAY, *RMP*'s current editors, former editors, authors, and others have taken a look back at how their respective fields have appeared in the journal. In addition, some of the topics will be further highlighted at the March and April 2019 meetings of APS during *RMP*-sponsored sessions. If you're attending either meeting, please join us!

What will the next 90 years bring? I would be foolish to predict, but I know something about the next 10: *RMP* will continue to follow the expansion of physics and the physics community. We now have an associate editor to encourage and solicit reviews on climate science, we have introduced biophysics and soft matter as independent efforts, and, notably, we are the only one of the APS and American Institute of Physics families of journals that has a devoted editor for astronomy and astrophysics. When our 100th anniversary comes along, take a look!

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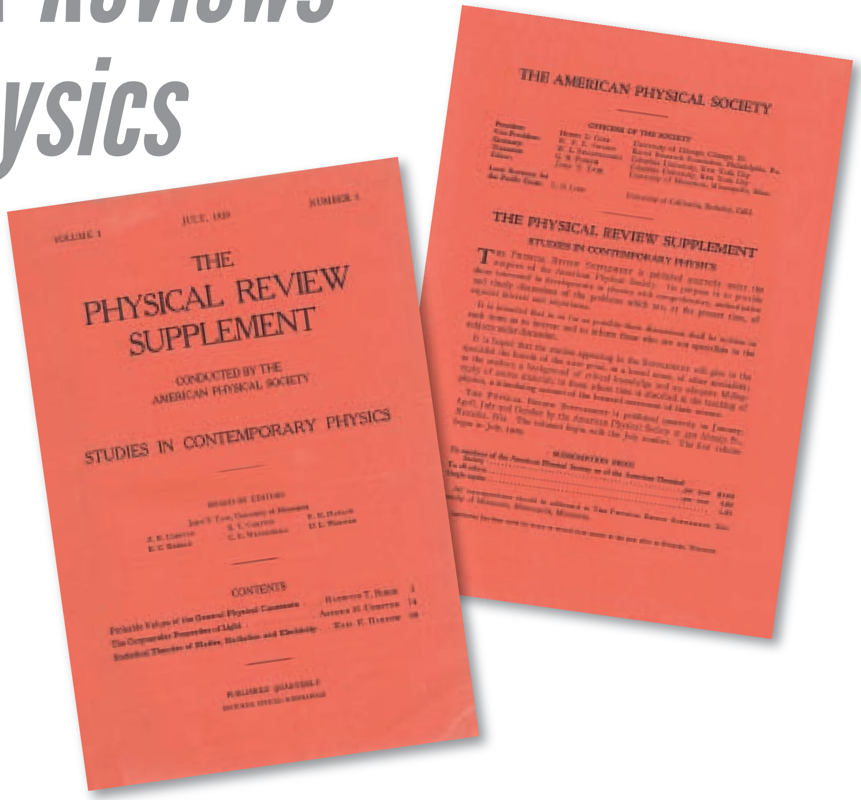
The history of *Reviews of Modern Physics*

Anthony F. Starace

As specialization increased over the course of the 20th century, the journal sought to keep physicists updated on what was happening in the growing number of subdisciplines.



The origins of *Reviews of Modern Physics* (*RMP*) date to 1928 when the editor of *Physical Review*, John Tate, polled 53 prominent American physicists about the desirability of a supplement devoted to review articles. Out of 48 replies, 46 were in favor, and the first one was printed in 1929 under the title *Physical Review Supplement*.[1] The journal was intended to give a specialist's viewpoint to physicists in other subdisciplines, a background of critical knowledge to physics students, and a stimulating account of progress in physics to those who were teaching the subject. A change to US Postal Service regulations about postage costs for supplements prompted Tate to drop the word "Supplement"; after 1930 the journal was known simply as *Reviews of Modern Physics*.

In addition to review articles, *RMP* frequently published special issues. Those included festschrifts for occasions such as Albert Einstein's 70th birthday, memorials such as the one for Enrico Fermi in 1955, and conference proceedings. Special publications were printed once or twice per year until 1969. From that time to the present, *RMP* has focused on scholarly review articles, with a few regular exceptions for Nobel Prize lectures, reports of American Physical Society study groups, and the Particle Data Group compilations.

The editors' perspective

In its 90 years of existence, *RMP* has been under the stewardship of only nine editors: John Tate (1929–41, 1947), J. William Buchta (1941–46, 1948–51), Samuel Goudsmit (1951–57), Edward Condon (1957–68), Lewis Branscomb (1969–73), David Pines (1973–95), George Bertsch (1996–2005), Achim Richter (2006–17), and Randall Kamien (2017–).

For much of *RMP*'s existence, the editor of *Physical Review* also served as managing editor of *RMP*. Associate editors have also played an important role in running the journal. Before 1967 there typically were six associate editors, each selected for a three-year term. Pines increased the number of associate editors to 11. Currently there are 16, each covering a particular subfield. The increase in the number of associate editors reflects the great expansion of physics and the increase of specialization.

The editors' editorial policy statements give us an interesting window into the history of *RMP*. The first such statement was made by Condon on the occasion of his retirement as editor in 1968. He began by saying, "I was ap-

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REVIEWS OF MODERN PHYSICS 90 YEARS

pointed Editor for the period 1957–1959, and my term in office was never extended . . . so for the past nine years I have been a usurper." But, he said, "no one else showed up to serve as Editor, so I merely kept on doing what I could."[2]

Condon graciously thanked all except those who promised to write reviews but did not. He also suggested that the art of writing a good literature review paper ought to be cultivated starting in graduate school. Generating such reviews, he wrote, "must be regarded as a personal responsibility" of every research physicist.

After Condon stepped down, editorials were no longer signed by the editor-in-chief alone but were drafted by the editor and the associate editors. In the first editorial published under Condon's successor, Branscomb, the *RMP* editorial team members argued that the importance of reviews increases dramatically as physics becomes more specialized.[3] They also pointed to the journal's editorial policy, printed on the back cover of every issue, which stated that "The best papers in the *Reviews of Modern Physics* should be milestones of physics, embodying the intellectual contributions of hundreds of others whose work appears in the original literature" and that *RMP* authors "assume responsibilities: a responsibility to these hundreds of authors whose work may be referenced . . . and an even greater responsibility to the reader, who is entitled to assume that a paper in Rev. Mod. Phys. is as complete, as objective, and as critical as it can reasonably be."

Branscomb and colleagues noted three problems in meeting those requirements: maintaining "the standards of quality," deciding "which papers among those of undoubted technical merit are appropriate," and encouraging "the writing of more reviews of the type described." They considered those problems in turn. "The maintenance of high standards," they wrote, "requires that judgments be made not only by the Editors . . . but also by experts on the specific topic of the paper." Thus, they said, *RMP* "intends to continue to solicit the advice of referees (usually two or more)." The second problem would be handled by giving priority to manuscripts that "are critical, comprehensive, and authoritative."

But the third and biggest problem was that "in a time when most of our colleagues express the desire to read good reviews, a diminishing fraction seems willing to devote the time and effort to write them." The editorial team said they would encourage more reviews by continuing "to impose no page charges on authors" and establishing a modest author honorarium.

In 1974, following a self-study by the *RMP* editorial board, Pines and the associate editors announced some new directions for the journal.[4] There had been a substantial increase in the number of specialized review journals, and *RMP* began listing review articles published in other journals to keep readers informed. The editors also hoped for more reviews that would help nonspecialists understand what was new and exciting about a particular field. To encourage authors, the editors decided "to relax the traditional requirement that a review be *complete*, provided the author has been a major contributor to the field in question." That was a notable change in policy and meant that authors could focus on their own contributions rather than attempt to cover the entirety of a field.

Further evolution to the present

The addition in 1992 of *RMP* Colloquia was announced as "an experiment."[5] According to Pines, the colloquia were "short articles intended to describe recent research of interest to a broad audience of physicists," highlight cutting-edge research, and "offer new insights into concepts which link many different subfields of physics." The editors of *RMP* designated oversight of the colloquia and responsibility for their content and readability to a six-member advisory committee chaired by theoretical physicist Ugo Fano.

When Bertsch became editor of *RMP* in 1996, he appointed me as the *RMP* colloquium editor and eliminated the old advisory committee structure. Bertsch, the associate editors, and I suggested topics, solicited authors, and identified referees for submitted manuscripts, and I worked directly with the authors to ensure the readability of their colloquia. That mode of operation continued with other colloquium editors during the editorships of Richter and Kamien.

Sometime in the mid 1990s, editorials were replaced by a one- to two- page enunciation called "What our editors are looking for" that appeared in the January issues of *RMP*. Those statements have since been replaced by the online "*RMP* Article and Colloquium Guidelines." Recent changes in the number of associate editors and their research areas can be found in *RMP*'s mastheads[6] from January 2001 to July 2015.

This article is an updated version of material in the Report of the APS Task Force to Review "Reviews of Modern Physics" *(29 January 1993). Task force members were Ira Bernstein, David Lee, Harold Metcalf, Gerald Miller, Robert Siemann, Clifford Will, and chair Anthony Starace.*

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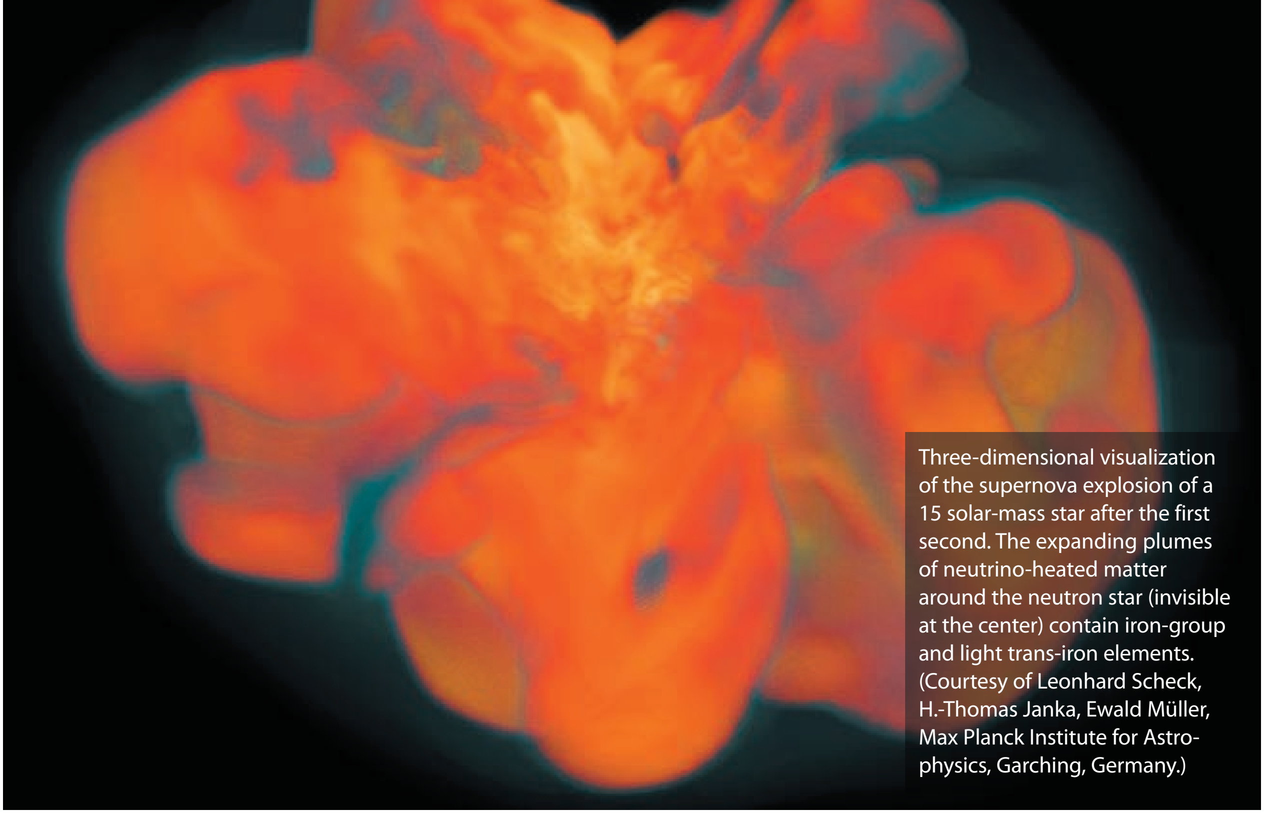

Three-dimensional visualization of the supernova explosion of a 15 solar-mass star after the first second. The expanding plumes of neutrino-heated matter around the neutron star (invisible at the center) contain iron-group and light trans-iron elements. (Courtesy of Leonhard Scheck, H.-Thomas Janka, Ewald Müller, Max Planck Institute for Astrophysics, Garching, Germany.)

The origin of the elements

Stan Woosley, Virginia Trimble, and Friedrich-Karl Thielemann

Determining where the elements of the periodic table come from has taken decades of interdisciplinary research in astronomy, chemistry, and nuclear physics.

What is the world made of? Ancient philosophers postulated four or five elements. Much later, Dmitri Mendeleev and Lothar Meyer extended the quest to a rapidly expanding table of chemical elements. Using spectral analysis techniques that they had pioneered, Robert Bunsen and Gustav Kirchhoff discovered Fraunhofer lines in the solar spectrum, which showed that the elements found on Earth also existed in stars, though in different proportions. The abundance tabulations of Victor Goldschmidt and later Hans Suess and Harold Urey showed a standard pattern for the solar system, which astronomers today extend for objects throughout the cosmos.[1] How could all those observations be explained?

Fred Hoyle promoted an idea in the context of the steady-state cosmological model that he favored: Whereas hydrogen was created continuously throughout the universe, other elements must be made in stars, with their explosive deaths as supernovae playing a dominant role.[2] Adherents of the Big Bang model, on the other hand, thought that perhaps all the heavy elements might be primordial.[3] That hypothesis faltered due to physicists' inability to bridge, at low density, unstable mass gaps for mass numbers 5 and 8.

Bringing together diverse theoretical arguments and observations, Margaret Burbidge, Geoffrey Burbidge, William Fowler, and Hoyle (B^2FH for short) made the compelling case for stellar nucleosynthesis.[4] Similar work

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was carried out by Alastair Cameron.[5] Stars had to gain their energy from making heavier elements out of lighter ones. Winds and stellar explosions offered a means of returning those newly synthesized elements to the interstellar medium, from which they found their way into later generations of stars. The notion of recycling was consistent with the fact that older stars contain less heavy elements. Some stars showed evidence of nuclear transmutation going on within them, while even exhibiting short-lived radioactivities at their surfaces.[6]

The four scientists of B^2FH tapped into a wealth of new laboratory data, especially nuclear reaction rates; many were measured at the Kellogg Laboratory by Fowler and colleagues. Their study brought systematic order to explaining element abundances and delineated all of creation—except for hydrogen—into eight processes. For the first time, every stable isotope was ascribed to a proposed synthesis process and a corresponding astrophysical setting. In addition to the already well-known hydrogen- and helium-burning reactions responsible for making helium and some isotopes of carbon, nitrogen, and oxygen, they included the alpha-, or capture-, process responsible for making intermediate mass elements from magnesium to calcium; the e-process responsible for the iron group abundances (in chemical equilibrium of nuclear reactions); the r-, s-, and p-processes of heavy-element production (the last responsible for proton-rich isotopes); and the x-process responsible for light species like deuterium, lithium, beryllium, and boron, now attributed to the Big Bang, cosmic-ray spallation, and neutrino interactions.

The B^2FH study summarized evidence for the operation of two distinct neutron-capture processes, r (rapid) and s (slow). The s-process was attributed to side reactions during helium burning that release neutrons, and the abundances reflected nuclear properties (the neutron-capture cross section). The r-process was attributed to unspecified explosive events. The requisite time scales were too short and the neutron density too high to occur in stable stars. Type I supernova light curves were attributed—correctly—to energy deposited by radioactive decay,[7] but the responsible isotope was misidentified as r-process californium-254 rather than e-process nickel-56. Despite uncertainty in the explosion mechanism, the rate of supernovae could account for the entire heavy-element inventory in the galaxy.

Much progress has been made over the years. The origin of the heavy s-process elements is now identified with winds blowing from the surfaces of low- and intermediate-mass stars, though the lighter s-process elements up to zirconium come from massive stars.[8] Computer simulations routinely replicate the evolution of stars and their elemental abundances.[9] Many adjustments to the original eight processes have occurred. The alpha process has been supplanted by the burning of carbon, neon, oxygen, and silicon, with heavy-ion fusion reactions ($^{12}C + {}^{12}C$, $^{16}O + {}^{16}O$) playing a greater role than previously realized.[10] Supernovae are modeled in three dimensions including hydrodynamic instabilities required for the explosion mechanism.[11–13] Nucleosynthesis during explosions produces many species via radioactive progenitors rather than directly. A notable example is ^{56}Fe, the mainstay of the e-process, which is actually made as radioactive ^{56}Ni, predominantly produced in type Ia supernovae.[4,12] Deuterium and most of helium are ascribed to the Big Bang.[14] The site of the r-process remained a mystery for 60 years with clear evidence only recently uncovered for a key role played by merging neutron stars.[15]

The combined nucleosynthesis of all participating sources in the evolution of galaxies has been examined repeatedly.[12,16] Questions remain about the role of the first stars, the exact ejecta compositions, and the use of related explosions for cosmology.[13,15] B^2FH and Cameron laid the foundations. Nuclear astrophysics became a quantitative science, one to which observers, stellar and galaxy modelers, and nuclear experimenters and theorists could all contribute.

The online version of this article includes a figure that shows how the assignment of elements to processes has changed since the publication of B^2FH in 1957.

