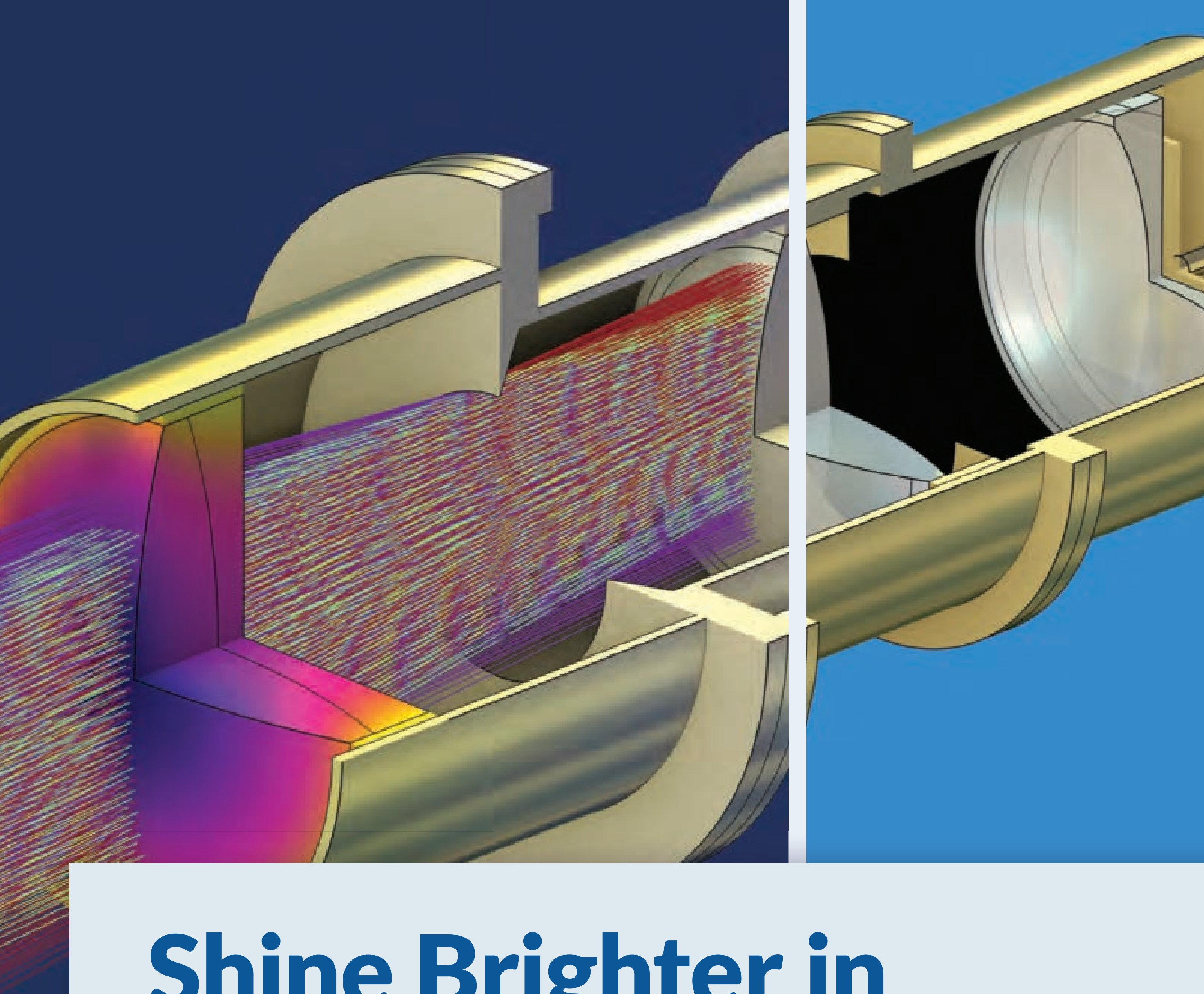


Shine Brighter in Optical Design

with COMSOL Multiphysics®

Multiphysics simulation drives the innovation of new light-based technologies and products. The power to build complete real-world models for accurate optical system simulations helps design engineers understand, predict, and optimize system performance.

» *comsol.com/feature/optics-innovation*

COMSOL

PHYSICS TODAY

September 2022 • volume 75, number 9

A publication of the American Institute of Physics

Siberia's ZEN STONES

Electric-powered spaceflight

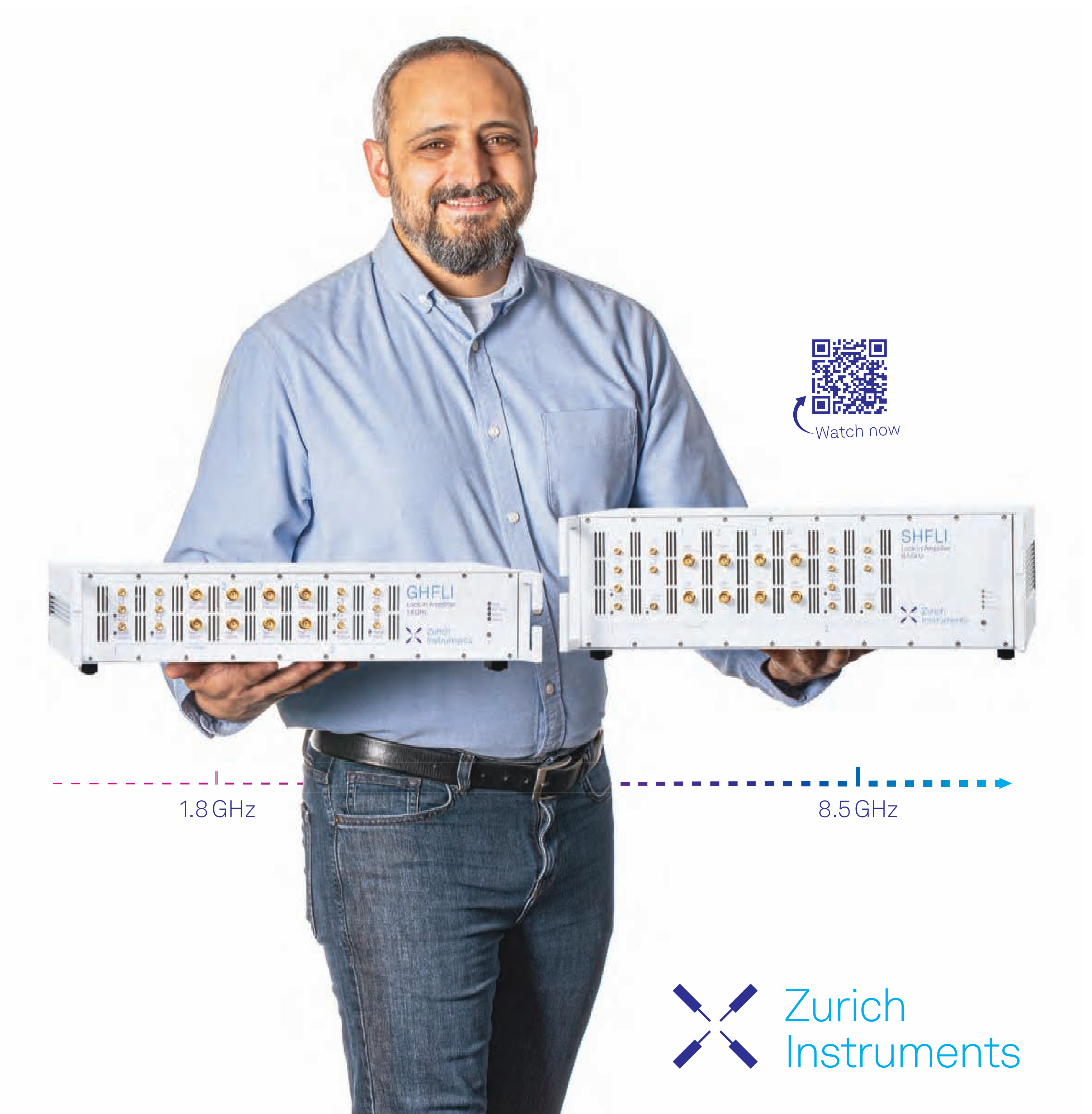
Ecological chaos

Carbon-ion cancer therapy

New

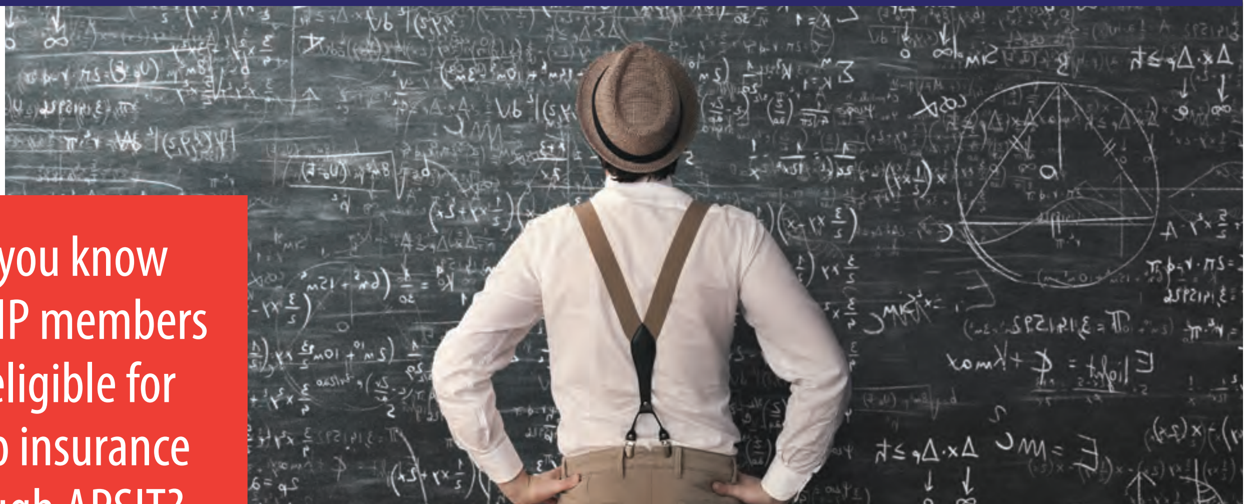
Trailblazers.

Meet the Lock-in Amplifiers that measure microwaves.



On the lookout for insurance?

Make sure these exclusive insurance rates don't pass you by.



Did you know that AIP members are eligible for group insurance through APSIT?

For over 50 years, APSIT has been trusted to insure science professionals with quality coverages designed to fit your needs. Find out more today!

Get a load of this.

Over 500,000 science professionals trust APSIT with their life, disability, accidental death and dismemberment, and long-term care insurance coverage needs.

APSITPLANS.COM/EXCLUSIVE

APSIT
INSURANCE FOR SCIENCE PROFESSIONALS

AIP
American Institute of Physics

APSIT's Group Term and 10-Year Level Term Life Insurance, Group Disability Income Insurance, and Group Accidental Death and Dismemberment Insurance policies are underwritten by New York Life Insurance Company, 51 Madison Avenue, NY, NY 10010. For more information, including features, costs, eligibility, renewability, limitations, and exclusions, visit the website link.

Program Administrators: Arkansas Insurance License #1322, California Insurance License #0F76076

221031-APSIT-PAD

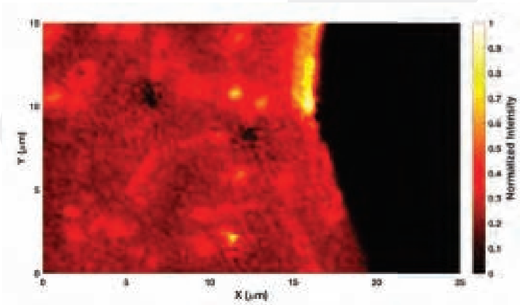
Excellence in Low Temperature Imaging

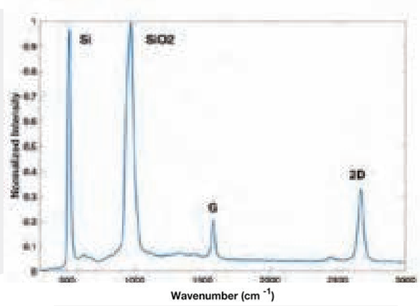
LT - NV Centre/Confocal Raman Microscope

High NA LT-APO Objective
0.82NA / 0.95mm WD
Scan Area
15x15µmx2µm @ 4K
Temperature Range
10 mK - 300K

- ☑ 48mm Outer Diameter
- ☑ XYZ Nanopositoner / Scanner for sample
- ☑ Z Nanopositoner for Cold objective
- ☑ XYZ Nanopositoner for NV/QTF Sensor

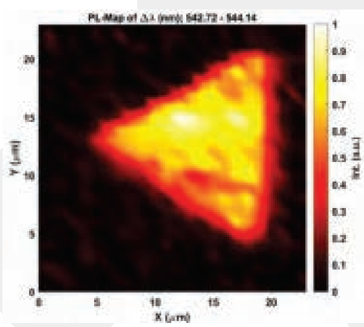
Single Layer Graphene Raman map*

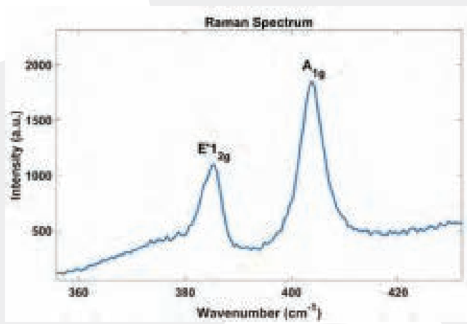


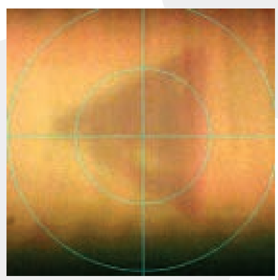


Single layer MoS2 Raman map*

Can be customised to fit in any cryostat





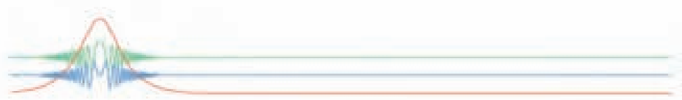


* Data courtesy of Furkan Ağlarcı, Çağlar Samaner, Serkan Ateş @ İzmir Institute of Technology, Turkey & Feridun Ay, Nihan Kosku Perkgöz @ Eskişehir Technical University, Turkey

NanoMagnetics Instruments
/NMInstruments

+44 7906 159 508
sales@nanomagnetics-inst.com
Suite 290, 266 Banbury Road Oxford OX2 7DL, United Kingdom

The next generation ***Lock-In Amplifiers***
Only from SRS !



DC to 4 MHz (SR865A)
DC to 500 kHz (SR860)
2.5 nV/√Hz input noise
Fast time constants

The SR86x series brings new performance to lock-in measurements — a frequency range of 4 MHz (SR865A) or 500 kHz (SR860), state-of-the-art current and voltage input preamplifiers, a differential sinewave output with DC offset, and fast time constants (1 μs) with advanced filtering.

And there's a colorful touchscreen display and a long list of new features ...

- ☑ Deep memory data recordings
- ☑ FFT analysis
- ☑ Built-in frequency, amplitude & offset sweeps
- ☑ 10 MHz timebase I/O
- ☑ Embedded web server & iOS app
- ☑ USB flash data storage port
- ☑ HDMI video output
- ☑ GPIB, RS-232, Ethernet and USB communication

It's everything you could want in a lock-in — and then some!

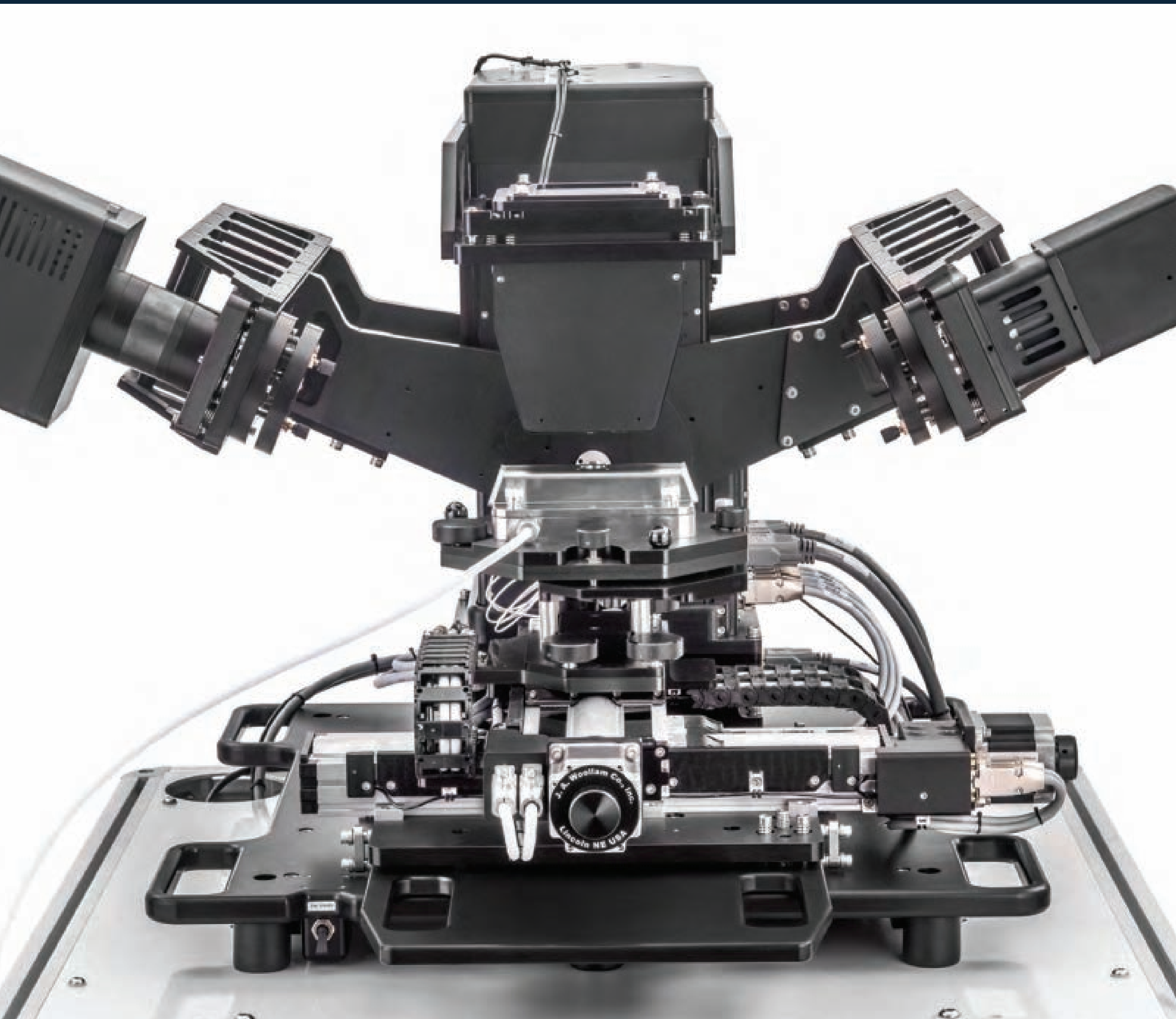
SR865A 4 MHz lock-in ... $7950 (U.S. list)
SR860 500 kHz lock-in ... $6495 (U.S. list)

SRS *Stanford Research Systems*

www.thinksrs.com/products/lockin.htm
Tel: (408)744-9040

Customized Instruments for Revolutionary Research

Explore your options when it comes to our industry-leading spectroscopic ellipsometers.



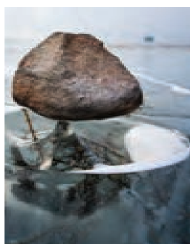
With over 100,000 possible configurations, our ellipsometers can be tailored to meet your research goals. Our worldwide network of representatives offer unparalleled service and support to help you get the most out of your ellipsometer. Contact us to learn more about our products and how they can be configured to meet your research needs.

J.A. Woollam

PHYSICS TODAY

September 2022 | volume 75 number 9

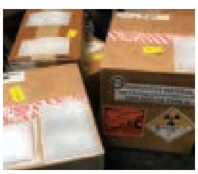
FEATURES



ON THE COVER: Sightings of rocks perched atop thin ice pedestals on a frozen lake are relatively rare. Known as Zen stones, they require the temperature to remain below freezing and the ice surface free of snow for several weeks. The winter climate at Russia's Lake Baikal, where this photo was taken, meets both conditions. The sublimation of surface ice occurs at a rate determined by the temperature, humidity, and amount of sunlight it receives. To learn more, see the Quick Study by Nicolas Taberlet on **page 62**. (Image by iStock.com/MikhailZykov.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org

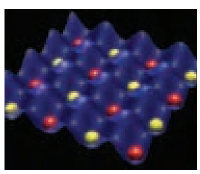


GAO

Government sting

Using forged licenses, the Government Accountability Office obtained from domestic suppliers small quantities of highly radioactive isotopes, which could be used to fashion a dirty bomb. The investigation shows how terrorists might hack the Nuclear Regulatory Commission's licensing process.

physicstoday.org/Sep2022a



NIST

Quantum computing

In the past five years, neutral atoms have emerged as dark-horse candidates in the race to build a quantum computer. Ben Brubaker details recent milestones for optical tweezer arrays loaded with alkali or, increasingly, alkaline-earth atoms.

physicstoday.org/Sep2022b

IUPAP

IUPAP centennial

As it celebrates 100 years, the International Union of Pure and Applied Physics is reflecting on how to remain relevant and serve the needs of physicists around the world in a changing geopolitical and social environment. Physics Today's Toni Feder reports on IUPAP's recent initiatives and future plans.

physicstoday.org/Sep2022c

Physics Today (ISSN 0031-9228, coden PHTOAD) volume 75, number 9. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, 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 110, 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.

Copyright © 2022, American Institute of Physics. Single copies of individual articles may be made for private use or research. Authorization is given to copy articles beyond the free use permitted under US Copyright Law, provided that the copying fee of $30.00 per copy per article is paid to the Copyright Center, 222 Rosewood Dr, Danvers, MA 01923. For articles published before 1978, the copying fee is $0.25 per article. Authorization does not extend to systematic or multiple reproduction or to republication in any form. In all such cases, specific written permission from AIP must be obtained. Send requests for permission to AIP Office of Rights and Permissions, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300; phone +1 516 576-2268; email rights@aip.org.

PHYSICS TODAY
www.physicstoday.org

DEPARTMENTS

The American Institute of Physics is a federation of scientific societies in the physical sciences, representing scientists, engineers, educators, and students. AIP offers authoritative information, services, and expertise in physics education and student programs, science communication, government relations, career services, statistical research in physics employment and education, industrial outreach, and history of the physical sciences. AIP publishes Physics Today and is also home to the Society of Physics Students and to the Niels Bohr Library and Archives. AIP owns AIP Publishing, a scholarly publisher in the physical and related sciences.

Board of Directors: David J. Helfand (Chair), Michael H. Moloney (CEO), Judy R. Dubno (Corporate Secretary), Susan K. Avery (Treasurer), Jonathan Bagger, Susan Burkett, Bruce H. Curran, Eric M. Furst, Jack G. Hehn, Mary James, Stella Kafka, Allison Macfarlane, Tyrone M. Porter, Efrain E. Rodriguez, Elizabeth Rogan, Nathan Sanders, Charles E. Woodward.

Officers: Michael H. Moloney (CEO), Gigi Swartz (CFAO).

SUBSCRIPTION QUESTIONS? +1 800 344-6902 | +1 516 576-2270 | **ptsubs@aip.org**

Editor-in-chief
Richard J. Fitzgerald *rjf@aip.org*

Art and production
Donna Padian, art director
Freddie A. Pagani, graphic designer
Cynthia B. Cummings, photographer
Nathan Cromer

Editors
Ryan Dahn *rdahn@aip.org*
Toni Feder *tf@aip.org*
Heather M. Hill *hhill@aip.org*
Abby Hunt *ahunt@aip.org*
David Kramer *dk@aip.org*
Alex Lopatka *alopatka@aip.org*
Christine Middleton *cmiddleton@aip.org*
Johanna L. Miller *jlm@aip.org*
Gayle G. Parraway *ggp@aip.org*
R. Mark Wilson *rmw@aip.org*

Online
Paul K. Guinnessy, director *pkg@aip.org*
Andrew Grant, editor *agrant@aip.org*
Angela Dombroski *atd@aip.org*
Greg Stasiewicz *gls@aip.org*

Assistant editor
Cynthia B. Cummings

Editorial assistant
Tonya Gary

Contributing editors
Rachel Berkowitz
Gizem Doğan
Andreas Mandelis

Sales and marketing
Christina Unger Ramos, director *cunger@aip.org*
Unique Carter
Krystal Amaya
Skye Haynes

Address
American Center for Physics
One Physics Ellipse
College Park, MD 20740-3842
+1 301 209-3100
pteditors@aip.org

PhysicsToday **@physicstoday**

AIP | American Institute of Physics

Member societies
ACA: The Structural Science Society
Acoustical Society of America
American Association of Physicists in Medicine
American Association of Physics Teachers
American Astronomical Society
American Meteorological Society
American Physical Society
AVS: Science & Technology of Materials, Interfaces, and Processing
Optica (formerly The Optical Society)
The Society of Rheology

Other member organizations
Sigma Pi Sigma Physics and Astronomy Honor Society
Society of Physics Students

GradSchoolShopper

presented by

AIP | American Institute of Physics

COLLEGE STUDENTS, ARE YOU GRADUATING SOON?

Find your future at **GradSchoolShopper.com** the most comprehensive directory of grad programs in the physical sciences.

Browse by sub-field

Sort programs by acceptance rate & application deadline

Get direct access to program faculty & research areas, and more!

Visit GradSchoolShopper.com to get started!

Physics Today has nearly

DOUBLE THE CONTENT

online.

Recent exclusive online content includes:

Rheologically speaking, avalanches are like earthquakes by Alex Lopatka

With the help of a professional snowboarder, researchers captured crack-propagation data from an avalanche in the Swiss Alps.

Find research news, commentaries, Q&As, and more at

PHYSICSTODAY.ORG

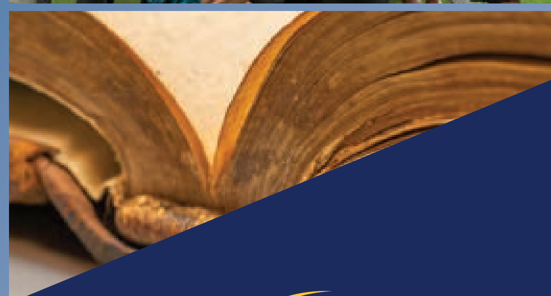
SUPPORT SCIENCE

At AIP Foundation, we're passionate about the impact of the physical sciences community, and with your support, we can strengthen our efforts to preserve the history of physics, foster future generations of physicists, and create a more diverse and equitable scientific enterprise.

AIP Foundation is an independent not-for-profit corporation launched in 2020 to generate philanthropic support for the American Institute of Physics, focused on history and student programs, our library, and actions to advance diversity.

Show your support of the physical sciences community through the following AIP programs:

- Center for History of Physics
- Niels Bohr Library & Archives
- Society of Physics Students
- Sigma Pi Sigma
- Diversity Action Fund



AIP FOUNDATION

To learn more about how you can support AIP programs visit **foundation.aip.org**

Commentary

Elitism in physics: What happens when the profession's cultural scaffolding comes down?

Distinguished by its difficulty, versatility, subtlety, and even profundity, modern physics stands among humanity's great technical and intellectual achievements. This success has been enabled by continuous cultural entrepreneurship, giving rise to methods, mentalities, and institutions that have together fostered both astonishing individual accomplishments and an expansive and powerful cooperative enterprise.

Thanks to the work of historians and social scientists, we have a serviceable understanding of the cultural work underlying the physical sciences. In particular, it is possible to trace a constant tension between the work of building up what physicists are capable of and building out the number of people who can wield those capabilities. For centuries, that story has been dominated by elites inventing new ways to replicate and propagate themselves.

ADMISSION OF THE SENIOR WRANGLER IN 1842, by Richard Bankes Harraden (1842, public domain). The senior wrangler was the highest-ranking student on Cambridge University's mathematical tripos exam.

Andrew Warwick's 2003 history of Cambridge University's mathematical tripos in the 19th century, *Masters of Theory: Cambridge and the Rise of Mathematical Physics*, is an extraordinary investigation of one of the first places where a physics elite was systematically trained. He details how private coaches, not lecturers, oversaw small groups who worked together to apply emerging analytical tools to a wide array of physical problems. Innovating new practices of pen-and-paper calculation and enthusiastically participating in the emerging world of university sport, they created a culture of intellectual manliness that could prepare students in mind and body to survive, and progressively intensify, the rigors of their work.

Although the coaching system stressed group learning, it also entrenched the idea that only the most capable were fit to be physicists. Its culture borrowed heavily from that of the Victorian British elite, and intended as a course of general education, the tripos fueled the British elite in return. Only the top "wranglers"—as identified on the publicly posted, rank-ordered results of the grueling, multiday tripos exam—actually went into the still very small enterprise of science.

Until well into the 20th century, the US boasted few elite theorists; instead, its physicists focused mainly on more pedestrian experimental work. World War II and the Cold War changed that culture as demands for scientific "manpower" spurred physics departments to develop pedagogical methods capable of vastly expanding the ranks of those who could apply cutting-edge mathematical and technological approaches. As the historian David Kaiser has shown, employers in industry appealed for talent by downplaying the elite nature of physics while advertising its professional comforts—"suburbanizing" it, as Kaiser puts it. That, of course, took for granted that, even as the discipline expanded, its demographics would still reflect not only its prior generations of elites but also the similarly white, male world of mid-20th-century American professionalism.[1]

Meanwhile, as the numbers of academic physicists also ballooned, a reconfigured culture of elitism took root in universities and was broadcast to the public with the flourishing of popular science. Caltech's Richard Feynman was one of the great cultural entrepreneurs of that era, constantly presenting himself as a curiosity-driven free spirit unlocking the secrets of the universe and his social surroundings alike. After building up that image for decades, he ultimately broadcast it to the world through his best-selling 1985 collection of anecdotes, *"Surely You're Joking, Mr. Feynman!": Adventures of a Curious Character.*

Ostensibly a populist, Feynman strongly implied that you, too, could learn about physics and the world by adopting an attitude similar to his. But the technical content of physics was relatively easy for him to master, and he habitually glossed over its difficulties, relating that his own frustration in physics derived principally from struggles to maintain creativity, not the grinding discipline needed for skills development.

That emphasis reflected a propensity among physicists to passively identify and promote students with the "right stuff," including in their efforts to more actively cultivate talent. At Caltech, Feynman's famously charismatic introductory undergraduate lectures focused on ideas rather than problem-solving, and they proved by his own admission to be of dubious pedagogical value, leaving even many of the school's brilliant students struggling.[2] (For a defense of the course, see the article by Matthew Sands, PHYSICS TODAY, April 2005, page 49.) More darkly, he was well known for the withering dismissiveness he directed at guest colloquium speakers he deemed unworthy, and he readily exploited his own star status to abnegate responsibility for departmental governance and to lighten his teaching load overall.[3]

Feynman was, of course, only one figure, but elitist values pervaded the profession. The anthropologist Sharon Traweek's classic 1988 study *Beamtimes and Lifetimes: The World of High Energy Physicists* shows that the norms of cutthroat competition, including the willingness to belittle others' work to advance one's own, were well accepted throughout the ranks of early-career researchers. Rewarding intensely competitive behavior was understood to be a sound way for labs and universities to allocate leadership positions to individuals talented and creative enough to handle them, though it also elevated certain personality types and people from backgrounds that better prepared them for the profession's demands.

When Traweek did her research, it was near the beginning of what is now a half century of effort to diversify the physics profession, waged in parallel with legal and political efforts to combat discrimination in professional settings generally.[4] Although progress has been made in the intervening years, physics still lags many professions in recruiting and retaining people from underrepresented groups, and its often-forbidding culture has contributed to the problem.[5]

But the presumption that it is actually necessary for the culture to be forbidding is eroding. Fewer giants traverse the landscape than in past eras, and elitism may be on the wane. That means not that talent has diminished but rather that it has become necessary to think harder about what talent is, how it is cultivated, how it operates communally, and how to build a culture in which it can thrive.

The culture of physics is already being reconfigured in departments and labs around the world. What those cultural changes look like on the ground should be constantly discussed in public forums, in specific detail, so that successful models can be replicated and adapted and problems diagnosed. As the scaffolding of elitism comes down, physicists have an obligation to invest in the cultural structure beneath it, to make it as durable as possible, creating still more powerful varieties of physics while opening the profession's doors to more people than ever before.

References

1. D. Kaiser, *Hist. Stud. Phys. Biol. Sci.* **33**, 131 (2002); *Am. Q.* **56**, 851 (2004).
2. R. P. Feynman, R. Leighton, M. Sands, *The Feynman Lectures on Physics*, vol. 1, Basic Books (2013), Feynman's Preface.
3. J. Gleick, *Genius: The Life and Science of Richard Feynman*, Pantheon Books (1992).
4. On the backdrop for legal and political efforts to advance women in science, see M. W. Rossiter, *Women Scientists in America: Forging a New World Since 1972*, Johns Hopkins U. Press (2012).
5. On the particular lack of progress for African Americans in physics and cultural factors involved, see AIP National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy, *The Time Is Now: Systemic Changes to Increase African Americans with Bachelor's Degrees in Physics and Astronomy*, American Institute of Physics (2020).

William Thomas
(wthomas@aip.org)
American Institute of Physics
College Park, Maryland

CONTACT PHYSICS TODAY

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

LETTERS

Wave generation beyond Earth

In their otherwise excellent article, "How does the wind generate waves?" (Physics Today, November 2021, page 38), Nick Pizzo, Luc Deike, and Alex Ayet missed an opportunity to note the interest and progress in that question as a physics problem beyond the narrow parameters of water and 1-bar air. Specifically, the possible presence of shoreline features on Mars—where transient paleoclimates may have allowed lakes and seas under a thin, carbon dioxide–rich atmosphere[1]—and the present-day existence of liquid-methane seas on Saturn's moon Titan under an atmosphere four times as dense as our own[2,3] have prompted planetary scientists to confront the topics laid out in the article and to sift through what aspects of the terrestrial paradigm are empirically specific to Earth. Extending wave mechanics to other environments and parameter regimes with different gravity and fluid properties fosters more fundamental understandings. Oceanography is no longer just an Earth science.

References

1. D. Banfield, M. Donelan, L. Cavaleri, *Icarus* **250**, 368 (2015).
2. A. G. Hayes et al., *Icarus* **225**, 403 (2013).
3. R. D. Lorenz, A. G. Hayes, *Icarus* **219**, 468 (2012).

Ralph D. Lorenz
(ralph.lorenz@jhuapl.edu)
Johns Hopkins Applied Physics Laboratory
Laurel, Maryland

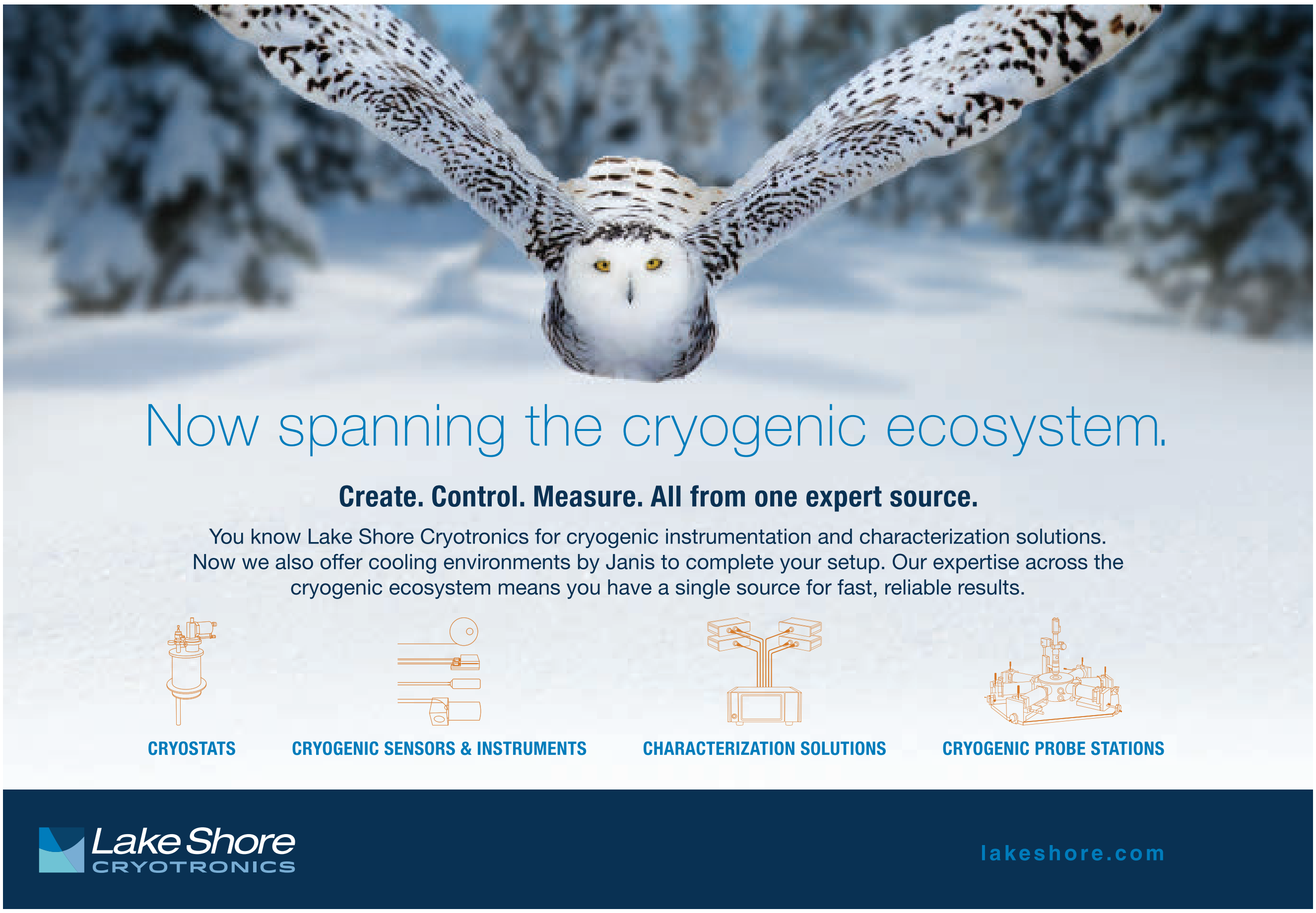
Remembering Steven Weinberg

In 2017 I had the honor of meeting Steven Weinberg—whose obituary appears in the October 2021 issue of Physics Today (page 72)—at the University of Texas at Austin. In the past I had used some of his writings from *Scientific American* and his books for my students at Wagner College, where I taught the honors lecture in astronomy. I had often corresponded with Steven from 1994 to 2018 about his concepts in astrophysics, and he answered many of the questions that my students submitted to me.

In my correspondence with Steven, I had mentioned that I was an active member of my community board on Staten Island, New York, where I reside. Because Steven knew that I worked with local politicians, he asked for my political support to help him get funding for the Superconducting Super Collider project. Although Congress terminated the project in 1993, Steven wrote me a wonderful email thanking me and invited me down to Austin for lunch. Several years later, I visited Steven at his office at the university. He showed me some interesting photos of his past achievements, and then we got into his car, and he drove me to a restaurant. I enjoyed having lunch with him and discussing the concepts of a multiverse, dark matter, and SETI.

Steven was a gentleman and a scholar. I will never forget my interactions with such a wonderful human being.

Harold Kozak
(kharold476@aol.com)
New York City




PHYSICS TODAY
OCTOBER 2022
MARK YOUR CALENDAR
4TH ANNUAL CAREERS & RECRUITMENT ISSUE
Enhanced exposure opportunities for recruiters and exclusive careers-focused content for job-seekers across the physical sciences
For more information on advertising in the special issue, contact Christina Unger-Ramos at cunger@aip.org

Ecology is more chaotic than previously thought

About a third of species show indications of unpredictable long-term behavior.

CHAOS HIDES in ecological systems. Chaotic dynamics are characterized by an extreme sensitivity to initial conditions and unpredictable long-term behavior. Here, they are represented by the so-called cobweb plot—playfully rendered in the right spiderweb—which is a simple model of chaotic population growth. Although ecological chaos was deemed rare in the 1990s, a new study suggests that, actually, about a third of populations are chaotic. (Illustration by Tanya Rogers.)

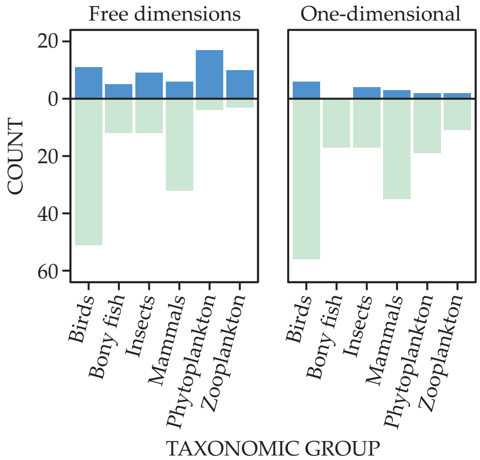
For the past decade, ecologist Stephan Munch has been convinced that chaos must be more common in ecological systems than the prevailing wisdom suggests. Chaos, which is marked by an extreme sensitivity to initial conditions, emerges in complex nonlinear systems (see the article by Adilson Motter and David Campbell, Physics Today, May 2013, page 27). Ecosystems teeming with interacting species and influenced by the weather—itself chaotic!—seem to be prime candidates. But when Munch mentioned the possibility of chaotic ecological behavior to his colleagues at the University of California, Santa Cruz, one response was simply, "Didn't we disprove that in the '90s?"

The 1990s had indeed seen numerous studies reporting that ecological chaos was rare. Chaos was first introduced to the field two decades earlier in simple theoretical models from Robert May, John Beddington, and their colleagues. The expectation was that chaos could explain the observed fluctuations in animal population sizes. And so ecologists sought evidence of chaos in empirical data, a quest that reached a fever pitch in the 1990s and culminated in a 1995 meta-analysis that found evidence of chaos in only around 10% of the surveyed population time series—the regularly occurring counts of species' population size at a given location.[1] After that, interest in the topic waned, and no similar analyses were conducted for over 25 years.

In that time, however, the available data improved and expanded. After discussions with Munch, Tanya Rogers, a research ecologist who collaborates with him at the NOAA Southwest Fisheries Science Center laboratory in Santa Cruz, decided that the many new empirical data sets warranted a new analysis. Rogers, Munch, and his graduate student Bethany Johnson hunted for indications of chaos in 172 population time series—notably more than the 27 series in the 1995 study. They now find evidence of chaos in over 30% of the populations, and even that number is likely conservative.[2] The result suggests it may be time to reintroduce chaos into ecology.

One fish, two fish

For the new analysis, Rogers pulled data from the Global Population Dynamics Database (GPDD).[3] The online repository hosts annual counts of the mammal and bird populations at various sites, weekly counts of zooplankton and other marine fauna, and other details for over 1800 species. The GPDD was started in 1994 by the Natural Environment Research Council's Centre for Population Biology at Imperial College London in collaboration with the National Center for Ecological Analysis and Synthesis at the University of California, Santa Barbara, and the University of Tennessee, Knoxville.



POPULATION DYNAMICS can be chaotic (top bars in blue) or nonchaotic (bottom bars in green). The number of chaotic populations identified varies dramatically with the choice of model used to fit the empirical data, particularly the model dimensionality. One-dimensional models (right), which are commonly used in ecology, identify fewer chaotic populations than models (left) that treat the dimensions—anywhere from two to six—as a fitting parameter for each data set. In the free-dimensions case, shorter-lived species, such as plankton and insects, demonstrate higher rates of chaos. Such species make up most of those on Earth and many of the populations people are interested in managing. (Adapted from ref. 2.)

It is the largest collection of population data in the world.

The handful of researchers and academics who manage the GPDD have gathered data from published literature and citation trails, data sets on the internet, professional contacts, and books, including long-out-of-print volumes. All data sets have at least 10 data points or 10 years of observation (typically those criteria are synonymous). Most are natural populations, meaning they are unmanaged by humans. And the GPDD team offers its subjective assessment of the data's quality as a score from one to five.

The sort of population data the GPDD collects originates from academics and various government agencies with research interests and practical concerns, such as managing food and pest species and conserving endangered ones. The NOAA National Marine Fisheries Service, for example, annually assesses the populations of fish and marine mammals in the Atlantic Ocean, the Gulf of Mexico, the Pacific coast, Hawaii, Alaska, and the North Pacific. The reports include species' geographic range, minimum-population estimates, population trends, and rates of human-caused deaths and injury, among other things. That information comes courtesy of a suite of technologies, including satellite tagging, drone imaging, acoustic sensing, and surveying on board research ships.

To understand the population data, one must disentangle different categories of behavior: stable, with long-term predictability and return to equilibrium; chaotic, with only short-term predictability; and random, with complete lack of predictability. Any natural process has some amount of random fluctuation, if only as a result of the randomness of the environment around it. So methods must distinguish between inevitable noise and genuine chaos.

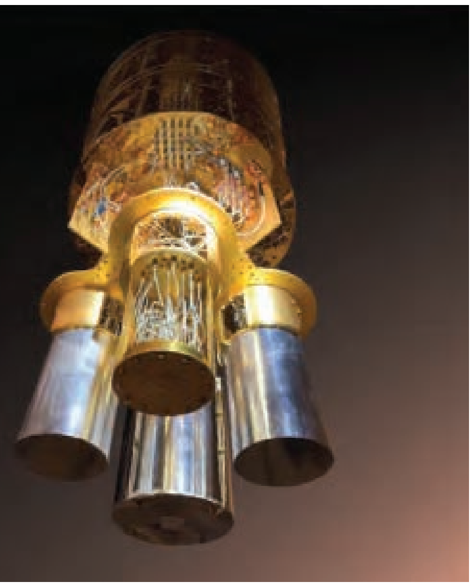
Exponential returns

How can one tell if a system is chaotic? In a model, the task is easy: Simply compare runs with minutely different initial conditions. If the trajectories converge over time, the system isn't chaotic. If they diverge, it is. Of course, real-life ecosystems can't be re-created with slightly distinct initial conditions. But a model can be fitted to experimental data and then analyzed for how much it converges or diverges—as quantified by negative or positive values, respectively, for the so-called Lyapunov exponent.

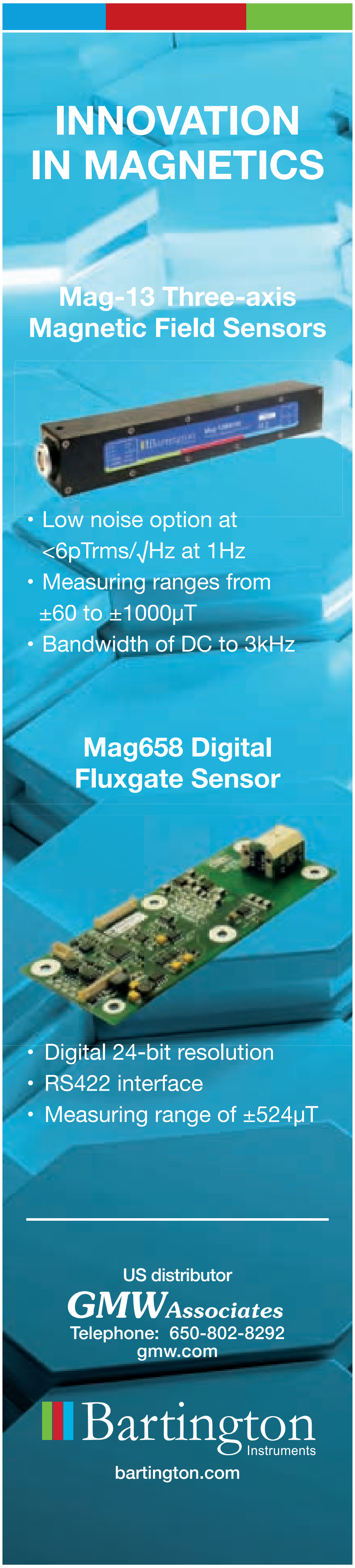
Chaos-detection models were largely developed for physical systems, such as chaotic fluctuations in laser emission, in which a small data set consists of thousands of data points with little error. In

bleximo

Powering Innovation through
Quantum Computing



FOR DETAILS
www.bleximo.com
sales@bleximo.com



ecological observations, a typical time series is at best hundreds of data points with plenty of error. Only some of the existing detection methods would reasonably translate to ecology, and no studies had methodically analyzed which ones.

To figure it out, Johnson simulated chaotic, periodic, and other nonchaotic systems and generated population data similar in quantity and quality to that available in the field. She then tested how well different types of models identified which simulated data were chaotic. “We weren’t trying to estimate a Lyapunov exponent to six decimal places,” says Munch. “We just wanted to get the sign right most of the time.” The best three models, the very best of which has been around since the 1990s, were then deployed on the real field data. The researchers found chaos surprisingly prevalent among the birds, fish, insects, mammals, and plankton they tested, as shown in the figure on page 15.

Some species are more prone to chaotic behavior than others. Shorter-lived species, including most plankton and insects, have higher rates of chaos than longer-lived species, including most birds and mammals. That trend could be because longer-lived species are less sensitive to the chaotic environment. Or it could simply be a by-product of data limitations. Time series must be taken over longer periods to reach the same number of population generations for mammals as for insects, and in the short term, chaotic dynamics look predictable. The world is populated by far more short-lived species than long-lived ones, so the chaos around us may well be more than the approximately 30% the researchers found.

Managing expectations

So what did older analyses get wrong? One issue is the simplicity of their models: Even today, many ecology studies use one-dimensional models that account for only a single variable. In a 1D model of a crow population, for example, the rate of change in the number of crows depends solely on the current number of crows. A 2D model might add in a dependence on the current number of, say, spiders available to eat. As shown in the figure on page 15, Rogers found that 1D models identified chaos in just under 10% of the observational time series, a value along the lines of older studies.

Another limitation in previous work was data availability. Species’ time series are longer now than they were in the 1990s. To get a sense of the influence of data time span, the researchers artificially truncated all the time series to 30 data points. In that case, they found that 24 of the 58 chaotic series were no longer classified as chaotic. On the other hand, for those series with 70 or more data points, 58% were chaotic.

Rogers explains that data limitations are still the biggest hurdle. The GPDD has more than 5000 time series for over 1800 species, but only the 172 she and her collaborators studied were of a sufficient length and quality to analyze. “Our study definitely highlights the value of long-term ecological data collection and increasing access to data,” says Rogers.

Whether a population is chaotic is not simply an academic or philosophical concern. Shorter-lived, disproportionately chaotic species make up many of the populations that people want to manage, either because they’re food sources, such as shrimp, or unwanted pests, such as algal blooms. Most management and conservation strategies are built around the idea of reaching and maintaining a stable equilibrium population, but that concept is meaningless for chaotic dynamics. Conservationists must instead find ways to leverage the short-term predictions still possible in chaotic systems.

Another open question is how climate change might influence the prevalence of ecological chaos. At a minimum, it’s likely to make chaos harder to detect, as the noise and disruptions render population dynamics—chaotic or not—more difficult to predict. As the environment changes and species migrate to more habitable climates (see Physics Today, September 2019, page 16, and November 2020, page 17), how will their population dynamics change?

Heather M. Hill

References

1. S. Ellner, P. Turchin, *Am. Nat.* **145**, 343 (1995).
2. T. L. Rogers, B. J. Johnson, S. B. Munch, *Nat. Ecol. Evol.* **6**, 1105 (2022).
3. J. Prendergast et al., Global Population Dynamics Database, Knowledge Network for Biocomplexity (2010), doi:10.5063/F1BZ63Z8.

A graphene temporary tattoo measures blood pressure

A far cry from the bulky, uncomfortable cuff, the ultralight sensor takes measurements of the vital sign without the wearer feeling a thing.

If you own a sphygmomanometer—the gadget with the inflatable cuff that's used to measure blood pressure—and if you're diligent about using it, you might take your own blood pressure as often as a few times a day. Otherwise, you probably get your blood pressure checked only when you visit a doctor, perhaps a few times a year.

Is that enough? Blood pressure varies over time, not just year to year or day to day, but sometimes minute to minute. It rises when we're active or feeling stressed, and it falls when we're relaxed. Individuals with so-called white-coat hypertension, who feel unduly nervous around doctors, might get their blood pressure checked only when it's unnaturally high—and thus end up saddled with medications or treatments they don't really need.

In a world of smart watches and fitness monitors that continuously monitor heart rhythm, skin temperature, sleep quality, and more, blood pressure stands out as a key quantity that's absent from the devices' suite of measurements. The sphygmomanometer is just too big and inconvenient.

To fill the blood-pressure data gap, Roozbeh Jafari (Texas A&M University), Deji Akinwande (the University of Texas at Austin), and their colleagues have developed a new blood-pressure sensor that's light and unobtrusive enough to be carried around everywhere.[1] The sensor uses a temporary tattoo made of graphene and protected by an ultrathin polymer film (the shiny patches in figure 1), and it works by measuring bioimpedance—essentially the tissue's resistance to an alternating electrical current—as blood pulses through the artery under the tattoo.

At the moment, converting bioimpedance to blood pressure is a task for a complicated machine-learning algorithm that requires hours of training on each new user. The researchers hope to develop their sensor into a plug-and-play device that's just as portable as a smart watch, so they can add blood pressure to the set of continuously monitored vital signs.

The body electric

The sphygmomanometer is a century-old technology. Its mechanism of operation hasn't changed much since Russian surgeon Nikolai Korotkov recognized, in 1905, the important distinction between systolic blood pressure (the highest pressure at the peak of a blood pulse) and diastolic blood pressure (the lowest pressure between blood pulses). To start, the cuff inflates until it squeezes an artery completely shut. Then the cuff gradually deflates until blood can push its way through on part, then all, of the heartbeat cycle. The result is a pair of pressures, measured in millimeters of mercury, that make up the standard blood-pressure measurement.

The need to squeeze hard enough to cut off blood flow explains why the sphygmomanometer cuff is so bulky and why its operation is so uncomfortable. Some emerging technologies can measure blood pressure using smaller, gentler pressure sensors.[2] But Jafari, Akinwande, and colleagues sought to create a blood-pressure gauge that doesn't measure mechanical pressure at all, but rather other quantities that are correlated with it.

FIGURE 1. SIX GRAPHENE ELECTRODES (the shiny patches), lined up over the left radial artery, measure bioimpedance in the wrist. Through a machine-learning algorithm, the bioimpedance data are converted into a blood-pressure measurement. (Courtesy of Roozbeh Jafari and Deji Akinwande.)

Jafari, an expert on machine-learning algorithms for biomedical applications, has been working for several years on estimating blood pressure from bioimpedance.[3] Blood is a fluid rich in ions, so it's a better electrical conductor than most other tissues are. When a blood pulse passes through an artery, the overall tissue impedance drops, as shown in figure 2. Furthermore, higher blood pressure is correlated with faster propagation of blood pulses. So if bioimpedance is measured at two spots on the same artery, the pulse transit time between them is another valuable piece of information.

Still, blood pressure and impedance aren't precisely linked by any simple, direct relationship. The blood-pressure measurement needs to be teased out from subtle features of the shape of the impedance curve over the pulse cycle. That's where machine learning comes in.

At first, Jafari and colleagues measured bioimpedance using conventional electrodes similar to those used to record electrocardiograms. The electrodes had to be held in place with a strong adhesive, so they could be uncomfortable to wear for a long time. Worse, as the adhesive layer deformed over time, the electrodes would shift position on the skin, which introduced measurement error. That's not practical for a device meant to collect measurements continuously.

Eye, robot

Meanwhile, Akinwande was exploring applications for biomedical sensors made from graphene. Ever since the two-dimensional carbon material burst onto the scientific scene almost two decades ago, researchers have been devising graphene-based technologies and experiments that previously would have been almost unimaginable. Says Akinwande, "I've been asking myself, what opportunities are there that only graphene can provide?"

Many of those opportunities have come in the area of flexible, wearable electronics. Graphene is a semimetal, so it can be fashioned into electrodes to pick up electrical signals from the human body or anywhere else. It's atomically thin, and it clings to the skin by van der Waals forces alone, with no adhesive required.

Even with a protective polymer layer on top, needed to keep the graphene from rubbing right off, the whole structure is only a fraction of a micron thick. (Conventional electronics can attach to the skin through van der Waals forces too—see PHYSICS TODAY, May 2019, page 16—but they're orders of magnitude thicker.) Graphene is thin and flexible enough to conform to all the wrinkles and corrugations of the skin without the wearer even noticing it's there.

Akinwande calls the electrodes "graphene electronic tattoos" because of their similarity to ink-based temporary tattoos: The graphene and polymer are layered onto a specially formulated tattoo paper, which is pressed against the skin and wetted with water to transfer the tattoo into place. Surprisingly rugged, the tattoos aren't damaged by daily activities or even gentle washing, and they can remain in place for up to a week before inevitably getting sloughed off with a layer of dead skin cells.

The tattoos' applications are manifold. In one of their experiments, Akinwande and colleagues placed the graphene tattoos on the skin around a subject's eyes to measure the electrical signals from the eye muscles and determine, with few-degree precision, where the subject was looking. They used the signals to pilot a robotic drone, which the subject could steer just by looking around the room.[4]

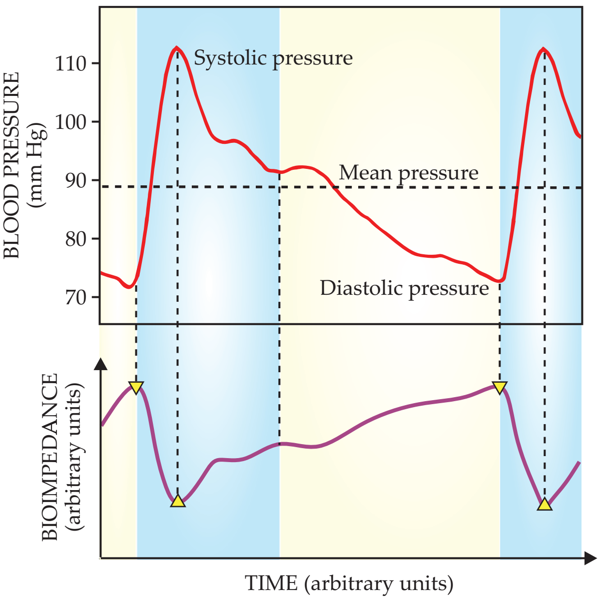


FIGURE 2. BLOOD PULSING beneath the electrodes shown in figure 1 changes the tissue's electrical conductivity, and thus its impedance. As sketched here, the blood-pressure and bioimpedance curves are inversely related to each other. To extract an absolute blood-pressure measurement, a machine-learning algorithm is fed data, such as the impedance peaks and troughs (yellow triangles) and the pulse transit time between two pairs of electrodes on the same artery. (Adapted from ref. 1.)

For blood-pressure measurements, the important thing about the tattoos is that they don't shift in position over time. Their steady measurements are ideal for training, then using, Jafari's machine-learning algorithm.

Continuous learning

As shown in figure 1, the new blood-pressure sensor uses six graphene patches lined up over the radial artery, on the side of the wrist nearest the thumb. Six more, not shown, cover the ulnar artery on the other side. In each set, the electrodes on each end inject an imperceptibly tiny electric current into the wrist. The other four are split into two pairs, each of which measures the induced potential difference, which is proportional to the impedance.

To train the machine-learning algorithm, the researchers had a handful of volunteers wear both the graphene tattoos and conventional sphygmomanometers for several hours while they performed activities designed to raise and lower their blood pressure. The researchers fed the machine-learning algorithm with several quantities extracted from the bioimpedance curves: the peak and trough of each pulse cycle, the maximum slope, and the pulse transit time, among others. By the end of the training, the algorithm was estimating both systolic and diastolic blood pressure to within about 5 mm Hg—an excellent result, as blood-pressure measurements go.

Obviously, most of the advantage of a lightweight blood-pressure gauge is negated if you have to wear a sphygmomanometer for hours to train it. Ideally, the researchers would like to be able to apply a graphene tattoo to a new subject and immediately get accurate blood-pressure readings. They're not there yet, but they hope to make progress by exploring different quantities from the bioimpedance curves—ratios rather than absolute values, for example—that might be less user-specific. And in a promising result, several days after the experiment they applied a new tattoo to one of the study participants. With no additional algorithm training, they got blood-pressure readings precise to within 10 mm Hg: not as good as in the original experiment, but still a useful measurement.

Jafari suspects that if continuous blood-pressure monitoring becomes standard, it could lead to a shift in thinking about blood-pressure measurement errors. Under the current paradigm, readings are taken infrequently, so each measurement and its error bars are treated in isolation. "But with continuous monitoring, the absolute error is less important," he says. "What's important is the trend. Does your blood pressure drop when you go to bed, and does it increase when you're stressed out? By how much?"

Another advantage of the tattoos is that they can be applied nearly anywhere on the body. A sphygmomanometer cuff is almost always wrapped around the brachial artery in the upper arm, and although the resulting measurement is presented as "your blood pressure," blood pressure is affected by local conditions, such as the stiffness of individual arteries, so it's not the same everywhere in the body. Patients with poor blood circulation, especially, can potentially benefit from data on blood pressure in different parts of the body—such as arteries in the neck that supply blood to the brain—that are too dangerous or impractical to probe with the century-old artery-squeezing technology.