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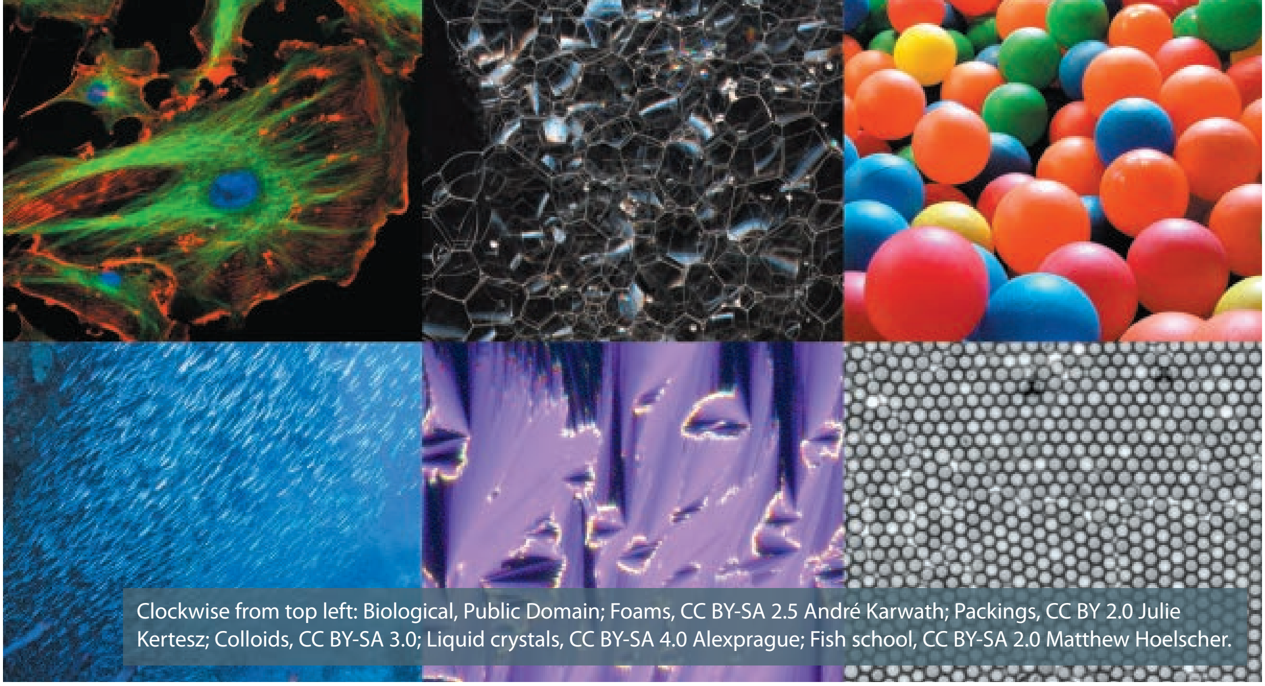

Clockwise from top left: Biological, Public Domain; Foams, CC BY-SA 2.5 André Karwath; Packings, CC BY 2.0 Julie Kertesz; Colloids, CC BY-SA 3.0; Liquid crystals, CC BY-SA 4.0 Alexprague; Fish school, CC BY-SA 2.0 Matthew Hoelscher.

From simple liquids to colloids and soft matter

Robert Evans, Daan Frenkel, and Marjolein Dijkstra

Soft matter, a diverse subject that crosses the boundaries of physics, chemistry, and materials science, continues to surprise with its rich phenomena.

In 1977 Victor Weisskopf published an essay entitled "About liquids," in which he argued that the existence of liquids is not at all self-evident: They belong to the "Who ordered that?" category.[1] "Assume that a group of intelligent theoretical physicists had lived in closed buildings from birth such that they never had occasion to see any natural structures," wrote Weisskopf. "They probably would predict the existence of atoms, of molecules, of solid crystals, both metals and insulators, of gases, but most likely not the existence of liquids."

It is not obvious that a separate state of matter should exist that is dense, disordered, strongly spatially correlated, and distinct from the gaseous and crystalline states. Weisskopf suggested in a throwaway sentence that the existence of liquids should necessarily follow from quantum mechanics. But is that true?

Until the 1950s, no theoretical framework existed to describe liquids. The great Lev Landau infamously argued that there is no theory of the dense liquid state. By the early 1970s, the field had changed significantly for two reasons. First, computer simulations made it possible to probe in unprecedented detail the microscopic behavior of simple, argon-like liquids by using first hard spheres and then the Lennard-Jones model. Second, a quantitative theory of the equilibrium structure and thermodynamic properties of liquids had emerged, accompanied by a growing understanding of the dynamics of simple liquids catalyzed by simulation studies.

An important assessment of the emerging theory appeared in 1976. As laid out in "What is 'liquid'? Understanding the states of matter,"[2] the structure of simple liquids is dominated by the harsh repulsions between the atomic cores, whereas thermodynamic properties depend on both the repulsive and attractive interactions, with the latter treated in a mean-field fashion. Remarkably, such ideas were present in the 1873 thesis of Johannes van der Waals.

Although the number of experimental and theoretical studies increased between 1976 and 1985, little about liquids appeared in *Reviews of Modern Physics*. That changed with the influential article of Pierre-Gilles de Gennes on

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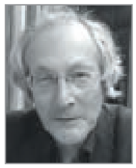

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the statics and dynamics of surface wetting.[3] The review, which admirably summarized the physics of the adsorption of fluids to substrates, interfacial tension, and surface phase transitions, focused primarily on simple liquids.

Of course, most molecules are not like argon: The Lennard-Jones model has its limitations. Nature provides polymers, surfactants, liquid crystals, and a whole zoo of colloidal particles that may or may not exhibit liquid phases. Those particles can combine to form an abundance of structures that are much richer than what's found in simple systems. Some of those diverse structures include membranes, gels and glasses, liquid-crystal phases, micellar solutions, and highly unusual crystalline phases.

Predicting the structure and dynamics of such complex phases of matter from the constituent building blocks and their interactions defines soft-matter science. Soft materials have properties that differ qualitatively from those of simple liquids; there is no corresponding states principle that enables one to map a polymer melt onto liquid argon. Although the behavior of soft materials often has no counterpart in other branches of physics, there can be profound links between different fields, such as the relationship between the director in smectic liquid crystals and the magnetic vector potential in superconductors,[4] or between the formation of disclination lines in nematic liquid crystals and the Kibble mechanism for the formation of topological defects (cosmic strings) as the early universe cooled.[5] De Gennes was renowned for making pertinent connections, as illustrated in his 1991 Nobel Prize in Physics lecture[6] and in the Nobel citation, which reads, "for discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers."

Colloids provide a crucial link between simple liquids and complex fluids and soft matter. Suspensions of micron-sized polymethyl methacrylate particles immersed in a solvent mimic to an extraordinary degree the hard-sphere system. For example, colloidal particles undergo a fluid-crystal transition at the density predicted for hard spheres by computer simulations.[7] No liquid–gas transition occurs, either experimentally or theoretically, because there is no interparticle attraction.

When a nonadsorbing polymer, or more generally a depletant, is added, the effective interaction between two colloids acquires an attractive piece whose range is set by the size of the depletant and whose strength is set by its concentration. That entropic depletion mechanism[8] was first put forward by Sho Asakura and Fumio Oosawa in 1954. And when the depletant is similar in size to the colloid, the phase equilibria mimic that of a simple fluid, with the concentration of the depletant equivalent to inverse temperature. Reducing the size of the depletant reduces the range of the attractive interaction, and liquid–gas coexistence becomes metastable with respect to the fluid–crystal transition, so there is no stable liquid phase. Theoretical studies[9,10] of such colloidal phase behavior in the 1990s were confirmed soon thereafter by beautiful experiments.[11]

Advances in imaging and tracking nanometer- to micrometer-sized particles ensure that colloids will continue to serve as a model system to investigate basic physical phenomena, including the glass transition, jamming, random packings,[12–14] two-dimensional melting,[15] quasicrystals, and more. Many of those phenomena are observed in various soft-matter systems, such as foams, emulsions, micellar systems, and granular matter.

The diversity of topics is a defining feature of the soft-matter field. It now covers sand piles, patchy colloids, self-propelled colloidal particles, microswimmers, DNA origami, bubbles, droplets, and membranes. Soft-matter systems can be highly correlated due to high packing fractions and often exhibit a high surface-to-volume ratio, multiple components across different length scales, and a complex topology and geometry. Those features combine to generate dramatic new phenomena. Unsurprisingly, there is no single unifying theoretical framework.

An exciting new area of study is active matter, in which the constituent particles are maintained out of equilibrium through a constant input of energy. Systems being studied as part of that vibrant subfield include bacteria swarms, cytoskeletons of living cells, vibrated granular matter, and self-propelled colloidal particles. New theoretical approaches are required to describe the diverse, emergent dynamical phenomena encountered.[16,17] Soft-matter physics is sometimes viewed as the science of big atoms. That is misleading. Complex fluids give rise to exceptionally rich behavior that certainly does not exist in argon.

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The Alcator C-Mod tokamak at MIT uses a strong magnetic field to confine plasma for fusion energy applications. (Photo by Mike Garrett, CC BY 3.0.)

Beams and plasmas

Wim Leemans

Progress in plasma physics and accelerator science research advances astrophysics, energy production, and many other scientific fields.

Plasmas are being studied for applications such as magnetic and inertial confinement fusion and in astrophysical phenomena. And accelerators, with their ever-increasing performance, are enabling new generations of light sources and the exploration of the frontiers of particle physics. By connecting those two scientific disciplines, researchers have learned that plasmas can support extremely large electric fields, which may be exploited to accelerate particles. Those fields can be generated using either intense lasers or particle beams to drive collective density waves, much like how a motorboat generates a wake on a lake's surface.

The successful combination of plasma and accelerator physics has resulted in the birth of new areas of research in which magnetized plasmas may be controlled to generate energy or in which light or particle beams are used to generate energetic particle beams, and those beams, in turn, are used to generate intense photon beams. In the past four decades, research with ever more intense laser and particle accelerator beams has increased our understanding of the interaction between ultra-intense light and matter. Those interactions arise from high-energy-density physics, nonlinear quantum electrodynamics, and radiation reaction forces, such as the creation of electron–positron pairs. The beams and plasma-physics section of *Reviews of Modern Physics* (*RMP*) has chronicled the key develop-

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ments and, through its highly cited papers, has been an important partner in training the next generation of scientists.

Magnetized plasmas found in laboratory tokamak settings or as astrophysical plasmas in nature are rich in kinetic phenomena and particle-wave interactions. Researchers have been trying for a long time to harness the potential of controlled plasma fusion for energy production; the first experiments to use magnetized plasmas happened in the 1950s (see the article by David Pace, Bill Heidbrink, and Michael Van Zeeland, PHYSICS TODAY, October 2015, page 34). To enable fusion reactions, the relatively low-density energetic plasmas must be confined for many seconds to several hours. Important topics that were covered in *RMP* include the physics of how electrons and ions behave in hot magnetized plasmas, the transport of energy and mass in a fusion reactor,[1] the excitation of waves,[2] and the heating of plasmas with driving currents.[3]

How turbulence affects the magnetized plasma as it relaxes toward an equilibrium state continues to interest researchers (see the article by Richard Hazeltine and Stewart Prager, PHYSICS TODAY, July 2002, page 30). Their understanding of complex behavior, such as magnetic reconnection[4,5] and nonlinear gyrokinetic theory,[6] is also fundamental for gaining control of the hot magnetized plasmas long enough to create a burning plasma suitable for generating copious amounts of energy.

Since the invention of the laser in 1960, nanosecond-duration laser pulses have progressed from containing tens of joules to megajoules of energy and have been used extensively to generate hot and dense plasmas. Scientists applied such technology to laser-driven, inertial confinement[7] and toward understanding astrophysically relevant, strongly coupled plasmas[8] in laboratory experiments[9,10] (see PHYSICS TODAY, September 2015, page 16). Those breakthroughs have enabled the exploration of matter in states relevant to the physics of supernovae, supernova remnants, interstellar shock waves, photoevaporated molecular clouds, photoionized plasmas, and planetary interiors (see the article by Philipp Kronberg, PHYSICS TODAY, December 2002, page 40).

The advent of ultra-intense femtosecond lasers has opened up access to new regimes of interaction between strong electromagnetic fields and plasma.[11] In the relativistic regime, the photon pressure exerted by the laser light can displace plasma electrons from ions. The resulting density waves that follow the laser pulse ripple through the plasma at velocities near the speed of light and support electric fields from a few to tens of gigavolts per meter; the electric fields can then accelerate electrons to high energies after they've traveled just a few centimeters[12] (see the article by Wim Leemans and Eric Esarey, PHYSICS TODAY, March 2009, page 44). Researchers are using such laser plasma accelerators to develop ultracompact, mobile devices for scientific and societal applications, such as studying soil samples or art objects on location or destroying cancer cells *in vivo*. The generated ultrashort electron beams can be used to produce x rays and gamma rays[13] for imaging and spectroscopy with femtosecond time resolution. As such, they aim to complement the existing kilometer-scale, state-of-the-art conventional accelerators and are driving advances in scientific tools, such as free-electron lasers[14] for smaller-scale laboratory or industrial settings. In addition, the interaction of relativistically intense laser beams with solid materials has produced intense high-energy photons that are of higher-order harmonics than the incident laser photons.[15]

At even higher laser intensities, the radiation pressure can result in ion motion and the generation of high-energy ion beams from dense target materials.[16] At laser intensities exceeding 10^{23} W/cm^2, nonlinear quantum electrodynamics phenomena emerge with electron–positron pair production and a breakdown of the vacuum when the field strengths approach the Schwinger field limit.[11,17]

This brief summary does not mention several topics in plasma physics and its intersections with other branches of physics, including Penning traps that have been used in antihydrogen production, plasmas for nanoassembly processing, and laser manipulation and acceleration of electrons.[18] As knowledge of plasma physics and the progress in laser- and particle-beam technology advances to open new frontiers, we foresee a continuing presence of exciting topics in beams and plasmas in the pages of *RMP*.

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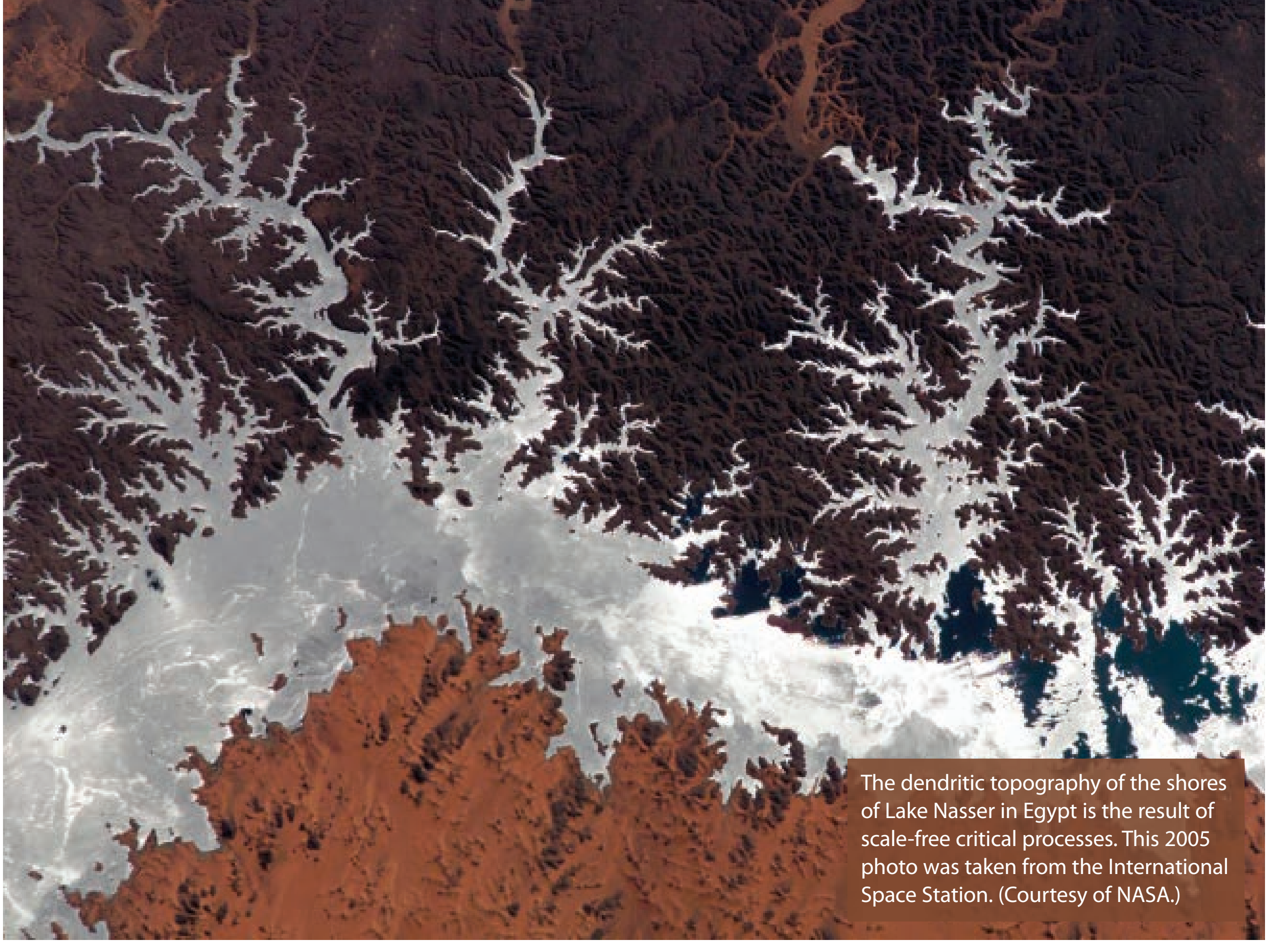

The dendritic topography of the shores of Lake Nasser in Egypt is the result of scale-free critical processes. This 2005 photo was taken from the International Space Station. (Courtesy of NASA.)

Theory of dynamic critical phenomena

Bertrand I. Halperin

New mathematical approaches have extended physicists' understanding of magnets, superfluids, and other complex systems.

When a system is brought to a critical phase transition, such as the gas–liquid critical point where the density difference between liquid and gas disappears, or the Curie point of a ferromagnet where the spontaneous magnetization disappears, many of its properties exhibit singular behavior. Beginning with Johannes van der Waals's work in the 19th century,[1] analyses of critical phenomena have largely focused on static properties, such as free energies, equilibrium expectation values and linear responses to time-independent perturbations. In classical statistical mechanics, static properties are determined by the equal-time correlation functions. However, critical singularities also occur in dynamic properties, such as multi-time correlation functions, responses to time-dependent perturbations, and transport coefficients. Those properties cannot be derived from the equilibrium distribution. A different approach is needed.

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In the 1960s and early 1970s, major advances occurred in the theory of critical phenomena. Important ideas that emerged included the introduction of critical exponents to describe how various static quantities diverge or go to zero as one approaches a critical point and the introduction of scaling laws, which lead to relations among the various exponents.[2] Renormalization-group methods gave a means for understanding scaling laws and gave methods for calculating critical exponents, at least approximately.[3] For that achievement, Kenneth Wilson was awarded the 1982 Nobel Prize in Physics. Importantly, those ideas led to an understanding that the static critical behavior of various systems could be divided into what were termed universality classes. The classes are sensitive to such features as the symmetry of the order parameter or the spatial dimension of the system, but they are independent of other microscopic details of the Hamiltonian, within a broad range.

As progress was made in the theory of static critical phenomena, physicists realized that ideas of scaling and universality classes, as well as renormalization group methods, could also be applied to dynamic properties.[4–6] The review article "Theory of dynamic critical phenomena," published in 1977 in *Reviews of Modern Physics*, provided a summary of the status of those theories[7] and promoted a classification scheme that remains in use today.

Two systems belonging to the same static universality class may belong to different classes of dynamic phenomena. That important distinction is true even away from a critical point. For example, both the classical Heisenberg ferromagnet and the antiferromagnet on a simple cubic lattice have essentially identical thermodynamic properties: One can map the antiferromagnet onto the ferromagnet simply by changing the signs of the spin vectors on one of the sublattices. However, the antiferromagnet has a dynamic property, a spectrum of spin waves, whose frequency is linear in the wavevector at long wavelengths, whereas the ferromagnet's spectrum is quadratic.

In general, the low-frequency dynamic properties of a system not at a critical point can be characterized by a hydrodynamic theory. Such a theory describes fluctuations of the conserved quantities and any additional slow variables that may occur when the equilibrium state has a spontaneously broken symmetry. The form of the theory depends sensitively on symmetry and on the Poisson brackets, or quantum mechanical commutation relations, among the slow variables. The universality classes for dynamic properties near a critical point depend on those features and on the parameters that affect the static critical properties, such as the spatial dimension.

An important quantity characterizing any dynamic universality class is the dynamic critical exponent z. It is defined so that at the critical point, the characteristic frequency for fluctuations of the order parameter at wavevector k is proportional to k^z, for small k. In some cases, the dynamic exponent z can be directly related to the static exponents.

For example, for the Heisenberg ferromagnet in three dimensions, theory[5] predicts $z = (5 - \eta)/2$, where η is a static critical exponent whose value is about 0.035. For the antiferromagnet, one has simply $z = 3/2$. By contrast, in the model of an Ising-like ferromagnet that interacts with an external heat bath, one finds that $z = 2 + x$, where x cannot be related to static exponents. It can be shown that $x \geq 0$, but its value for three dimensions ($d = 3$) is unknown. What is known is that a renormalization group calculation[6,8] near the case of four dimensions finds a small nonzero x, given to lowest order in an expansion in $4 - d$ by $x = 0.0134(4 - d)^2$.

Experimentally, the most accurate studies of critical behavior have been made at the superfluid–normal transition of liquid helium-4. Scaling theory[4,9] predicts that the thermal conductivity λ should diverge here as $\lambda \sim (\xi C_p)^{1/2}$, where $\xi \sim 1/(\delta T)^{0.67}$ is the correlation length of the order parameter at a temperature difference δT above the critical point, and C_p is the specific heat at constant pressure, which has a sharp cusp maximum at the transition point. Experiments agree well with the prediction over four decades of δT.

In recent years, interest has shifted to critical behavior at, or near, a zero-temperature phase transition, where quantum effects play a decisive role.[10] There, static and dynamic quantities are intimately mixed, and many new phenomena are encountered. Nevertheless, ideas such as dynamic scaling, universality classes, and the dynamic exponent z continue to figure prominently in the quantum regime.

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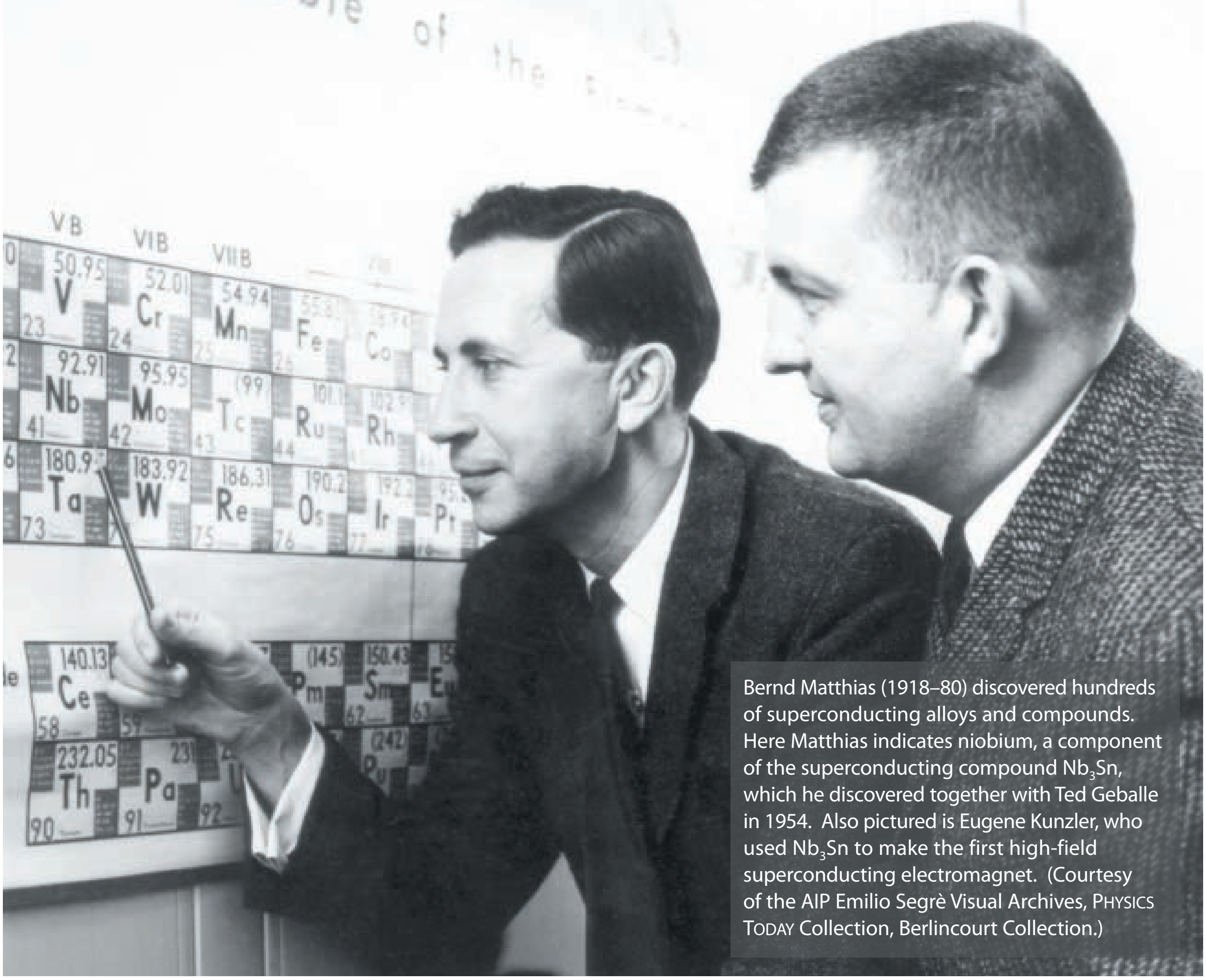

Bernd Matthias (1918–80) discovered hundreds of superconducting alloys and compounds. Here Matthias indicates niobium, a component of the superconducting compound Nb_3Sn, which he discovered together with Ted Geballe in 1954. Also pictured is Eugene Kunzler, who used Nb_3Sn to make the first high-field superconducting electromagnet. (Courtesy of the AIP Emilio Segrè Visual Archives, PHYSICS TODAY Collection, Berlincourt Collection.)

Progress in superconductivity

Arthur Hebard and
Gregory Stewart

One of the subtlest phenomena in physics has been subjected to more than a century of experimental and theoretical investigations.

One hundred years or so from now, humanity could be enjoying the benefits of room-temperature superconductivity with lossless transmission of electric currents and high-efficiency transport. A historian of physics of that time would undoubtedly be curious about how we came to fully comprehend the origins of that mysterious phenomenon in which dissipation-free motion of electrons in macroscopic systems is routinely achieved.

A natural place to start such a study would be with review papers that have been highly cited and were recognized in their day as providing thorough status reports and insightful suggestions for future research. Articles about superconductivity published in *Reviews of Modern Physics* (*RMP*) would certainly qualify. *RMP* is the world's premier physics review journal with the highest impact factor. Many of its articles have garnered thousands of citations within 10 years of publication.

RMP reviews are rigorously refereed. By their very na-

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ture, they establish accepted timelines for the evolution of a field. The 1911 discovery of the zero-resistance state in distilled mercury by Heike Kamerlingh Onnes was a serendipitous event made possible by his 1908 landmark demonstration of liquefied helium. It wasn't until 1933 that the expulsion of magnetic fields from a superconductor during its transition to the superconducting state—the Meissner–Ochsenfeld effect—was recognized, along with the earlier discovered zero resistance, to uniquely define the superconducting state. The ensuing phenomenological theory of superconductivity generated reviews of concepts critical to the development of high-field superconducting magnets[1] (work by Eugene Kunzler, shown in the photo, and others) and theories of flux-flow dissipation[2] associated with thermal activation of vortices (Alexei Abrikosov's quantized flux lines) past or over pinning centers.

Phenomenological treatments of superconductivity converged with the trail-blazing publication of the Bardeen-Cooper-Schrieffer (BCS) theory,[3] which took into account the quantum mechanical nature of bound aligned pairs, or Cooper pairs, of interacting electrons embedded in a collective state of composite bosons. Because the bosons are immune to the influence of other electrons, charge moves without resistance. The analogous condensation of pairs of helium-3 atoms into superfluid phases of composite bosons has spawned a still incomplete but fascinating understanding of unconventional, non-BCS superconductivity in other materials—namely, in heavy-fermion systems[4] and high-T_c cuprates.[5] Multicomponent order parameters,[6] experimental schemes to determine order-parameter symmetry,[7] proximity coupling of superconductors to ferromagnets,[8] and the surprising occurrence of high-T_c superconductivity in the layered iron pnictides[9,10] all add to the breadth of phenomena associated with unconventional superconductivity.

As Bernd Matthias (shown in the photo) would have insisted in pointing out, progress in discovering new superconductors has always been linked to the clever performance of making the correct material. For example, the discovery[4] of the first unconventional heavy-fermion superconductor, $CeCu_2Si_2$, in 1979 took a whole year of refining the proportion and treatment of ingredients before the superconducting phase could be prepared convincingly as a bulk compound, rather than as a minority second phase. The unconventional superconductor that increased T_c from about 35 K to 93 K all at once in early 1987 was first reported[11] as a mixture of phases with nominal composition $Y_{1.2}Ba_{0.8}CuO_4$. Further materials efforts were needed before the correct composition of $YBa_2Cu_3O_7$ could be identified. And some conventional superconductors—such as molybdenum, whose T_c of 0.9 K was first discovered in 1962 by Matthias and Theodore Geballe[12]—superconduct only after the last few parts per million of magnetic impurities are removed.

Our future historian of physics would certainly want to complement their survey of reviews of superconductivity by looking at compendia, collections, and tutorials from other sources. Such publications are not necessarily reviews. Rather, they identify in detail the highlights of a landscape from which reviews have already nucleated or might soon emerge. In that category, a particularly useful compendium on superconducting materials classes ranging from conventional to unconventional[13] presents a juxtaposition of 32 materials classes by 32 sets of authors with 32 unique perspectives and opinions.

In reporting to colleagues, our historian would carry the message that authors of *RMP* reviews of superconductivity had collectively acted like what might be called superconductors. Like a conductor in an orchestra pit, they tried to organize the fascinating and diverse phenomenology surrounding them. To recognize where the score is heading, it is necessary to identify the hot areas emerging from established reviews—for example, on topological superconductors[14] or graphene.[15] Specific recent examples might include the occurrence of interfacial superconductivity in two-dimensional crystalline materials[16] or the emergence of unexpected high-T_c superconducting phases at extreme pressures.[17] The ubiquity and promise of superconductivity in the worldly sphere discussed here and even out to the stars[18] guarantees that reviews on the subject area will not only monitor but will also be essential for progress.

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This painting by Lukos Hey imagines a disused railway station in Prague's Vyšehrad district projected onto a Hopf fibration, a topological function that describes a 3-sphere (a 4D version of a sphere) in terms of a 3D sphere and a set of circles. (©Lukos Hey, http://lukoshey4.webnode.com.)

Tying it all together

Paul M. Goldbart and Randall D. Kamien

Topology has emerged as a crucial and fruitful component of modern physics.

Georges Friedel had his nematic threads,[1] Paul Dirac had his monopole,[2] and Alexei Abrikosov had his flux line.[3] Very different systems and very different scientists, but deep down they all captured the same idea: Integers cannot vary continuously. The number of times a closed curve winds around a point under smooth evolution in time and space—both position and momentum space—must be invariant.

Integers arise in physics through degrees of freedom that take values on circles, tori, annuli, and any number of manifolds that are not simply connected—in other words, manifolds with holes or handles around which a path can wind. The mathematical way to study the paths falls under the field of topology. Some say that in topol-

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ogy, a coffee cup and a doughnut are the same because one can be distorted into the other. But that picturesque trope can be stated from the point of view of the surface as well. A doughnut has closed paths that go around its hole just as a coffee cup has closed paths that go around its handle. If we lived on a doughnut, we could go around the hole some integer number of times and return to our starting point. Moreover, we cannot change the net number of times we go around (going around one way is the negative of going around the other way). As the doughnut deforms into a coffee cup, the winding number does not change—it cannot unless we tear the doughnut and reconnect it.

When everything changes smoothly, the winding number must change smoothly as well. But how can an integer change smoothly? It cannot. That is the essence of topology. Because an integer cannot relax smoothly, it must remain constant, even as the surface is smoothly distorted. The winding is a feature not just of doughnut handles but of degrees of freedom in ordered media.

For instance, in the two-dimensional model of two-component unit vectors—the XY model—the angle that each spin makes with the x-axis is defined only up to 360°. Thus the angle can wind as the path moves around a particular point, a defect. More generally, the Nambu–Goldstone modes that map out the degeneracies of a broken symmetry state are coordinates for the space of equivalent ground states, the ground-state manifold (think of the wine-bottle potential).

Continuous distortion of one function into another goes by the mathematical term homotopy. In 1958 Charles Frank applied homotopy theory to the phase changes of liquid crystals.[4] In the early 1970s, Maurice Kléman and Gérard Toulouse,[5] Grigory Volovik and Vladimir Mineev,[6] and Dominik Rogula[7] abstracted Frank's innovation and showed how homotopy theory could be extended from spheres and other simple surfaces to ground-state manifolds. The result was a coherent framework for studying defects, not just in liquid crystals but also in superconductors, superfluids, and other systems. Those singularities are seen as topological defects.

In 1979 N. David Mermin penned a classic, pedagogical article in *Reviews of Modern Physics* (*RMP*) on topological defects from which many practitioners learned homotopy theory.[8] Together with Louis Michel's *RMP* contribution[9] and Sidney Coleman's Erice lectures,[10] a new understanding emerged. The application of the powerful body of modern mathematical results—in this case algebraic topology and homotopy theory—cleared up in one fell swoop what had been a mélange of isolated results, cobbled together by intuitive but unsystematic, error-prone methods.

Viewed from that perspective, the flux line and the nematic defects are all the same; they are characterized by the first homotopy group of a circle. But the mathematical framework extends to hedgehogs in ferromagnets and nematics through the second homotopy group of the sphere. The seminal work of Tony Skyrme on meson theory takes advantage of the third homotopy group of the sphere.[11] The Dirac monopole, also characterized by the first homotopy group of a circle, is the first application of those ideas to Yang–Mills fields in general, themselves characterized by their associated Lie groups. The unified language led to unanticipated insights into quantum field theory, high-energy physics, and condensed matter.