Johanna Miller

References

1. D. Kireev et al., *Nat. Nanotechnol.* (2022), doi:10.1038/s41565-022-01145-w.
2. S. Yang et al., *Opt. Quantum Electron.* **53**, 93 (2021).
3. B. Ibrahim, R. Jafari, *IEEE Trans. Biomed. Circuits Syst.* **13**, 1723 (2019).
4. S. K. Ameri et al., *npj 2D Mater. Appl.* **2**, 19 (2018).

Jamming connects granulation and flow

A unified model that describes how powders behave when they get wet could inform industrial processing of such products as ceramics and chocolate.

Cake recipes typically instruct bakers to add wet ingredients to a powdery flour mixture. Adding just the right amount of moisture is critical to making batter: Too little liquid results in dry clumps, whereas too much produces a watery mess. But just the right amount makes a smooth, flowing batter.

Incorporating liquids into powders is also common in industrial materials processing. The applications typically fall in different parts of the wetness spectrum: Production of powdered laundry detergent, for example, employs so-called wet granulation—a small amount of added liquid binds microscopic particles in small clumps, or granules. In the mixing of cement, on the other hand, the desired product is a high-solid-content dispersion that can be poured.

Those processes are more complicated than just mixing components in the right ratios. Inactive ingredients might be added to achieve certain properties. Protocol matters too: Changing how the components are added and how they get mixed together can significantly alter the final product. And for large-scale processes, those factors can all affect the amount of energy needed to do the mixing.

With so many variables to tune, researchers face a daunting task when it comes to optimizing a mixing process. They typically focus on the small region of parameter space around their desired product. Now Daniel Hodgson and Wilson Poon at the University of Edinburgh in the UK and their collaborators provide a broader view.[1] The results of their experiments, which span the fluid-to-granulation transition, point to frictional jamming as the primary mechanism behind granulation. They also suggest that simple rheological measurements can be sufficient to predict granule properties.

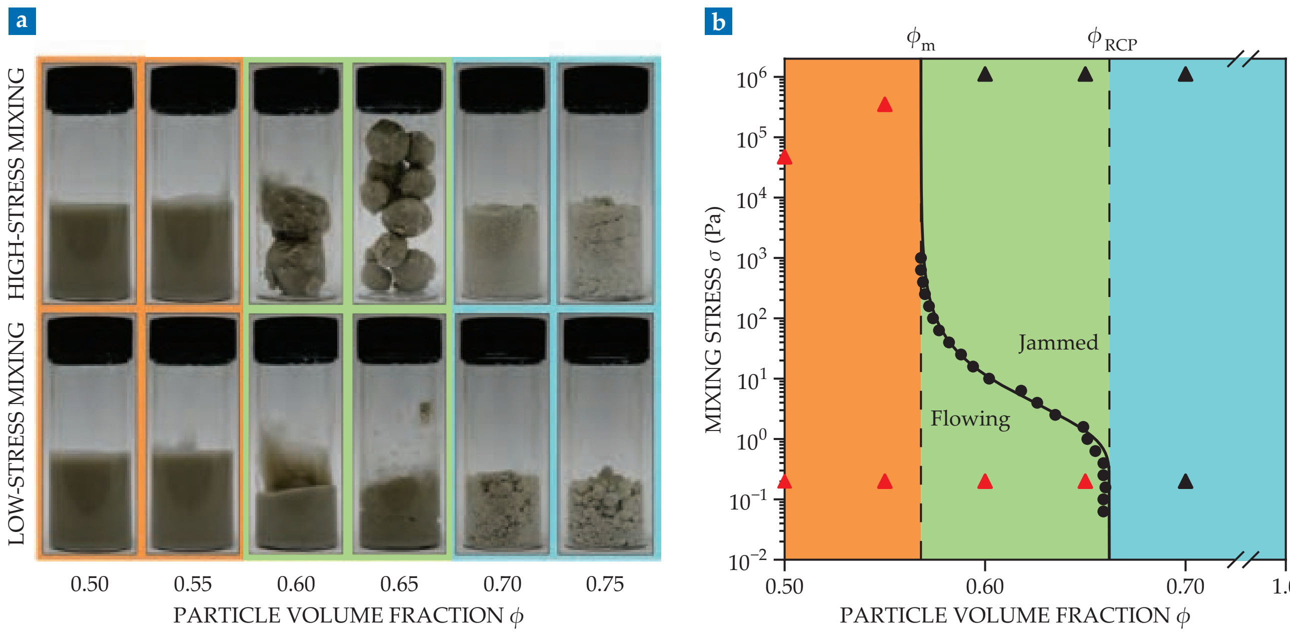


FIGURE 1. GRANULATION of glass spheres suspended in glycerol depends on both particle volume fraction ϕ and the mixing stress σ. **(a)** Suspensions are always fluid at sufficiently low particle fractions (orange), and above a certain fraction they're always granulated (blue). In between (green), the phase depends on how the components are mixed. **(b)** Rheological measurements (black dots) of where a suspension jams as a function of volume fraction confirm the three granulation regimes: liquid flow below a minimum value $\phi_m = 0.568$, solid granules above the random-close-packing density $\phi_{RCP} = 0.662$, and transient granules between those values. Black and red triangles correspond to the granulated and fluid samples, respectively, in panel a. (Adapted from ref. 1.)

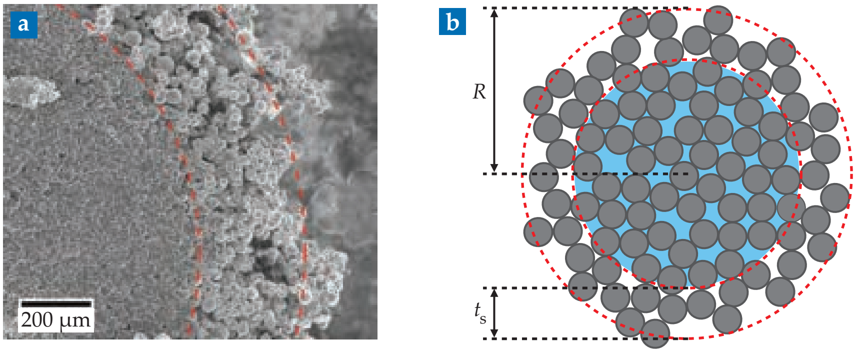


FIGURE 2. GRANULAR INTERIORS are difficult to observe because the clumps often fall apart while being cut open. **(a)** A microscope image of a granule that survived the process. **(b)** Each observed granule consisted of a wet, jammed core and a nearly dry, powdery shell. The shell thickness t_s is needed to predict the average granule radius R for a given particle fraction and mixing protocol. (Adapted from ref. 1.)

A sticky situation

Although experiments on dense suspensions and granulated materials have largely focused on either freely flowing or fully granulated materials, theorists have been working to develop a single physical picture that links the two phases.[2] After all, both are achieved by mixing the same kinds of components—liquids and powders—just under different conditions. Granules form when the dispersed particles become jammed, meaning they're stuck in a disordered configuration and can't rearrange. (See the Quick Study by Jasna Brujic, Physics Today, November 2010, page 64.) But why, and under what conditions, do dispersed particles become jammed?

The friction-driven jamming picture arose as part of a change in how the rheology community understood why particulate suspensions undergo shear thickening—an increase in viscosity with increased applied stress. Shear thickening had been attributed to groups of particles being forced by the surrounding flow to move together as a whole. Now it's understood to arise from forcing particles into frictional contact with a sufficiently high applied stress that prevents them from sliding past each other.

One promising explanation for the onset of granulation involves the same underlying physics. If interparticle contacts are lubricated by a thin layer of liquid, a liquid–powder mixture should be able to flow as long as the solid-volume fraction ϕ remains below the random-close-packing value ϕ_{RCP}—the maximum volume fraction achievable by filling a space with randomly packed objects, which is about 64% for uniformly sized spheres. If the interparticle contacts are unlubricated, though, static friction between particles further impedes flow. Mixtures would then become solid at some $\phi < \phi_{RCP}$.

But the connection between frictional interparticle contacts and granulation remained speculative. A proposed picture in which history-dependent flows affect a suspension's route to granulation, for example, was still plausible.[3] And experimental evidence one way or the other was lacking. "If you look in the literature, dense-suspension rheology and granulation are totally separate fields," says Hodgson. "They are nearly never tackled in the same work or the same way."

To flow or not to flow

Filling in that knowledge gap was the goal of Hodgson's PhD research. For the powder in their experiments, Hodgson and coworkers chose glass spheres with an average diameter of 10 μm. The polydisperse particles more closely mimicked the materials used in industrial settings, and since they were cheaper than the monodisperse ones often used in colloidal experiments, the researchers could produce larger-volume samples. Glycerol was chosen as the liquid because its high density and viscosity prevented noticeable sedimentation in fluid samples for the few hours each experiment lasted.

Figure 1a illustrates how volume fraction and mixing stress affected the final material. The liquid and solid components in each sample first underwent high-stress mixing (top row) and then subsequent low-stress mixing (bottom row). Three regimes emerged: At $\phi = 0.55$ and below, the suspensions flowed; at $\phi = 0.70$ and above, permanent granules formed. Intermediate volume fractions produced large granules after high-stress mixing, but the granules were transient—they relaxed into fluids following low-stress mixing.

To understand the physical origins of the three regimes, the researchers turned to steady-state flow measurements: They subjected the fluid samples to a constant stress and measured the viscosities. The suspensions thickened under stress, as expected, and the viscosity diverged at some value ϕ_J; above that value, the samples no longer flowed. Where the viscosity diverged depended on the stress.

Using their measurements of $\phi_J(\sigma)$, shown as black dots in figure 1b, the researchers constructed a phase diagram for the suspensions. At the lowest stresses, suspensions flowed for volume fractions up to $\phi_{RCP} = 0.662$, consistent with lubricated interparticle contacts. Samples with higher volume fractions were always granulated. With increasing stress, the volume fraction at which flow stopped fell until it reached a minimum value of $\phi_m = 0.568$. Below that value, samples were always fluidlike. Between ϕ_{RCP} and ϕ_m, whether a sample was solid or fluid depended on the stress. The samples in figure 1a (represented as triangles in figure 1b) fell neatly into the appropriate regions of the phase diagram.

"Crucially, Hodgson and coworkers show experimentally that there is indeed a mapping between granulation behavior and steady-state flow behavior," says Mike Cates, a professor of mathematics at the University of Cambridge. A direct connection between steady-state flow measurements and granulation would not be possible if history-dependent hydrodynamics were involved. Additionally, says Cates, "the results further confirm the key role of interparticle friction rather than any of several alternative explanations that have been proposed to explain the wider scenario of shear thickening."

A peek inside

Hodgson and coworkers used mass conservation to tease out the structures of the clumps formed in the granulated samples. For a given stress σ, the maximum amount of powder that can be trapped in the liquid phase is set by ϕ_J; any remaining particulate must be left behind in a separate dry phase.

But no loose powder was present in the granulated samples, so Hodgson cut some of the granules open to look inside. “The granules you end up with are very brittle,” he notes. “I had to do it many, many times to even get the small number of images we did get.” In those few images, he saw wet, jammed cores surrounded by dry particulate shells (see figure 2a). X-ray tomography measurements confirmed the general structure.

From that insight about the granules’ structure, Hodgson and coworkers wrote down a formula for a sample’s average granule radius R as a function of ϕ, σ, and the shell thickness t_s (see figure 2b). The predictions for R in both low- and high-stress conditions agreed with their observations.

The formula also predicted when the granules should come together and make a flowing suspension. Those particle fractions—$\phi = 0.55$ and 0.66 for high- and low-stress mixing, respectively—are the same ones at which the steady-state flow data predicted the transition between flow and granulation.

With so few images of granule cross sections, the researchers had to leave t_s as a fitting parameter in their formula. That approach yielded different parameters for high- and low-stress mixing, which may indicate another structural difference caused by the protocols. But that’s still speculation. A better understanding of what determines t_s is needed so its value can be calculated or measured—hopefully as easily as ϕ_J, which can be gathered through straightforward rheological measurements. That capability will likely be important for predicting what size granules an industrial mixing protocol will produce.

Other factors may further complicate predictions. How liquid is added to a powder, for example, can affect granule structure: Introducing it as an aerosol rather than large droplets could link particles with small capillary bridges instead of trapping them in a jammed liquid–particle core. And if interparticle interactions aren’t purely repulsive, qualitatively different properties could emerge in both the fluid and granulated states.

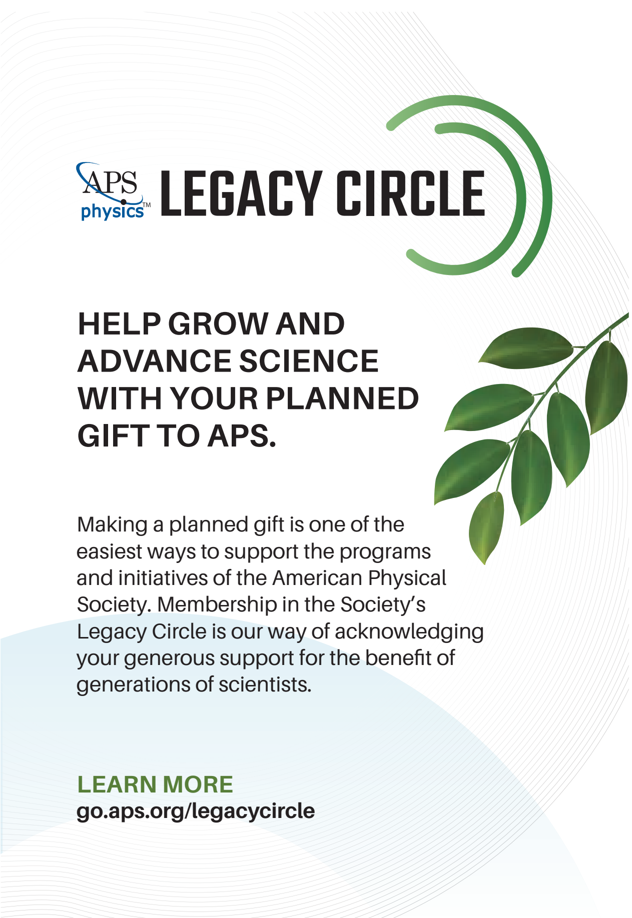
In a collaboration that included industry partners at Mars Chocolate, the authors of the paper observed that reducing friction shifts the onset of granulation in chocolate conching—the mixing of powdered cocoa, sugar, and milk with cocoa butter to produce chocolate’s distinctive texture.[4] And, notes Hodgson, “because we’re dealing with the underlying fundamental physics, we’re not sector specific.” The same underlying physics and phenomenology should also apply to concrete production, for example. And since surfactants used in many systems to reduce friction are derived from petrochemicals, adjusting friction can also be an opportunity to move to a more environmentally sustainable formulation.

Christine Middleton

References

1. D. J. M. Hodgson et al., *J. Rheol.* **66**, 853 (2022).
2. M. E. Cates, M. D. Haw, C. B. Holmes, *J. Phys.: Condens. Matter* **17**, S2517 (2005); M. Wyart, M. E. Cates, *Phys. Rev. Lett.* **112**, 098302 (2014).
3. M. E. Cates, M. Wyart, *Rheol. Acta* **53**, 755 (2014).
4. E. Blanco et al., *Proc. Natl. Acad. Sci. USA* **116**, 10303 (2019).

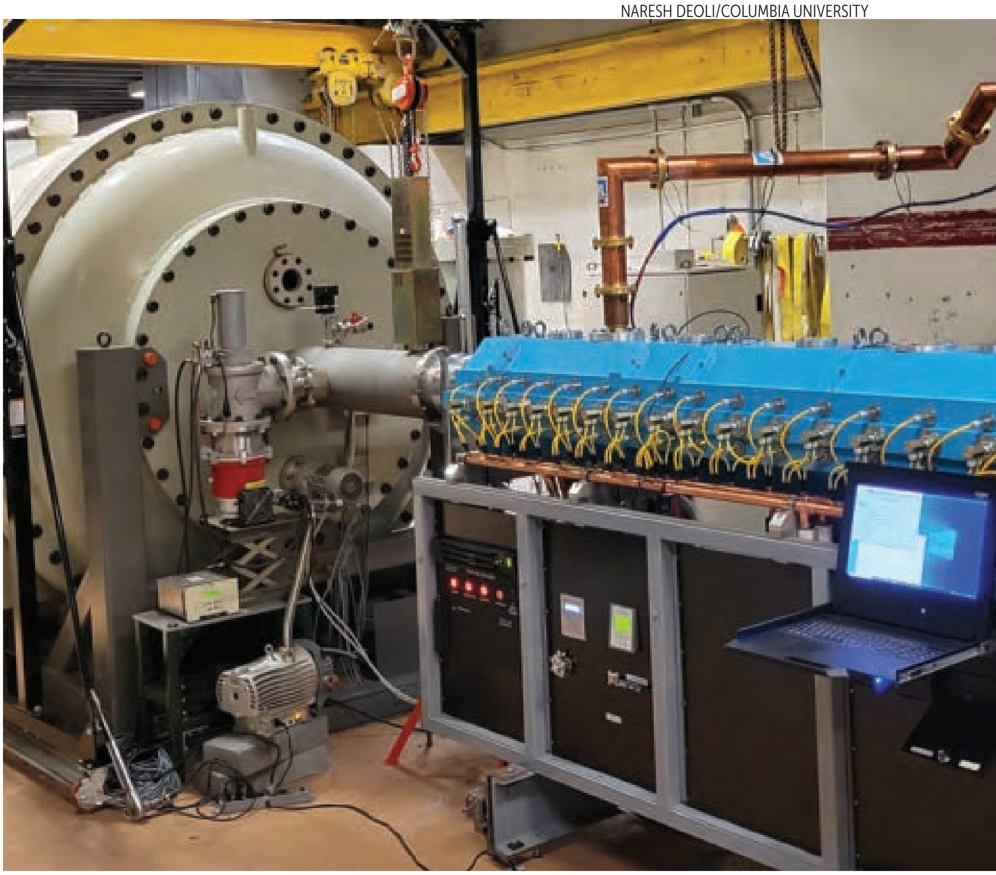
PT



Slow but steady progress seen for carbon-ion cancer therapy

Although Japan has adopted the treatment modality for a broad range of cancers, carbon ions continue to lack the validation provided by randomized clinical trials.

NARESH DEOLI/COLUMBIA UNIVERSITY



A LINAC BOOSTER (blue) attached to the end of the existing linac at Columbia University's Radiological Research Accelerator Facility has become the first instrument in the US dedicated to research on heavy-ion radiation therapy. Installed earlier this year, the booster doubles the energy of the particles coming out of the linac and triples their range in tissue, university officials say. It will be used in preclinical research.

Decades after adoption in Asia, and following several false starts, carbon-ion cancer therapy may finally be coming to the US. In May, Mayo Clinic broke ground in Jacksonville, Florida, on a facility that will produce beams of carbon ions to treat cancer tumors.

The new center, which will also offer proton and conventional x-ray therapies, is expected to treat its first patients with carbon-ion beams in 2027, says Chris Beltran, chair of Mayo's division of medical physics. Mayo will provide the estimated $233 million for the facility, and it has contracted Hitachi to build the synchrotron.

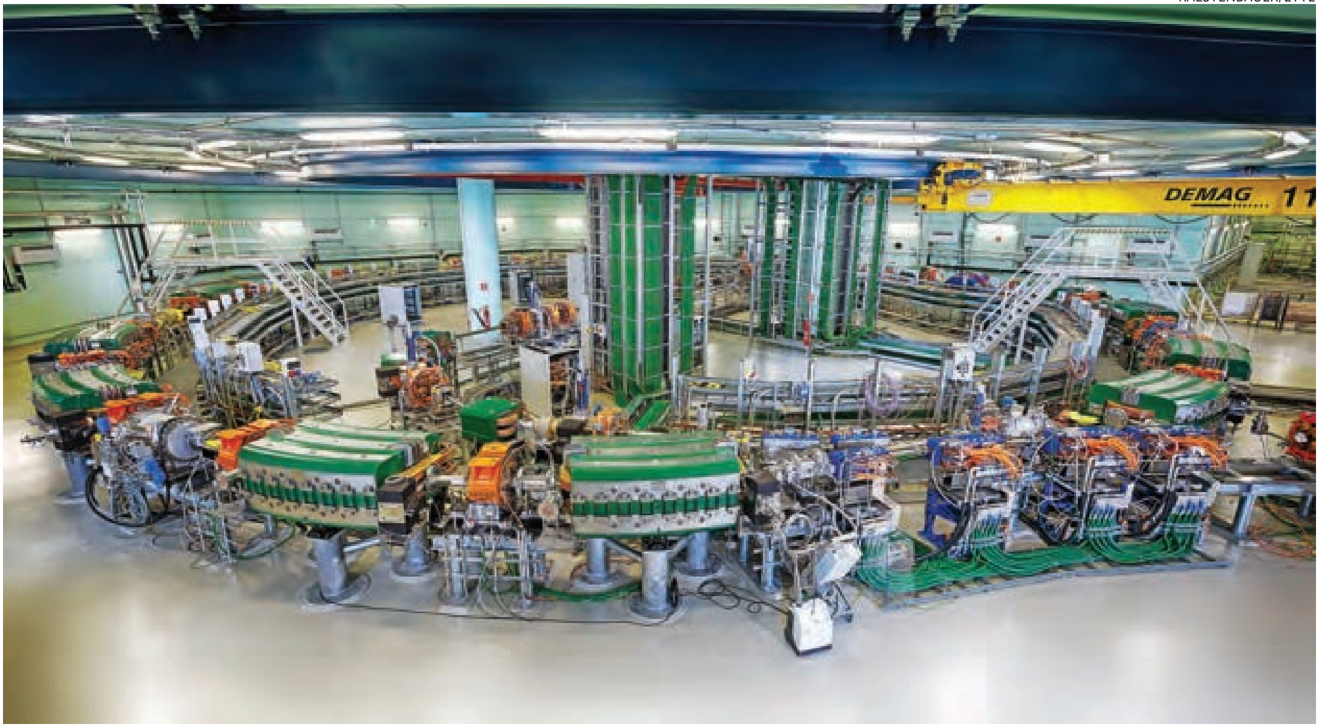
When the Jacksonville center opens, the US will have completed a circle that began with pioneering clinical trials in the 1970s at Lawrence Berkeley Laboratory's Bevalac heavy-ion synchrotron. Led by Joseph Castro of the University of California, San Francisco, those trials established the safety and biomedical activity of carbon beams. Yet that work ended before trials of the treatment's efficacy when the Department of Energy shut down the Bevalac in 1993.

Japan took notice of the research, opening the first of that nation's seven carbon-ion therapy facilities in Chiba in 1994. Europe's first carbon-ion therapy center, located in Heidelberg, Germany, began treating patients in 2009 (see PHYSICS TODAY, June 2015, page 24). Italy followed in 2012 with a center in Pavia, outside Milan. Germany's second carbon-ion center, in Marburg, opened in 2015. Europe's newest facility, located in Wiener Neustadt, near Vienna, Austria, began treatments in 2019. China has two therapy centers, located in Shanghai and Wuwei, which have operated since 2014 and 2019, respectively.

Five other centers are under construction—two in South Korea and one each in China, France, and Taiwan—according to the Particle Therapy Co-operative Group, a nonprofit organization that promotes the science, technology, and clinical application of particle therapy. China has another facility in the planning stage.

Plans for at least three other US carbon-ion treatment projects have stalled over the past decade. Before the start of the COVID-19 pandemic, the University of Texas Southwestern Medical Center (UTSW) completed the design for a treatment center in Dallas, selected Toshiba as the vendor, and was prepared to break ground in 2020. Hak Choy, a since-retired UTSW radiation oncologist who was the project's chief proponent, says he had organized an international clinical trial that would have had patients travel to Japan and Italy for treatment. But UTSW management balked at the expense, fearing that hospital revenues would plunge during the pandemic, he says. "It is a risky project from the university's point of view, because there is no guarantee of reimbursement [by Medicare, Medicaid, and insurers]," he says. "It's not clinically proven, but there is a physics theory and biolog-

KAESTENBAUER/ETTL



THE SYNCHROTRON at MedAustron, a proton and carbon-ion cancer therapy center in Wiener Neustadt, Austria. Carbon-ion energies range from 120 to 400 MeV, and proton energies of 60 to 250 MeV are available. The higher the particle energies, the greater the beam's penetration depth into the body.

ical theory for why it is beneficial."

UC San Francisco had also proposed a center and, like UTSW, received a planning grant in the mid 2010s from the National Cancer Institute (NCI) to pay for design efforts.

Best Medical International, a privately held manufacturer of radiation oncology equipment, has been working with Brookhaven National Laboratory since 2012 to develop a carbon-ion therapy system, through cooperative R&D and technical-assistance agreements. Krishnan Suthanthiran, Best Medical's president, says he still expects a system to be ready for installation in two years, possibly at a Best-owned property in Pennsylvania.

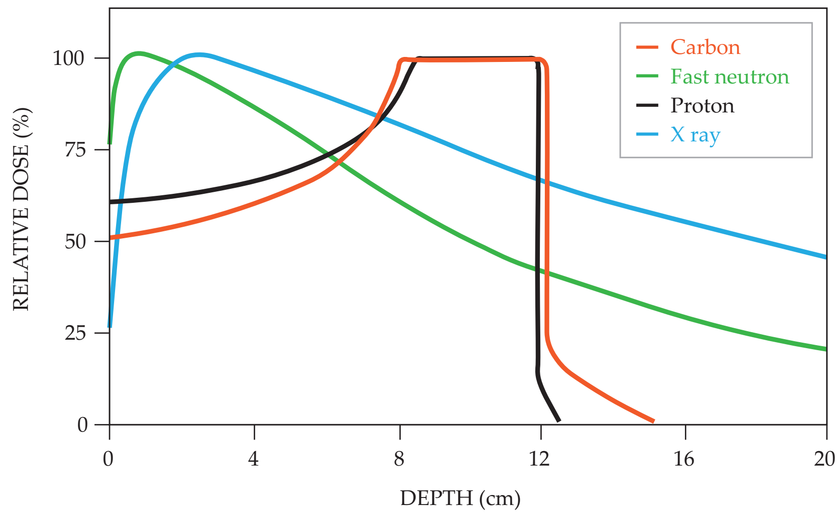
Chicken and egg

In addition to the prohibitive expense, a major impediment to carbon-ion therapy in the US is the lack of published evidence for its benefit over other forms of radiotherapy. "Despite being out there for 20 or 30 years, there's not a document or a clinical practice . . . where I can say if you have prostate or breast cancer, then this paper says you should get carbon," says Jeffrey Buchsbaum, the medical officer in the clinical radiation oncology branch at NCI. "There is a lack of peer-reviewed literature in robust, random trials," which are the standard in the US.

Yet despite a similar lack of published randomized clinical trials comparing proton therapy to conventional x-ray therapy, the US has broadly accepted proton therapy. The first proton-therapy center in the US, at Loma Linda University Medical Center in Southern California, opened in 1990, with support from a congressional earmark. Today, the US leads the world in the number of proton facilities, with 41, according to the Particle Therapy Co-operative Group. A half dozen NCI-sponsored and other randomized trials on proton therapy are nearing completion or publication.

Mayo Clinic is moving forward on the Jacksonville facility without assurances of regulatory approval. Beltran says it's hoped that the Food and Drug Administration will look at all the data and methods that have been used elsewhere. "Hopefully we can leverage the published research for FDA clearance and do more clinical trials going forward." Approval under an investigational-device exemption allows devices to be used in a clinical study to collect the safety and effectiveness data needed to support a premarket approval application and subsequent approval stages.

Without full regulatory approval, public and private health insurers are unlikely to pay for carbon-ion treatment. But hospitals will need operating revenues to pay off the loans they take out to build facilities. In Germany, the government paid half of the €120 million ($122 million) cost of the Heidelberg center. As the first in the country, Heidelberg was able to arrange agreements with insurers to pay for clinical trials, says Oliver Jäkel,



CHARGED-PARTICLE protons and carbon ions will deposit most of their energies at the target tumor site, leaving healthy tissue in front of and behind the lesion largely unscathed. X-ray beams begin to gradually lose energy soon after contacting the body. (Adapted from D. K. Ebner, T. Kamada, *Front. Oncol.* **6**, 140, 2016.)

head of the division of medical physics in radiation oncology at the German Cancer Research Center. The loan was paid off in seven years.

Considerable *in vitro* evidence shows that carbon therapy works, says Jäkel, but randomized clinical trials are difficult because of the length of time required to obtain meaningful data, around 10 years. Criteria for inclusion in trials is highly specific, and many trials don't conclude, because the number of patients is insufficient. Although centers could work better together, he says, there still aren't enough of them to supply a sufficient number of patients.

Joseph Lidestri, a physicist and engineer at Best Medical, says Japanese scientists haven't been given proper credit for the clinical research they have done with carbon ions, even if their trials haven't been randomized. "They did all the hard work for the last 30 years, and you have people who want to mystify carbon therapy and say we don't know enough yet. You just have to look hard, and you'll find it."

David Brenner, director of the Center for Radiological Research at Columbia University Medical Center, says he's been motivated in his research on heavy-ion therapy by the results from Japan on treating pancreatic cancer with carbon ions. Noting that survival rates for that cancer type, typically 25% to 30%, haven't improved over the past three decades, he says, "They've got numbers more like 60% for three-year survival."

With grants from NCI and New York State, Brenner's lab this year added a booster to its linac that will enable production of high-energy ions ranging in atomic number from helium to carbon. If the same long-range biological effects of carbon could be achieved with helium ions, he says, the size and expense of the accelerator required would be "inordinately" reduced. At 60 m in circumference and with tons of concrete needed for shielding, the synchrotron to be built by Mayo would be impossible to accommodate for hospitals in urban settings like Columbia's.

The Quantum Scalpel Project, which manages and operates Japan's Chiba carbon-ion-treatment hospital, says it is developing a carbon-ion system that, at 20 m × 10 m, could be installed in an existing hospital.

Painting tumors

Unlike photons, both protons and carbon ions lose most of their energy all at once at the end point of their transit. Known as the Bragg peak, the phenomenon allows a beam to be precisely tailored to the shape and depth of the tumor, leaving the healthy tissue in front of and behind the tumor largely unscathed.

But carbon-ion therapy deposits more energy than protons, producing a greater biological effect. Carbon ions produce multiple irreparable double-strand breaks in DNA, while protons create only single-strand DNA breaks, for which cells have

THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

TENURE-TRACK FACULTY POSITIONS IN EXPERIMENTAL AND THEORETICAL PHYSICS

The Department of Physics invites applications for several tenure-track faculty positions at the Assistant Professor level. An applicant must possess a PhD degree in physics or related field and provide evidence of strong research productivity. Appointment at Associate Professor level or above will also be considered for candidates with exceptional records of research excellence and academic leadership.