Indeed, although crystals and other ordered media offer a natural arena for observing topological defects, defects are not always visible. As Michael Berry observed, sometimes they are in more abstract configuration spaces.[12] For instance, when viewed appropriately, a winding and its associated "defects" let researchers understand anomalies in quantum field theory as obstructions to defining a basis in Hilbert space.[13] Ideas from homotopy theory lend themselves to quantum computing,[14] topological materials,[15] and entangled polymer loops.[16] Most recently, they illuminated particle-vortex duality, which transmutes bosonic and fermionic statistics.[17]

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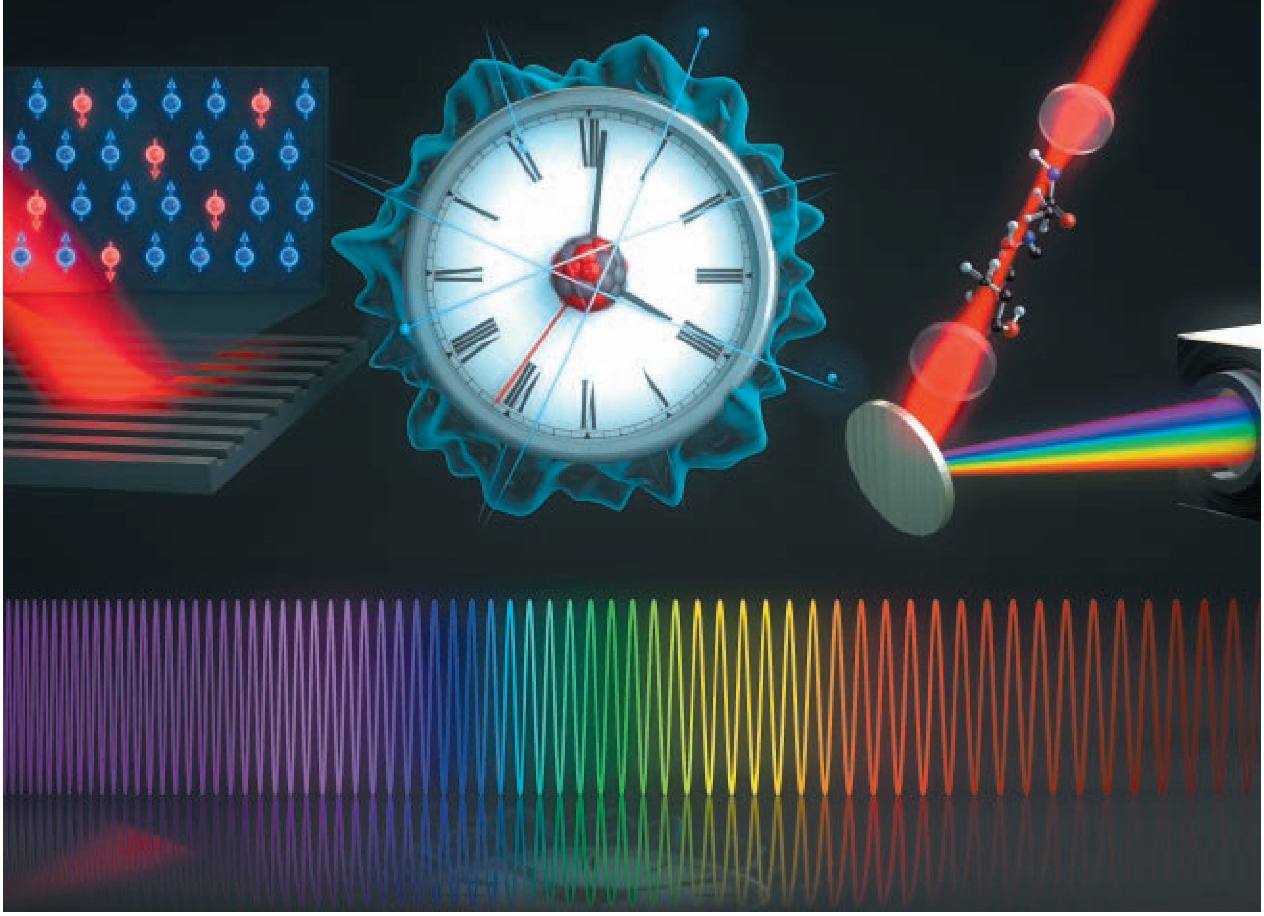
YE GROUP AND STEVE BURROWS, JILA

Coherent light brightens the quantum science frontier

Margaret M. Murnane and Jun Ye

Controlling coherent light across a vast spectral range enables ultraprecise measurements and the quantum control of atomic, molecular, and condensed-matter systems.

The laser was invented about 60 years ago[1]—30 years after the founding of *Reviews of Modern Physics*. That novel light source opened up new windows to the natural world and transformed our understanding of many areas of science. Today, the ability to control every aspect of light—phase, spectrum, waveform, pulse duration, polarization, and individual photons—can be used to coherently probe and manipulate quantum systems.

Research topics include quantum communication via entangled photons, quantum materials manipulation using ultrafast pulses, gravitational-wave detection using long-baseline interferometers, and precision spectroscopies with ultrahigh spectral and temporal resolutions. Indeed, the recent scientific progress on coherent light sources requires the ultimate quantum control over light, atoms, molecules, and solid-state environments, a feat accomplished by the strong synergy between fundamental science and innovative technologies.

With laser light's high temporal and spatial coherence, researchers now can produce waveforms that span the visible and IR regions of the spectrum (see the article by Arthur Schawlow, PHYSICS TODAY, December 1982, page 46). Moreover, by harnessing the nonlinear optical process of high-harmonic generation (HHG),[2] they can extend

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laser-like coherence over the entire UV and soft-x-ray regions.[3,4] Our review showcases how the stunning control of light is revolutionizing ultraprecise measurements and ultrafast science.[5-7]

The control of optical phases dominates laser science research. In the spectral domain, continuous-wave lasers are providing dramatically enhanced resolving power to expose ever-finer energy structures of matter. Ultrastable lasers that maintain optical phase coherence for tens of seconds make it possible to investigate optical transitions of electrons to an excited state with nearly 1 part in 10^{16} resolution.[8] New science has emerged, such as testing for fundamental symmetries, developing sensors of increasing sensitivity, probing the quantum nature of many-body physics, and searching for new physics beyond the standard model. The best atomic clocks are now based on stable light interacting with atomic quantum matter controlled by laser fields (see PHYSICS TODAY, March 2014, page 12). With significant increases in the quality of the atomic transition and the improved control and evaluation of systematic effects, optical atomic clocks have progressed[9] to an accuracy of 10^{-18}.

With the increased temporal resolution enabled by the combination of ultrafast lasers and extreme nonlinear optics, researchers can probe the fastest electron–electron interactions, which occur on femtosecond to attosecond time scales.[7] As those lasers produce pulses in a periodic train via mode locking, a comb structure emerges in the frequency domain. Then phase stabilization can be applied to the pulse train to control both the repetition frequency and the optical carrier frequency.[10] The broad spectral coverage of a frequency comb provides phase control of optical frequency markers across intervals of many hundreds of terahertz and enables ultraprecise measurements and optical standards that are more than 100 times better than before.[9]

Until recently, coherent light sources at wavelengths shorter than the UV were not widely available. Fortunately, HHG, which produces a series of attosecond pulses or pulse trains, has allowed for exquisite spatial coherence and temporal coherence at wavelengths from the UV to the soft-x-ray region. HHG originates from a nanoscale quantum antenna that is created as an atom undergoes strong ionization in an intense femtosecond laser field.[11,12] Although the emission from each atom emerges as dipole radiation, when the light fields from millions to billions of atoms are coherently combined with subangstrom spatial and subattosecond temporal precision, a bright, directed HHG beam is produced.[3]

Because HHG fields are created by manipulating the radiating electron wavefunction of an atom, the resulting quantum coherence of HHG light sources is making it possible to control x-ray light with visible lasers (see the article by Henry Kapteyn, Margaret Murnane, and Ivan Christov, PHYSICS TODAY, March 2005, page 39). By adjusting the driving laser wavelength, researchers can now simultaneously generate a coherent supercontinuum spanning the IR, visible, UV, and soft-x-ray regions–over 12 octaves in bandwidth.[4] Moreover, by adjusting the HHG geometry, they can fully control the direction, spectrum, polarization, divergence, and vortex charge of high-harmonic beams, which is important because extreme-UV (EUV) and x-ray optics are expensive and challenging to manufacture.

The unique properties of HHG are propelling discoveries in other fields. It's now possible to capture the dynamic electronic band structure of a material or the fastest coupled interactions between charges, spins, and the lattice that give rise to remarkable properties of quantum materials.[13] HHG has also been used to uncover new regimes of nanoscale energy flow and to develop metrologies for next-generation nanotechnologies.[14]

Moreover, HHG from a high-repetition laser can, with the help of a femtosecond enhancement cavity, stabilize the generated pulse train to produce a frequency comb in the EUV.[15,16] That discovery demonstrates a beautiful connection between the two manifestations of coherent light in the spectral and temporal domains. The exceptional coherence properties of the EUV comb open up applications in precision measurement, frequency metrology,[17,18] and angle-resolved photoemission spectroscopy.

The revolution in producing coherent light continues at all measurement extremes, whether narrow spectral coverage, narrow spectral width, new photon energy scales, or ultrashort pulses. The frontier of light–matter interaction is entering a new phase that is driving scientific discoveries and novel technology development. Researchers are addressing many overarching scientific questions by using lasers, and we foresee more exciting developments on light appearing in the pages of *Reviews of Modern Physics*.

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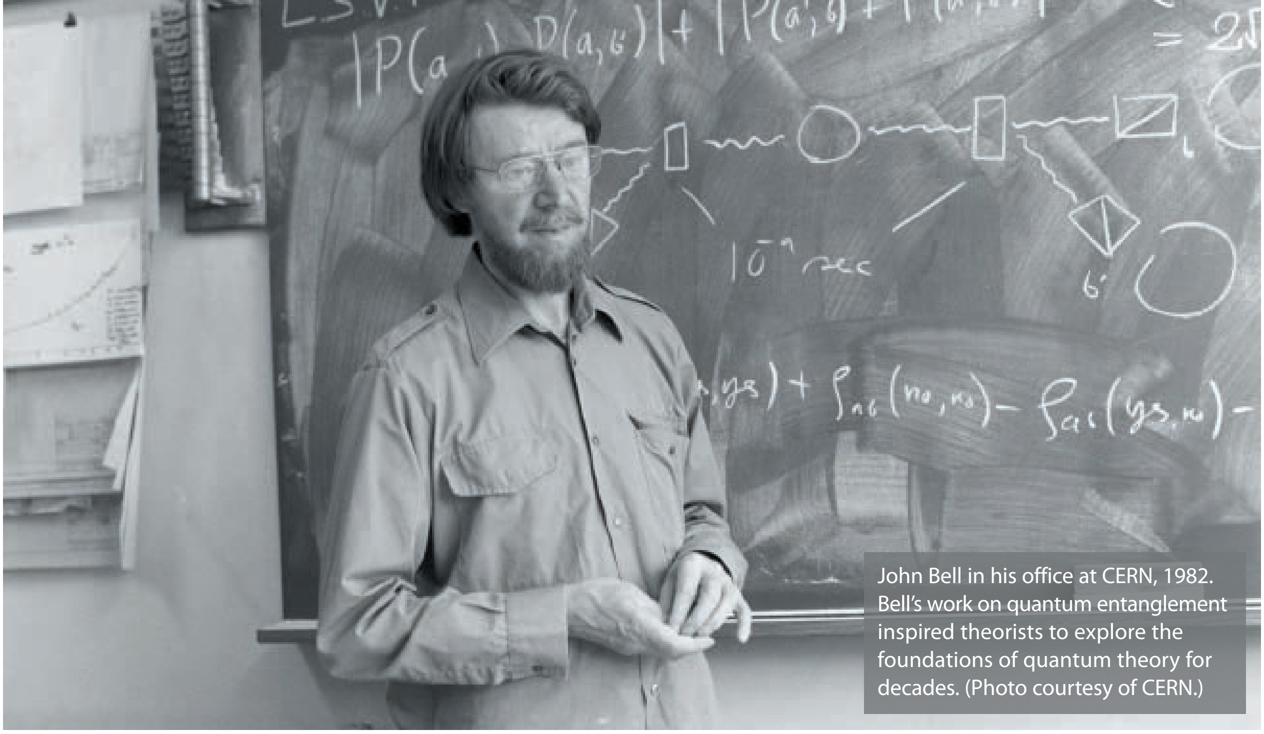

John Bell in his office at CERN, 1982. Bell's work on quantum entanglement inspired theorists to explore the foundations of quantum theory for decades. (Photo courtesy of CERN.)

Quantum foundations

David P. DiVincenzo and Christopher A. Fuchs

More than a century after the birth of quantum mechanics, physicists and philosophers are still debating what a "measurement" really means.

It's sometimes said that the field of quantum information and computing ought to be called applied quantum foundations. That's because so many of the ideas that first arose when scientists began thinking deeply about the mysteries of quantum theory—entanglement, Bell inequality violations, parallel worlds, interference of probabilities, and quantum contextuality—are now seen to be resources for attaining feats in information processing unimaginable in a classical world. Not only has *Reviews of Modern Physics* (*RMP*) nurtured that vibrant young field, it deserves credit for laying its very foundation.

Arguably the most far-reaching article on quantum foundations to come through the pages of *RMP* was also its first: Richard Feynman's 1948 "Space-time approach to non-relativistic quantum mechanics."[1] Well-known for introducing the technique of path integrals, the paper goes deeper in presenting what Feynman considered the distinguishing mark between classical and quantum physics. At issue was how probabilities for the outcomes of an actual measurement are calculated in terms of the probabilities given by unperformed measurements. Feynman's resolution was to introduce the amplitude calculus, but the foundational statement on which it was based was quite clear: "We are led to say that the statement, '*B* had some value,' may be meaningless whenever we make no attempt to measure *B*."

Hidden variables

But maybe there is a way to preserve the notion that unperformed measurements have unrevealed values after all, perhaps at the cost of giving up some less-cherished classical intuition. That was the subject of three groundbreaking papers in *RMP*'s 1966 volume.[2–4] In a 1952 non-*RMP* paper, David Bohm proposed the first hidden-variable extension of nonrelativistic quantum theory:[5] A spinless particle actually could be modeled as having a preexistent position and momentum despite Niels Bohr's edict of "complementarity." Indeed, researchers showed in the years since that there are many ways to supplement quantum theory with hidden variables; Bohm and Jeffrey Bub wrote in *RMP* about one such way.[3] The only deciding factors seemed to be the inventors' intuitions and their hopes that the new hidden-variable models might lead to new physics.

Yet in 1952 a young John Bell was already thinking "How could this be?" For John von Neumann had "proved" years earlier the impossibility of hidden-variable extensions of quantum theory. Bell's paper[2] (which had accidentally languished for two years in the *RMP* editorial office!) and Bohm and Bub's papers[3,4] tackled the

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question head-on. The common conclusion was that von Neumann's theorem and later refinements of it rested on overly restrictive assumptions that the various hidden-variable models simply shrugged off. Most portentous was a line at the end of Bell's paper: "It would . . . be interesting . . . to pursue some further 'impossibility proofs,' replacing the arbitrary axioms [I] objected to . . . by some condition of locality, or of separability of distant systems." In fact, Bell had already settled his question in the intervening years: No local hidden-variable model could ever be up to the job of reproducing quantum theory's statistics, he concluded. In other words, all successful hidden-variable models must have what Albert Einstein dubbed "spooky action at a distance."

Is locality a less cherished principle to give up than the idea that unperformed measurements have preexistent (but yet to be seen) outcomes? Einstein in 1948 had already expressed the conundrum with admirable clarity: "Without . . . an assumption of the mutually independent existence . . . of spatially distant things . . . physical thought in the sense familiar to us would not be possible. Nor does one see how physical laws could be formulated and tested without such a clean separation."[6] In the years after Bell, the points were made increasingly sharp, culminating 45 years after Einstein's statement with one of the most powerful and thorough presentations of what is at stake with those considerations: David Mermin's *RMP* analysis of the then newly discovered three-particle Greenberger-Horne-Zeilinger paradox.[7]

It from bit

Unperformed measurements either have no outcomes or they have some but with spooky action at a distance. Is there any other option besides those? Might unperformed measurements have all possible outcomes? As strange as it might seem, that question too was first explored in the pages of *RMP*—through Hugh Everett III's seminal paper on the many-worlds interpretation of quantum theory.[8] His idea was that the universe obeys a giant Schrödinger equation, and there is no such thing as "measurement" in any preferred or fundamental sense. There is only physical interaction as specified by the Hamiltonian of the universe, and that interaction leads the universe to continuously branch into parallel worlds.

As John Wheeler argued in a companion piece to the paper, a key attraction to the many-worlds view is that it seems to offer a way forward for quantizing general relativity.[9] Yet the Everett interpretation has not been without its problems. Most prominent among them is how one can justify the particular probability calculus of quantum theory from its completely deterministic picture. Since 1957 a surprising number of distinct potential solutions have been proposed for that fundamental problem, with still no consensus at hand. But *RMP* has been there too, with Wojciech Zurek's comprehensive analysis of what the notion of decoherence brings to the table.[10]

Wheeler eventually had his own problems with Everett's interpretation,[11] but the influence he had on all the interpretations discussed here is interesting in its own way. Wheeler was the PhD adviser of both Feynman and Everett when they were doing their foundational work, and Zurek was his postdoc. In the last 25 years of his life, Wheeler landed on a peculiar thought. He desperately wanted to know "Why the quantum?" and it was his conjecture that whatever the answer, it should be of an "information-theoretic color."