We seek experimental candidates in quantum matter and quantum information, including quantum and low-dimensional materials, materials with strong electronic correlations, cold atoms, quantum optics, and quantum enabled technologies. We also seek theoretical candidates in condensed matter theory, statistical physics, neural networks or data analytics.

Appointees are expected to assume teaching responsibilities for undergraduate and graduate courses, and to conduct vigorous research programs. Further information about the Department is available at http://physics.ust.hk.

Starting salary will be highly competitive and commensurate with qualifications and experience. Fringe benefits including medical and dental benefits, annual leave and housing benefits will be provided where applicable. The initial appointment prior to tenure will normally be on three-year contract terms. A gratuity will be payable upon successful completion of a contract.

Application Procedure: Applicants should submit their application including CV, cover letter, complete publication list, research statement, teaching statement, and three reference letters, via **AcademicJobsOnline.org** at:
https://academicjobsonline.org/ajo/jobs/16290

Please quote reference number "PHYS2509" in your application materials.

Screening of applications begins immediately, and will continue until the positions are filled.

repair mechanisms. In addition, carbon beams scatter less—just 3 mm at 27 cm depth in the body, the maximum required to reach most tumors—compared with 13 mm for protons, says Lidestri. That makes for a sharper scalpel and a smaller "lateral penumbra" of damage to surrounding tissue. It also permits more precise beam scanning—so-called painting—to cover the entirety of the tumor mass.

Both protons and carbon ions can treat complexly shaped tumors such as those growing around the spinal cord, where a dose distribution that has a hole in the center can be created, says Jäkel. Carbon-ion beams can be more precisely shaped. Other cancers where carbon treatment is indicated in Germany include skull and brain tumors and a type of salivary-gland tumor.

In Japan, carbon-ion treatment is indicated for a long list of tumors. As of March, of the 14 000 patients that were treated with carbon ions at the Chiba center, prostate cancer was by far the most common, followed by bone and soft tissue, lung, head, neck, lacrimal, pancreatic, and liver cancers and postoperative recurrences of rectal cancers. Prostate cancer, for one, generally responds very well to conventional radiation therapy.

Lidestri notes that 50% of all current cancer patients will receive some form of radiation therapy, and about 15–20% of them are candidates for proton therapy, he says. About 12–13% of proton candidates might better benefit from carbon ions, he estimates. "I'm very careful to say that carbon-ion therapy isn't a silver bullet. It's just a different tool."

One tantalizing implication from Japan's positive results with pancreatic-cancer patients is an observed long-term reduction in metastasis. "The relatively long time from first diagnosis implies that carbon ions are doing something that's improving the metastatic disease problem," says Brenner. "In general, radiotherapy is aimed at the primary tumor, and the goal is to eradicate the tumor cells. If carbon ions are doing something good in two or three years, that tells us that something different is going on."

Cancer grows because it can remain undetected by the immune system. In theory, the prevention of metastasis comes from the carbon-ion-induced double-strand breaks, which somehow create a new signaling path for the immune system to recognize cancer cells throughout the body, says Beltran.

But advanced cancer-treatment modalities other than carbon-ion therapy, including nonradiological ones, are also progressing. NCI has devoted "many millions" to support clinical trials comparing protons to photons, notes Buchsbaum, and it is currently funding four grants totaling between $20 million and $25 million over five years for studying helium- and carbon-ion beams in cells and animal models. NCI paid to have heavy-ion beams at Brookhaven and the Italian center qualified for those experiments. "NCI is supportive of carbon therapy; we've put a lot of money into the research," Buchsbaum says.

Nonetheless, he says, carbon ions need to be evaluated in the context of all other treatment types. "The rest of the world hasn't stood still. There's [chimeric-antigen-receptor] T-cell therapy, immunotherapy, drug therapy, and better surgery. Carbon therapy isn't competing in the same world as when Berkeley was doing experiments."

David Kramer

New telescopes seek the cosmic dark ages

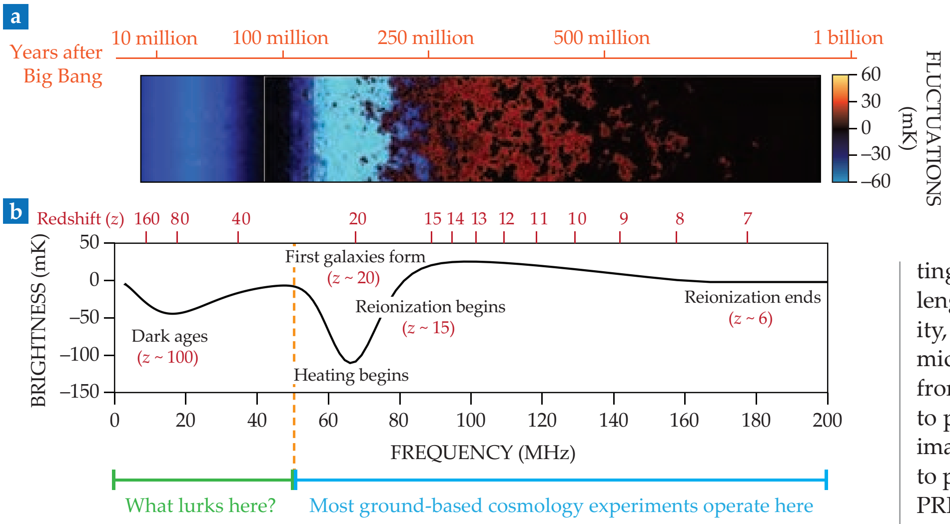
Radio astronomers look to far-flung locations to detect low-frequency signals that emanate from the ancient universe.

While reading an in-flight magazine article in 2016 about biodiversity on South Africa's Marion Island in the subantarctic Indian Ocean, the cosmologist Cynthia Chiang became intrigued by its remoteness and relative ease of access. Then a lecturer at the University of KwaZulu-Natal in Durban, Chiang submitted a proposal to the South African National Antarctic Programme to conduct the first astronomy experiment on the isolated island. The program, which typically supports climate, weather, and biodiversity studies at the island's research base, agreed to fund it. Now that ongoing experiment is part of a bigger effort to detect the faint, low-frequency radio signals that theorists predict would come from the earliest periods of the universe.

Shortly after the Big Bang, the universe cooled enough for the first neutral atoms to condense and release photons, creating the cosmic microwave background (CMB). Cosmologists refer to the interval between the formation of the CMB and the appearance of the first stars as the "cosmic dark ages." During that period, the universe consisted mostly of neutral hydrogen gas. As a hydrogen atom relaxes from one energy level to another through the flip of an electron spin, it releases a low-energy photon at a wavelength of 21 cm, corresponding to microwave radiation at 1420 MHz. As the universe expanded, that early radiation was redshifted to extremely low radio frequencies. Tuning radio antennas to detect the redshifted hydrogen line at frequency bands below 50 MHz is the only known way to map the distribution of matter in the dark ages (see figure on page 26).

Observing below 50 MHz presents a major challenge because the extremely faint signals are obscured by human-generated radio-frequency interference (RFI) and by radio noise from radiation in the Milky Way and the solar wind interacting with Earth's atmosphere. But it offers a big payoff: Radiation from the cosmic dark ages is unaffected by other astrophysical sources and could provide an untainted map of the early universe's structure. In contrast to the CMB photons, which all originated simultaneously, traveled to Earth uniformly from every direction, and provide a two-dimensional snapshot of the universe's surface at that moment, the dark ages signal contains 3D information. Because the hydrogen emitted radiation over a long period, measuring fluctuations in the signal can establish the distance to each point of emission.

Obtaining upper limits on 21 cm fluctuations during the dark ages could provide powerful constraints on theories about fundamental aspects of our universe, including inflation and exotic dark matter. The 2021 report *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*, by the National Academies



COSMIC DARK AGES. Probing the cosmic dark ages and the first several hundred million years of the universe's history involves detecting the redshifted 21 cm emission from the hydrogen that permeated the ancient universe. **(a)** This timeline shows the evolution of fluctuations in the 21 cm brightness. **(b)** This graph presents the frequency and average brightness of the redshifted 21 cm line in the universe's early epochs. (Adapted from J. Pritchard, A. Loeb, *Nature* **468**, 772, 2010.)

of Sciences, Engineering, and Medicine, stresses the importance of overcoming technology challenges that stand between us and several hundred thousand years of cosmic history. To detect those faint signals, experimental cosmologists are now taking steps to establish radio antennas in locations free of RFI, including in the Arctic, on the Moon, and in space.

Radio challenges

"When scientists first started doing 21 cm low-frequency astronomy, they described it as doing astronomy from the bottom of a swimming pool," says Jonathan Pritchard, a theoretical cosmologist at Imperial College London. That's because Earth's ionosphere reflects and refracts radiation at those frequencies. The result is a distorted, wobbly sky that makes picking out faint low-frequency signals nearly impossible.

One way to detect the redshifted 21 cm line is with a single dipolar radio antenna that measures the average signal over a large swath of sky. Complicating that technique are radio emissions from galaxies between the source and the receiver. It's hard to know if the signal is real, says Philippe Zarka, an astrophysicist at the Paris Observatory. "With just one antenna, galactic foregrounds are all mixed together."

The other established method to detect the 21 cm line uses an antenna array that measures the correlations of signals recorded by different antennas. "You can make resolved images of the sky, where you see the point sources," says Zarka. Analyzing power spectra of the sky background at different frequencies, after detecting and removing the foreground, he explains, could make it possible to detect fluctuations in the remaining cosmological signal.

Few telescopes have surveyed the radio sky at tens of megahertz. State-of-the-art ground-based measurements date from the 1950s, when pioneering radio astronomer Grote Reber caught glimpses of the 2.1 MHz sky at 5° resolution from an antenna array that he built in Tasmania. In 1974 the *Radio Astronomy Explorer-2* lunar orbiter made observations at 4.7 MHz with a resolution of 10°. And in 1976 and 1999, the Dominion Radio Astrophysical Observatory in Canada surveyed the northern sky at 10 MHz and 22 MHz, with 2° and 1.5° resolution, respectively. Modern radio antenna arrays can make observations with resolutions of less than 1° but only at much higher frequencies.

"Background noise has been the limiting factor for many surveys to date," says Chiang, who is now at McGill University in Montreal. Her Marion Island astronomy proposal led to a field study to measure emissions in a range of 50–150 MHz, corresponding to the time when hydrogen was beginning to heat up as the first stars formed. The name of the experiment was Probing Radio Intensity at High-Z from Marion, or PRI^{Z}M.

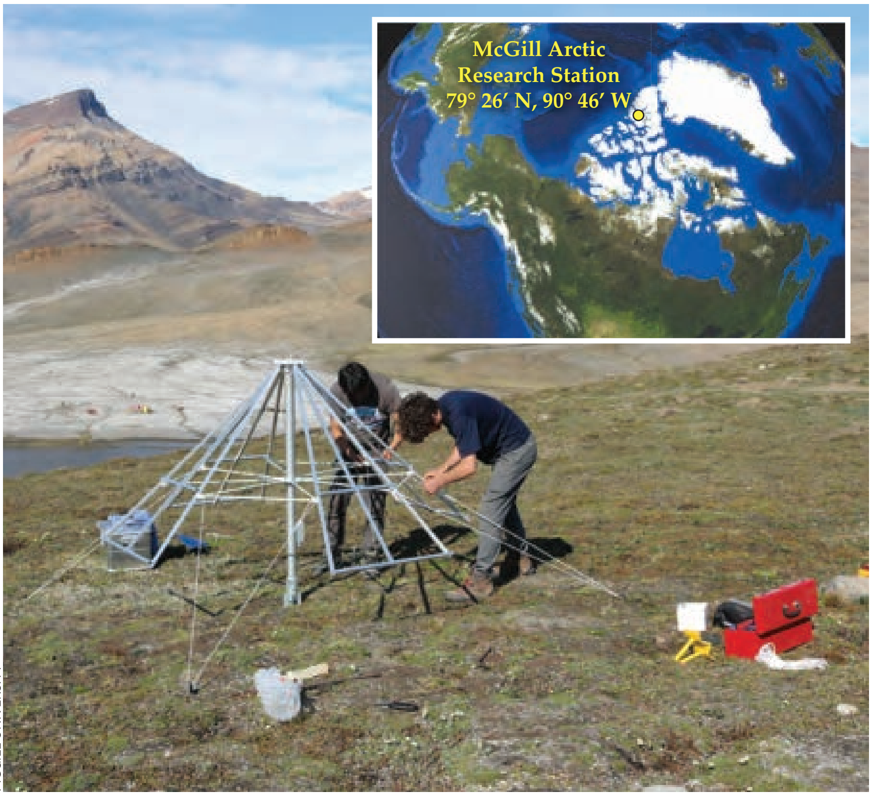
One of PRI^{Z}M's goals was to learn about RFI in the remote setting of Marion Island. Logistical challenges included once-per-year accessibility, harsh weather, and wire-chewing mice. But unparalleled low-RFI spectra from the experiment led Chiang in 2017 to propose an array of radio antennas to image the low-frequency sky. "We wanted to push toward the dark ages," she says. PRI^{Z}M led to the Array of Long Baseline Antennas for Taking Radio Observations from the Subantarctic, or ALBATROS.

Marion's quiet RFI environment and staff-supported research station made it ideal for ALBATROS. Pursuing yet more-remote locations, Chiang looked to expand the experiment from a latitude of 46° S in the subantarctic to the McGill Arctic Research Station, a seasonal field facility located on a Nunavut island at 79° N in northern Canada (see inset next page). Not only is the island far removed from terrestrial RFI sources, but the Arctic winter offers six months of darkness, without solar reflection from Earth's ionosphere.

With support from Natural Resources Canada's Polar Continental Shelf Program, the Canada Foundation for Innovation, and the National Sciences and Engineering Research Council of Canada, Chiang locked in a multiyear commitment in 2018 to set up 10 antennas at the McGill outpost. Making sure the instruments operate reliably is a challenge because "you can't have someone stay over winter in the Arctic to fix things," notes Taj Dyson, then an undergraduate at McGill who helped with the first test in Nunavut. (Dyson is now a graduate student at Stanford University.)

Off the grid

Chiang and her team began to build antennas based on a design originally developed for the Owens Valley Long Wavelength Array in California, and they added electronics to boost the response at low frequencies. The researchers installed the first two antennas this summer and intend to complete the array, consisting of the 10 antennas separated by up to 20 km, by 2025. A 2019 summer



MCGILL UNIVERSITY

STUDENTS INSTALL a dipole radio antenna at the McGill Arctic Research Station in the summer of 2019. The site is located 8 km inland at Expedition Fjord on the unpopulated Central Axel Heiberg Island of Nunavut (inset). The station consists of a small research hut, a cook house, and two temporary housing structures.

test run at the McGill Arctic Research Station established minimal human RFI from nearby sources. The only RFI detected was from the ionosphere.

During 2020 and 2021, the team developed an off-grid version of their antenna suitable for Arctic winter. On the Marion Island research base, solar panels and batteries could provide year-round electricity, but the dark Arctic winter precluded relying on solar power. So the researchers commissioned a specially designed hybrid system that combined solar panels and fuel cells and could power the antenna through an Arctic winter. Chiang and her team built a custom support structure (see photo at left) for the fuel cell case and solar panels that she "hopes will be able to survive being used as a scratching post by the occasional musk ox."

Because the Arctic wilderness cannot support power-hungry data servers, data storage poses another challenge for the team. Anticipating 100 terabytes of data each year for each antenna station, the researchers took a do-it-yourself approach and constructed shelves of hard drives plugged into a multiplexer. Each antenna will write to a drive until full, then switch that drive off and write to the next one. "Then we'll collect the hard drives and send home hundreds of terabytes in duffel bags," says Chiang.

Pritchard, the Imperial College cosmologist, expects valuable information about dark ages cosmology even if just one antenna survives the Arctic winter. "They'll learn a lot about what's going on in the ionosphere at these low frequencies and map galactic foregrounds in a way that will help with RFI removal more generally," he says.

To the Moon

While the Arctic may be one of the best places on Earth for radio observations, other researchers plan to take dark ages cosmology to the Moon. "Both terrestrial RFI and the ionosphere become negligible on the lunar farside surface," says Jack Burns, a cosmologist at the University of Colorado Boulder who works on the science and data analysis efforts on two

THYRACONT
Vacuum Instruments

Smartline PROFINET EtherCAT 4.0

Smartline Vacuum Transducers
Digital. Durable. Intelligent.

The digital vacuum gauges of the Smartline™ product family comply with OPC UA.

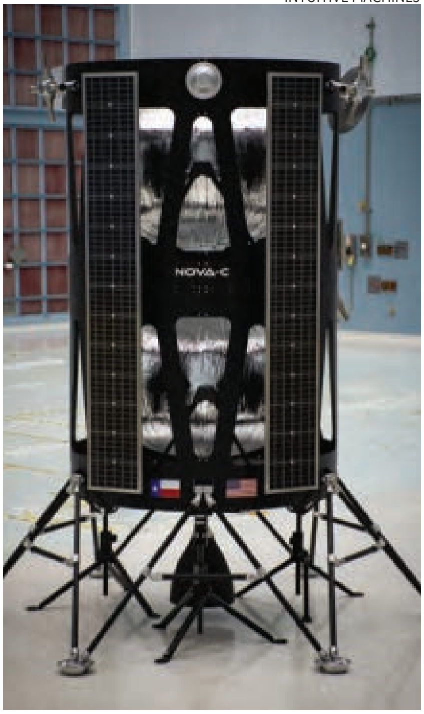
- **Measuring range:** 1200 to 5x10^{-10} mbar (900 to 5x10^{-10} Torr)
- **Output:** RS485 interface and 0-10 V, EtherCAT or Profinet interface
- **Optional LCD display**
- **Industry 4.0:** Smartline™ products support predictive maintenance

Visit us at Motek 2022: hall 1, booth 1908

INTELLIGENT VACUUM MEASUREMENT SINCE 1970

www.thyracont-vacuum.com

INTUITIVE MACHINES



THE *NOVA-C* lunar lander is scheduled to deliver a radio antenna to the Moon in early 2023 as part of a NASA project to peer into the universe's ancient past.

upcoming missions. Anticipating an RFI spectrum orders of magnitude cleaner than what's available on Earth, Burns and his colleagues in 2018 and 2019 successfully applied through a NASA program that has scheduled putting an antenna on the Moon by early 2023.

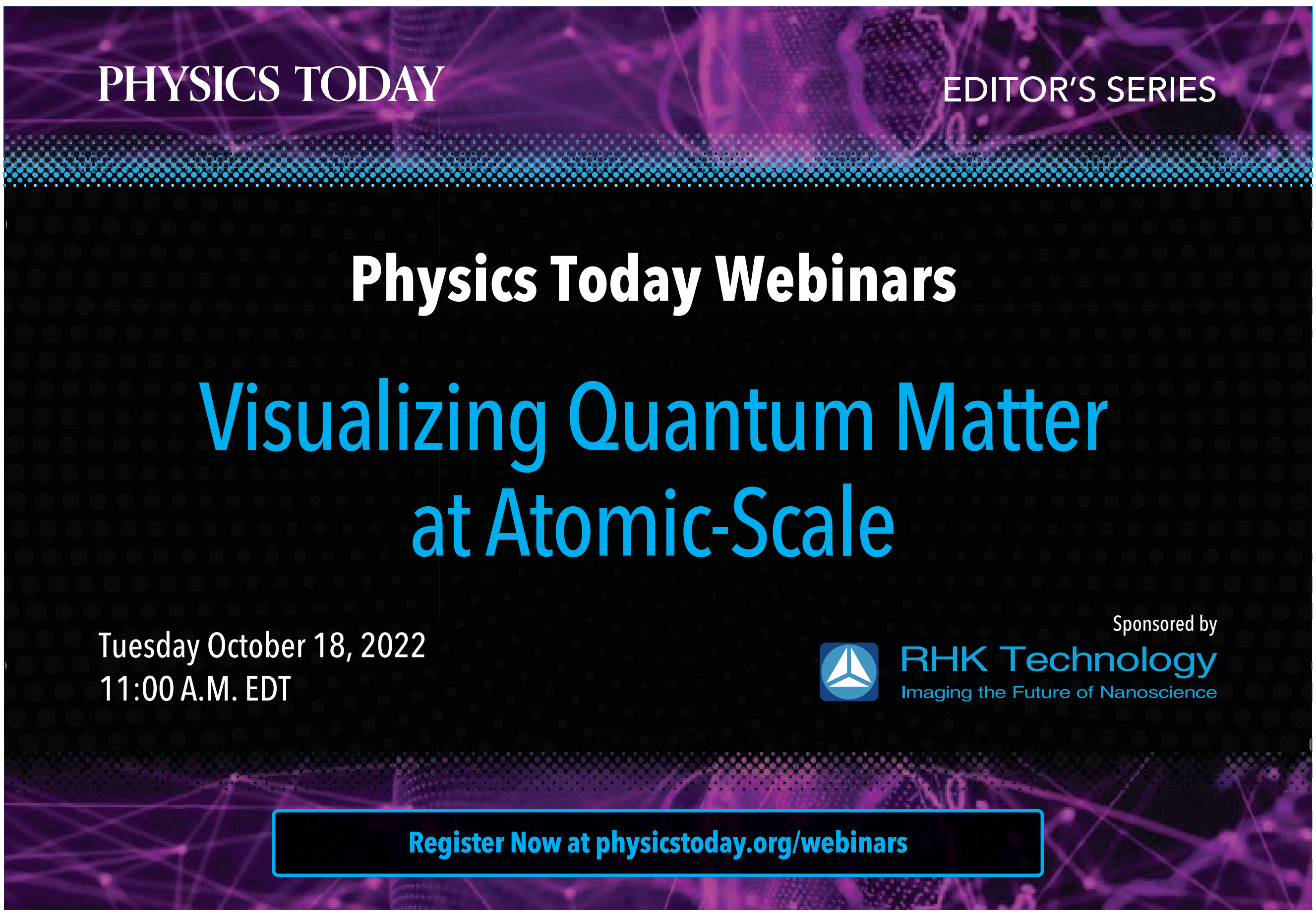
From a wide field of proposals, NASA's Commercial Lunar Payload Services project selected two proof-of-concept radio science experiments, led by Robert MacDowall at NASA's Goddard Space Flight Center and by Stuart Bale at the University of California, Berkeley. The first one will launch on a SpaceX Falcon 9 rocket to deliver instruments to the nearside of the Moon to investigate the solar-wind-induced plasma on the surface (see photo at left). The other experiment involves ferrying instruments for cosmological observations to the farside of the Moon, where batteries will power the antenna during the lunar night. Simulations have already identified potential radio-quiet landing sites with low RFI.

Yet another plan to measure the 21 cm line to study the dark ages involves launching satellites into lunar orbit. Xuelei Chen, a cosmologist at the National Astronomical Observatories of the Chinese Academy of Sciences, hopes to find even more ideal observing conditions in space. In addition to avoiding surface reflections, Chen points out one big advantage: "A satellite is simpler than a lander because you don't have to land!"

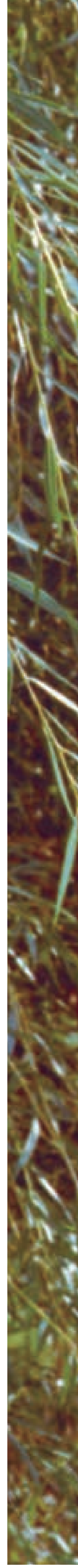
But space-based observations have their own challenges, including how to calibrate the proposed array of nine dipole antennas in orbit. And the orbiting antennas will require control over RFI generated by both the satellites and by the instruments themselves. Engineers also need to ensure efficient data communications between the satellites. And each satellite will require precise orbital-motion and flight information for interferometry calculations.

The sounds from the early universe will likely be very soft and easily lost in other noise. But according to Chiang, placing antennas in remote areas on Earth and in space will increase the odds of detecting an unambiguous signal that contains information about the origin of the universe.

Rachel Berkowitz PT


INITIAL
CONDITIONS
A Physics History
Podcast
Listen to weekly episodes wherever
you stream your podcasts.
aip.org/initialconditions

PHYSICS TODAY
EDITOR'S SERIES
Physics Today Webinars
Visualizing Quantum Matter
at Atomic-Scale
Tuesday October 18, 2022
11:00 A.M. EDT
Sponsored by
RHK Technology
Imaging the Future of Nanoscience
Register Now at physicstoday.org/webinars

Ronald E. Mickens is the Distinguished Fuller E. Callaway Professor Emeritus of Physics at Clark Atlanta University in Georgia. A mathematical physicist by trade, he has also published several articles and monographs on the history of Black scientists.



The trailblazing career of WILLIE HOBBS MOORE

Ronald E. Mickens

The first African American woman to earn a PhD in physics remains little known. But her legacy is enormous.

There was a time when I believed that Shirley Ann Jackson, who received her PhD in physics from MIT in 1973, was the first African American woman to attain that degree. I realized that view was incorrect around 1984, when I learned that Willie Hobbs Moore (1934–94) finished her PhD in physics at the University of Michigan in 1972. At that time, for more than a decade I had been collecting data on African Americans with advanced degrees in physics—and had even published a list of Black physicists. Needless to say, learning about Moore came as a welcome surprise for me.

The fact that Moore received her degree from Michigan was of additional interest to me because of the long-standing connection between its physics department and that of Fisk University in Nashville, Tennessee. While I was at Fisk, first as an undergraduate student in 1960–64 and later as a professor, the physics department had several faculty members who obtained their doctorates from Michigan, including Nelson Fuson in 1938, James Lawson in 1939, and Herbert Jones in 1959. Moreover, Elmer Imes, who received his BA and MA from Fisk in 1903 and 1915, respectively, became the second African American to earn his PhD in physics, from Michigan in 1918 (see my article in Physics Today, October 2018, page 28).

For some unexplained reason, Moore and I never ended up at a conference or workshop together. We never met! By the time I gained a better

Willie Hobbs Moore (left) with her daughter, Dorian, in the 1980s. (Courtesy of the Ronald E. Mickens Collection on African-American Physicists, AIP Niels Bohr Library and Archives.)

understanding of who she was, her research, her career in industrial research and management, her role as a mentor, and her community involvement, she had died of cancer. One of my greatest personal and professional regrets is that I didn't have the opportunity to meet her in person. I am certain that the two of us would have had much to discuss.

Over the past several decades, however, I have been in contact with several individuals who knew Moore (shown in figure 1), including family members, former students and mentees, and her PhD adviser. All of them provided a consistent narrative about her personality and how she dealt with others: They found her to be highly intelligent, witty, and quick to verbally respond to what we would now call microaggressions. They characterized her as being even-tempered, empathetic, kindhearted, and curious. They said she was an excellent teacher. Many of them recalled her large glasses, her fast-talking nature, and her mild, yet distinct, New Jersey accent.

FIGURE 1. WILLIE HOBBS MOORE, circa 1978. (Courtesy of the Ronald E. Mickens Collection on African-American Physicists, AIP Niels Bohr Library and Archives.)

My interests in the history of science have led me to write about many African American physicists. So when I found out that Moore was the first Black woman to receive a PhD in physics, I was curious about her family life and scientific accomplishments. Certainly, a knowledge of her life would be of importance to understanding the many roles that Blacks have assumed in helping to create the general collective culture of the US.

The year 2022 marks the 50th anniversary of Hobbs's PhD, so I can think of no better time to introduce Moore's impressive life and career to the readers of PHYSICS TODAY. She is an example of an African American woman physicist who succeeded as a researcher and administrator while simultaneously providing leadership and guidance to her family and community.

Early life

Willie Hobbs was born on 23 May 1934 in Atlantic City, New Jersey. Her father, William, was a plumber and small businessman, and her mother, Bessie, was a housewife and worker in a local hotel. Hobbs had two younger sisters, Alice and Thelma.

In high school, Hobbs was a straight-A student who was especially strong in mathematics and science. It was thus no surprise that her guidance counselor suggested that she continue her education in engineering. Although no one in Hobbs's extended family had ever received a college degree, she chose to attend the University of Michigan. Later, Hobbs credited her many successes to her close-knit and supportive family, stating that she and her two sisters were "raised with the expectation that they would always do their best."[1]

Hobbs arrived at Michigan in 1954, the same year that the US Supreme Court struck down legalized school segregation in the landmark *Brown v. Board of Education* case.[2] Entering the College of Engineering, she successfully completed the requirements to earn two degrees in electrical engineering: a BS in 1958 and an MS in 1961.

Although Hobbs had no difficulties in her academic studies and was generally held in high regard by her professors, she faced the same type of discrimination that generations of Black students had faced at US universities, including Michigan (see box 1), during the 20th century. About a year before graduation, for example, she encountered the chairman of another engineering college department. In response to her greeting, he stated, "You don't belong here. Even if you manage to finish, there is no place for you in the professional world you seek."[3] That comment vividly illustrates how even Black individuals who possessed advanced degrees were not guaranteed either academic or professional employment.

Family, finances, and employment

Hobbs's first job after finishing her master's degree was at the Bendix Aerospace Systems Division in Ann Arbor, Michigan. As a junior engineer in 1961–62, her duties included calculating the radiation from various types of plasmas and writing proposals. She followed that up in 1962–63 with a year at the Barnes Engineering Company in Stamford, Connecticut, where she worked on approximating the IR radiation from the wakes of space reentry vehicles.

"She had the ability to be taken seriously yet have fun; be firm yet flexible; stress accountability while reinforcing team ethics. As a manager, Dr. Moore accepted no excuses for incompetence and laziness."

On 17 August 1963, Hobbs married Sidney Moore, with whom she eventually had two children, Dorian and Christopher. Sidney had received a BS in mathematics from Jackson State University in Mississippi and an MS in educational psychology from the University of Michigan. He was a faculty member at Michigan's Neuropsychiatric Institute for 38 years before he retired in 1997. Dorian completed her bachelor's degree and MD at Michigan; Christopher received his undergraduate degree from Michigan State University.

The same year that she married Sidney, Moore returned to Ann Arbor to accept a job as a system analyst at Sensor Dynamics, where she was responsible for the theoretical analysis of stress-optical delay devices and reported to the vice president. She also made formal and informal presentations to company executives and visitors.

In 1965 Moore returned to the University of Michigan as a research associate at the Institute of Science and Technology, where she modeled optical hypersonic wakes and verified existing flow-field models. She also consulted with fellow employees to aid them in using existing techniques with which they were not familiar.

Moore's next move, in 1967, was to KMS Industries in Ann Arbor, where, as a system analyst, she was responsible for supporting the optics design staff and establishing computer requirements for the optics division. Only two years later, she left KMS to take a senior analyst position at the Datamax Corp in Ann Arbor. There, she headed the company's analytic group and evaluated the performance of company products. She was also involved in long-range planning with respect to library requirements, computer needs, and projected employee requirements.

One reason why Moore changed jobs so frequently during the 1960s and early 1970s was due in large part to the financial needs she faced in helping support a growing family. Another factor was her 1966 decision to return to the University of Michigan to begin working on a PhD in physics. She financed her education by working part-time at the university, KMS, and Datamax.

Graduate studies and later career

One year into her doctoral work, in 1967, Moore began studying under the renowned spectroscopist Samuel Krimm (see figure 2). Her PhD work centered on a theoretical study of the secondary chlorides in polyvinylchloride (PVC) polymers, which are the world's third-most produced synthetic plastic polymers. PVCs have a broad range of applications and are used, for example, in pipes, plastic bottles, packaging, plumbing, and phonographic records and as insulation for electrical cables.

In her dissertation,[4] Moore calculated the vibrational modes of several nonlinear organic molecules containing secondary chlorine atoms (see box 2). If a molecule contains N atoms, then there are $3N - 6$ vibrational modes and associated frequencies, each of which corresponds to a separate degree of freedom, which generally represents either a bond length or a bond angle. The molecule oscillates about the equilibrium values of those bond lengths or angles. Those generalized coordinates and their time derivatives can be denoted, respectively, by q_i and dq_i/dt, where $i = 1, 2, \ldots, N$. In the harmonic oscillator approximation, the kinetic energy T and potential energy V can be expressed as sums of quadratic terms in those variables. From those two expressions, the Lagrangian can be constructed as $L = T - V$, from which the equations of motion can be directly calculated.

If the values of q_i are selected properly, then the solutions to the equations of motion can be represented as sums of the periodic trigonometric functions whose arguments contain the vibrational frequencies and their associated phases. The coefficients of the kinetic energy terms can be directly calculated, but it is more difficult to determine the coefficients of the quadratic expressions for the potential energy. That information is generally derived from experimental data, which can be accomplished by fitting the theoretical values of the frequencies using a technique such as the method of least squares. That methodology requires both accurate data and expertise in various aspects of computational and mathematical sciences.

In her investigation, Moore aimed to obtain a complete potential field that could be used in normal coordinate analyses to predict the vibrational modes of all secondary chlorides. After she determined that potential field, she used vibrational spectroscopy to ascertain the structure of PVCs. With that data, she obtained and verified a force field for secondary chlorides and used it to calculate the vibrational frequencies of crystalline PVC.

"Dr. Moore emphasized the importance of understanding the cultural and political environment of working for a Fortune 500 company. . . . After every meeting with senior leadership [she] would ask us to summarize not the meeting but rather provide our perceptions of the participants. . . . We realized that once we understood the political undercurrents, we were able to navigate much easier."

FIGURE 2. THE SPECTROSCOPIST SAMUEL KRIMM WAS Moore's doctoral adviser at the University of Michigan. He and Moore coauthored several papers on secondary chlorides. (Courtesy of Samuel Krimm and the AIP Emilio Segrè Visual Archives.)

Box 1. Michigan's legacy of discrimination

Willie Hobbs Moore was only one of many Black students to face discrimination at the University of Michigan. (And in that regard, Michigan was far from unique.) An illustrative example is the situation that confronted John Franklin, who studied chemical engineering at Michigan in the late 1940s and early 1950s. In a 2016 letter to Michigan's dean of engineering, the African American aerospace engineer Alec Gallimore, Franklin recalled how the discrimination he had faced at the university led him to change careers:

> I have never told this story to anyone before but I will tell you. I was standing outside and I heard this professor telling to another one "black students are inferior and have no place in this school." I turned to him and said "you do not know what the hell you are talking about." I did not know that he would be my thermodynamics professor. He gave me a D+ which I knew I didn't deserve. Thanks to the Dean and the faculty, they voted not to have me repeat the course because of my high grade average.
>
> Other students, with lower grade averages, were invited to join the honor society but not me.
>
> I could not get a job as an engineer, so I went to medical school.[8]

Upon completing her PhD in 1972, Moore stayed at Michigan in a postdoctoral position in the department of physics and the Macromolecular Research Center from 1972 to 1977. During that period, she, Krimm, and several other collaborators published more than 13 papers on their research. When I corresponded with Krimm in 1999, he recalled Moore as "an intelligent and creative person [who] always had a positive attitude and showed it in her approach to problems that arose in research, moving purposefully to solve them." He believed that if not for "financial considerations she would undoubtedly have progressed in the academic area."

In 1977 Moore accepted a position as an engineer with the Ford Motor Company. After a series of promotions, she advanced to the executive level. A highlight of her career was the significant role she played in extending the use of Japanese-style manufacturing and engineering methods at Ford in the 1980s. That effort was codified in a 1985 book she wrote jointly with Yuin Wu, titled *Quality Engineering Products and Process Design Optimization*, which explains the application of the "robust design" methods of Japanese engineer Genichi Taguchi.[5]

Moore, the person

Although I never had the opportunity to meet or communicate with Moore, I have discussed her life and career with several individuals who knew her as a friend or colleague. All of them gave similar evaluations and recollections of their experiences with Moore. Carla Traci Preston, for example, first met Moore as an 18-year-old engineering student intern at Ford. She went on to hold a range of managerial positions at the company and was employed there for 15 years. In a 2004 email, she stated that Moore was "one of the most significant and influential people in my life." (The pull quotes throughout this article are from Preston's reminiscences of Moore.)

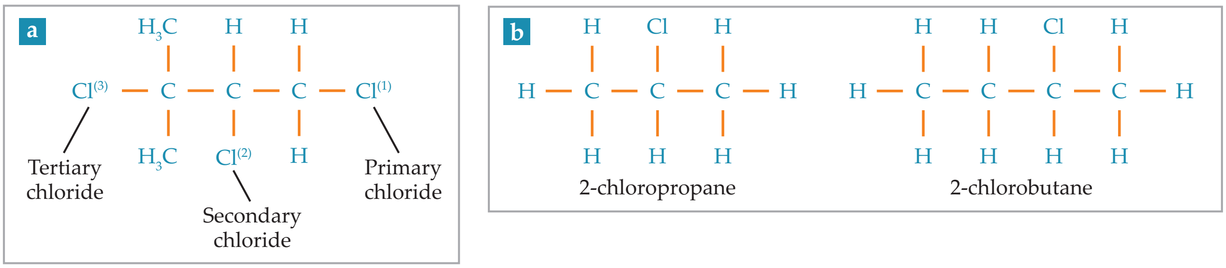
Moore also left a mark on Donnell Walton. Currently a director at Corning Inc, Walton got to know Moore through her tutoring work while he was a graduate student in applied physics at Michigan. He and Moore quickly forged a wonderful friendship. The two often had lunch with other Michigan graduate students in science and engineering. As he explained to me in a 1999 letter, those lunches often included "countless debates on the design of experiments and the education of engineering and graduate students." It came as a major shock to Walton when Moore died not long after they first met.

Moore's personal mantra was "You've got to be excellent."[6] She and her husband, Sidney, taught their children (seen in figure 3) to not use their "blackness as an excuse not to excel. No excuses. But sometimes when you teach that without balancing it with the unfairness of the real world, we do our chil-

FIGURE 3. MOORE (front row, right) with her husband, Sidney (front row, left); her children, Dorian (second row, middle) and Christopher (second row, left, with flower); and two family friends. (Courtesy of the Ronald E. Mickens Collection on African-American Physicists, AIP Niels Bohr Library and Archives.)

Box 2. Secondary chlorides

A complex organic molecule containing a chlorine atom chemically bonded to a carbon atom is termed primary, secondary, or tertiary, depending on how many other carbon atoms are bonded to that carbon atom. In the molecule depicted in panel a, for example, $Cl^{(1)}$ is bonded to a carbon atom that is bonded to only one other carbon atom, which means that $Cl^{(1)}$ is a primary chloride. $Cl^{(2)}$ is bonded to a carbon atom that is bonded to two other carbon atoms, so $Cl^{(2)}$ is a secondary chloride. Because $Cl^{(3)}$ is bonded to a carbon atom that is bonded to three other carbon atoms, it is a tertiary chloride. Panel b illustrates two of the secondary chloride compounds investigated in Moore's research, 2-chloropropane (C_3H_7Cl) and 2-chlorobutane (C_4H_9Cl).



dren a disservice."[7] She always insisted, however, that failure was not an option.

Moore was active in several community clubs and organizations in Ann Arbor, particularly those concerned with the education of Black youth. She contributed many of her efforts to tutoring and teaching at the Saturday Academy for African American Students, a community-run program that provided science and mathematics instruction for children in primary and secondary schools.

Moore was also an active member of several national organizations founded by college-educated Black women and dedicated to public service. They included the Delta Sigma Theta sorority, the Links, and Jack and Jill of America. All three groups support programs that assist the African American community. A person of faith, Moore was a member of Ann Arbor's Bethel African Methodist Episcopal Church. After a long fight with cancer, Willie Hobbs Moore died on Monday, 14 March 1994, in her Ann Arbor home.

Legacy

Moore's legacy is impressive. First and foremost, she was an extremely productive and creative scientist. Second, her personal skills helped her effectively manage a broad range of projects at several corporations. Finally, she was active in numerous community-based programs that helped enhance the educational, social, financial, and political status of African Americans in Ann Arbor.

Her accomplishments were widely recognized. In 1991 *Ebony* magazine named her one of the 100 most promising Black women in corporate America. And in 1995 she was posthumously given the inaugural Edward Bouchet Pioneer Award by the National Conference of Black Physics Students.

On 17 March 2004, a symposium was held at the University of Michigan in honor of two prominent Black physics alumni: Elmer Imes and Moore. The keynote address was given by John Marburger III, science adviser to then-president George W. Bush. Michigan's president, Mary Sue Coleman, also gave remarks. During the symposium, Krimm gave a talk about the joint research he and Moore carried out in the 1970s, and I presented a summary of Imes's research, career, and family.

> **"Dr. Moore also taught us that if we plan for the long term, expect the unexpected and prepare to modify/revise the plan as needed. Always have a goal in mind and once you achieve it, celebrate the accomplishment, but move on to the next goal."**

In 2018 Michigan's electrical and computer engineering department established an alumni lecture in honor of Moore. The lecture recognizes graduates from traditionally underrepresented groups who are leaders in their field and serve as role models for the engineering community because of their leadership, impact on society, and service.

This essay is adapted and expanded from my article "Willie Hobbs Moore (1934–1994)," in Notable Black American Women, Book III, *J. C. Smith, S. Phelps, eds., Gale (2003), p. 443.*

REFERENCES

1. D. M. Green, *The Michigan Engineer*, Winter 1994.
2. Center for History of Physics at AIP, "Willie Hobbs Moore: The First African American Woman to Earn Her Ph.D. in Physics" (Summer 2014).
3. Ref. 1.
4. W. H. Moore, "A vibrational analysis of secondary chlorides," PhD thesis, U. Michigan (1972).
5. G. Taguchi, *Introduction to Quality Engineering: Designing Quality into Products and Processes*, Asian Productivity Organization (1986).
6. C. Lorentson, "Spotlight on women in electrical engineering history: Willie Hobbs Moore," PowerStudies Inc (25 October 2017).
7. R. Grantham, "A Driving Force at Ford," *Ann Arbor News*, 4 February 1991.
8. *The Michigan Engineer*, Spring 2017, p. 8.

PT

FINDING THE RIGHT PROGRAM FOR YOU

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

Find Your People and Grad Program at the 2022 Physics Congress

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

Samantha Pedek, 2022 Program Co-chair

Samantha Pedek

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

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

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

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

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

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

NETWORKING TIPS

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

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

BE AN SPS INTERN

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

www.spsnational.org/programs/internships.

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

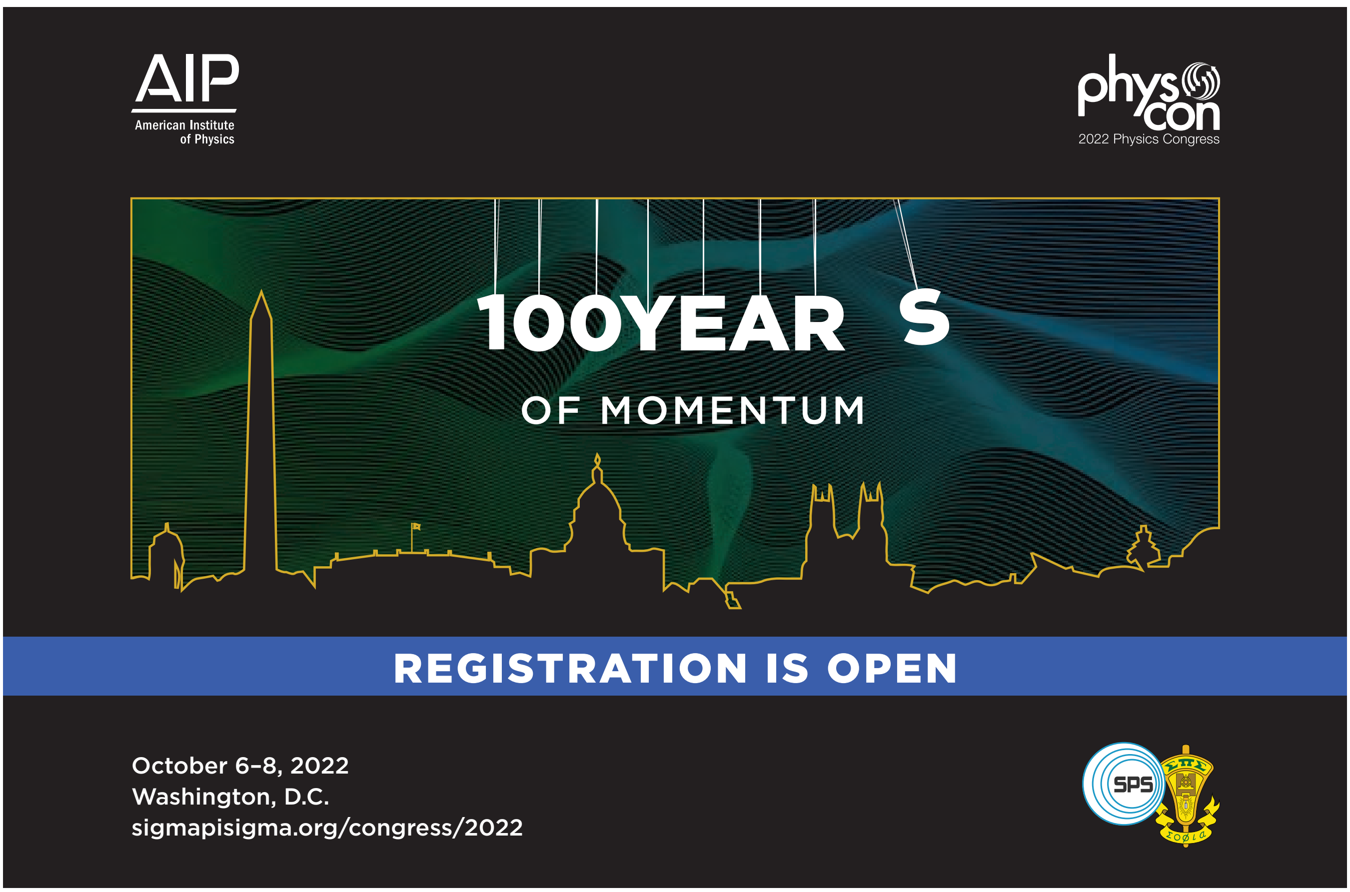
A more subtle opportunity to build your network as a young professional is to engage with attendees you don't already know, between events or at meals. Shuffling between workshops, plenaries, and banquets will be hundreds of people with lived experiences similar to yours. Be adventurous and sit at a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

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

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

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

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



ELECTRIC PROPULSION OF SPACECRAFT

NASA/GRC

Igor Levchenko is a research scientist at the Plasma Sources and Applications Center at Nanyang Technological University in Singapore. **Dan Goebel** is a fellow and senior research scientist at NASA's Jet Propulsion Laboratory at Caltech in Pasadena, California. **Katia Bazaka** is a professor in the College of Engineering and Computer Science at Australian National University in Canberra.

Igor Levchenko, Dan M. Goebel, and Kateryna Bazaka

The electrification of spacecraft could significantly extend the useful life of billion-dollar missions in outer space.

The worldwide effort to decarbonize energy systems has set the stage for an era of electrically driven mobility. Cars, buses, heavy trucks, and trains are increasingly switching to electrical propulsion. Drones are already in the air and plans are underway for electric flying taxis to revolutionize personal and on-demand transportation systems.[1] Denmark and Sweden are preparing to replace their domestic fleet of airplanes with fossil-fuel-free versions by 2030, when all-electric 186-seat passenger airplanes will enter into service. Before then, smaller, 100-seat Wright Spirit electric airplanes[2] are due out in 2026.

Electrical pump-feed rocket engines have also made their way into launch systems. Indeed, five years ago Rocket Lab used that technology to deliver to orbit a commercial payload of several satellites. Many small satellites already use electric propulsion thrusters in space, with SpaceX's Starlink constellation being the most prominent example. (See references 3 and 4 to learn more about thruster designs and applications on various types of spacecraft.)

Yet many more space assets—from small probes and satellites to large spacecraft—continue to rely on conventional chemical-based propulsion. For now, the electrification of in-space mobility systems lags behind that of Earth systems. But that may soon change.

Longer life means better value

Many electric propulsion systems intended for outer space have already been proved efficient and reliable.[5] If implemented on future missions, those systems could extend the life of prominent, billion-dollar space programs. Examples abound of programs currently limited by chemical-propulsion capabilities. Launched in 2009 with only 12 kg of chemical fuel, the *Kepler* space telescope, illustrated in figure 1, had to stop its search for exoplanets after nine years in deep space because it no longer had hydrazine propellant. (The mission was renamed *K2* in 2014 after NASA had to stabilize the spacecraft's pointing.) *Kepler*'s thrusters used that fuel to correct its drift and maintain the telescope's orientation toward a specific target and its data transmission to Earth.[6] All other systems, including *Kepler*'s solar-cell-based power, still operated normally.

Like the *Kepler* mission, the *Dawn* mission was forced to end when it depleted the chemical propellant used to orient its solar panels toward the Sun and its communication instruments toward Earth.[7] *Dawn* (illustrated in figure 2) was launched in 2007 and cost nearly a half billion US dollars. It was NASA's first science mission to use solar-electric-powered ion thrusters (see box 1) and reach two of the largest objects in the asteroid belt—the dwarf planet Ceres and the protoplanet Vesta—to collect priceless data on the formation of our solar system.[8]

Dawn would have had to burn more than 6000 kg of on-board chemical propellant to reach and orbit those asteroids. Fortunately, it accomplished both by sending only 400 kg of xenon propellant through the electric thrusters. That design decision significantly reduced the size of the launch vehicle and the cost of the mission. Had the *Kepler* and *Dawn* missions been configured with an all-electric-propulsion system—either a modern ion or Hall thruster system, for instance—it's likely that both would still be able to continue their cutting-edge research into the next decade.

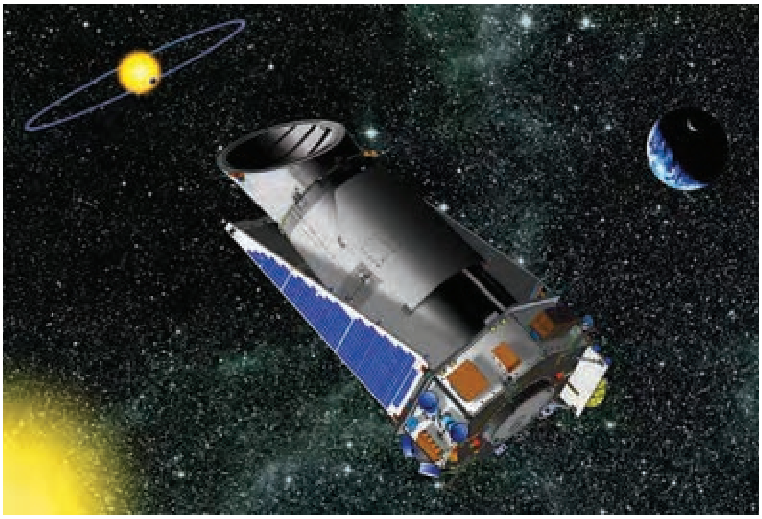


FIGURE 1. THE *KEPLER* SPACE TELESCOPE, shown here, ceased its operation in 2018 because it had run out of hydrazine propellant**.** As a result, *Kepler* could no longer point with the accuracy needed to continue its original mission. Electric propulsion systems would have avoided that problem. They consume much less propellant per unit thrust and produce much higher specific impulse. (Courtesy of NASA.)

Although 10 years may seem like a long time for a spacecraft to operate, their financial costs typically are on the scale of billions of dollars. And their development spans many years; in fact, it often takes decades to design and build them. One of the most famous space-based systems, the *Hubble Space Telescope*, has been subject to five manned servicing missions since its launch in 1990. The last of those missions extended its life past 2020. But sending a service mission to refuel the *Kepler* space telescope is technologically out of the question—at least for now. As it follows an Earth-trailing trajectory, *Kepler* will reach the other side of the Sun by 2035, putting it effectively out of reach. For missions like *Kepler*, using more efficient electric thrusters would have been the most logical way to extend their lifetimes.

Even for *Hubble*, its remaining hydrazine fuel is only sufficient to maintain target alignment for a few more years. Its hydrazine thrusters are also not powerful enough to raise *Hubble* from its orbit of 568 km, and the telescope could potentially spiral back to Earth by 2028. Importantly, *Hubble* uses reaction wheels and magnetic torquers—devices that interact with Earth's magnetic field but do not require any fuel—for orientation control. Even so, the devices are efficient only at low orbits, where the magnetic field is relatively strong. An efficient

FIGURE 2. *DAWN* was NASA's first deep-space mission that used electric propulsion to reach and orbit two bodies in the asteroid belt—Vesta and Ceres. The spacecraft's gridded ion thrusters used 400 kg of xenon to accomplish the mission. Chemical thrusters would have required more than 6 tons of additional fuel. (Courtesy of NASA.)

electric propulsion system capable of raising the orbit could have kept it active for several more years, perhaps long enough for the next generation of manned space systems to become available for another service mission.

Improved stability and control

Beyond the low fuel efficiency and other challenges intrinsic to chemical-based space thrusters, many proposed future missions cannot be realized using traditional, thermodynamics-based thrust systems.[9] Colonizing Mars and establishing other distant outposts require fast and reliable transportation of large manned and cargo spacecraft over millions of kilometers. As with *Dawn*, using electric propulsion for those missions can potentially reduce the amount of propellant that has to be launched into space by nearly an order of magnitude.

On the other end of the spectrum in mission size is an emerging industry of ultrasmall spacecraft known as CubeSats. A few kilograms in size, they fly in formation or as constellations that require equally small thruster systems. Those systems must not only be efficient but also deliver thrust with unprecedented precision. That's also critical for space-based observatories sensitive enough to capture faint signals, such as ripples in spacetime, and provide data to help solve other curiosities of the universe, including how the quantum vacuum works and the mysteries of repulsive gravity and negative energy.

China's Taiji mission and the European Space Agency's LISA (Laser Interferometer Space Antenna) mission are examples of formation-flying, network-based space observatories. To a large extent, their success will depend on the ability of individual satellite probes to maintain their position and orientation with respect to the source of a target signal and to each other while millions of kilometers apart.[10]

Both missions' satellites have drag-free control with ultrahigh precision and ultrastable operation that cannot be achieved by hydrazine thrusters. Other types of conventional thrusters, such as cold-gas systems, do not have the level of specific impulse and control needed to sustain for years the propulsion requirements of those systems. Not surprisingly, the recently launched *Taiji-1* powered by ultrasmall, high-precision electric thrusters, and *LISA Pathfinder*, shown in figure 3, demonstrated precision attitude control using an

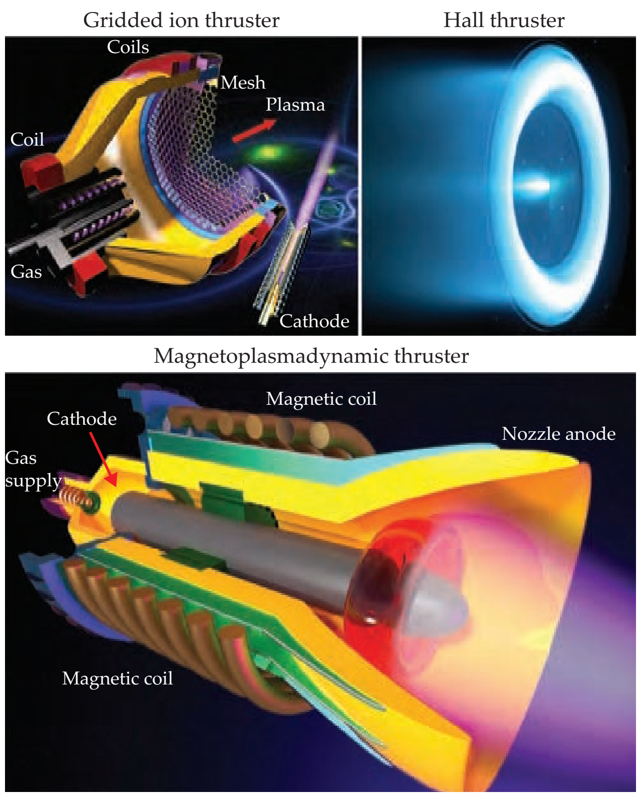
Box 1. Electric propulsion thrusters for space missions

Space electric propulsion systems can be broadly classified as electrothermal, electrostatic, and electromagnetic. Each type of thruster fills an important niche, as the entire spectrum of electric propulsion technology spans five orders of magnitude in power and about two orders of magnitude in specific impulse—the exhaust velocity of the propellant.[17]

Electrothermal thrusters are the simplest system, using thermodynamic principles of gas acceleration in nozzles. As a result, they feature a relatively low specific impulse, though it is usually higher than that of corresponding chemical systems. Among electrostatic thrusters, two types are considered mature, space-proven technologies: the gridded ion thruster (top left, adapted from I. Levchenko et al., *Nat. Commun.* **9**, 879, 2018) and the Hall thruster (top right, courtesy of NASA). In the gridded ion thruster, propellant gas is ionized in a magnetized chamber and the ions are accelerated by two or more high-voltage (mesh) grids that provide thrust. A cathode mounted outside the thruster provides electrons to neutralize the ion beam and avoid charging the spacecraft.

In the Hall thruster—named after US physicist Edwin Hall—the propellant ionized in the annular channel is accelerated by crossed electric and magnetic fields to produce thrust. As in the case of the gridded ion thruster, a cathode is needed to ionize the propellant gas and to neutralize the ion beam. The cathode could be installed outside the chamber or in the center of the thruster. The Hall thruster includes several magnetic coils and an integrated magnetic circuit (neither of which are shown) to ensure that the magnetic field is properly oriented in the acceleration chamber.

In electromagnetic thrusters, the propellant is accelerated in the form of quasi-neutral plasma. That method stands in contrast to electrostatic thrusters, which accelerate ions or electrically charged particles. As a result, electromagnetic thrusters, unlike gridded ion thrusters, are not limited by electric space charge. Several types of electromagnetic thrusters are currently under consideration. They include pulsed thrusters, magnetoplasmadynamic (MPD) thrusters, and helicon thrusters. Importantly, MPD thrusters, such as the one shown in the bottom image (adapted from I. Levchenko et al., *Phys. Plasmas* **27**, 020601, 2020), promise to generate high thrust at high power—up to 10^5 W—and hence could be considered for cargo and personal transportation missions to Mars.



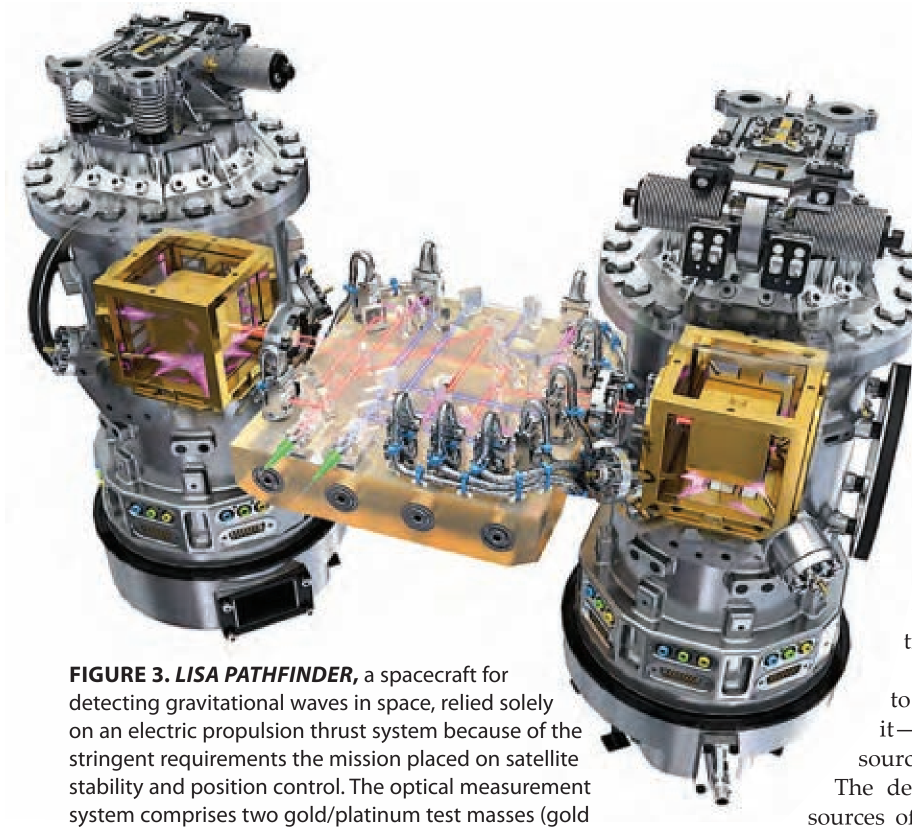


FIGURE 3. ***LISA PATHFINDER*****,** a spacecraft for detecting gravitational waves in space, relied solely on an electric propulsion thrust system because of the stringent requirements the mission placed on satellite stability and position control. The optical measurement system comprises two gold/platinum test masses (gold cubes), each enclosed within an electrode housing in compact vacuum chambers. The optical bench of the laser interferometer is arranged between the test masses. (Image courtesy of the European Space Agency/Medialab.)

electric propulsion colloid-thruster system.[11] *LISA Pathfinder* was launched in 2015 and operated until 2017.

The unique demands of those new ambitious missions—and a significant increase in the population of small satellites during the past decade (see figure 4)—may provide the impetus necessary to drive wider electrification across all sizes of space-thrust platforms.

Barriers to adoption

The path to higher-efficiency, lower-cost missions is not without its challenges. Electric thrusters were first used roughly 60 years ago, but their use was limited until about 20 years ago by the lack of sufficient electrical power on spacecraft. Since that time, improvements in the efficiency and size of solar arrays have increased the power available on both communications satellites and deep-space spacecraft to more than 20 kW. NASA's next solar-electric mission, the Gateway space station, will include the Power and Propulsion Element (PPE), which will likely have a 60 kW solar array to power the transport of cargo to the Moon and ultimately to Mars. Ion and Hall thrusters now routinely run at power levels of 1.5–5 kW and are in development to run at 12.5 kW for the PPE and up to 20 kW for prototypes at NASA's Glenn Research Center, so power and thruster technology finally exists that can take advantage of electric power available in space.