In fact, Wheeler's perspective was in no small part responsible for the field of quantum information. One of us (Fuchs) was lucky enough to be under Wheeler's tutelage at the time, and it led to a quest for how to think about quantum states consistently as (subjective) information. The end point was a view of quantum theory called quantum Bayesianism, or QBism, which also made its debut in *RMP*.[12] One of the things that sets QBism apart from the other interpretations is its reliance on the technical details of quantum information to amplify Feynman's point—that the modification of the probability calculus in quantum theory indicates that something new is created in the universe with each quantum measurement. Only it takes the formalism of quantum information to see it with the greatest clarity. (See the Commentary by N. David Mermin, PHYSICS TODAY, July 2012, page 8.)

Indeed, by the example of QBism, one might wonder whether quantum foundations is "applied quantum information" instead. So the subject comes full circle. Whatever the future directions in quantum foundations research, history bears out that *RMP* will be there publishing the deepest and most far-reaching articles on the subject.

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The Eightfold Way, by Helaman Ferguson, is a tetrahedral sculpture at the Mathematical Sciences Research Institute in Berkeley, California. Murray Gell-Mann applied the term eightfold way to the organization of subatomic hadrons. (Photo by Ivars Peterson.)

Constructing the theory of the standard model

Mary K. Gaillard and Paul Langacker

It took decades to discover the quarks, leptons, and gauge and scalar bosons that make up our current picture of particle physics.

We begin with quantum electrodynamics (QED), which successfully combines classical electrodynamics, quantum mechanics, and special relativity. QED inherits the gauge-transformation symmetry—called $U(1)$ in group-theoretical language—that classical electromagnetism possesses. QED is also renormalizable; that is, it is well defined mathematically: Infinities that appear at intermediate stages disappear when the theory is expressed in terms of a finite number of measured quantities, such as mass and charge.

The first theory of weak interactions was Enrico Fermi's postulate in 1933 that nuclear decay arises from the coupling of the neutron to the proton, electron, and neutrino at a single point in space and time. The Fermi theory successfully described weak interactions at low energies, but it couldn't be fundamental; unlike QED, the Fermi theory is not renormalizable. Some, but not all, of the infinities are removed by replacing the coupling at a point with the exchange of heavy, electrically charged W^+ and W^- bosons.

That inability to remove all infinities in the calculations was one problem with the theory. Another was the strong suppression of certain processes that did not conserve "strangeness."

Asymptotic freedom

Unlike electrons, neutrinos, and other leptons, hadrons are particles that interact via the strong nuclear force. The structure of the hadron spectrum suggested that the interaction was invariant under an eight-dimensional generalization of the rotation group called $SU(3)$. The structure also led to the proposal in 1964 that hadrons are each composed of three fractionally charged, spin-½ quarks. The up and down quarks make up the nucleons and other nonstrange matter, whereas the strange quark is among the constituents of strange hadrons.

You might think that the Δ^{++}, a hadron with charge +2, would be made of three up quarks, and experiment

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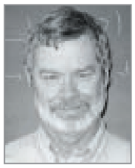

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shows that indeed it is. But each quark has spin ½, so how can three coexist in the ground state? Fermi statistics, which prevents the three constituents of a nucleon from occupying a totally symmetric state, necessitated the introduction of a new quantum number called color. Each quark of a given "flavor"—the species of an elementary particle—had to come in one of three "colors": red, green, or blue. (See the article by O. W. "Wally" Greenberg, Physics Today, January 2015, page 33.)

The color, electric charge, and spin of the quarks were confirmed in lepton–nucleon scattering and electron–positron annhilation experiments. Meanwhile, low-energy pion physics established that strong interactions are mediated by vector bosons. The experiments revealed that strong interactions grow weaker with increasing energy; they are said to be asymptotically free. And yet at low energies, interactions become very strong and confine the quarks inside hadrons. (See Physics Today, December 2004, page 21.)

In 1954 Chen Ning Yang and Robert Mills extended $SU(2)$ isospin symmetry, which interchanges protons and neutrons, to a local form analogous to the $U(1)$ of QED. The extension implied the existence of three self-interacting vector bosons, which perhaps could partially mediate the strong interactions. That idea never worked out because there was no satisfactory way to generate vector boson masses, but the mathematics of gauge invariance was later reapplied and became the basis of our understanding of the weak and strong interactions.

Spontaneous symmetry breaking

In particle physics, spontaneous symmetry breaking refers to the symmetry loss in solutions to the equations of motion in a system's lowest energy state. However, hopes that such symmetry breaking could lead to new realizations of strong-interaction symmetries were largely eliminated by the Nambu–Goldstone (NG) theorem: Spontaneous symmetry breaking would lead to the existence of massless, spin-0 NG bosons.

Of course, no massless, spin-0 particles exist. In the 1960s several physicists realized that there is a loophole to the theorem; the twin problems of unwanted NG bosons and the nominal masslessness of the Yang–Mills gauge bosons would "cure" each other. The NG bosons become modes of the now-massive gauge particles. (See Physics Today, December 2008, page 16.) Simple versions of that Brout-Englert-Higgs (BEH) mechanism also implied the existence of a massive, spin-0 Higgs boson. (See Physics Today, December 2013, page 10.) But little attention was initially given to such ideas, because researchers were thinking in terms of strong interactions, where the BEH mechanism did not appear to be relevant.

The ultimately successful application of Yang and Mills's work to the electroweak interactions combines the $U(1)$ symmetry of QED with a local weak interaction version of an $SU(2)$ symmetry. When the combined symmetry is broken by the BEH mechanism, the force-carrying vector bosons are manifest as a massless photon and the massive W^+, W^-, and Z particles.

The problem of an overlarge prediction for strangeness-violating processes still remained. That conundrum was resolved by postulating a fourth quark, called charm, whose interactions would provide the destructive interference needed to cancel out strangeness-changing interactions.

Concurrent with the experimental confirmation of charmed hadrons[1] was the discovery of a new charged lepton, called τ. It led to the prediction of new quarks called bottom b and top t. The new generation of quarks and leptons introduced just enough extra complexity into the weak interactions to allow for violation of *CP* (combined charge conjugation and parity) symmetry in the weak interactions.

A major breakthrough was the proof that Yang–Mills theories, like QED, are renormalizable, a property that holds even when the gauge symmetry is spontaneously broken. The proof put the electroweak theory,[2] with charm included, on firm footing.

Quantum chromodynamics was developed[3] in the early 1970s, soon after the electroweak theory. The interactions between quarks are mediated by eight spin-1 gluons, the analogues of the photon and W and Z particles of the electroweak theory. Whereas the photon does not have an electric charge, the gluons carry color charges and interact with each other, which leads to asymptotic freedom and color confinement.

The original standard model assumed that the neutrinos are massless. But later observations of neutrino oscillations and flavor conversions implied the existence of tiny but nonzero masses.[4]

The standard model is undoubtedly correct to an excellent approximation,[5] but it leaves many questions unanswered. Those include the origin of neutrino masses, the values of the fermion masses, and the explanation for apparent fine-tunings, such as the extremely small ratio of the weak-interaction and gravity energy scales. Similarly, the standard model does not include a quantum theory of gravity or explanations for the excess of matter over antimatter and for the nature of the dark matter and energy in the universe. Promising ideas have been proposed to account for all those shortcomings, but clearly much remains to be discovered.

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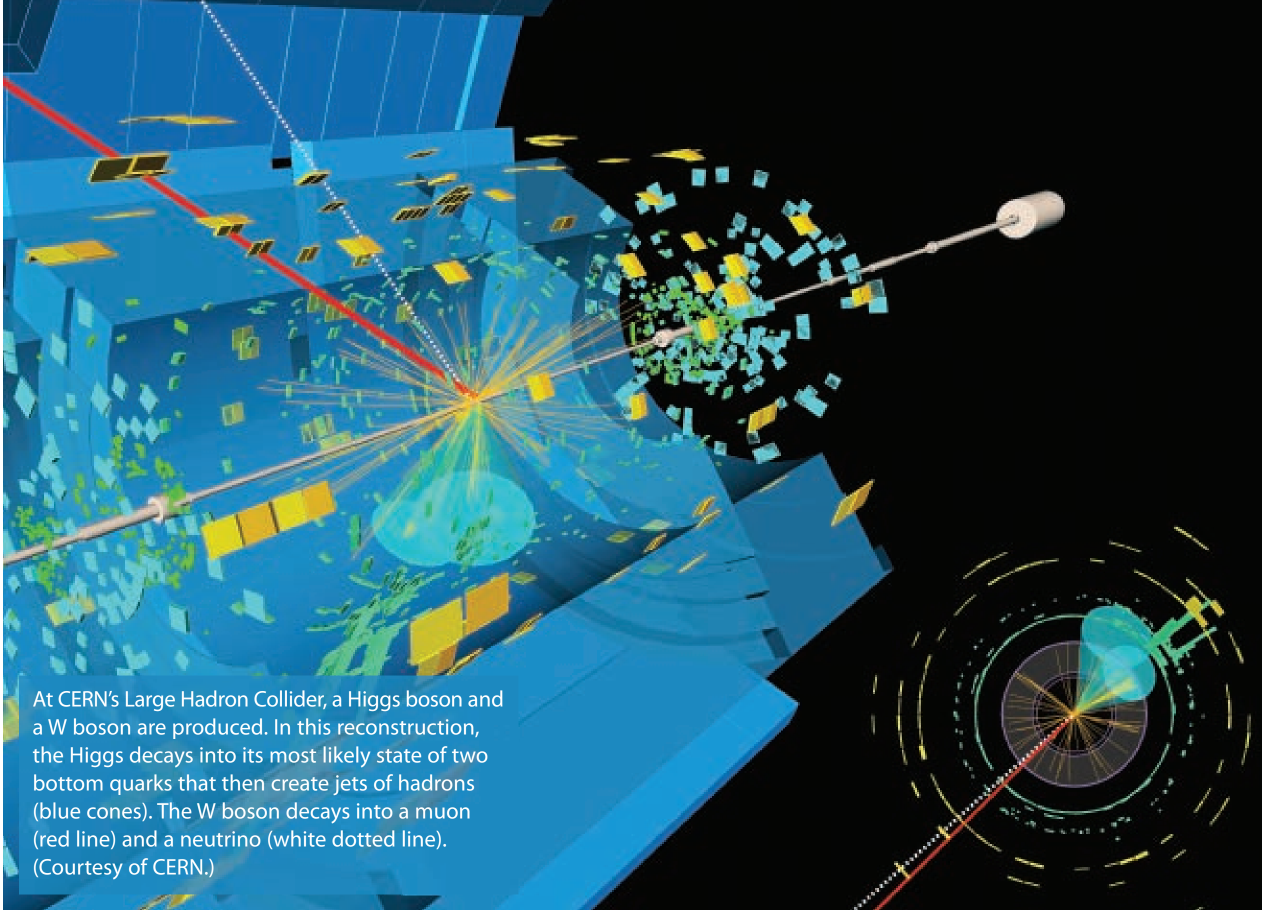

At CERN's Large Hadron Collider, a Higgs boson and a W boson are produced. In this reconstruction, the Higgs decays into its most likely state of two bottom quarks that then create jets of hadrons (blue cones). The W boson decays into a muon (red line) and a neutrino (white dotted line). (Courtesy of CERN.)

Experimental basis of the standard model

Paul Grannis and Vera Lüth

Understanding the subatomic particles and the interactions among them required the development of ever more sophisticated experiments—from early cloud chambers to huge, multielement detectors.

Particle physics evolved from its roots in cosmic-ray and nuclear physics when scientists realized that there are more fundamental constituents of matter than just protons and neutrons. Over many years, increasingly sophisticated experiments provided the information needed to develop the underlying theoretical concepts. Although the primary experimental results on which the emerging standard model (SM) was built were published elsewhere, *Reviews of Modern Physics* has been pivotal in putting them into context.

Broken symmetries in the weak interaction

Symmetries have been central to the development of the SM. The demonstration that weak-interaction decays are not invariant under spatial reflection[1] showed that they violate parity symmetry. More surprisingly, the combined operation of matter–antimatter interchange (*C*) and spatial reflection (*P*) was found to be violated in neutral kaon decays[2] at the 0.1% level. There was no explanation for that effect until it was recognized in 1973 that a model with three generations of quark pairs would also allow for *CP* violation in decays of neutral B mesons,[2] which was observed in 2001. The similarity between the weak and

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electromagnetic interactions, and the observed short range and parity violation of the weak interaction, implied the existence of massive, spin-1, force-carrying bosons with both vector and axial-vector components. The W^+, W^-, and Z^0 bosons discovered[3] at the CERN proton–antiproton collider in 1983 verified that prediction.

The nonconservation of probability predicted in processes involving those bosons at high energy was ultimately "repaired" by the Higgs mechanism responsible for spontaneous symmetry breaking of a unified electromagnetic and weak interaction. The symmetry breaking provided the *raison d'être* for the observed massless photon and massive W^+, W^-, and Z^0 bosons and for the spin-0 Higgs boson discovered[4] in 2012.

The observation that neutrinos produced from the decay of a pion into a muon and a neutrino subsequently interact to produce muons but not electrons[5] was a surprise and meant that these neutrinos differ from those produced from nuclear beta decays. Another great surprise was the realization that neutrinos from the Sun[6] and from particle decays in atmospheric cosmic-ray showers[7] transform from one type to another. Those findings—and the discovery[8] of the τ, the third charged lepton—revealed that there are three generations of charged lepton and neutrino pairs and that at least two of the neutrinos have nonzero mass.

Revealing the strong interaction

The notion that mesons and baryons are composed of quarks was bolstered experimentally[9] in the early 1970s. Three quark flavors—up, down, and strange—were sufficient to explain the patterns of the known hadrons until 1974, when experiments at Brookhaven and SLAC revealed a new meson carrying a fourth quark flavor, charm.[10] Subsequent experiments at Fermilab found the even heavier bottom and top quarks[11] and thus established that, just as for the leptons, there are three generations of quark pairs.

The SM theory of the strong interactions was built on such observations as highly inelastic scattering of electrons and neutrinos from nucleons.[12] The scattering first revealed the nucleon's point-like constituents, thus supporting the quark picture, and subsequently showed the characteristic momentum-transfer dependence of their coupling to gluons—the mediators of the strong force—that is at the heart of quantum chromodynamics (QCD). Experiments verified calculations of many hadronic cross sections at high energy[13] and thereby established the validity of QCD as the theory of strong interactions.

Although the SM has by now been verified by thousands of measurements, it remains a mysterious success. For instance, it contains 26 *ad hoc* parameters—masses, mixing angles, couplings, and so on—that, if modified, would lead to an unrecognizably changed universe.[14] And although the SM edifice is well founded, it is manifestly incomplete!

Tools and instruments

The pioneering measurements discussed here would not have been possible without the increasing sophistication and power of experimental tools.[15] Accelerators evolved from tabletop cyclotrons to colliders tens of kilometers in circumference. Instruments that measure particle reactions grew in size, complexity, and precision—from early cloud chambers to huge multielement electronic detectors. The revolution in computing greatly expanded the reach of experiments. And newly developed technologies have found applications in medicine, industry, national security, and other sciences.[16]

The rapidly expanding base of knowledge about the SM needed an evolving compendium of numerical information about the properties of the myriad particles and their interactions. *Reviews of Modern Physics* published frequent updates of such information, beginning with a 1964 article on particle properties.[17] In fact, the journal has served as an archive of the fundamental constants of our science since its first article, "Probable values of the general physical constants," was published.[18]

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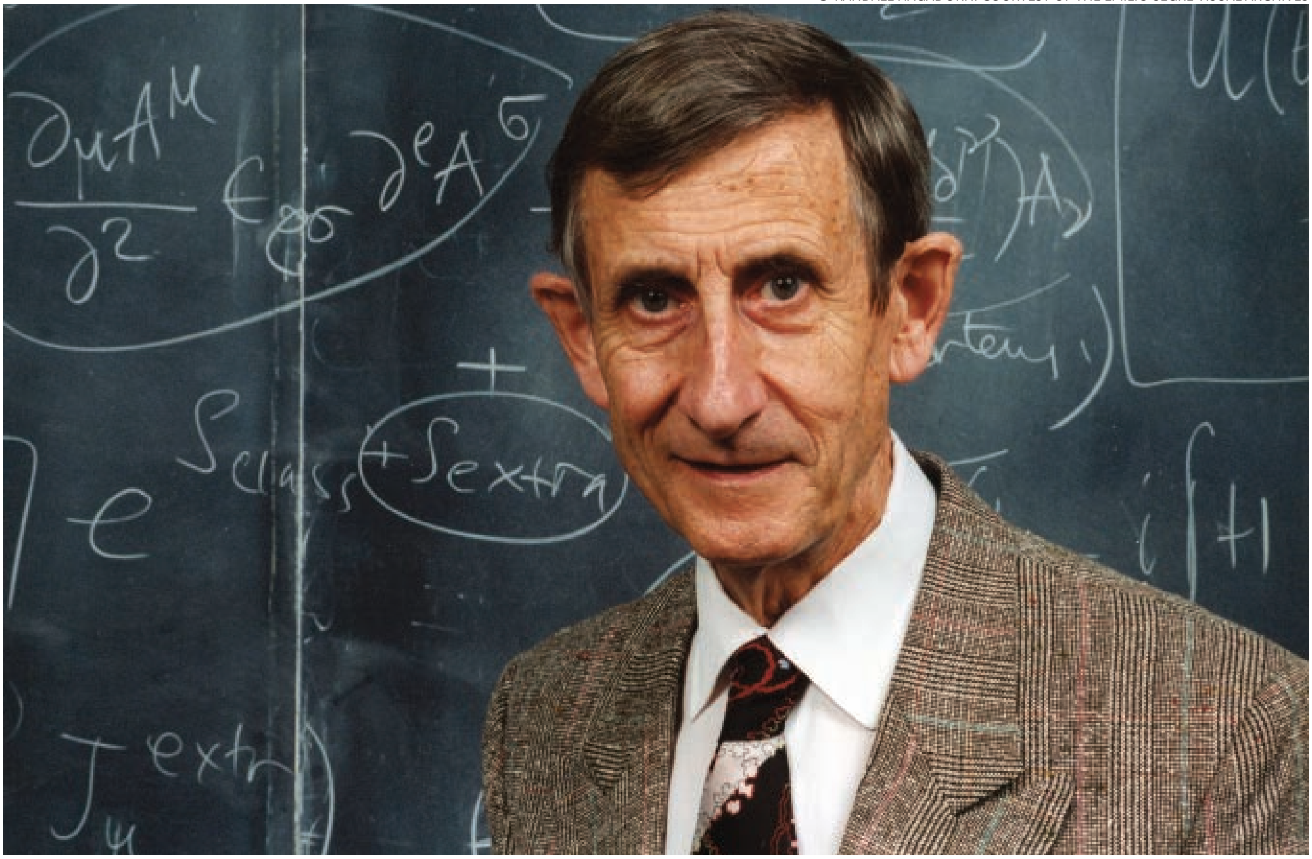
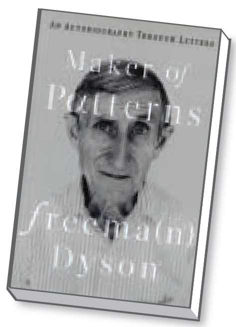


Letters from a remarkable life in science

Maker of Patterns
An Autobiography Through Letters
Freeman Dyson
Liveright, 2018.
$27.95



Freeman Dyson was a good son. When he left his native Britain in 1947 to study physics with Hans Bethe at Cornell University, he wrote to his parents often about his new life in the US. Up to that point he'd been chiefly a mathematician, but his writing showed him to be an astute social observer. "The American picnic is not exactly what we understand by the term," he said in one letter. "It starts out with fried steak and salads, cooked on an open-air grille, and served with plates, forks, and other paraphernalia; this sort of thing, like the elegance of the average American home and of the women's clothes, seems to me rather a rebirth of the Victorian era, flourishing over here by virtue of the same conditions that nourished it in England. . . . I often feel that Victorian England and modern America would understand each other better than either understands its contemporaries."

Dyson, now 95, is one of the great physicists of the 20th century. He is also the author of roughly a dozen popular books that describe many of his exploits in science and writing. His latest book, *Maker of Patterns: An Autobiography Through Letters*, provides a rich supplement of anecdotes and observations.

Seldom was Dyson the first to discover something big. Instead, he is notable for being among the first to blaze new territory across a range of research. He made significant contributions to adaptive optics, random matrices (a sort of statistical mechanics for nuclei), the scientific approach to the search for extraterrestrial intelligence, the use of fields in condensed-matter physics, the study of the late universe, the consequences of not-so-constant fundamental constants, and the stability of matter. He also contributed to advances in climate change modeling when he worked at Oak Ridge National Laboratory in the 1970s.

The nonscientific public, if they know of Dyson at all, will have heard about his skepticism of the impact of climate change. That skepticism has put him at odds with many of his friends who, like him, hold generally progressive political views.

Physicists chiefly know Dyson for his contribution to the development of quantum electrodynamics in the late 1940s. In a 1949 paper for *Physical Review*, he synthesized two rival theories: the field approach developed by Sin-itiro Tomonaga and Julian Schwinger, and Richard Feynman's so-called path-integral approach. Because of his explanatory powers, the young Dyson—then just 25—became the bearer of the new quantum gospel to physicists in the US and Europe. For several years the diagrams used to depict quantum interactions, now known as Feynman diagrams, were called Feynman–Dyson graphs.

The 1965 Nobel Prize in Physics recognized Tomonaga, Schwinger, and Feynman for their quantum electrodynamics work; Dyson did not share in the award. But as his letters show, he knew even as the work was being done that the other three men were the true discoverers and he was merely the expositor. In a letter to his parents in 1948, he described a journey he made to try out his new ideas on Feynman at Cornell: "He said he had given his copy of my paper to a graduate student to read, then asked the student if he himself ought to read it. The student said no, and Feynman accordingly wasted no time on it and continued chasing his own ideas. Feynman and I really understand each other; I know that he is the one person in the world who has nothing to learn from what I have written, and he doesn't mind telling me so. That afternoon Feynman produced more brilliant ideas per square minute than I have ever seen anywhere before or since."

In addition to his scientific work, Dyson has some important engineering achievements, such as helping to develop adaptive-optic techniques and designing an intrinsically safe nuclear reactor that is still in use today for training and for producing medical isotopes. More important still is Dyson's work as a popularizer. For many decades now, mostly in the pages of the *New York Review of Books*, his essays have helped readers understand what it's like to be a scientist. His mathematical, scientific, and engineering skills have allowed him to estimate and describe the efficacy of various physical phenomena—a talent especially suitable for imagining the prospects for humans to travel to the far corners of the solar system.

What makes Dyson's letters a remarkable window into US history is that he is no mere expert; he was a witness to many of the events he describes. Consider one final example. In August 1963, when he was living in Washington, DC, and working at the Arms Control and Disarmament Agency, Dyson wrote two letters home to his parents. The first described his role in shaping the Limited Test Ban Treaty and the testimony he gave before the Senate.

The second, written a day later, described Dyson's participation in a march in DC and a speech he heard from one of its organizers. "From two till four they had the official speeches at the Lincoln Memorial. It was very effective to have the huge figure of Lincoln towering over the speakers," he wrote. "The speeches were in general magnificent. All the famous negro leaders spoke, except James Farmer, who sent a message in writing from a Louisiana jail. The finest of them was Martin Luther King, who talks like an Old Testament prophet. He held the whole 250,000 spellbound with his biblical oratory. I felt I would be ready to go to jail for him anytime."

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PABLO_K/ISTOCK/THINKSTOCK

The not-so-secret science ecosystem

The Secret Life of Science

How It *Really* Works and *Why* It Matters

Jeremy J. Baumberg
Princeton U. Press, 2018. $29.95

Jeremy Baumberg has an idea: Let's think of science as "a restlessly evolving ecological system." If we identify the key species and subspecies and the sources of competition, we can characterize the ecosystem as a whole and seek ways to improve it. That ecological analogy is the "secret" out of which Baumberg has spun an ambitious yet frustrating new book, *The Secret Life of Science: How It* Really *Works and* Why *It Matters*.

Baumberg dubs his two major species of scientist "simplifiers" and "constructors." Simplifiers seek "to understand the world's natural scientific system." Their archetypal science is the search for the Higgs boson. Simplifiers have the most authority in cosmology, biology, and particle physics. Constructors use the insights of the simplifiers "to synthesize new scientific domains." Their archetypal science is developing the implications of Maxwell's equations. Most of the world's roughly 8 million scientists, Baumberg writes, are constructors, but simplifiers get the most media attention.

Other participants in the global scientific ecosystem work for journals, universities, governments, subdisciplines, and the media. Survival of the fittest and descent with modification create intense competition within and among those agents. The result is a global scientific environment that is in "rude health"—handsomely funded and producing plentiful results—but is skewed by growing tensions and global competition. Participants feel trapped in a system over which they have no control.

Throughout the book, Baumberg explores the workings of science through that rather loose ecological analogy. He examines Nobel Prizes, for instance, and determines that three-quarters of awardees from 1952 to 1981 were simplifiers, but constructors received the majority from 1982 to 2011, a reflection of the rise of constructor science. He also writes about the harmful role of competition, which he says has fed a "clamor for attention" in the media and has created a proliferation of interchangeable conferences.

Sometimes Baumberg's use of the analogy grows glib and thin, such as when he writes, "Just as sunlight corresponds to the funding needed to develop science, people are more like the rain that fertilizes everything, the water cycle of the science ecosystem." At other times, the analogy spins out of control. Describing the impact of competition on conference talks, he writes, "Each iridescent butterfly of an idea strives for the most dramatic wings to flash sunlight-flecked colors into the furthest distance, hoping for a better mate." As the book goes on, Baumberg's science ecosystem grows more complex and difficult to follow.

None of it is wrongheaded. What's exasperating is Baumberg's claim that he is observing virgin territory. There is "no good place to find a description of the way science actually works," he writes. Really? One wonders about John Ziman's excellent books *Real Science: What It Is, and What It Means* (2000) and *An Introduction to Science Studies: The Philosophical and Social Aspects of Science and Technology* (1984), both of which offer detailed portraits of the complex network that makes up modern science. Baumberg's chapters on scientific publishing and media attention would have profited from Bruce Lewenstein's studies on that subject, and he could have learned much from Daniel Sarewitz's studies of science policy. In this very magazine, Catherine Westfall and I have compared scientific research with an evolving ecosystem (May 2016, page 30). In *The Secret Life of Science*, Baumberg prefers to reinvent the wheel.

Baumberg says that he aims to write like a mainstream sociologist of science. Yet he appears to have consulted none of the relevant sociological literature, and the book has no footnotes or bibliography. It has the feel of a blog that wants to be considered the bird's-eye view on the subject. And in fact, Baumberg does have a blog, www.thesciencemonster.com, which he mentions four times. I wish that the Princeton University Press reviewers had insisted that Baumberg engage with more of the relevant literature. Researchers customarily cite and discuss related work not to be fussy or pedantic but out of a deep scholarly motive; it enables readers to consider a new piece of research with respect to what else is known. Without that information, it is impossible for Baumberg's readers to gauge how much of what he is telling us here is *really* a secret and how much is already in the public domain.

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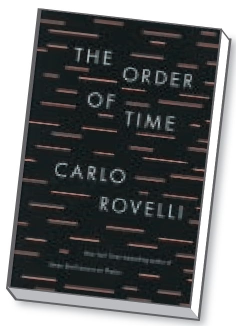
DIUNO/ISTOCK/THINKSTOCK

Is the future as real as the present?

The Order of Time
Carlo Rovelli
Riverhead Books, 2018. $20.00



Carlo Rovelli has written a lovely, thoughtful, and poetic book about the nature of time. A topic as old as thought itself, it is occasionally consigned to the category of "too philosophical for serious physicists." But, as Rovelli so lucidly explains, a fundamental change in the understanding of time was both an ingredient and a result first of special relativity and then of general relativity, and further rethinking may be required to understand quantum gravity and fundamental open questions in cosmology. His book also highlights how central time, along with the closely related quantities of energy and entropy, is to essentially every aspect of our experience and understanding of the physical world.

Rovelli, a professor at the Center for Theoretical Physics in Marseille, France, has thought long, hard, and unusually deeply about time—not just in the context of his central field, quantum gravity, but also in statistical mechanics, quantum foundations, and even evolutionary theory. That lifetime of thinking comes through in *The Order of Time*. Although compact, approachable, and clear, the book is dense with ideas and insights. It's appropriate for a broad readership, from those who want just a taste of what could (or should) reconfigure their intuitions about time to researchers who will enjoy Rovelli's framing of important issues, the links to questions outside of physics, and his provocative theses.

The Order of Time is organized into four sections. The first recounts the developments in physics that refute our intuitive understanding of time as a smooth, unidirectional, rigid, and universal flow from past to future. Time is not universal (special relativity), or rigid (general relativity), or continuous (quantum theory), or fundamentally unidirectional (classical versus statistical mechanics). Physicists generally know those arguments well, but Rovelli gives some beautifully clear metaphors, such as genealogy for the partial time ordering of events, and a useful and careful framing of the major scientific issues surrounding our understanding of time.

The book's second part discusses how we should conceptualize time in modern physics, especially in anticipation of further advances in fields such as quantum gravity. Rovelli contends that "the world is made of events, not things." That should be taken with a grain of salt—"things" are quite useful to think about—but he is clearly right that human bias tends toward "thingification." For fundamental physics, events such as particle interactions, quantum measurements, or signal receipts are often of much greater interest.

The block-universe view of time holds that all events are laid out through spacetime with "equal reality," with future events just as fixed and immutable as those in the past. Rovelli's treatment of that conception in the third section is interesting and subtle. He enthusiastically accepts the lack of a preferred direction for cosmic time and acknowledges that the basic equations connecting times are all deterministic and time reversible. But he rejects the implications that the future and the present are equally real and that "nothing happens" because everything has in a sense already happened. Our understandings of past, present, future, and "real" are all local approximations, he argues, and should not be extrapolated to reality as a whole.

It was a bit unclear to me whether Rovelli's view on the block universe would hold equally true in a universe that was purely classical or governed by a deterministically evolving "wavefunction of the universe," or if instead it relies on his "timeless" formulation of quantum gravity and cosmology. But his discussion shows how enormously subtle—and unresolved in physics—the relationship is between different notions of time.

The final portion confronts, and attempts to bridge, the description of time in fundamental physics with our experience of time as situated, thinking, acting observers embedded in a particular physical universe. The section covers several aspects, from the rather technical to the deeply humanistic. Primarily, the discussions are both enlightening and, I'd hold, the right way to think about those issues, although a few topics, such as thermal time, occupy a frustrating ground between too technical and not technical enough.

I was intrigued but unconvinced by Rovelli's scheme to avoid the so-called "past hypothesis," which defines the early universe as one occupying an extraordinarily low-entropy state. Entropy growth underlies time, which, as Rovelli eloquently expresses, underlies everything we experience. Moreover, the entropy gap implied by the past hypothesis is a cosmic store of information and order that provided the raw material out of which all chemical, gravitational, biological, and other forms of order in our universe ultimately derive. But, Rovelli argues, it isn't necessary for the universe to have had a low-entropy state; it just needed to be low entropy *from a particular point of view.*

I don't really see how that can work. Although one could identify subsystems with respect to which the universe appears low entropy, I can't see how it would continue to be low entropy despite the progression of time either forward or backward. I'm not sure that Rovelli really sees how it works, either—he as much as admits that it is a desperate measure to avoid the past hypothesis. But there may be a core of an idea here that could be made to work, perhaps with additional ingredients, such as cosmological inflation.

Those scientific issues, however, should not detract from what is so delightful about this book. It is infused with wisdom, warmth, and intelligence. A reader looking for a more detailed understanding of issues of time in physics would do well with a weightier work like Sean Carroll's excellent *From Eternity to Here: The Quest for the Ultimate Theory of Time* (2010). But although low in mass, Rovelli's book is heavy with insight and will give all readers a taste of the mysteries of time. It will lead nearly any reader to consider many things in a new light.

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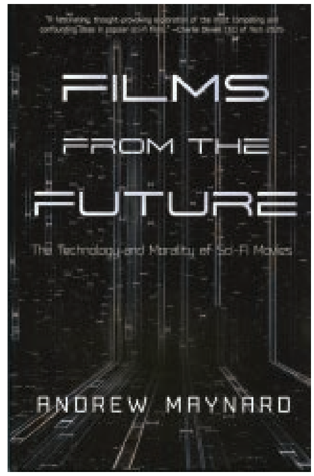
NEW BOOKS & MEDIA

Films from the Future

The Technology and Morality of Sci-Fi Movies

Andrew Maynard
Mango, 2018. $27.99

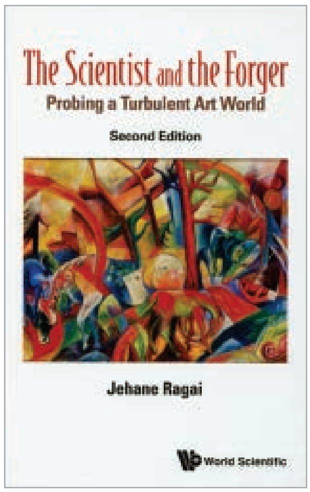


From resurrection biology and human cloning to artificial intelligence and genetic manipulation, imagined technologies form the backbone of science fiction. In *Films from the Future*, physicist Andrew Maynard discusses the promises and potential pitfalls of technologies from 12 of his favorite movies—some blockbusters, like *Jurassic Park* (1993), and some more obscure, like *The Man in the White Suit* (1951). Part cautionary tale, part message of hope, Maynard's narrative is both entertaining and thought-provoking. —CC

The Scientist and the Forger

Probing a Turbulent Art World

Jehane Ragai
World Scientific, 2018 (2nd ed.). $68.00

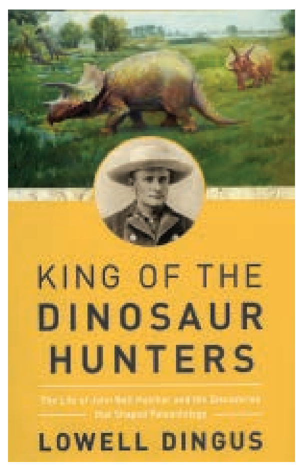


Jehane Ragai, an emeritus professor of chemistry at the American University in Cairo, Egypt, takes the reader on a tour through the fascinating world of art forgery in the second edition of *The Scientist and the Forger*. Ragai covers the science of forgery detection but also emphasizes other signs that a piece of art might be fraudulent, such as the lack of a paper trail establishing ownership. The chapters string together anecdotes about different forgers and forgeries in a way that can sometimes feel disjointed, but readers interested in art will find much to intrigue them. The book's beautiful color images add another level of appeal. —MB