Another issue is thruster lifetime and energy storage. The satellite communications industry has embraced electric thrusters for on-orbit station-keeping of geostationary communications satellites because they reduce the amount of propellant needed by a factor of 5 to 10 to provide the required 15-year satellite life. But the application can handle only about an hour of thrusting per day.

Providing 5 kW of power, modern lithium-ion batteries have plenty of capacity to run electric thrusters in most station-keeping applications. One major benefit of the batteries is that they allow the thrusters to make the orbital adjustments required to insert a satellite into its assigned orbit. That orbit-raising function requires operating a thruster for hundreds to thousands of hours at a time. No other battery technology is currently available—or even foreseen—that can provide such energy. Likewise, for most propulsion applications in deep space, the thrusters must run for weeks to years at a time, with lifetimes in the tens of kilohours.

Thus all-electric spacecraft will need either to generate electric power on-board or to receive it—in a form known as beamed energy—from a source that may be millions of kilometers away.[12] The development of compact, light, and efficient sources of electric energy on a spacecraft is far from trivial. Similarly, beaming energy across vast distances requires exceptional pointing precision to minimize losses and on-board infrastructure to convert an incoming beam of light into electrical energy.

Solar cells that use novel materials and advanced architectures currently represent the best and most widely used means of on-board energy generation. Even at their maximum output, however, conventional solar panels are unlikely to supply enough energy to meet all the energy needs of future satellites throughout the solar system. Simply increasing the size of the panels will increase a satellite's mass, can render it more cumbersome to maneuver, and may restrict the field of view for on-board instrumentation.

Despite plans to construct large solar arrays capable of delivering hundreds of kilowatts of power near Earth for cargo and manned missions, exploring deep space and remote planets using solar panels is infeasible. The reduction in available light to power the spacecraft becomes simply too significant as it moves away from the Sun. (See examples of Sun-powered electric-propulsion-driven deep-space missions in box 2.) Thus missions to deep space and remote planets would require sources of electric power other than solar cells.

The most obvious alternative source of power for deep-space missions is nuclear systems. Yet scaling down fission reactors to a realistic size and mass while maintaining low specific power—the electrical output power divided by the mass of the power system—has been difficult and expensive to achieve. Flying nuclear reactors seem unlikely anytime soon unless substantial investments are made to mature the technology for space applications and change public perception about its safety. The NASA SP-100 (space-reactor prototype) program was supposed to design a fission reactor to become a standard deep-space power system, but it was canceled partly because of its high cost.

Other concepts based on thermonuclear fusion systems may provide solutions for high power in deep space and reduce the travel time of missions by nearly half. But developing them assumes that fusion technology can be perfected on the ground and transferred into space in a reasonable time and cost. One of the main motivations for research into nuclear power for space propulsion is the considerable energy-density gain that can be realized with nuclear fuel in place of conventional chemical combustion.[13]

Advanced propulsion systems using high-power solar arrays, beamed energy, or nuclear fusion could help to achieve NASA's plans for a manned Mars mission. The reduced travel times would effectively cut the harmful effects of space travel, such as radiation and weightlessness, on the crew. What's more, the ability of a nuclear engine to supply both power and propulsion makes it suitable for a broad range of space missions—robotic and manned.[14]

Apart from those energy issues, the high price of commonly used xenon propellant—currently more than \$2000 per kg—is also a problem. Not surprisingly, SpaceX's Starlink network uses krypton, which is not as efficient as xenon and requires much larger tanks to store the same mass, but it is much cheaper. Another approach is to use sublimating solid propellants such as iodine, which is predicted to make the whole system simpler and less expensive. Two of us (Levchenko and Bazaka) recently reported on the first demonstration in space of an iodine thruster designed by a team led by Trevor Lafleur and Dmytro Rafalskyi (see "For an efficient electric propulsion system, use iodine," PHYSICS TODAY online, 2 December 2021),[15] and we expect further efforts to implement the solid propellant. The Massachusetts-based Busek company already sells iodine-propellant thrusters.

Another challenge for the wider adoption of electric propulsion platforms in deep-space missions is the obvious requirement for safety and reliability. That requirement sometimes warrants opting for simpler, well-proven systems at the expense

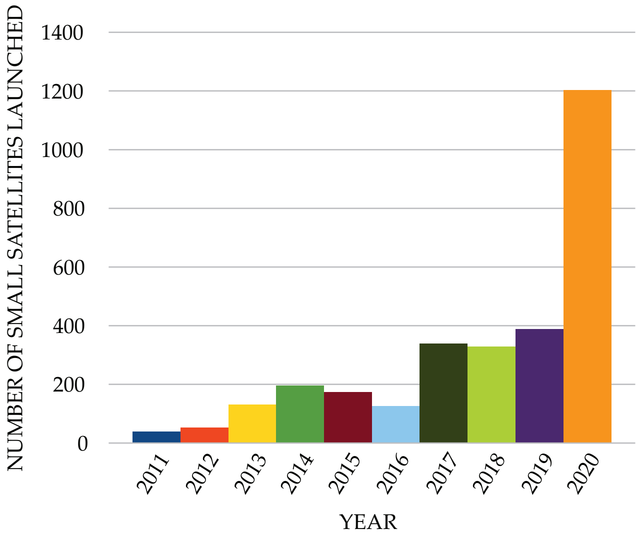


FIGURE 4. THE NUMBER of small satellites launched worldwide each year grew dramatically between 2011 and 2020. (Data are from E. B Salas, "Number of small satellites launched worldwide 2011–2020," Statista, 2021.)

Box 2. Electric thrusters in deep space

Like multiple-satellite systems, such as Starlink and OneWeb, which operate at low-Earth orbits, several deep-space missions are also using electric propulsion thrusters. One of them, the *Psyche* mission, is NASA's next deep-space science probe, designed to investigate a unique metal-rich asteroid about 200 km in diameter. The spacecraft is equipped with huge solar panels, each one 75 m^2 in area, that are capable of powering Hall thrusters 500 million km from the Sun. Scheduled for launch in the next two years, the mission will cruise through outer space for three to five years before looking deep into the history of terrestrial planets.

BepiColombo is a joint international mission between the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) that was launched in 2018. It is currently performing flybys of Mercury, which it will orbit starting in 2025 and begin a complex investigation using two orbiters, one built by ESA and the other by JAXA. The interplanetary trip is supported by four gridded ion thrusters, each capable of consuming up to 4.5 kW of electric power supplied from two 14 m solar panels.

The Power and Propulsion Element is another example of a solar-powered electric propulsion system. With a total mass of 8 tons and 60 kW of electric power, it is scheduled to be launched in 2024 and will operate as part of Gateway, a future international space station orbiting the Moon. The spacecraft's solar arrays will supply electric power to station equipment, and its Hall thrusters will deliver the system to lunar orbit and are capable of changing the station's orbit around the Moon. Testing near the Moon will determine whether similar systems could be used to explore Mars.

of their efficiency and cost. Moreover, all deep-space missions go through years of design work. During that process, many trade-offs are made between various systems, including electric and chemical propulsion. To cite one example, for the *New Horizons* mission—the first probe to Pluto—scientists selected chemical systems for its onboard propulsion.

Where to from here?

Electric propulsion thrusters offer several exciting opportunities that have not been sufficiently embraced by current R&D communities. More work is needed in the following areas:

▸ Higher thrust efficiency produced by higher-power, long-lived electric thrusters to support planned manned expeditions and cargo missions to Mars and possibly other celestial objects.[16] That goal requires developing the next generation of high-power ion and Hall thrusters and alternative electric thruster technologies, such as magnetoplasmadynamic thrusters, to provide the desired combination of high power, high specific impulse, low mass, and small size.

▸ Ultrahigh precision in controlling the thrust with ultralow noise for highly sensitive space astronomical observatories and for fine satellite control within formation-flying constellations.

▸ Ultracompact electric thrusters for controlling small satellites—particularly those with masses less than 10 kg—to make them capable of active maneuvering, formation flying, and orbit change.

▸ Alternative power sources in space beyond solar power, such as nuclear or beamed-power systems coupled to high-power electric propulsion systems.

REFERENCES

1. T. Bowler, "Why the age of electric flight is finally upon us," *BBC News*, 3 July 2019.
2. E. Garay, "Electric planes are coming sooner than you think," *AFAR*, 4 March 2022.
3. D. Lev et al., *Acta Astronaut.* **159**, 213 (2019).
4. K. Holste et al., *Rev. Sci. Instrum.* **91**, 061101 (2020).
5. I. Levchenko et al., *Nat. Astron.* **4**, 1012 (2020).
6. NASA Jet Propulsion Laboratory, "NASA Retires Kepler Space Telescope" (30 October 2018).
7. NASA, "NASA's Dawn Mission to Asteroid Belt Comes to End" (1 November 2018).
8. M. D. Rayman, *Acta Astronaut.* **176**, 233 (2020).
9. I. Levchenko et al., *Nature* **562**, 185 (2018).
10. W.-R. Hu, Y.-L. Wu, *Natl. Sci. Rev.* **4**, 685 (2017).
11. G. Anderson et al., *Phys. Rev. D* **98**, 102005 (2018).
12. I. Levchenko et al., *Nat. Photonics* **12**, 649 (2018).
13. J. Slough, "The Fusion Driven Rocket: Nuclear Propulsion Through Direct Conversion of Fusion Energy," NASA (25 March 2019).
14. S. A. Cohen et al., *J. Br. Interplanet. Soc.* **72**, 37 (2019).
15. I. Levchenko, K. Bazaka, *Nature* **599**, 373 (2021); D. Rafalskyi et al., *Nature* **599**, 411 (2021).
16. K. Button, "Coming soon: Electric propulsion plan for Mars," *Aerospace America*, July/August 2017.
17. For detailed descriptions of thruster types, see I. Levchenko et al., *Phys. Plasmas* **27**, 020601 (2020). PT

THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

TENURE-TRACK FACULTY POSITIONS IN PARTICLE PHYSICS AND COSMOLOGY

The Department of Physics invites applications for several tenure-track faculty positions at the Assistant Professor level in experimental and theoretical physics. The target areas of the search are Theoretical High Energy Physics and Cosmology, Experimental Particle Physics and Observational Cosmology. Applicants must possess a PhD degree in physics or a related field. The successful candidates should have a strong track record of research (the ones with an interdisciplinary background are especially encouraged to apply). Appointments at the rank of Associate Professor or above will be considered for candidates with an exceptional record of research excellence and academic leadership. In addition to pursuing a vibrant research program, appointees are expected to engage in effective teaching at the undergraduate and graduate levels.

The current faculty in the particle physics and cosmology group at The Hong Kong University of Science and Technology include Professor Andrew Cohen, Professor Tao Liu, Professor Kam-Biu Luk, Professor Kirill Prokofiev, Professor George Smoot, Professor Henry Tye, and Professor Yi Wang. The department is expanding its effort in this area by hiring additional new faculty in theory and experiment. Further information about the Department can be found at http://physics.ust.hk.

Starting salary will be highly competitive and commensurate with qualifications and experience. Fringe benefits including medical and dental benefits, annual leave and housing benefits will be provided where applicable. The initial appointment prior to tenure will normally be on three-year contract terms. A gratuity will be payable upon successful completion of a contract.

Application Procedure: Applicants should submit their applications along with CV, cover letter, complete publication list, research statement, teaching statement, and three reference letters.

High Energy Theory and Cosmology (PHYS1017H):
https://academicjobsonline.org/ajo/jobs/16291

Particle Physics Experiment (PHYS1017P):
https://academicjobsonline.org/ajo/jobs/16292

Observational Cosmology (PHYS1017C):
https://academicjobsonline.org/ajo/jobs/16293

Screening of applications begins immediately, and will continue until the positions are filled.

COLLEGE FACULTY

DO YOU HAVE A GRADUATE PROGRAM IN THE PHYSICAL SCIENCES?

List your graduate program **FREE, ANYTIME** on the redesigned **GradSchoolShopper.com**—now more user friendly, mobile optimized and targeted directly to the most physics undergraduates than ever before.

Contact info@GradSchoolShopper.com to get started!

GradSchoolShopper

presented by

AIP | American Institute of Physics

HOW TO BECOME A SUCCESSFUL PHYSICIST

An apprentice (right) glues parts of a double bass under the watchful eye of a teacher (left) at the Swiss School of Violin Making in Brienz on 5 June 1969. (Image from Photopress Archiv/Keystone/Bridgeman Images.)

Carl Wieman is a professor of physics and of education at Stanford University in California.

Carl Wieman

All scientists and engineers solve research problems by calling on relevant knowledge to make a series of common, critical decisions.

Physics graduate students may find it confusing and intimidating to figure out how to become a successful physicist. The good ones they see apparently know an enormous amount of stuff and come up with solutions before the student even understands the problem. Advisers can find it similarly difficult to figure out how to best guide their graduate students to become good physicists and may wonder, "What do I need to teach them, and how should I do that?" Although students have demonstrated success in physics courses, they often struggle when given a research problem. What is the source of their difficulties, and how can one best help them improve?

This article is intended to help students, advisers, and teachers understand what is needed to become a skilled physicist and what is the most efficient and effective way to reach that goal. The solutions to those problems can benefit all students and advisers in science. They are based on cognitive-science results of studies on the general acquisition of expertise and my current research group's extensive work on expertise in science and how it is learned. That interest grew out of my own struggles with advising PhD students in my atomic-physics group.

The primary characteristic of a successful physicist is being a good problem solver. Real physics problems are those pursued in research. Solving such problems involves a far more complex set of mental processes than are needed for even the most difficult textbook problem. Unlike real problems, textbook problems provide all the information needed and have a single well-defined path to a solution.

"Solving" is defined as everything a physicist does in their research, from selecting a suitable problem, to carrying out the lengthy process of obtaining results, to finally presenting those results and their implications to the community. That definition, however, is too broad to be useful. Becoming a good physics problem solver is typically learned through trial and error, but that method of learning is quite inefficient for such a complex task. There are just too many errors that can be made during the problem-solving involved in physics research.

Cognitive-science research shows that people improve learning efficiency by practicing the set of specific cognitive tasks required for their area of expertise.[1] Although that approach is based on learning research, it is uncoincidentally quite similar to the ideal master–apprentice method for traditionally teaching a craft (see figure 1). The master decomposes the craft into a set of specific subskills, gives the apprentice a set of increasingly challenging tasks to practice each one, and intersperses feedback on how to improve. The apprentice practices each subskill to a reasonable mastery and then uses them together to produce the desired product. In the case of physics problem-solving, my research team and I have identified the necessary subskills as a set of problem-solving decisions.

Much of the past research on scientific problem-solving has looked at expert–novice differences, usually in how they organized their knowledge to solve puzzles and simple textbook problems. That work looks at only a small fraction of the true process. There are many anecdotal descriptions of problem-solving methods in math and science.[2] Nearly every introductory physics textbook has its own problem-solving method, but little evidence has shown whether those methods are correct, complete, or effective for learning to solve authentic problems.

Decisions decisions

My research group interviewed some 50 skilled scientists and engineers ("experts"), including physicists, on how they solved authentic problems in their discipline. We analyzed the interviews in terms of the decisions made during the solving process. Decisions were defined as instances when an expert selected between competing alternatives before taking some action. To my surprise, we found that the same set of 29 decisions occurred over and over (see the box on page 50). Nearly all of them showed up in every interview, and they essentially defined the problem-solving process.[3]

The decisions were always made with limited information. To reach their decisions, the experts answered such questions as the following: "What information is needed to solve this problem?" "What assumptions and simplifications are appropriate?" "What is the most difficult or uncertain aspect of my solution plan?" If complete information was available, then the steps to follow were just procedures that required little thought and so were seen as relatively unimportant. With limited information, the decisions can never be certain; rather, they are educated guesses or judgments, albeit highly informed ones. The problem-solving skill was in the quality of the judgments. The experts often noted that research breakthroughs came from recognizing the significance of some additional information that other researchers had overlooked.

Whereas the decisions the experts needed to make were common to all disciplines, how they came to each decision was not. When making any of those decisions, the experts called on specific disciplinary knowledge and experience. Most of the relevant knowledge was common in a discipline and different across disciplines. Experts who solved interdisciplinary problems still called on an established body of knowledge in essentially the same way, although it spanned more than one academic discipline.

Knowing what information to apply and how to apply it was essential to making every decision well. Meaningful learning of the knowledge in a discipline, therefore, must include mastering how to make good decisions with that knowledge. That means that knowledge-free problem-solving is a meaningless concept.

We found that all the experts organized their disciplinary knowledge in a way that was optimized for making decisions. We describe that knowledge-organization structure as a "predictive framework." Such frameworks are mental models that embody all the key features relevant to the problem and their relationships via an underlying mechanism. The frameworks are used to predict the behavior of the system being modeled when any of the variables are changed. As our experts explained to us, when they made decisions, they continually ran thought experiments using the frameworks.

An early and repeated decision in the problem-solving process was to determine which predictive framework was most suitable to the problem (decisions 5 and 23; see the box on page 50 for this and the other decisions mentioned throughout this article). The complexity of the model and mechanism was selected to match the needs of the problem.

Consider, for example, a physicist working on a research problem involving laser cooling. A predictive framework they might initially adopt would include the momentum of the light, the mass and momentum of atoms, the conversion between the two forms of momentum because of light scattering, and the dependence of the scattering rate on the frequency of the light and the Doppler shift. As they carried out experiments and collected data, they might decide that the data were reliable (decision 18) but inconsistent with the predictions of the framework (decision 19). That may lead them to modify their predictive framework by, for example, adding the AC Stark effect and its spatial variation across the laser beam.

The set of decisions

The list of decisions is organized into somewhat arbitrary categories represented in figure 2 and in more detail in the box on page 50. It roughly corresponds to the order in which they appear during the solving process. No one, however, follows such a simple, time-ordered process. Based on new information and reflection, experts frequently jump to a different step in the process and revise earlier decisions, conclusions, and plans.

Few physicists will be surprised to see the decisions on the list. What is more notable is that a finite list of 29 seems sufficient to characterize the entire problem-solving process across all sciences and engineering. They provide a much more specific guide as to what is important to master to become a successful physicist or, for that matter, any flavor of scientist or engineer.

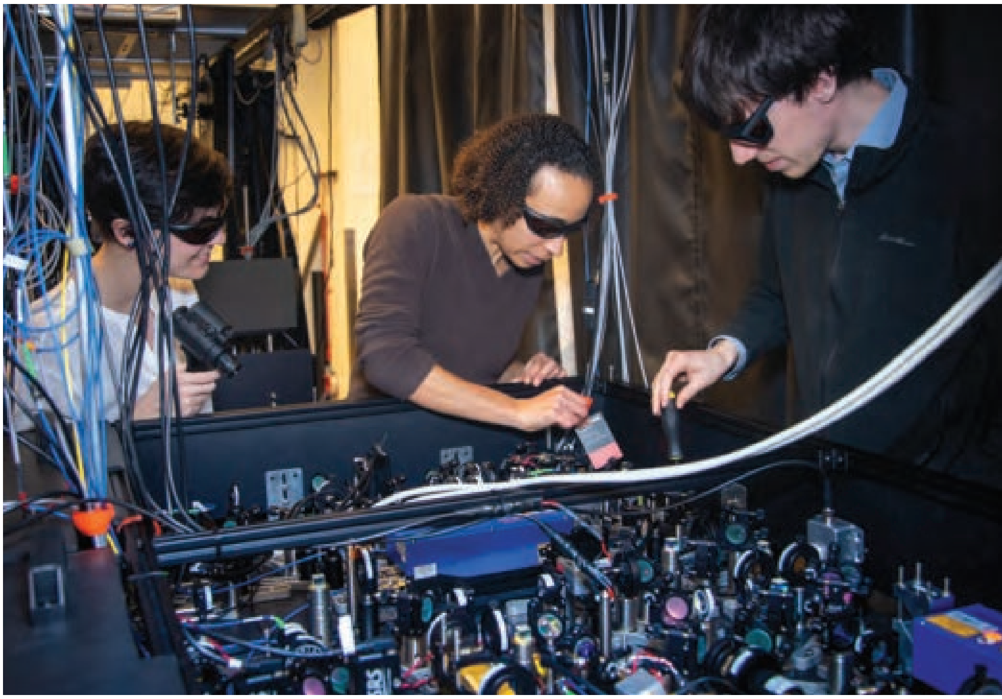


FIGURE 1. MONIKA SCHLEIER-SMITH (center) works in her cold-atom lab with students Emily Davis (left) and Eric Cooper (right). Experts in various building and craft occupations have taught the necessary trade skills to apprentices by giving them an increasingly complicated set of tasks to complete followed by regular feedback. Such an approach is also one of the best ways for students to learn to be successful physicists, according to cognitive-psychology research. (Courtesy of Dawn Harmer.)

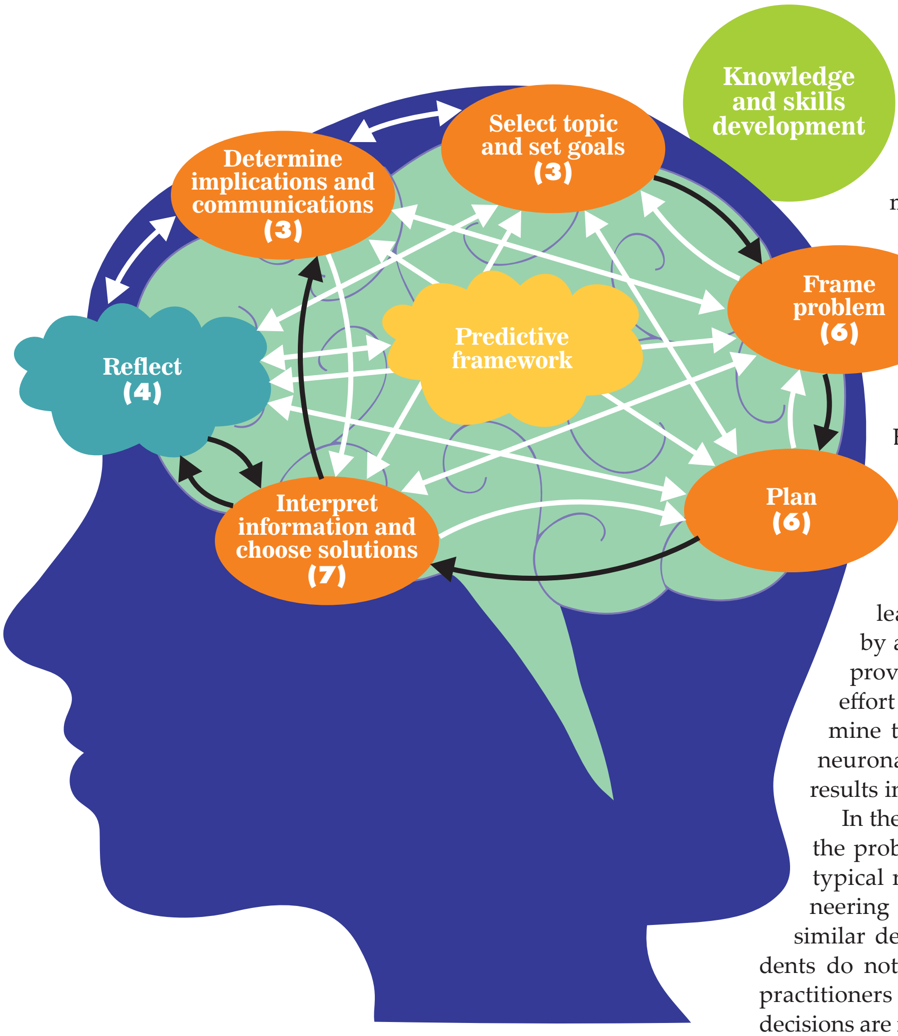


FIGURE 2. SOLVING PHYSICS PROBLEMS. The black arrows represent a hypothetical but unrealistic order of decision making that begins with selecting a research direction and identifying goals for the project. The white arrows represent more realistic iteration paths. Decisions are grouped into categories for presentation purposes; the parentheticals indicate the number of decisions that need to be made in each category. Although both knowledge and skills development are not decisions per se, based on interviews with physics experts about how they solve problems, the two are commonly mentioned themes. (Adapted from ref. 3.)

In addition to the decisions, which were our focus, the experts volunteered common areas of general skills they saw as important elements of expertise in their fields.

Stay up to date in the field by learning relevant new knowledge, ideas, and technology from literature, conferences, and colleagues.

Develop intuition and experience to improve problem-solving.

Enhance interpersonal and teamwork skills—for example, how to navigate collaborations, manage a team, and strengthen communication—particularly as they apply in the context of the different problem-solving processes.

Improve one's efficiency by practicing time management, including learning to complete certain common tasks efficiently and accurately.

Cultivate an attitude, or motivation, which includes persevering in the task despite obstacles, dealing with stress, and having confidence in decisions.

Becoming a highly skilled physicist requires developing those common skills and learning to make decisions well.

The cognitive psychologist K. Anders Ericsson and collaborators have demonstrated the process by which people become experts in many disciplines,[1] and my group has applied those ideas to teaching physics.[4,5] The level of mastery is primarily determined by the amount of what Ericsson has labeled "deliberate practice." It entails identifying the specific subskills involved for expertise in the discipline, usually by a good teacher or coach. The learner intensively practices those specific subskills individually and then in combination. That practice is interleaved with frequent targeted feedback, typically by a teacher or coach, and reflection on how to improve. The focus, intensity, and extent of the mental effort is critically important. Those factors likely determine the extent to which the desired changes in the neuronal connections in the brain are achieved, which results in improved capabilities.

In the case of physics, the subskills to be mastered are the problem-solving decisions. We have found that for typical realistic problems in any given science or engineering discipline, skilled practitioners tend to make similar decisions with similar justifications, whereas students do not.[6] The mismatch between students and skilled practitioners is understandable if one notes how few of the decisions are required, and hence practiced, in solving the typical textbook or exam problems encountered in courses (see figure 3). That also explains the puzzle that originally got me interested in physics-education research some decades ago. Namely, why is there so little correlation between students' performance in their physics courses and their ability to do physics research?

Deliberate practice in the research setting

Research always involves problem-solving, and decisions arise naturally. When conducting research, the learner should explicitly focus on the decisions from the list, think about which ones are encountered during the research process, and practice making those decisions. Then they should reflect on how and why they made each decision they did and how subsequent results indicate how each one could have been improved. They should also seek out the adviser or more experienced members of the research group to discuss their process for making those decisions and get feedback on it.

The adviser should also encourage the student to carry out that type of practice by identifying when a specific decision needs to be made and challenging them to make it. The adviser may then discuss the student's choices and justifications and point out what aspects were good and what could be improved. That process is a much more effective educational experience than simply telling the student what the decision should be.[7] But speaking from extensive personal experience, I know that human nature strongly inclines a person in an advisory position to instead make the decision and tell the student. It may be more efficient in the short term for advancing the research,

THE NATURE OF PHYSICS PROBLEM-SOLVING

Below are 29 sets of questions that students and physicists need to ask themselves during the research process. The answers at each step allow them to make the 29 decisions needed to solve a physics problem. (Adapted from reference 3.)

A. SELECTION AND PLANNING

1. What is important in the field? Where is the field heading? Are there advances in the field that open new possibilities?

2. Are there opportunities that fit the physicist's expertise? Are there gaps in the field that need solving or opportunities to challenge the status quo and question assumptions in the field? Given experts' capabilities, are there opportunities particularly accessible to them?

3. What are the goals, design criteria, or requirements of the problem solution? What is the scope of the problem? What will be the criteria on which the solution is evaluated?

4. What are the important underlying features or concepts that apply? Which available information is relevant to solving the problem and why? To better identify the important information, create a suitable representation of core ideas.

5. Which predictive frameworks should be used? Decide on the appropriate level of mechanism and structure that the framework needs to be most useful for the problem at hand.

6. How can the problem be narrowed? Formulate specific questions and hypotheses to make the problem more tractable.

7. What are related problems or work that have been seen before? What aspects of their problem-solving process and solutions might be useful?

8. What are some potential solutions? (This decision is based on experience and the results of decisions 3 and 4.)

9. Is the problem plausibly solvable? Is the solution worth pursuing given the difficulties, constraints, risks, and uncertainties?

Decisions 10–15 establish the specifics needed to solve the problem.

10. What approximations or simplifications are appropriate?

11. How can the research problem be decomposed into subproblems? Subproblems are independently solvable pieces with their own subgoals.

12. Which areas of a problem are particularly difficult or uncertain in the solving process? What are acceptable levels of uncertainty with which to proceed at various stages?

13. What information is needed to solve the problem? What approach will be sufficient to test and distinguish between potential solutions?

14. Which among the many competing considerations should be prioritized? Considerations could include the following: What are the most important or most difficult? What are the time, materials, and cost constraints?

15. How can necessary information be obtained? Options include designing and conducting experiments, making observations, talking to experts, consulting the literature, performing calculations, building models, and using simulations. Plans also involve setting milestones and metrics for evaluating progress and considering possible alternative outcomes and paths that may arise during the problem-solving process.

B. ANALYSIS AND CONCLUSIONS

16. Which calculations and data analysis should be done? How should they be carried out?

17. What is the best way to represent and organize available information to provide clarity and insights?

18. Is information valid, reliable, and believable? Is the interpretation unbiased?

19. How does information compare with predictions? As new information is collected, how does it compare with expected results based on the predictive framework?

20. If a result is different from expected, how should one follow up? Does a potential anomaly fit within the acceptable range of predictive frameworks, given their limitations and underlying assumptions and approximations?

21. What are appropriate, justifiable conclusions based on the data?

22. What is the best solution from the candidate solutions? To narrow down the list, decide which of those solutions are consistent with all available information, and which can be rejected. Determine what refinements need to be made to the candidate solutions. For this decision, which should be made repeatedly throughout the problem-solving process, the candidate list need not be narrowed down to a single solution.

23. Are previous decisions about simplifications and predictive frameworks still appropriate in light of new information? Does the chosen predictive framework need to be modified?

24. Is the physicist's relevant knowledge and the current information they have sufficient? Is more information needed, and if so, what is it? Does some information need to be verified?

25. How well is the problem-solving approach working? Does it need to be modified? A physicist should reflect on their strategy by evaluating progress toward the solution and possibly revising their goals.

26. How good is the chosen solution? After selecting one from the candidate solutions and reflecting on it, does it make sense and pass discipline-specific tests for solutions to the problem? How might it fail?

Decisions 27–29 are about the significance of the work and how to communicate the results.

27. What are the broader implications of the results? Over what range of contexts does the solution apply? What outstanding problems in the field might it solve? What novel predictions can it enable? How and why might the solution be seen as interesting to a broader community?

28. Who is the audience for the work? What are the audience's important characteristics?

29. What is the best way to present the work to have it understood and to have its correctness and importance appreciated? How can a compelling story be made of the work?

but that approach is far less effective educationally and for producing skilled researchers in the long run.

An adviser typically trains new research students by giving them small projects to work on, usually a piece of the group's larger research agenda. The decisions list provides guidance on what sorts of projects are likely to be the most educationally beneficial. Ericsson's work has shown the importance of having practice tasks that are just above the student's ability so they can finish those tasks only with intense effort. To be effective, therefore, practice projects should have neither too few nor too simple decisions for the student to make, nor should the projects have decisions that are of such complexity that the student finds them impossible.

The downside of the research environment is that the nature and pace of the work can make it difficult for the student to practice the full set of decisions, particularly the repeated practice and improvement at making a particular decision. Although decisions 16–26 will come up frequently and repeatedly during research, many of the earlier ones appear less often, and some need to be made without consulting the student. For example, many of the problem-definition and planning decisions occur when the adviser develops proposals to fund the work and hire students and postdocs.

To address that weakness, the student (or postdoc) and adviser should seek out opportunities to review those previous decisions and how they were made. Whenever possible, the adviser should challenge the student to think of alternatives and then discuss why those alternatives would usually not be as good. Of course, if the student comes up with an improvement, so much the better. Additionally, the student could apply for graduate fellowships, such as from NSF's Graduate Research Fellowship Program, that require them to write a research proposal, which should include making and justifying those first decisions.

Deliberate learning in the classroom

In the typical physics course, students practice and learn to make very few problem-solving decisions. Seldom are any encountered in a lecture, and only two or three of the 29 decisions are called for in doing typical homework or non-project-based laboratory courses. In a lecture, the outcomes of the decisions are presented, usually without the student ever recognizing that the decision needed to be made.

With good teaching, however, most of the decisions can be made an explicit part of course activities. For example, students in introductory physics,[4] advanced undergraduate,[5] and advanced graduate[8] courses can work through authentic problems in class. Those problems are simpler than most research problems, but they involve many more decisions than standard textbook problems. In solving authentic problems in class, students make and justify many of the decisions explicitly in consultation with their peers and get regular feedback and guidance from the instructor (see figure 3). Similarly, solving homework or exam problems can involve explicitly justifying various decision choices. Of course, including all 29 decisions is impractical, but the instructor can select those they find particularly important in the context.

At their best, courses do have an advantage over the research setting: Thoughtful instructors have the freedom to assign problems that give students practice in making various decisions, including the repeated practice of making particularly important decisions. My personal preference in undergraduate courses is to make every problem solution include identifying important features (decision 4), determining what information is needed (decision 13), planning the solution process (decision 15), and evaluating potential solutions (decision 26). Problems can be varied to probe other decisions and call on a variety of physics knowledge. Courses have the disadvantage of the decisions always being more artificial than in the research setting, but that issue can be minimized with careful thought, usually by ignoring the textbook!

For students to make decisions, they must learn a substantial amount of physics knowledge. The best way to learn that knowledge is to witness its importance when it's used to make the problem-solving decisions. The traditional practice is for the instructor to teach physics knowledge to the students and then later give them problems so that they can practice using that knowledge. A much more effective approach is to give them a meaningful problem to struggle with first and then provide them with the knowledge they need to figure it out.[9] When information is presented as useful for solving certain kinds of problems, the brain stores that information so that it is readily accessed and applied when needed to solve novel related problems.

Whereas most of the 29 decisions are applicable for problem-solving at every level of a physics education, a few are only appropriate for advanced graduate students and postdocs. Deciding on the state of the field (decision 1), the broader implications of the research results (decision 27), the audience (decision 28), and the most effective way to present research results (decision 29) all require extensive exposure to current research and attitudes in the field. Most of the other decisions are suitable for every level of student to practice, but the physics topics and knowledge necessary to make them needs to be appropriate to the course and level of the student. That specific physics knowledge is usually set by the problem context.

A student in a graduate class can practice making such decisions even when the decisions are not part of the curriculum. Every new physics concept and calculational technique the graduate student sees was originally the solution to an authentic physics problem. They can ask themselves what decisions called for that solution? How was the problem framed (decisions 4 and 5)? What approximations were used (decision 10)? Where would the solution method apply and not apply (decisions 25 and 26)? Discussing such questions with peers and usually the instructor will benefit their learning.

In deciding how to use the instructional time, teachers should remember that the body of physics knowledge learned in school will always be a small fraction of the knowledge needed in a physics career. The skill of making good problem-solving decisions, however, will always remain essential.

Most important and difficult

To be a successful physicist requires mastering how to make all 29 decisions, but the reflection decisions (decisions 23–26) are arguably the most difficult to learn. They require students to examine their own thinking, which is challenging for three reasons. First, having that kind of perspective on one's own thinking is just difficult. Talking through the ideas with others can help. Second, a good physicist tends to be consumed with

FIGURE 3. TEXTBOOK PHYSICS PROBLEMS—including this one **(a)** to calculate the acceleration of m_2 assuming a massless pulley and rope—don't require much decision making and often lack any context that motivates a student to solve them. **(b)** Real-world physics problems, such as determining the requirements necessary for a rocket to launch the *James Webb Space Telescope*, are societally relevant. Yet they can be too difficult because of the many complex decisions that must be made. **(c)** An example of an authentic but skill-appropriate physics problem calls for a student to calculate the weight that can be pulled up to a treehouse using a rope over a branch and to decide whether it's worth the time and money to buy a pulley for the job. Authentic problems are designed to include many decisions and be more relevant but still need to be approachable for those with limited knowledge and decision-making skills.

the immediate challenge of the work—for example, how to improve the vacuum, how to reduce the jitter in the detector trigger, or how to create faster code for evaluating that complex integral. Shifting mental gears to put those thoughts aside and think more broadly is hard. I find it helpful to schedule blocks of time in my week to think about those reflective decisions.

The third and probably most serious difficulty in making good reflective decisions is confirmation bias. It's a well-established psychological tendency for humans, once they have decided on an answer that they think is correct, to be strongly prepossessed toward maintaining that belief. Confirmation bias causes them to suppress thinking about alternatives and interpret all new evidence in a way that confirms their belief. I suspect most of the serious errors in physics have been the result of such bias. Students (and scientists in general) should practice fighting against it when making reflective decisions.

Despite the difficulty in learning them, the reflection decisions are also the most important. They are the error-correction decisions of the problem-solving process and allow students to catch when they have made a poor decision and fix it. Frequently, corrections happen when new information becomes available or the relevance of overlooked information is recognized, such as why an assumption that was made does not apply. An adviser should have their students explicitly practice decisions 25 and 26, test their solutions, and try to come up with the ways their decisions could fail, including alternative conclusions that are not the findings that they were hoping for. Thinking of such failure modes is something that even many experienced physicists are not very good at, but our research has shown that it can be readily learned with practice.

The set of decisions for how to become a good physics problem solver also provides a good framework for measuring a person's strengths and weaknesses in solving authentic physics problems. I am sure many advisers are like I was: Although I knew a student was failing to solve the research problems I gave them to work on, I didn't know why or how I could help them improve.

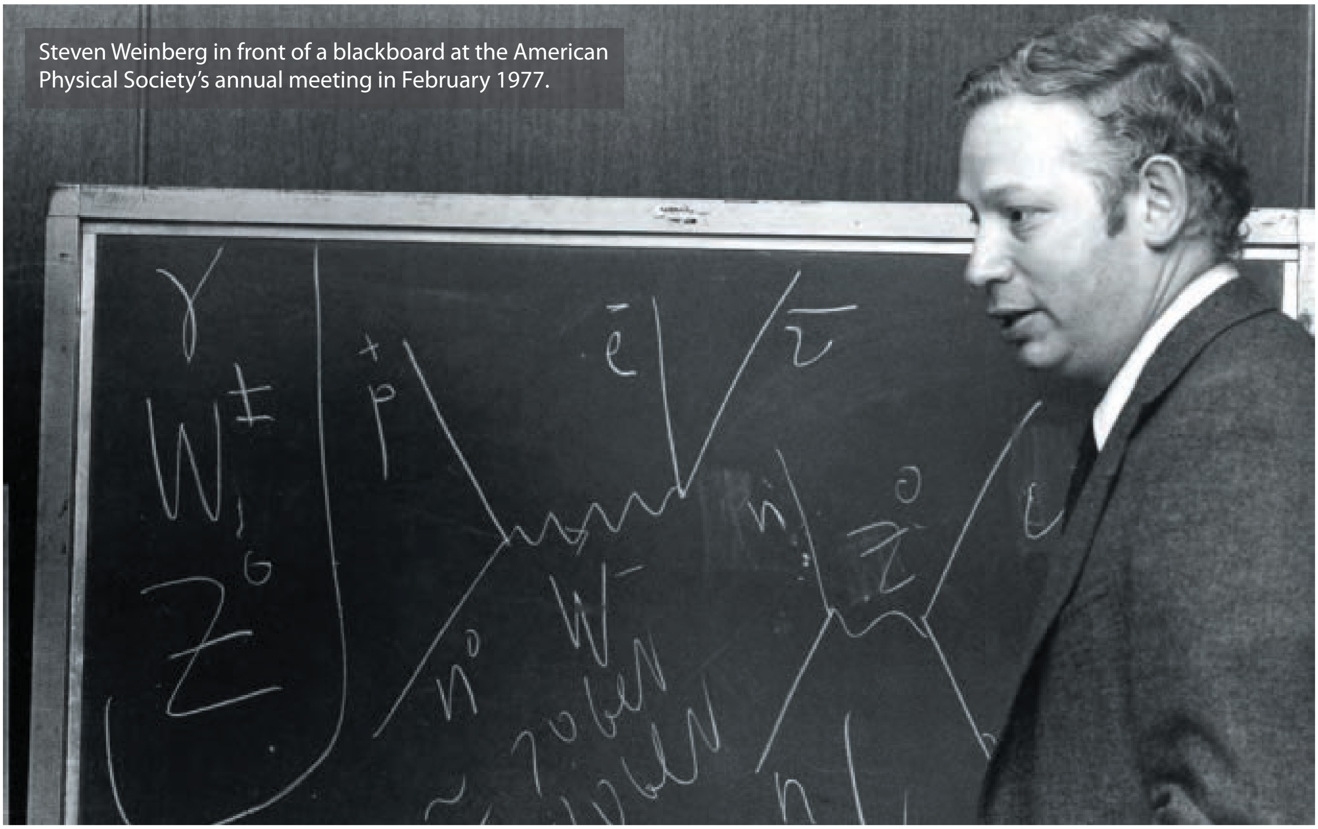
My group has now developed tests in several areas of science and engineering based on those problem-solving decisions. We give the student a realistic scenario and then ask them to make and justify a representative subset of the decisions. We then compare their responses with those of experts in the field. Typically, students are quite poor at making those decisions despite having successfully completed courses that covered the relevant knowledge. But the more experience they have had in doing authentic problem-solving, the more expert-like they tend to be in their decisions. If properly taught, the skills are quite learnable.

This work was supported by the Howard Hughes Medical Institute. The research was led by Argenta Price and carried out by many members of my group.

REFERENCES

1. K. A. Ericsson, R. T. Krampe, C. Tesch-Römer, *Psych. Rev.* **100**, 363 (1993); A. Ericsson, R. Pool, *Peak: Secrets from the New Science of Expertise*, HarperOne (2017).
2. G. Polya, *How to Solve It: A New Aspect of Mathematical Method*, 2nd ed., Doubleday (1957).
3. A. M. Price et al., *CBE—Life Sci. Edu.* **20**, ar43 (2021).
4. L. Deslauriers, E. Schelew, C. Wieman, *Science* **332**, 862 (2011).
5. D. J. Jones, K. W. Madison, C. E. Wieman, *Phys. Rev. ST Phys. Educ. Res.* **11**, 020108 (2015).
6. E. Burkholder, L. Hwang, C. E. Wieman, *Educ. Chem. Eng.* **34**, 68 (2021).
7. N. G. Holmes, B. Keep, C. E. Wieman, *Phys. Rev. Phys. Educ. Res.* **16**, 010109 (2020).
8. G. P. Lepage, *Am. J. Phys.* **89**, 317 (2021).
9. D. L. Schwartz, T. Martin, *Cogn. Instr.* **22**, 129 (2004).

PT



Steven Weinberg in front of a blackboard at the American Physical Society's annual meeting in February 1977.

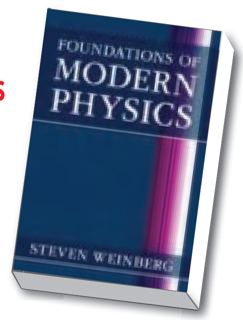
AIP EMILIO SEGRÈ VISUAL ARCHIVES/WEBER COLLECTION

Steven Weinberg's final textbook

Foundations of Modern Physics

Steven Weinberg

Cambridge U. Press, 2021. $44.99



In spring 2021, the brilliant theoretical physicist Steven Weinberg sat down virtually with my colleague Andrew Strominger as part of a series of book talks I've been organizing at the independently run Harvard Book Store. The two spoke about popular books Weinberg had written, including *The First Three Minutes: A Modern View of the Origin of the Universe* (rev. ed., 1993), *To Explain the World: The Discovery of Modern Science* (2015), and *Third Thoughts* (2018).

During my discussions with Weinberg in preparation for the talk, he mentioned that he had a new textbook coming out, but we worried that discussing a pedagogical work might be too dry for a public-facing event. We were wrong. *Foundations of Modern Physics*, published shortly before Weinberg's death last summer, is a beautiful book that synthesizes the first two years of undergraduate physics and takes the reader on a historical journey up through the discovery of quantum field theory in the mid 20th century.

The book is a result of Weinberg teaching an upper-level physics course at the University of Texas at Austin called Modern Physics and Introduction to Thermodynamics. Weinberg's colleague, Roy Schwitters, had taught that course for many years, but Schwitters never found a textbook that covered all the relevant material. When Schwitters retired, Weinberg asked to teach the course so that he could write a textbook for it, and *Foundations of Modern Physics* is the result.

The course was aimed at undergraduates who had already taken the introductory physics sequence through quantum mechanics. Weinberg began writing the textbook by supplementing a review of material the students had already learned with real applications and back-of-the-envelope or dimensional arguments. Structuring the book topically, he divided it into seven chapters: one each on early atomic theory, thermodynamics and kinetic theory, early quantum theory, relativity, quantum mechanics, nuclear physics, and quantum field theory.

Whereas many textbooks forgo historical notes, Weinberg delights the reader by adding terse yet apt context to the physical concepts he introduces. In fact, those notes are so well placed that I got a better sense of the flow of ideas in physics over time than ever before. The book goes over some introductory concepts before synthesizing an array of undergraduate-level ideas. The slim 300-page volume includes just enough material to make the book appealing and readable, but far too much, I think, for it to be used as a textbook for a one-semester course.

Weinberg's writing reads less like a textbook and more like a story—although, to be sure, he includes many substantial derivations. Along with equations, he shows a clear interest in how physicists measure things. It is as if he is imagining what students might be puzzled by and then solves those problems.

For instance, when introducing Coulomb's law, Weinberg notes that the French physicist could not measure charge directly with the equipment available to him in the 18th century. Instead, he noticed that if he touched a charged body to a similarly sized uncharged body of the same material, both the charge of the first body and the force between the two bodies were reduced by a factor of two. And when discussing the discovery of the electron, Weinberg mentions the brilliant air pump developed by Heinrich Geissler that made the discovery possible.

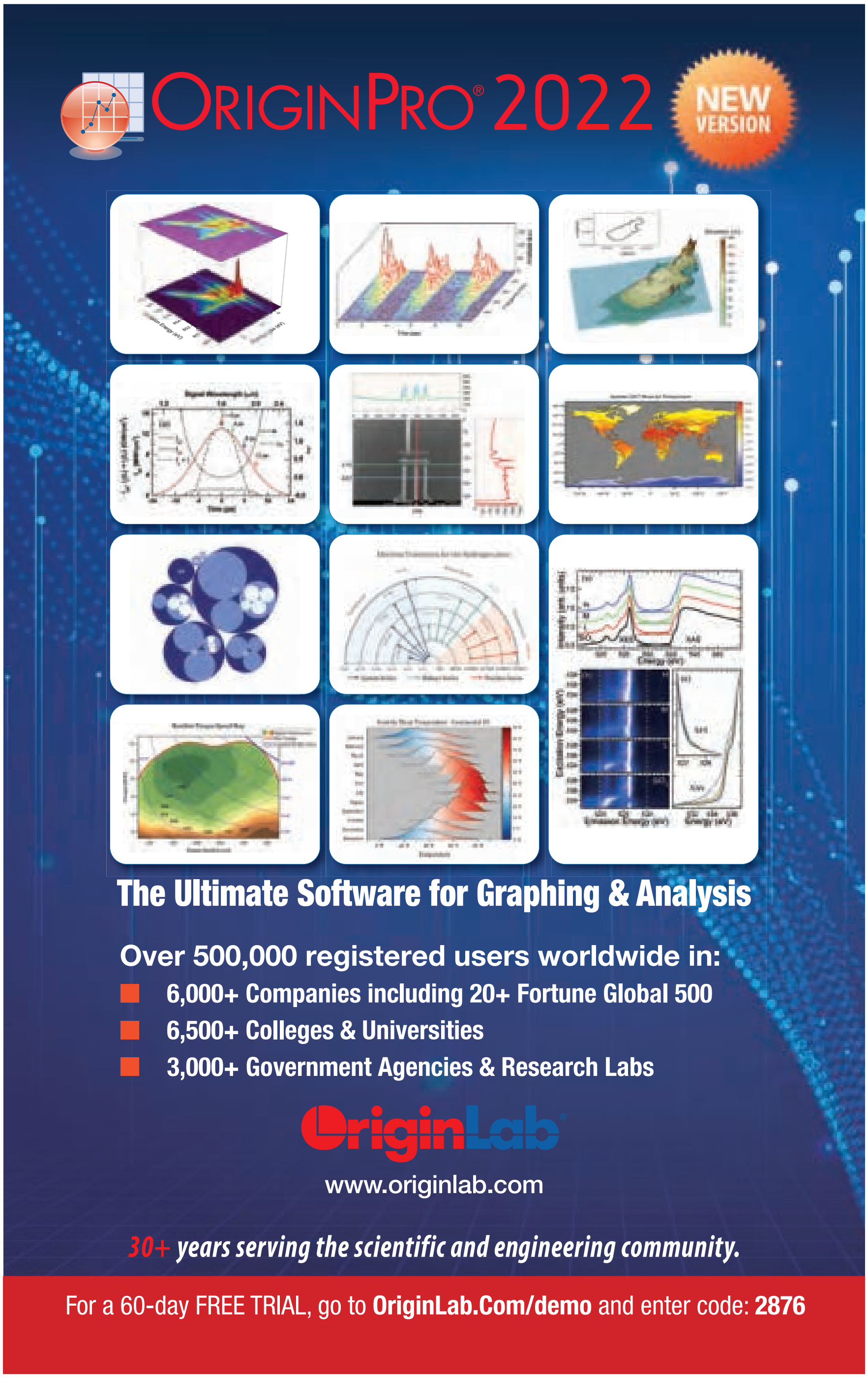
As an experimentalist, I am used to first looking at diagrams and data plots, and I was initially surprised that few figures were included in the book. I thought they might have added something to the clarity of the discussion. But when I reread a descriptive passage I had not at first been able to visualize, I found that Weinberg's prose was impressively vivid. I could see fine without any figures.

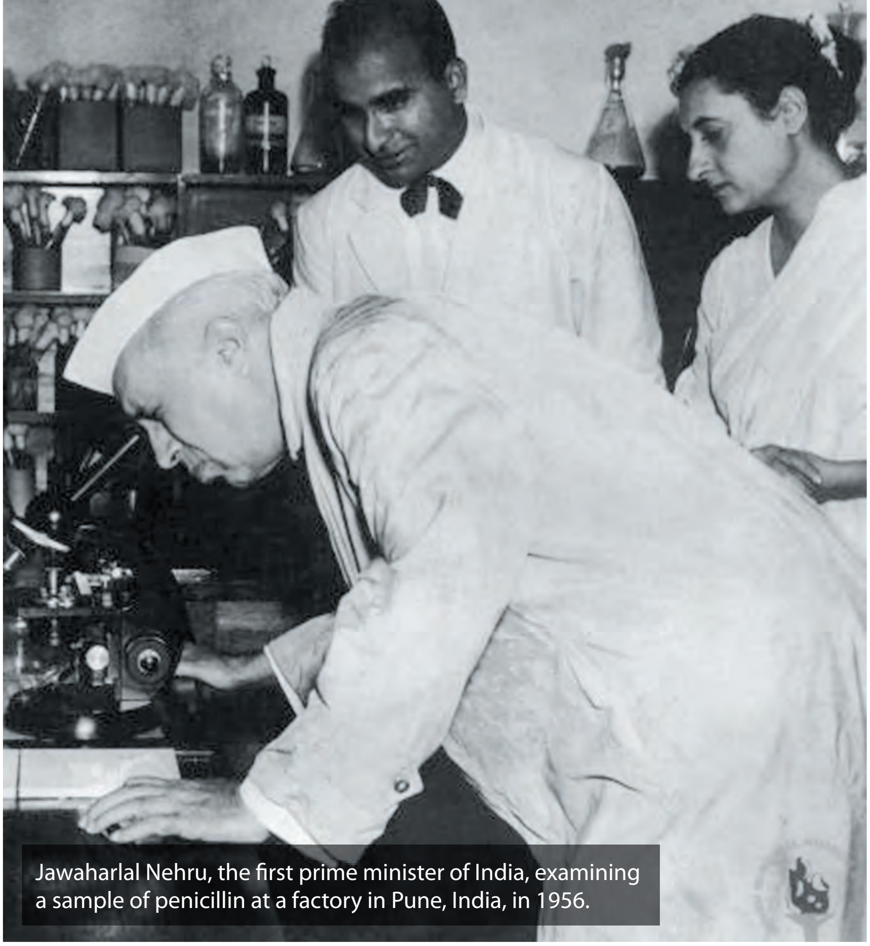
Although it passes as a textbook, *Foundations of Modern Physics* is many things. It is a way for physicists to review what they have learned early in their studies and to think physically about what they know. It is also a source of relevant historical details and instruction for readers about topics and facts they weren't previously familiar with. Although I have picked up a bit of nuclear physics here and there over the years, I never studied it in a class. So I read that portion of the book as if I were an undergraduate student encountering the material on nuclear physics in an academic setting for the first time, and I was very pleased.

But is this a textbook for undergraduates or incoming graduate students? It could be—if it is used carefully. It is certainly appropriate for advanced graduate students and faculty, who will be delighted and inspired to use it when teaching many introductory courses. I read the book slowly and episodically: Just 10 pages at a time provided enough for a week's worth of thinking. I will certainly use the parts about elementary-particle physics when I next teach that course. And I already included things I learned from the book when I taught premeds this past spring.

Of course, everyone will want to have *Foundations of Modern Physics* on their bookshelf. There is always something new to be found in it, and—similar to having a conversation about physics with Weinberg—there is never a dull moment when reading it.

Melissa Franklin
Harvard University
Cambridge, Massachusetts





UTCON COLLECTION/ALAMY STOCK PHOTO

Jawaharlal Nehru, the first prime minister of India, examining a sample of penicillin at a factory in Pune, India, in 1956.

Searching for religion in the laboratory

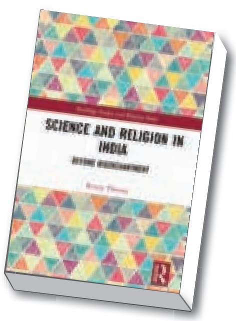
Science and religion are categories that are too big for the responsible historian, philosopher, or sociologist to use. They are lazy terms: When invoked, they almost always presume what they purport to explain. That is why surveys of, say, physicians and their views of God are rarely rewarding. Their conclusions are written into their questions from the get-go.

And yet, people in the world today often invoke the divide—sometimes expressed as conflict, sometimes as complement—between science and religion. Despite our critical scruples, we cannot ignore that those categories are in fact used by people to organize their daily lives. And despite the significant body of scholarship now devoted to explaining the history of disputes about the relationship between science and religion, we lack clear accounts of how people actually use those terms to navigate the world today.

Enter Renny Thomas. His brief book *Science and Religion in India: Beyond Disenchantment* has a bold claim: to rethink conventional narratives of the relationship between science and religion. Thomas's novel contribution is to study how religion is practiced in the laboratory. Rather than searching for religion in the places we are trained to look for it—such as mosques, temples, and churches—Thomas followed scientists around an elite scientific research institute in Bangalore, India, and asked them probing questions about God, belief, and devotion every step of the way.

Science and Religion in India
Beyond Disenchantment

Renny Thomas
Routledge, 2021.
$160.00



The book builds on historical studies of science in colonial and postcolonial India as well as scholarship in the field of science and technology studies. It brings together the well-known laboratory studies of the sociologist-cum-philosopher Bruno Latour with the work of Ashis Nandy and Shiv Visvanathan, two social theorists whose writings about science in modern India have wide applicability for the rest of the world.

India is an important site to test standard narratives of science and religion, not because it is unlike other nations, but precisely because it shares so much in common with them. The assertion in the preamble of the Indian constitution that India is a "secular" nation did not do away with religion, just as religion has not disappeared from the rest of the globe. In India—as elsewhere—it is best to see religion as a part of modern life rather than a stubborn holdover from the premodern past.

Still, science has a marked place in India, which makes a study of science and religion there particularly valuable. Jawaharlal Nehru, the first prime minister of India, gave science a central place in the building of a new Indian nation-state. A responsibility "to develop the scientific temper" was written into the constitution, and a cadre of scientists and engineers took on the responsibility of constructing a modern India that would be distinguished from the past by science.

At the same time, religious reformers asserted that Hinduism contained the metaphysical core of modern science. And today, discussions of science and religion remain common fare in public intellectual life in India. Thomas did not go to one of India's largest scientific research institutes looking for religion. Rather, religion found him: While he was conducting fieldwork at the institute, the International Society for Krishna Consciousness parked a mobile "science and religion library" on the campus.

Laboratories produce many different things—including papers, theories, and new particles. But they also produce new types of people. And those people are sometimes religious. *Science and Religion in India* shows the particular types of religious individuals produced within Indian laboratories. The book is at its best when it allows the scientists Thomas interviewed to speak for themselves. Those scientists develop distinct strategies to theorize the place of religion and science in their lives. If they shy away from employing the dichotomy of science and religion, those scientists often think through different binaries: For example, they might classify some activities as cultural but not religious, others as spiritual but not religious, and still others as religious but not superstitious.

Although *Science and Religion in India* does an admirable job of breaking down binaries, it falters when talking about "the West," which becomes the sort of monolith that Thomas otherwise seeks to dismantle. Take, for instance, the discussion of atheism among Indian scientists, which forms the most exciting chapter in the book. Thomas states that "the Western understanding of atheism as a philosophy of godlessness and anti-religious sentiment does not apply in the Indian context." He argues that while a figure like Richard Dawkins is often invoked by Indian scientists, very few of them are actually like Dawkins.

But even if there is a fundamental difference between Dawkins and most Indian scientists, the famed biologist should be seen in India the same as he is in Europe or America: as one resource among many that scientists can choose to invoke or ignore in styling their beliefs and practices. (Nobody is really like Dawkins, but his 2006 book *The God Delusion*, it should be noted, has been translated into Tamil and Bengali, and the English edition is readily available in Indian airports and bookstores.) Western atheism is in turn a term that can be—and is—invoked or dismissed by Indian scientists. It is better left as a category used by the scientists themselves rather than one used by scholars to analyze their actions.

That minor quibble, however, should not detract from Thomas's accomplishment. *Science and Religion in India* joins a growing set of recent books that explore the modernity of both science and religion in contemporary India: Dwaipayan Banerjee's *Enduring Cancer: Life, Death, and Diagnosis in Delhi* (2020), Ajantha Subramanian's *The Caste of Merit: Engineering Education in India* (2019), and Banu Subramaniam's *Holy Science: The Biopolitics of Hindu Nationalism* (2019). They help us see the surprising ways people in the world wrestle with the imperfect categories—such as science and religion, tradition and modernity, East and West—that are humanity's collective inheritance.