King of the Dinosaur Hunters

The Life of John Bell Hatcher and the Discoveries That Shaped Paleontology

Lowell Dingus
Pegasus Books, 2018. $35.00

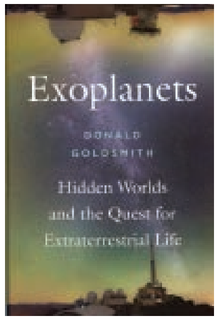


John Bell Hatcher was a prolific 19th-century collector of prehistoric fossils and bones, including the first *Triceratops* skeleton. In *King of the Dinosaur Hunters*, paleontologist Lowell Dingus concentrates on Hatcher's professional life. He delves into Hatcher's extensive travels, fossil collecting, and all the minutiae associated with those activities, including letters to employers, expenses, and conflicts with his fellow paleontologists. The book provides little detail about Hatcher's personal life and is aimed primarily at paleontology devotees interested in knowing more about the challenges of early fossil hunting. —CC

Exoplanets

Hidden Worlds and the Quest for Extraterrestrial Life

Donald Goldsmith
Harvard U. Press, 2018. $24.95

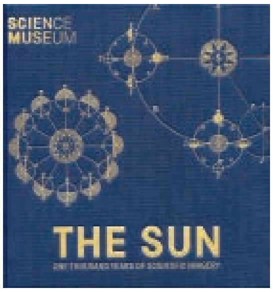


Astronomer Donald Goldsmith considers the past and future of exoplanet science in his new book, which is aimed at a scientifically informed but nonexpert audience. He recounts early efforts to detect planets outside our solar system and explains the breakthroughs in detection methods that enabled astronomers to find the first exoplanets. He also gives an informative account of where known exoplanets are and what they might be like, along with a tantalizing glimpse at what might come next for astronomers as they search beyond the solar system's bounds. —MB

The Sun

One Thousand Years of Scientific Imagery

Katy Barrett and Harry Cliff
Scala, 2018. $27.95



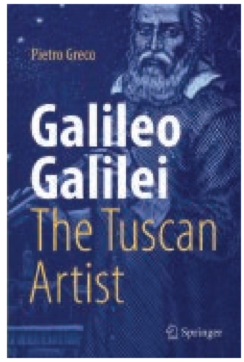
Created to accompany a special exhibition at London's Science Museum, *The Sun* highlights sketches, paintings, and photographs from the museum's solar imagery collections. Illustrations range from a 12th-century monk's sunspot drawings in an illuminated manuscript, to an 18th-century Spirograph-like representation of the solar system, to photographic close-ups of the Sun taken by orbiting spacecrafts. Authors Katy Barrett and Harry Cliff, both curators at the museum, showcase the creativity of astronomers, theologians, and artists over the past millennium. —CC

Galileo Galilei

The Tuscan Artist

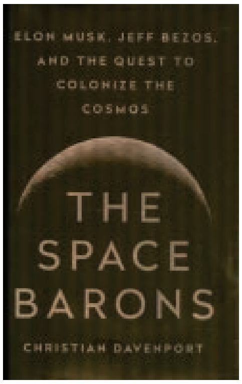
Pietro Greco
Springer, 2018. $44.99

In this full-length biography, science writer Pietro Greco delves into the life and times of the celebrated Italian polymath and Renaissance man Galileo Galilei. Although "artist" may not be the first word that comes to the reader's mind regarding Galileo, the book's subtitle is actually a quote from *Paradise Lost*, in which John Milton refers to his famous contemporary. Milton's words acknowledged that Galileo excelled not only in science but also in philosophy, theology, and the arts. Drawing on an extensive bibliography and filled with digressions and trivia, this 383-page book aims to be an in-depth portrait of a man Greco calls "a real superstar, probably the first big star of the modern age." —CC



The Space Barons

Elon Musk, Jeff Bezos, and the Quest to Colonize the Cosmos

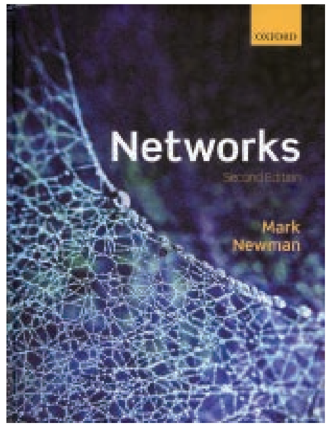


Christian Davenport
PublicAffairs, 2018. $28.00

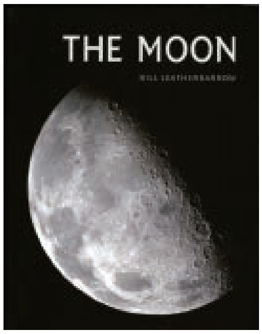
Christian Davenport, a journalist for the *Washington Post*, dives into the world of private spaceflight in this new volume. *The Space Barons* focuses on billionaires Jeff Bezos and Elon Musk, each of whom has invested part of his personal fortune in the future of commercial space travel. Davenport tells an entertaining story of the rivalry between Bezos's Blue Origin and Musk's SpaceX and provides readable short biographies of both men. Quotes from interviews with Bezos, Musk, and other major players in the spaceflight industry are particularly illuminating. —MB

Networks

Mark Newman
Oxford U. Press, 2018 (2nd ed.). $65.00



University of Michigan physicist Mark Newman first published his textbook *Networks* in 2010, but as he says in the introduction to the second edition, the science of networks is moving quickly. The new and updated *Networks* adds sections on topics including multilayer networks, complex contagion, and network synchronization. It also includes updates to other sections of the book and new exercises for students. Newman aims the first 10 chapters at students in a general-knowledge course on networks; later chapters will require knowledge of linear algebra and more. —MB



The Moon

Bill Leatherbarrow
Reaktion Books, 2018. $40.00

The Moon has fascinated humans since ancient times. In this brief history of lunar science, amateur astronomer Bill Leatherbarrow discusses how human understanding and knowledge of the Moon has progressed from the earliest observations with the naked eye to an increasingly more sophisticated understanding with the invention of the telescope and the advent of space travel. Nicely illustrated with drawings, maps, and photographs, the book ends with a chapter extolling the virtues of backyard astronomy and detailing the necessary equipment, the lunar features to look for, and the benefits of citizen science. —CC PT

Focus on analytical equipment, sensors, and instrumentation

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

Two-stage rotary vane pump

The Pascal 2021 HW two-stage rotary vane pump from Pfeiffer Vacuum is suitable for applications that generate water vapor, such as low-temperature sterilization and drying. An optimized design and gas ballast system allow large volumes of vapor to be pumped before the vapor can condense in the mechanism, which prevents accumulation of fluid that could adversely affect the service life of the pump and the oil. The company claims the Pascal 2021 HW has the highest vapor capacity in its class. The materials used in its manufacture make the pump resistant to aggressive chemicals such as hydrogen peroxide. Temperature management by the user can prepare the pump to deliver vapor in just a few minutes. If the steam capacity is inadvertently exceeded, a safety device prevents water from flowing into functional sections. ***Pfeiffer Vacuum Inc****, 24 Trafalgar Sq, Nashua, NH 03063-1988, www.pfeiffer-vacuum.com*

UV–visible spectrophotometer

Agilent designed its Cary 3500 UV-Vis spectrophotometer system to help life sciences, pharmaceutical, and academic researchers accurately and efficiently characterize new biological entities before their adaptation into therapeutic products. The system can also monitor the quality of those products throughout their development. It is available in several configurations, including a multizone multicell that optimizes laboratory productivity by allowing up to four simultaneous temperature experiments across eight cuvette positions. Rapid and accurate temperature control permits experiments at faster ramp rates than ever before, according to Agilent. Using solid-state digital Cary temperature probes that control experimental temperature from inside the cuvette, researchers can ramp the sample's temperature to 30 °C/min. ***Agilent Technologies Inc****, 5301 Stevens Creek Blvd, Santa Clara, CA 95051, www.agilent.com*

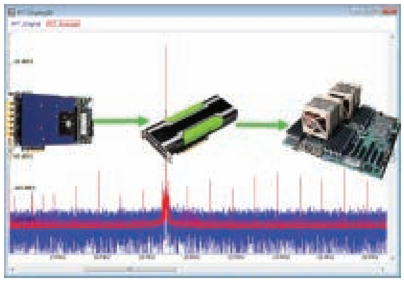
Arbitrary function generator

The AFG31000 arbitrary function generator (AFG) series from Tektronix features a nine-inch capacitive touch screen—the largest screen available on an AFG, according to the company. The series offers advanced capabilities for efficiently and economically characterizing a device under test (DUT). Those include the InstaView feature, which monitors and displays the waveform under study at the DUT with no need for additional cables or instruments. The advanced-waveform-sequencer mode allows the instrument to segment its waveform memory, which can be up to 128 Mpts, into up to 256 entries. Users can drag and drop both long and multiple waveforms into the sequencer and define how they are outputted. The ArbBuilder tool allows arbitrary waveforms to be created and edited directly on the instrument instead of on a PC. ***Tektronix Inc****, 14150 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com*

Pulsed high-intensity light systems

Xenon has introduced its XS-Series scalable pulsed light systems for room-temperature printed electronics (PE) sintering of conductive inks on flexible substrates. According to the company, the systems deliver high peak power with low heat and let users work with large coverage areas with high uniformity. The XS-Series models X-1100, S-2200, and S-2210 are built on a common platform with a common user interface. The economical X-1100 delivers up to 9 joules/cm^2 of radiant energy per pulse. Users can set up pulsed-light profiles and test processes critical to the success of new PE applications. With high peak radiant power of up to 4 kW/cm^2, the S-2200 provides state-of-the-art thermal management for researchers working with new nanomaterials on heat-sensitive substrates that require rapid sintering. The compact S-2210 is designed to treat wide areas (150 mm × 150 mm) with high-intensity pulsed light for applications that require high uniformity of up to 3%. It delivers a maximum pulse energy output of 18 kJ/cm^2 with a long pulse duration of 100–5000 μs. ***Xenon Corporation****, 37 Upton Dr, Wilmington, MA 01887, www.xenoncorp.com*

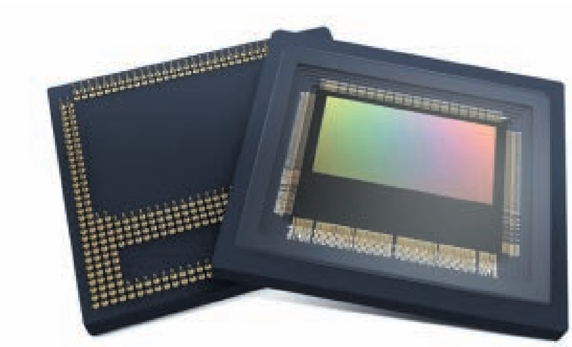
Signal enhancement package for digitizers



A new signal-averaging package from Spectrum combines a digitizer and a CUDA graphics card. CUDA is a parallel computing platform and programming model created by Nvidia for general computing on graphical processing units (GPUs). The package uses Spectrum's CUDA Access for Parallel Processing (SCAPP) and latest digitizer products to harness the power of CUDA-based GPU cards. Using remote direct memory access transfers, SCAPP users can port data directly to the GPU, where high-speed time- and frequency-domain signal averaging can be performed without the length limitations typically found in averaging products. The package is suitable for applications that involve low-level signals or have signal details that are lost due to high amounts of noise. Such applications include mass spectrometry, radar, LIDAR, sonar, radio astronomy, and biomedicine. ***Spectrum Instrumentation Corp****, 15 Warren St, Ste 25, Hackensack, NJ 07601, https://spectrum-instrumentation.com*

Compact FTIR spectrometer

Bruker has launched its Invenio S FTIR research spectrometer for advanced routine analysis and spectroscopic research. It replaces the previous Tensor spectrometer series. The Invenio S features Bruker's permanently aligned RockSolid interferometer, CenterGlow IR source, temperature-controlled deuterated triglycine sulfate detector, and fail-safe diode laser. The optional Transit Channel provides an additional, easily accessible sample space and allows instantaneous, software-controlled switching between measurement techniques. The compact design provides bench space for external accessories that can expand the instrument's capabilities to include IR microscopy and imaging, thermogravimetric analysis, high-throughput screening, and vibrational circular dichroism. ***Bruker Optics Inc****, 40 Manning Rd, Billerica, MA 01821, www.bruker.com*

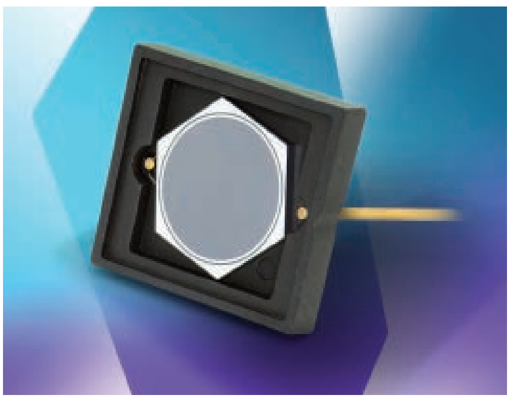


High-speed multispectral imaging sensor

Teledyne e2v has added an 11 MP detector to its Lince image sensor family. The Lince11M CMOS image sensor is designed for applications that require 4K resolution at very high shutter speed. The standard sensor combines 4K resolution at 710 fps in an advanced photo system type-C format. The Lince11M can be used for high-throughput in-line inspection and with strobed lighting for imaging that is multispectral or multifield, including bright field, dark field, and backlight. It can serve as an alternative to line-scan sensors to improve defect classification where uniform image sharpness across all directions is critical. The sensor offers a peak quantum efficiency of 60% and a large full well capacity to maximize the signal-to-noise ratio in shot-noise-limited applications. ***Teledyne e2v US Inc**, 700 Chestnut Ridge Rd, Chestnut Ridge, NY 10977, www.teledyne-e2v.com*

Terahertz spectrometer

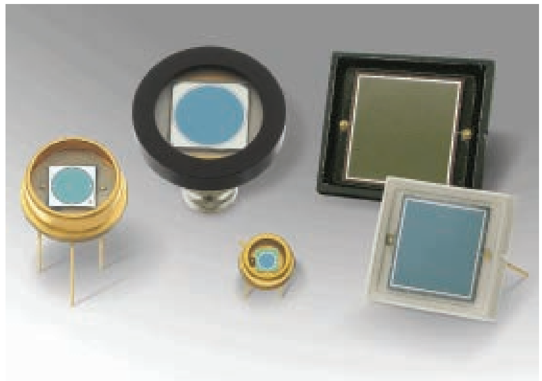
The Newport THz-TDS from MKS Instruments is a state-of-the-art system for terahertz time-domain spectroscopy and femtosecond spectroscopy with UV to near-IR pump and far-IR probe. It incorporates Newport's quality optics, optomechanics, balanced detector, vibration control, delay-line stages, and LabVIEW-based software. The THz-TDS supports various ultrafast amplifiers and optical parametric amplifiers as sources. It features a broad pump–probe delay range and high pump–probe delay resolution. A high-speed stage allows rapid acquisition of terahertz waveforms, and Newport's Suprema series optical mounts reduce thermal fluctuations. The instrument can be tailored to meet users' needs and can be upgraded and reconfigured to support other ultrafast spectroscopy techniques as research needs evolve. ***MKS Instruments Inc**, 2 Tech Dr, Ste 201, Andover, MA 01810, www.mksinst.com*



Circular photodiodes for radiation detection

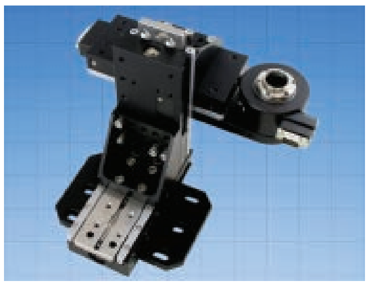
Opto Diode, an ITW company, has released its AXUV20A circular photodetectors for radiation, electron, and photon response in the extreme-UV, visible, and near-IR wavelength ranges. The devices have an active area of 5.5 mm diameter and are sensitive to electrons with energies as low as 100 eV. The minimum photodiode shunt resistance is 100 MΩ. Reverse breakdown voltage is typically 10 V, with a minimum of 5 V. Other features include capacitance typically at 4 nF, with a maximum of 10 nF, and a rise time of 2 µs. Operating and storage temperatures range from −10 °C to 40 °C in ambient environments and from −20 °C to 80 °C in nitrogen or vacuum. A cover plate protects the photodiode chip and wire bonds. ***Opto Diode Corporation**, 1260 Calle Suerte, Camarillo, CA 93012, https://optodiode.com*

Planar-diffused silicon photodiodes



OSI Optoelectronics offers UV-enhanced planar-diffused silicon photodiodes designed for low-light-level detection in the UV spectral range. According to the company, its UVD and UVE photodiodes provide advantages over inversion-layer and other photodiodes. For example, they deliver lower capacitance and faster response times. The UVD photodiodes peak at 970 nm; the UVE devices peak at 720 nm and suppress the near-IR, so they can be used for applications that require blocking that spectral region. Both products can be biased for lower capacitance, wider dynamic range, and high-speed response times. They can be operated in the photovoltaic (unbiased) mode for situations that require low drift with temperature variations. Applications include spectroscopy, fluorescence, medical instrumentation, pollution monitoring, and UV exposure meters. ***OSI Optoelectronics Inc****, 12525 Chadron Ave, Hawthorne, CA 90250, www.osioptoelectronics.com*

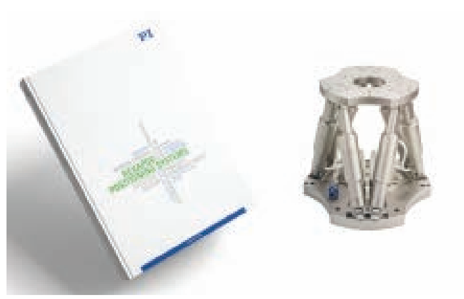
Motorized 3D/4D stage



Applied Scientific Instrumentation's precise, compact 3D/4D motion control system is designed to move samples around fixed optics. Three linear stages include XYZ translation elements and travel options of 25, 50, 100, or 200 mm. Each axis can be chosen separately. The linear stages' smooth, accurate motion is achieved through the use of closed-loop DC servomotors, crossed-roller bearings, high-precision lead screws, and high-resolution encoders for positioning feedback. The stages can move uniformly at very slow speeds for in-motion acquisition. An optional motorized rotating stage can be employed for a theta axis. The company offers various compatible stage controllers that provide automatic backlash correction and can communicate with a host computer by RS-232 or USB connection. ***Applied Scientific Instrumentation****, 29391 W Enid Rd, Eugene, OR 97402, www.asiimaging.com*

NEW LITERATURE

Hexapod positioning systems catalog



Physik Instrumente has published a catalog on its parallel-kinematic motion and positioning systems for precision automation and alignment applications in fields such as optics, photonics, aerospace, medical engineering, and laser technology. Its 130 pages provide background information and feature various hexapod motion and positioning systems, known as Stewart platforms, with six degrees of freedom, high resolution, and repeatability in the submicrometer and nanometer range. The hexapods offer travel ranges from a half-inch to several hundred millimeters and load ranges from 0.5 kg to several tons. The multiaxis systems can be optimized for high load, speed, and precision. The load, speed, and precision class determine the type of drive used, whether electrodynamic, electromechanical, or piezoelectric. ***Physik Instrumente LP****, 16 Albert St, Auburn, MA 01501, www.pi-usa.us* PT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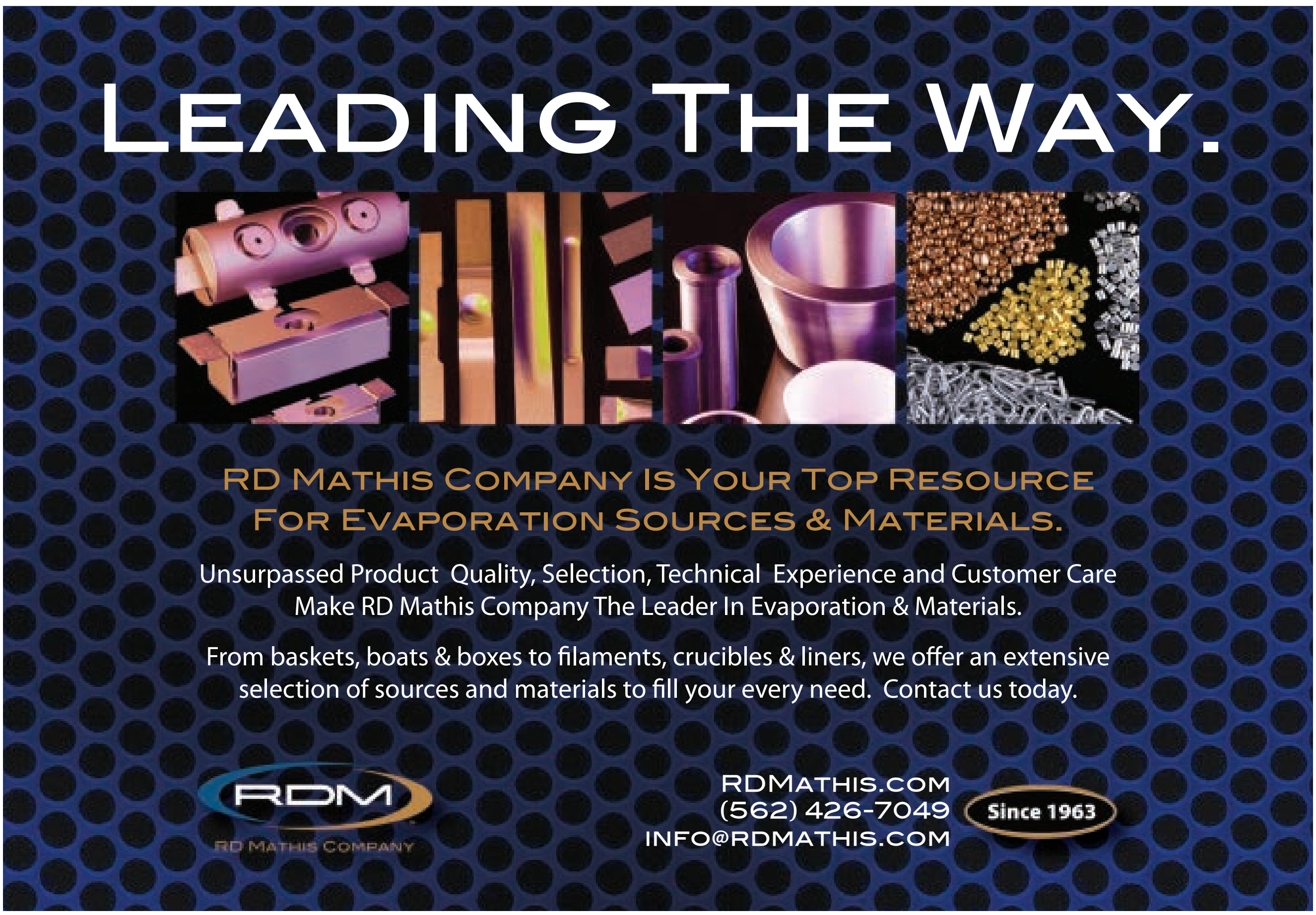
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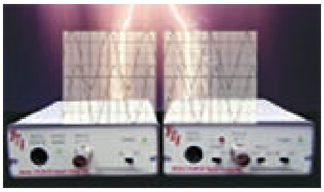

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OBITUARIES

Riccardo Giacconi

Riccardo Giacconi, one of the most influential figures in scientific research over the past 60 years, died on 9 December 2018 in La Jolla, California.

Riccardo received a share of the 2002 Nobel Prize in Physics for pioneering contributions to astrophysics. He conceived and executed a series of missions that established x-ray astronomy as an essential discipline of astronomy. He then revolutionized optical astronomy and was pivotal in establishing the world's foremost millimeter-wave observatory. Many in the astronomy community base their research on data from observatories he conceived, built, or critically influenced.

At heart a physicist, Riccardo was driven to explore the universe. His outstanding scientific capabilities were complemented by extraordinary leadership and management skills. He had a deep belief in a scientific approach to problem solving and to establishing systematic processes. He insisted that instruments and observatories be built to answer driving scientific questions. A key factor underlying his success was the legendary dedication and drive of the research teams he assembled, which could be traced directly to Riccardo's deep commitment to creating an environment of intellectual honesty and trust.

Born in Genoa, Italy, on 6 October 1931, Riccardo received his doctorate in 1954 from the University of Milan, where he studied cosmic rays. He went to the US in 1956 as a Fulbright Fellow at Indiana University, then moved to Princeton University. In 1959 he joined American Science and Engineering Inc in Massachusetts, where he carried out the pioneering rocket flights that discovered the first cosmic x-ray sources.

Riccardo had gradually become convinced that studying the short-wavelength domain, characteristic of high-energy processes in nature, was essential to a deep physical understanding of the universe. With strong conviction and remarkable persistence, Riccardo developed a blueprint for the new field of x-ray astronomy and persuaded NASA to support a program of research and technology development. As early as the mid 1960s, he envisioned a subarcsecond imaging x-ray capability on the scale of NASA's current *Chandra X-Ray Observatory*.

In 1970, NASA, with Riccardo as principal investigator, launched *Uhuru*, the first satellite dedicated to x-ray astronomy. It demonstrated that luminous x-ray sources in our galaxy were powered by accretion onto compact stars in binary systems. At least one of those stars, Cygnus X-1, provided the first compelling evidence for the existence of black holes.

The merging of x-ray astronomy into the mainstream of astronomy was accelerated in the late 1970s with Riccardo's next great achievement, the *Einstein Observatory*. By then he had moved to the Harvard–Smithsonian Center for Astrophysics (CfA), where he led the new high-energy astrophysics division. *Einstein*'s imaging capabilities revealed that essentially all types of astronomical objects radiate in the x-ray band. Riccardo also initiated a guest-observer program enabling all astronomers to use *Einstein*.

Riccardo was asked to direct the new Space Telescope Science Institute (STScI) in 1981. He recruited first-rank scientists and operations staff to oversee the science ground system for the *Hubble Space Telescope* (*HST*) and to formulate an approach to conducting its science program that could serve the entire astronomy community.

In 1993 Riccardo was recruited as director general of the European Southern Observatory (ESO), where he oversaw the building of the Very Large Telescope and set ESO on a path to working with global partners on the Atacama Large Millimeter/Submillimeter Array (ALMA). In 1999 he returned to the US to serve as president of Associated Universities Inc, the managing organization of the National Radio Astronomy Observatory. Before he retired in 2004, construction was initiated on the Expanded Very Large Array and ALMA.

Riccardo inspired several generations of students and colleagues. He also encouraged diversity before it became the norm. In the 1970s several women were already in his relatively small x-ray group. In the early 1980s, Riccardo recruited to the STScI several early career women who rose through the ranks and now occupy some of the most senior positions in astronomy. He strongly supported the first Women in Astronomy workshop and conceived of the Baltimore Charter for Women in Astronomy.

Riccardo was keenly aware of the need to share science results with the general public. Even before the *HST* was launched,

NASA/MSFC

Riccardo Giacconi

he established an outreach group at the STScI and close ties to science journalists. *HST* public outreach became a model for astronomy.

Science writer Simon Mitton characterized Riccardo's approach as "a new way of doing business" in astronomy. One key to Riccardo's success and a testament to his drive and vision was that he set future directions before he moved on: *Chandra* was already being planned when he left CfA; studies were under way for what became the *James Webb Space Telescope* when he left the STScI; and the European Extremely Large Telescope was being planned when he left ESO.

Riccardo's conviction about the importance of x-ray astronomy was formally confirmed by his Nobel Prize. All of astronomy continues to reap the benefits of Riccardo's systematic approach to answering fundamental science questions and of his unique scientific vision and management abilities.

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QUICK STUDY

Laura Merner and **Anne Marie Porter** are survey scientists at the Statistical Research Center of the American Institute of Physics (publisher of PHYSICS TODAY) in College Park, Maryland.

The power and pitfalls of focus groups

Laura Merner and Anne Marie Porter

A moderated discussion can help clarify the concerns and opinions of the physics community. But if it's not arranged and analyzed with care, even well-meaning efforts can lead to problems.

Focus groups, which are a research methodology in the social sciences, can be useful tools for exploring the perspectives and experiences of physics-community members. In academic settings, they can be used to answer questions such as "How can teachers better engage students in physics classrooms and labs?" (see the article by Natasha Holmes and Carl Wieman, PHYSICS TODAY, January 2018, page 38), "What would improve student and teacher experiences in a physics department?" and "What are the unique experiences of minority students in physics departments?" The results of a focus-group study can help improve classrooms, labs, departments, and university policies.

In this article, we describe how best to conduct focus groups for science departments. During a session, a discussion is held with multiple participants—ideally four to eight—to address a specific issue. Focus groups typically last for 60–120 minutes and are facilitated by a researcher who asks a series of predetermined questions; depending on a group's goals, those questions can be structured or open-ended. The discussion format can be particularly valuable when group members build on each other's responses and debate any differences of opinion.

The first step is to ensure that a focus group is the most appropriate method to answer the questions. In general, focus groups are most effective when the researcher wants to collect descriptive, detailed data on the experiences of numerous people. And they are best used for answering questions about the following:

- Opinions: What do participants think about a certain topic? For example, what teaching approaches do students like or dislike in physics courses?
- Perspectives: What are participants' personal experiences with a certain topic? For example, how do students interact with teachers and staff in a physics department?
- Needs: How can the organizers of the discussion better serve a given population? For example, what do students need to succeed in physics courses?
- Evaluations: Is a program or product having the desired impact? For example, how effective is the physics program at the university?

Focus groups are not as useful for assessing research questions about actions and behaviors or controversial and sensitive topics. During discussions, people may say what they do, but the researcher has no way of knowing what they actually do. Experiments and observations are better methods of learning about actual behaviors. In addition, people may not feel comfortable discussing controversial issues among strangers and may refrain from expressing their views candidly. Extra attention would need to be paid to group composition and confidentiality. To make people feel more comfortable, it may be more appropriate to form the group around certain demographic characteristics, such as age or gender.

Focus groups are not useful for learning about the opinions of an entire population. Focus groups involve a small number of people, whose opinions might not reflect the opinions of a larger group. Surveys would be a more appropriate method for large groups.

How do you form a focus group?

It is not enough to ask the right questions. As the chair of a physics department or task force, say, you need to ask the right people to participate. Discussions should include all relevant perspectives, even if that means assembling more than one group. If all those perspectives are not represented, then the data will be incomplete. For example, when considering how to best revamp the physics curriculum at a school, you may include only faculty in the focus group sample. By not asking students their opinions, you would not have all the requisite data to effectively answer your research question. That problem often arises because the most convenient group to sample may not be the most appropriate group.

Controversial topics especially may mandate more than one focus group. But even for less contentious topics, conducting the same interview with multiple groups can provide a more robust data set for analysis. Having multiple groups will also allow for comparisons between them.

In focus groups, researchers gather narrative data, qualitative data on opinions and perspectives, and observational data. Narrative data encompass everything said during the sessions, which are typically recorded and transcribed. The transcript can be coded and analyzed for important themes related to the research questions. Every word can be a data point. Coding of qualitative data sets is a well-established research technique used across the social sciences to organize and sort vast amounts of data. Through that process, a story may start to form that offers critical insights into your research question.

Observational data are typically the notes taken during the

IT'S POOR FORM FOR A FOCUS GROUP FACILITATOR to influence participants. In this fanciful sketch of a focus group discussing instant replays in professional tennis matches, the facilitator, John McEnroe, doesn't hold back his opinion. (Image by Abigail Malate.)

focus group by a researcher who assists the facilitator. They include nonverbal data, such as tone of voice, facial expressions, body language, and the degree of the participants' engagement. The response of an individual to someone else's statement can provide valuable information that can be missed in the narrative data.

Who should facilitate a focus group?

It is vital to the integrity of the research that the facilitator should not have a stake in its outcome. Anyone with such a stake would have a personal bias that can influence participant responses and threaten the data's validity. Participants may be less willing to be honest with a project stakeholder, or a stakeholder may cause participants, sometimes unintentionally, to respond in a particular way. Working with someone outside your research team, organization, or department will provide the most objective, high-quality results.

It is not easy to conduct a focus group, and a successful session requires a trained and qualified moderator. A facilitator has many roles. Among other tasks, he or she sets the tone for the group, leads the discussion, ensures that it stays on topic, asks questions, and maintains an environment in which everyone can participate equally. If a facilitator performs any of those tasks poorly, the data will be affected.

An effective facilitator is also aware of how his or her own actions can shape the behavior of a focus group. Just as the facilitator reads the body language and tone of participants, participants respond to the cues and tone of the facilitator. If a facilitator looks skeptical of a participant's response to a question, that could affect how that participant shares for the rest of the session. Conversely, if a facilitator looks pleased with a response, that could influence other participants to respond in that same way.

The relationship between a facilitator and participants needs to be understood before organizing a focus group. As the head of a department, you may be a trained facilitator, but asking your students to discuss their experiences with you is not likely to work. Anyone familiar with the participants could bias the results, since participants may try to please that person; also, group members may be less honest with someone in a position of authority over them.

The focus group process, step by step

To start the process, you must first determine whether a focus group is a good fit for your overarching research question. Once you have decided to use one (or more), invite a social scientist to help plan it and design the discussion questions. You will need to think about what financial resources are available for hiring a facilitator and offering cash, gift cards, or other incentives to the participants.

Next, consider who needs to be included in the conversation and whether you have access to the appropriate people. How many individuals should be in each session? How many sessions should be conducted? How long will each session take?

Third, prepare your questions. Be sure they are appropriate for your audience and are free of bias. They should be compatible with an open-ended, freewheeling discussion. It is also important that they yield the kind of data that can be analyzed—social science expertise is especially valuable in that regard.

Fourth, conduct the focus groups, analyze the data, and share your results with others. Then, finally, you can start to take meaningful actions based on the findings.

Focus groups are a valuable tool that can be used to better understand perspectives, experiences, and opinions. However, the data they generate are easily biased and misused. When poorly designed or run by ill-trained facilitators, focus groups produce meaningless results. If you are interested in using focus groups, work closely with trained social scientists throughout the project to avoid that outcome.

Have questions about focus group research? Feel free to reach out to the Statistical Research Center at the American Institute of Physics to better understand the topic. Contact Laura Merner at lmerner@aip.org.

Additional resources

▶ Center for Innovation in Research and Teaching website, "Effective Focus Group Questions."

▶ Research and Marketing Strategies Inc, "How to Write a Focus Group Moderator's Guide," *Research Bunker* (20 September 2012). PT

A Martian ice mound

This past December marked the 15th anniversary of the arrival of the European Space Agency's *Mars Express* at the red planet. Although the orbiter's original mission was to last only 687 days, or one Martian year, it has been extended multiple times—currently through the end of 2020. *Mars Express* is the longest ESA mission still in operation.

This overhead, natural-color composite view of the Korolev crater was assembled from observations by the spacecraft's High Resolution Stereo Camera taken during five different orbits. At a latitude of 73° N, the crater is located in the northern lowlands just south of a broad dune field that partially encircles the north polar ice cap. It has a diameter of 82 km and is filled with a mound of water ice some 1.8 km thick, comparable in volume to Canada's Great Bear Lake. Despite lying outside the ice cap, the deposit is stable year-round because the crater acts as a natural cold trap: It retains a layer of cold air that insulates the ice below it. (Image 412943 © ESA/DLR/FU Berlin, CC BY-SA 3.0 IGO, cropped from original.) —RJF

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