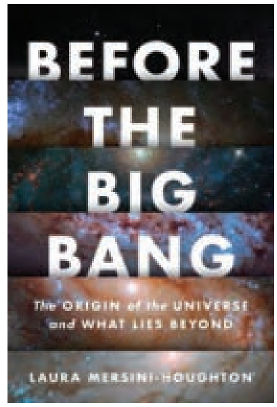
Eric Moses Gurevitch
Vanderbilt University
Nashville, Tennessee

NEW BOOKS & MEDIA

Before the Big Bang

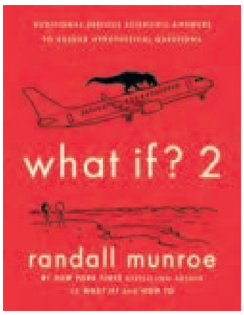
The Origin of the Universe and What Lies Beyond

Laura Mersini-Houghton
Mariner Books, 2022. $27.99



Inspired by quantum entanglement and wormholes—the latter of which they clumsily explain with a pen running through a paper folded in half—Marvel blockbuster films have helped familiarize the public with the concept of the multiverse. Although it might seem like science fiction, the notion of a multiverse is central to Laura Mersini-Houghton's *Before the Big Bang*, as is her fondness of what she calls the "freedom to think for [herself]." Laying out questions about the universe's origins through a series of personal stories, she argues that the multiverse theory is testable. Readers will likely be impressed by the intimacy with which Mersini-Houghton shares memories of her childhood in Albania, which laid the groundwork for her approach to the multiverse theory. —GD

What If? 2



Additional Serious Scientific Answers to Absurd Hypothetical Questions

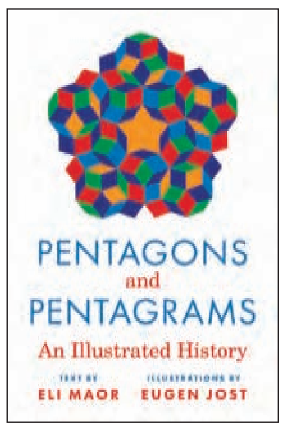
Randall Munroe
Riverhead Books, 2022. $30.00

A sequel to 2014's *What If?* by Randall Munroe, author of the popular Web comic *xkcd*, Munroe's latest book continues to address the multifarious questions posed by followers of his *What If?* blog. Using the latest scientific research and his trademark wit, Munroe responds to head-scratchers like the following: If a firefighter's pole could be built from the Moon to Earth, how long would it take to slide down it? How many Wint-O-Green Life Savers are needed to create a lightning bolt? If everyone opened their fridge or freezer at the same time, would that lower the air temperature? Munroe's simplistic, stick-figure-style illustrations enhance the amusing and informative text. —CC

Pentagons and Pentagrams

An Illustrated History

Eli Maor; ill. Eugen Jost
Princeton U. Press, 2022. $24.95



An entire book about two simple shapes? The thought of reading nearly 200 pages about pentagons and pentagrams might seem like the recipe for a snoozer, but Eli Maor's new book, illustrated by Eugen Jost, is anything but boring. Geometry buffs will enjoy Maor's beautiful annotations to Euclid's proof of the construction of a regular pentagon. But Maor also delves into the cultural history of the pentagon, which has a special place in most societies because our hands have five fingers. Most medieval fortresses, for example, were built in the shape of a pentagon because the five-sided construction encloses a space larger than a square of equivalent perimeter while also reducing the "dead zones" at the corners where attackers could shelter from defenders' fire. —RD PT

NEW PRODUCTS

Focus on lasers, imaging, microscopy, and photonics

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

Andreas Mandelis

Nano-optical microscope and imaging

NeaSpec, part of Attocube, has introduced a new generation of its neaScope nano-optical microscope products based on needle-tip-enhanced nanoimaging and spectroscopy. The neaScope series operates in the visible, IR, and terahertz ranges. It is suitable for use in various scientific research fields, such as nano-optics, 2D materials, plasmonics, polymers, materials and life sciences, semiconductor research, and cryogenic and ultrafast studies. Models begin with the basic IR-neaScope, which provides nanoscale IR imaging and spectroscopy based on probing laser-induced photothermal expansion with an atomic-force-microscope tip. The more advanced IR-neaScope^{+s} detects elastically scattered light from the atomic-force-microscope tip. Other models offer polarization-resolved mappings, terahertz near-field imaging and spectroscopy, and ultrafast pump-probe and tip-enhanced Raman spectroscopy; one model realizes multifunctional research in cryogenic environments. ***Attocube Systems AG and NeaSpec**, Eglfinger Weg 2, D-85540 Munich-Haar, Germany, https://www.neaspec.com*

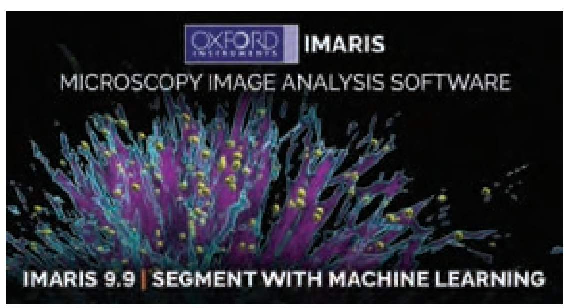
Radiation-tolerant laser

NeoPhotonics has designed a radiation-tolerant version of its ultrapure light Nano-ITLA (integrable tunable-laser assembly) for use in communications among low-Earth-orbit satellites. Optical networking companies employ NeoPhotonics's current Nano-ITLA laser in advanced terrestrial, coherent, pluggable modules and high-speed embedded systems. To enable reliable operation in space—which is a hostile environment for telecommunications electronics and related hardware—the new laser introduces enhancements such as an adaptive approach to extend its operational lifetime in a radiation-flux environment. In addition, radiation-tolerant software enhancements mitigate the corrupting effects of ionizing radiation on the RAM and flash memory that microprocessors rely on. ***NeoPhotonics Corporation**, 3081 Zanker Rd, San Jose, CA 95134, www.neophotonics.com*

Dual-color stimulated Raman scattering

With its novel dual-color stimulated Raman scattering (DC-SRS) system, the deltaEmerald instrument from APE allows simultaneous imaging of two vibrational bands. Optimal signal-to-noise performance and a background-subtraction capability make it suitable for SRS microscopy. Two Stokes pulses separated by 85 cm^{-1} and modulated at different frequencies are overlapped with the tunable pump pulse. The pulse length of ~1 ps, 10–15 cm^{-1} bandwidth, and hundreds-of-milliwatt output power in each beam are appropriate parameters for coherent Raman imaging. The solid-state laser and optical parametric oscillator, combined with the shot-noise-limited pulses of all three beams, facilitate fast image acquisition. Fully automated tuning, power control, and temporal and spatial overlap of all three beams are provided. A ~100 fs output at 1030 nm allows for efficient second-harmonic generation and two-photon imaging. Applications include fingerprint, metabolic, cell, and plant imaging and microplastics discrimination. ***APE GmbH**, Plauener Strasse 163–165, Haus N, 13053 Berlin, Germany, www.ape-berlin.de*

Software for microscopy image analysis



Imaris, an Oxford Instruments brand, has released the latest version of its software for microscopy image analysis. To save time, Imaris 9.9 facilitates connectivity with open-source tools important for researchers' specific needs. It adds a new segmentation method for pixel classification, which is powered by Labkit, an open-source Fiji plug-in. The result is a seamless workflow from Imaris to Labkit and back to Imaris. The machine learning pixel classification, with an intuitive, interactive training mode, broadens the diversity of images for analysis because it enables electron microscopy segmentation and shape recognition. To facilitate the connection between open-source software packages and Imaris, the 9.9 version lets users directly import label images as surfaces or position data as spots. Once imported, those components are compatible with other Imaris tools such as statistics reporting, spatial analysis, and high-resolution animations and snapshots. ***Oxford Instruments plc**, Tubney Woods, Abingdon OX13 5QX, UK, https://nmr.oxinst.com*

Multispectral line-scan camera

Teledyne DALSA has added a new model to its Linea product line. The high-resolution Linea ML 8k line-scan camera provides spectrally independent RGB (red, green, blue) and near-IR outputs for accurate detection of defects without spectral interference. According to the company, that makes the multispectral camera uniquely capable of handling challenging inspection applications by detecting defects both on and under the surface of a variety of materials, components, and products. In a single scan, it can inspect banknotes, passports, and other high-security print items and accurately detect defects on and under the surface of products such as semiconductor wafers and printed circuit boards. The Linea ML 8k multispectral camera uses Teledyne DALSA's latest CMOS 8k quad linear sensor with a pixel size of 5 μm. It delivers a maximum line rate of 70 kHz each for the four lines using a Camera Link HS fiber-optic interface. ***Teledyne DALSA**, 605 McMurray Rd, Waterloo, ON N2V 2E9, Canada, www.teledynedalsa.com*

Extreme-UV and soft x-ray camera

Andor Technology, an Oxford Instruments company, has launched its Marana-X-11 scientific CMOS platform for ultrafast soft-x-ray and extreme-UV tomography and high-harmonic-generation imaging. According to the company, it represents a significant technological advancement for applications that traditionally use slow-scan CCDs. Optimized for the 80 eV–1 keV region, Marana-X-11 delivers high quantum efficiency, high dynamic range, a low noise floor, and 48 fps operation and thereby enables dynamic photon-starved applications. Its high-resolution, back-illuminated, uncoated 4.2 MP sensor features a 32 mm diagonal field of view with 11 μm pixels. The sensor has the flexibility to analyze a wide range of sample configurations and address demanding spatial- and spectral-resolution needs. The electronic shutter, combined with a USB 3 or robust long-distance CoaXPress data interface, enables easy integration into a broad range of vacuum-based high-energy experimental setups. ***Andor Technology Ltd**, 7 Millennium Way, Springvale Business Park, Belfast BT12 7AL, UK, https://andor.oxinst.com*

UNIVERSITY OF OREGON | Physics

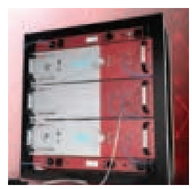
The Department of Physics at The University of Oregon invites applications for a faculty position to start in Fall 2023. We are seeking to hire in any area of physics synergistic with existing areas of research in our department. These areas include astrophysics/cosmology, atomic/molecular/optical physics, biological physics, hard and soft condensed matter physics, and particle physics. There are also strong campus-wide initiatives in environmental science, data science, and bioengineering.

Applicants should have a Ph.D. and an outstanding research record. The successful candidate will be expected to build a world-class research program, teach graduate and undergraduate courses with distinction, and perform university service and public outreach. Women, members of underrepresented groups, and scientists at early stages in their academic career are strongly encouraged to apply. We foster a welcoming and inclusive climate in our department for our undergraduates, graduate students, faculty, and staff via our active climate and diversity committee and through programs such as North Star and SAIL. We seek a colleague who will join us in these strong efforts.

Candidates are asked to apply by completing the online application; including submitting a letter of application, a curriculum vitae, the contact information for three professional references, a research statement, a teaching statement, and a diversity statement.

For more instructions on the application process and to apply, please use this link:
https://careers.uoregon.edu/en-us/job/529434/assistant-professor-of-physics

Lasers for quantum applications



NKT Photonics has made its Koheras Harmonik frequency-converted mode-hop-free fiber lasers available in wavelengths suitable for quantum research: 780 nm, 840 nm, and 1064 nm for rubidium; 317 nm, 813 nm, and 1064 nm for strontium; 532 nm and 1762 nm for barium; and 399 nm, 556 nm, 638 nm, 770 nm, and 1064 nm for ytterbium. The lasers feature up to 10 W of power, low noise, and a linewidth below 200 Hz. They are ultrastable, highly reliable, and alignment- and maintenance-free, and can be mounted in a rack or placed upside down. Harmonik lasers are pumped by the company's low-noise fiber lasers in the near-IR, which allows them to be locked to frequency references at either their fundamental or converted wavelengths. A state-of-the-art fiber-delivery system handles high power, preserves the low-noise laser properties, and delivers single-mode light at all wavelengths. ***NKT Photonics Inc**, 23 Drydock Ave, Boston, MA 02210, www.nktphotonics.com* PT

Get nervous before a job interview?

You’re not alone.

Physics Today Jobs has several resources on our website for job seekers, including recorded webinars led by experts to help you navigate the job interview process with ease.

Find your future at
physicstoday.org/jobs

PHYSICS TODAY

Judith Lynn Pipher

The "mother of infrared astronomy," Judith Lynn Pipher, passed away in her hometown of Seneca Falls, New York, on 21 February 2022 from pancreatic cancer.

Born on 18 June 1940 in Toronto, Ontario, Canada, Judy received her BS in physics and astronomy from the University of Toronto in 1962 and her PhD in astronomy from Cornell University in 1971. She wrote her thesis, "Rocket submillimeter observations of the galaxy and background," with Martin Harwit as her adviser. Judy became a faculty member in the physics and astronomy department at the University of Rochester in 1971.

Judy taught countless students at Rochester. Numerous undergraduates received their educational foundation from her, while many graduate students achieved their PhDs under her helpful, thoughtful, and inspiring tutelage. Judy instilled within all of her students and coworkers a desire to achieve more. She inspired colleagues and served as a powerful mentor and guide to many scientists throughout their careers.

Over the course of Judy's academic career, she was an author on numerous papers covering various topics relevant to IR astrophysics. Her early contributions to the field included measurements of the galactic background and measurements of reddening—that is, extinction due to dust along the line of sight—for planetary nebulae and star-formation regions.

A pioneer in IR instrumentation, Judy, along with James Houck, designed a black paint that had three-dimensional structure, which made it suitable as an absorber for far-IR wavelengths. Judy built and operated a lamellar grating spectrometer for the far-IR that was then used on the Kuiper Airborne Observatory.

TO NOTIFY THE COMMUNITY about a colleague's death, visit https://contact.physicstoday.org and send us a remembrance to post.

Select submissions and, space permitting, a list of recent postings will appear in print.

With fellow Rochester astronomer Stewart Sharpless, Judy studied many H II regions, most of which were originally cataloged by Sharpless, including S106, a particularly spectacular bipolar H II region that has been a target of virtually all ground- and space-based IR observatories since. Much of Judy's career was spent using photometric and spectroscopic IR data to study and understand star-formation regions in the Milky Way and in starburst galaxies such as Messier 82.

In 1982, with the acquisition of an indium antimonide CCD, Judy and William Forrest, also at Rochester, were able to produce the first direct images of Saturn, Jupiter, and the Moon. (Previous images were assembled using raster scans from single-pixel detectors.) That enormous step forward for IR astronomy helped to propel the development of the *Spitzer Space Telescope*—originally called the *Space Infrared Telescope Facility*—which was launched in 2003 and decommissioned in 2020. It used a later version of the IR detector arrays, based on a 256 × 256 InSb array hybridized to a CMOS readout. Judy and Forrest's development of IR detector arrays facilitated IR instruments used by astronomers around the world to produce many thousands of journal articles over the past four decades, and it revolutionized both ground- and space-based IR astronomy in the process.

In the mid 1990s, Judy and Forrest continued to develop new detector technologies, specifically long-wavelength-cutoff mercury cadmium telluride arrays. Those arrays targeted wavelengths out to 10 μm instead of the more traditional 2.5 μm cutoffs of the arrays in use at the time. The goal was similar to their effort in the 1980s—to produce detector arrays that could be used with astronomical space telescopes. By 2013 the effort was a success and the arrays were proposed for use in the *Near-Earth Object Surveyor* (formerly the *Near-Earth Object Camera*). The long-wavelength HgCdTe arrays have been matured into a 2048^2 format with low noise, low dark current, and high quantum efficiency suitable for space-based astronomy. Still longer-wavelength versions extending out to about 15 μm have been produced.

Judy's broader impacts on the community are widely felt. Not only was she one of the original trailblazers in using array technology for IR astronomy, but she was one of a very small handful of women doing hands-on laboratory research in the area. That earned her the nickname the "mother of infrared astronomy." She served as an editor of the *Astrophysical Journal*, and the asteroid 306128 Pipher is named in her honor.

Judith Lynn Pipher

NASA/COURTESY OF AIP ESVA/ERICKSON COLLECTION

Judy was inducted into the National Women's Hall of Fame in Seneca Falls in 2007 and helped to recognize the achievements of women across a broad array of disciplines when she subsequently joined the hall's board of directors. In addition, she served as a board member of the Cayuga Lake Watershed Network, an organization devoted to protecting critical natural resources, and of the Seneca Museum of Waterways and Industry, home of the Seneca Falls Visitor Center.

Judy was a pillar of the science community both personally and professionally. Her strength, intellect, courage, and kindness sustained us both through difficult times and continue to inspire us. Not only did Judy give us fabulous new views of the universe through her scientific work, she helped us see with clarity and humanity.

Amy Mainzer
University of Arizona
Tucson
Craig McMurtry
University of Rochester
Rochester, New York PT

LOOKING FOR A JOB?

Job ads are now located throughout the magazine, alongside the editorial content you engage with each month. Also find hundreds of jobs online at physicstoday.org/jobs

LOOKING TO HIRE?

Enjoy the power of print plus online bundles any time as well as impactful exposure packages & discounts for our special Careers issue each October. Post online-only jobs anytime at physicstoday.org/jobs

Questions? Email us at ptjobs@aip.org

PHYSICS TODAY | JOBS

Nicolas Taberlet is an associate professor at the University of Lyon in France. His research specialties are the physics of granular materials and pattern formation in ice structures.

The mysterious balancing stones on frozen lakes

Nicolas Taberlet

During the cold, dry Siberian winter, one can occasionally spot stones perched on impossibly thin pedestals of ice. How do they get there?

Among those who live in a cold enough climate, who has never thrown a large pebble onto the pristine surface of a frozen lake in the hope of breaking the ice? In the Siberian winter on Lake Baikal, any attempt is bound to fail, as the ice typically reaches up to 3 meters thick—enough to support the weight of an 18-wheeler.

But initial disappointment can turn to amazement: After a few weeks sitting on the surface, the stone ends up balancing on a thin pedestal of ice, while the surface around it gradually vanishes into thin air. The phenomenon is manifest in the formation of Zen stones, shown in the figure, so-called because of their resemblance to stacks of rocks sometimes found balancing in Japanese Zen gardens.

Sightings are rare, possibly because specific meteorological conditions are required. Not only must the temperature remain below freezing but the ice surface must remain free of snow for several consecutive weeks. The climate at Lake Baikal meets both conditions: The air temperature is below freezing for an average of five months per year, and precipitation is rare in winter. Thus, the melting of ice is virtually impossible, and the region's exceptionally low humidity mainly causes the ice to sublimate.

I was struck at how little explanation exists in the literature and set out to reproduce the effect in the lab.

The umbrella effect

In the case of water, the direct phase transition between the solid state and a gas occurs at negative temperatures (in Celsius) and in a very dry atmosphere. What's more, it's a slow, endothermic surface process, which therefore requires a constant flux of external energy. Sunlight does the job in nature, either directly in clear weather or diffusely in overcast conditions. Sublimation causes the ice to vaporize at a rate set by the temperature, humidity, and amount of sunlight it receives. From the average winter solar irradiance at the lake and water's latent heat of sublimation, I estimate the sublimation rate of an ice surface at about 2 mm per day.

A pebble placed on the ice blocks that light, however, and its shade hinders the sublimation beneath it. The rate, nearly zero underneath, gradually increases with distance from the center. The stone therefore acts as an umbrella, which protects the ice from solar irradiance. Known as differential ablation, the process forces the pebble to remain at a constant altitude on an increasingly taller and narrower foot of ice until it eventually falls off. Its lifetime atop the pedestal is roughly the half width of the stone divided by the ablation rate—about 40 days for the stone in panel a of the figure.

Sublimation is not the only possible factor at play. The melting temperature of water decreases with applied pressure. And between 100 MPa and 1 GPa, ice can start melting at temperatures as low as −10 °C. The pressures that Zen stones exert on the ice remain far below that range, however, and any melting would only cause the pebble to sink into the ice. Moreover, ice is known to slowly deform over time—a phenomenon known as plastic creep—which explains why glaciers can flow down mountains. But that too only causes the stone to sink.

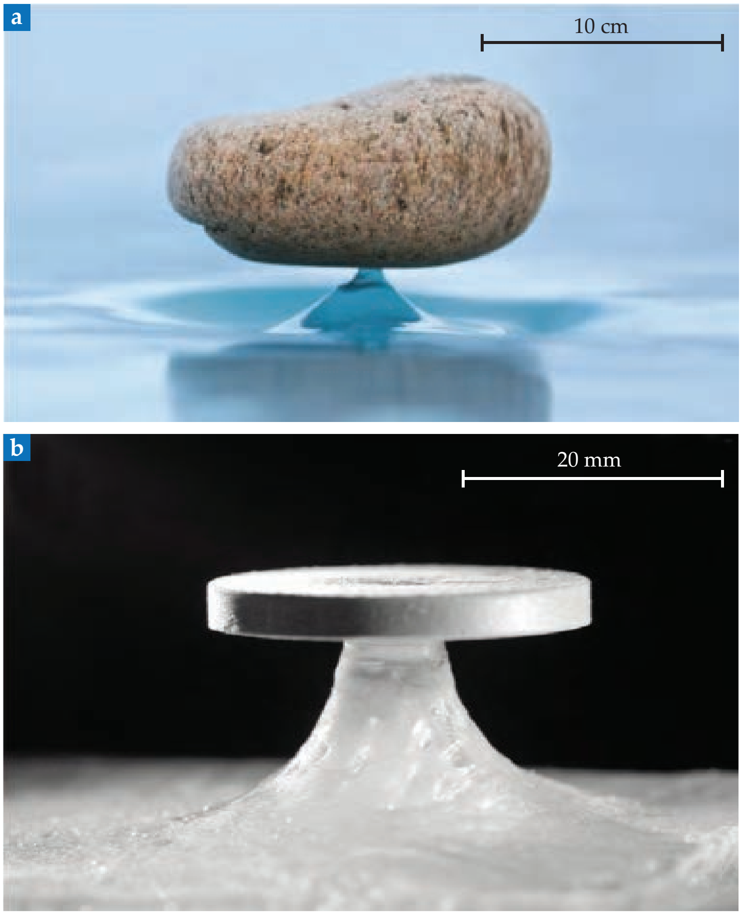
As another possible factor, small wind-driven ice particles could potentially create mechanical wear. But the smooth surface of the ice pedestals shows no evidence of erosion. And the typical time required for that ablation process is far longer than the lifetime of a natural Zen stone.

Stones in the lab

To convince my University of Lyon colleague, Nicolas Plihon, and myself of the simple sublimation hypothesis, we reproduced the phenomenon in a laboratory-scale experimental setup. We placed an aluminum disk—a proxy for the stone—on the surface of a block of ice within a commercial lyophilizer, a device whose temperature, pressure, and humidity favor sublimation. The external energy used to sublimate the ice came not from sunlight but from IR radiation of the walls of the vacuum chamber, which remained at room temperature.

In the absence of a stone, the ablation is nearly isotropic and mimics the relative isotropy of natural diffuse sunlight in overcast weather. And its considerably greater sublimation rate of typically 8–10 mm per day allowed us to accelerate the physical mechanism. Indeed, obtaining Zen stones from actual pebbles and disks was straightforward.

The figure's panel b shows the results we achieved using a 30 mm aluminum disk after 40 hours of sublimation. With the disk initially placed either on the ice surface or embedded inside the ice, the IR forced the ice to sublimate only partially—the disk's shade prevented it from vanishing completely.



ZEN STONES in nature and the lab. **(a)** On Lake Baikal a stone rests on a narrow ice pedestal. **(b)** In a laboratory, this 30 mm aluminum disk rests on a flat ice surface after sitting in a lyophilizer for 40 hours. (Adapted from *Proc. Natl. Acad. Sci. USA* **118**, e2109107118, 2021.)

Among other results, our experiments confirmed that the disk's thermal properties had little effect. (In some cases, we used copper disks, whose thermal conductivity and specific heat greatly exceed those of aluminum disks we used in other cases.) They supported our conclusion that the umbrella effect is the predominant mechanism.

Dip around the pedestal

One interesting difference exists between natural and laboratory-made Zen stones. In nature a dip always surrounds the ice foot. But that feature was never encountered in our lab experiments. Whereas the umbrella effect is clearly responsible for the pedestal's formation, a detailed energy balance of the system reveals second-order phenomena. Like any other material, ice and stone emit blackbody IR radiation in a range whose intensities depend on the temperature and the material's emissivity.

In nature, because of sunlight or ambient wind, the ice and stone are unlikely to remain at the same temperature throughout the day. And that, in turn, causes an imbalance between them. More specifically, if the stone is a few degrees warmer than the ice, the IR it radiates into the ice (in addition to that from sunlight) can exceed that emitted by the ice itself. The effect becomes important in the later stages of Zen-stone formation—when a stone sits on a tall and thin pedestal—as thermal contact is reduced.

Two competing effects are therefore at play: the umbrella effect, which protects the ice, and the excess energy from the stone, which instead accelerates the sublimation and carves out a cavity in the stone's vicinity. While the former is responsible for the formation of the ice pedestal in the early life of a Zen stone, the latter is responsible for the dip forming around the ice foot in the later stages.

The excess energy is absent in our experiment because of three factors: The lyophilizer was operated in a high vacuum, metal was used for Zen stones, and such stones were smaller, all of which favor a good thermal equilibrium between the disk and the ice.

Glacier tables

In addition to Zen stones, other intriguing formations consisting of a rock resting on a thin pedestal can be found in nature. In a hoodoo, for instance, a hard stone protects a tall column of fragile sandstone from rain and frost-driven erosion. And in a so-called glacier table, a large rock on a low-altitude glacier ends up on a tall foot of ice. The latter case is akin to the Zen stones of Lake Baikal because it involves differential ablation of an ice surface. But the glacier tables' rock formation, shape, and dynamics are broadly different.

Glacier tables appear on temperate glaciers where the ice (remaining at 0 °C) simply melts because of the warm ambient conditions. Depending on its size and shape, a rock atop the ice can provide enough thermal insulation to either hinder the ice from melting (a process that leads to the formation of the ice pedestal) or increase the ice's melting rate (a process that leads to the rock sinking into the ice). A recent study has shown that the differential melting of ice for glacier tables is predominantly caused by heat exchange with the surrounding air.

The umbrella effect, which controls the formation of Zen stones, is therefore only a secondary factor for glacier tables. Conversely, although a material's thermal properties, such as conductivity and specific heat, are crucial for glacier tables, they are insignificant to the formation of Zen stones. Any opaque object left on a sublimating ice surface is likely to wind up atop a narrow foot. Indeed, far from the romantic image sometimes conjured by a Zen stone, the frozen bodies of deceased penguins in Antarctica can occasionally be found perched on top of narrow ice pedestals.

Additional resources

► N. Mangold, "Ice sublimation as a geomorphic process: A planetary perspective," *Geomorphology* **126**, 1 (2011).
► N. Taberlet, N. Plihon, "Sublimation-driven morphogenesis of Zen stones on ice surfaces," *Proc. Natl. Acad. Sci. USA* **118**, e2109107118 (2021).
► M. Hénot, N. Plihon, N. Taberlet, "Onset of glacier tables," *Phys. Rev. Lett.* **127**, 108501 (2021).

PT

BACK SCATTER

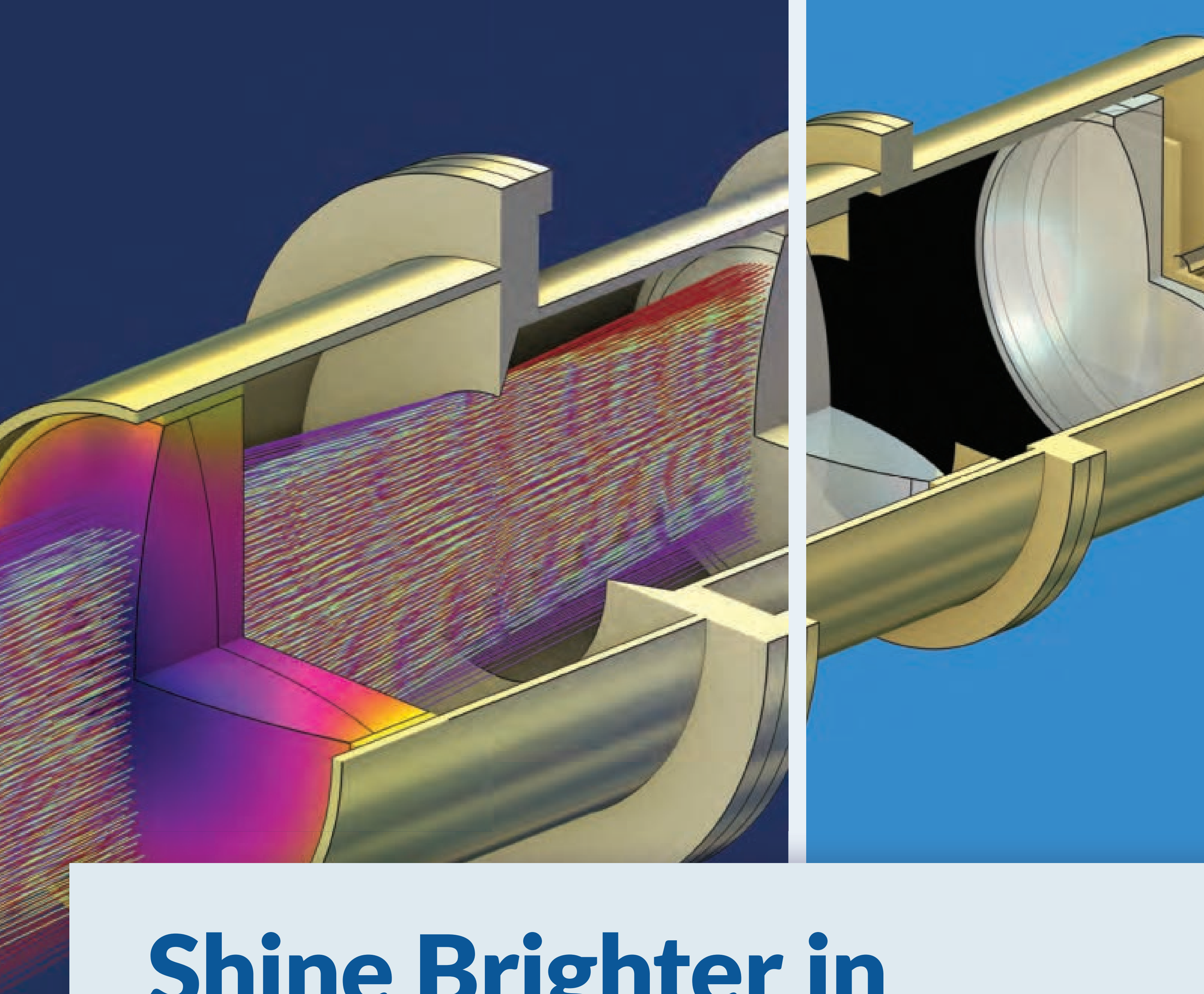
Living chiral crystals

Conventional crystals typically form when the attraction between constituent atoms or molecules overcomes any thermal agitation in the system. Active crystals, in contrast, can form when mobile particles self-organize into a regular ordered structure. Such behavior has been observed previously in colloidal and bacterial systems. The composite photo here shows starfish embryos that have spontaneously formed a two-dimensional living crystal. Each of the hundreds of floating embryos spins clockwise. Those individual motions pull water toward each embryo and downward and collectively produce a chiral rotation of the few-millimeter-sized crystal. Light yellow indicates the embryos' initial positions; dark blue, their ending positions.

Tzer Han Tan (now with the Max Planck Institute of Molecular Cell Biology and Genetics), Alexander Mietke, Nikta Fakhri, and their MIT colleagues found that a starfish crystal can persist for tens of hours. But unlike previously studied active crystals, the starfish assembly's motion is a result of the embryos' development. In the first 40 or so hours of growth, each embryo has an asymmetric elongated shape whose major axis is oriented perpendicular to the fluid surface. As they spin clockwise, groups of them spontaneously organize into 2D hexagonal clusters. What remains a mystery, however, is the evolutionary advantage of the spontaneous active crystal. (T. H. Tan et al., *Nature* **607**, 287, 2022; image courtesy of Nikta Fakhri.) —AL

TO SUBMIT CANDIDATE IMAGES FOR BACK SCATTER VISIT https://contact.physicstoday.org.


GradSchoolShopper
MAGAZINE | FALL 2022
Guide to Grad School
in Physics, Astronomy,
and Related
READ NOW!
gradschoolshopper.com/magazine
programs are looking for in applicants
How to get great letters of recommendation
Pathways to medical physics
The physics GRE explained
presented by
AIP
American Institute of Physics
SPS



Shine Brighter in Optical Design

with COMSOL Multiphysics®

Multiphysics simulation drives the innovation of new light-based technologies and products. The power to build complete real-world models for accurate optical system simulations helps design engineers understand, predict, and optimize system performance.

» *comsol.com/feature/optics-innovation*

COMSOL

MathWorks®

MATLAB SPEAKS DEEP LEARNING

With MATLAB® you can build deep learning models using classification and regression on signal, image, and text data. Interactively label data, design and train models, manage your experiments, and share your results.

mathworks.com/deeplearning

© 2022 The MathWorks, Inc.

Semantic segmentation for wildlife conservation.