PHYSICS TODAY

August 2020 • volume 73, number 8

A publication of the American Institute of Physics

# DOES NEW PHYSICS LURK INSIDE LIVING MATTER?

Nanosensors mitigate vision loss

X-ray photography at Wellesley College

Nuclear plants to manufacture hydrogen

# PHYSICS TODAY

August 2020 | volume 73 number 8




## FEATURES


### 26 Sarah Frances Whiting and the "photography of the invisible"

**John S. Cameron and Jacqueline Marie Musacchio**

A team of women working in the physics laboratory at Wellesley College carried out some of the first successful x-ray experiments in the US.

### 34 Does new physics lurk inside living matter?

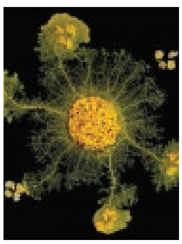
**Paul Davies**

The link between information and physics has been implicit since James Clerk Maxwell introduced his famous demon. Information is now emerging as a key concept to bridge physics and biology.

### 42 Nanotubes from layered transition metal dichalcogenides

**Janice L. Musfeldt, Yoshihiro Iwasa, and Reshef Tenne**

The two-dimensional materials form one- and zero-dimensional hollow structures with a host of promising mechanical, optical, and electrical properties.

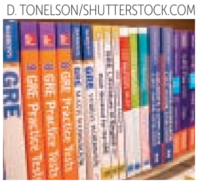



**ON THE COVER:** At the cellular level, various physical mechanisms allow for signaling and can lead to cooperative behavior. Slime molds, like the one shown here, provide an example: They are aggregations of single cells that self-organize and behave coherently as if they were one organism. As Paul Davies discusses in his article on **page 34**, some physicists are bridging the conceptual gulf between physics and biology by incorporating the patterns of information flow into thermodynamic models. (Photo courtesy of Audrey Dussutour, CNRS.)

## Recently on PHYSICS TODAY ONLINE

www.physicstoday.org

D. TONELSON/SHUTTERSTOCK.COM



### ▶ Going GRE-free

Many universities are temporarily forgoing graduate applicants' GRE scores due to the pandemic. Independently, some departments have been dropping the test requirement permanently because of concerns that it leads to inequity in admissions and doesn't predict grad school success.

***physicstoday.org/Aug2020a***

LOS ALAMOS NATIONAL LABORATORY

### ▶ Explosion monitor

What if the data from diverse geophysical instruments worldwide could be fused and analyzed for improved detection of explosions, particularly nuclear ones? Sarah Scoles describes the efforts of Los Alamos physicist Joshua Carmichael to create a reliable multiphysics explosion-detection model.

***physicstoday.org/Aug2020b***

ROMAN MAGER/UNSPLASH

### ▶ Racism in physics

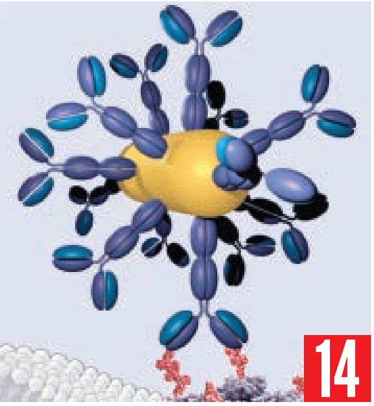
Charles D. Brown II, a physicist at the University of California, Berkeley, recounts in a commentary the numerous instances of anti-Black racism and bias that he has experienced in physics and academia. He concludes with a call to hire, advocate for, and listen to Black scientists.

***physicstoday.org/Aug2020c***

**Physics Today** (ISSN 0031-9228, coden PHTOAD) volume 73, number 8. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to Physics Today, American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Views expressed in Physics Today and on its website are those of the authors and not necessarily those of AIP or any of its member societies.

# PHYSICS TODAY

www.physicstoday.org



14

49

60

## DEPARTMENTS

**8 From the editor**

**10 Readers' forum**

Letters

**14 Search & discovery**

Near-IR nanosensors help blind mice see • Photoelectron spectra explain how ammonia solutions become metallic

**20 Issues & events**

Could hydrogen bail out nuclear power? • New 5G exemption may jam GPS devices

**49 Books**

Experimental expectations versus realities — *Tim Maudlin* • A social history of eclipse expeditions — *Clark Glymour* • New books & media

**53 New products**

Focus on lasers, imaging, nanoscience, and nanotechnology

**56 Obituaries**

John Theodore Houghton

**58 Quick study**

The warmth of wind power — *Lee Miller*

**60 Back scatter**

Restraining respiratory droplets



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

**Senior director of news & magazines**
Larry Fishbein *lfishbein@aip.org*

**Editor-in-chief**
Charles Day *cday@aip.org*

**Managing editor**
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**
Melinda Baldwin *mbaldwin@aip.org*
Toni Feder *tf@aip.org*
Martha M. Hanna *mmh@aip.org*
Heather M. Hill *hhill@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 editor**
Andreas Mandelis

**Sales and marketing**
Christina Unger Ramos *cunger@aip.org*
Unique Carter
Krystal Dell
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**
Acoustical Society of America
American Association of Physicists in Medicine
American Association of Physics Teachers
American Astronomical Society
American Crystallographic Association
American Meteorological Society
American Physical Society
AVS: Science & Technology of Materials, Interfaces, and Processing
The Optical Society
The Society of Rheology

**Other member organizations**
Sigma Pi Sigma Physics Honor Society
Society of Physics Students
Corporate Associates


OXFORD INSTRUMENTS
Proteox™
Next Generation Thinking
Integrated high magnetic fields
High stability superconducting magnets with fast sweep capability and low flux noise for high quality quantum transport measurements
Rapid sample exchange for quick turnaround
Increased experimental throughput with high density DC and RF lines to facilitate a wide range of measurements
High performance dilution unit
10 mK base temperature with optimised flow for ultra stable, low noise performance and active control to 30 K
Secondary Inserts for flexible wiring assemblies
Capacity for up to 140 coaxial cables, scaling experimental services has never been easier
The Proteox™ dilution refrigerator from Oxford Instruments
A step change in system modularity
nanoscience.oxinst.com/proteox

# FROM THE EDITOR

# The time is now

Charles Day

PHYSICS TODAY's September 1966 issue included an interview with Herman Branson, who was chair of Howard University's physics department at the time. Among the questions he fielded about the state of Black people in physics was, "Do you feel that the science community is biased to any degree?" He replied, "I don't think so. . . . Scientists (and especially physicists) are among the most liberal people to be found anywhere."

Branson's response evidently shocked his fellow African American physicist Tannie Stovall of the Linear Accelerator Laboratory in Orsay, France. He submitted a rebuttal, which appeared in PHYSICS TODAY's December 1966 issue. "Branson has painted a dangerously rosy picture of the black man in physics," Stovall wrote. "I would like strongly to take issue with this view."

How could Branson believe that racial bias was absent from science in 1966? I can't be sure. He might have harbored a belief that persists today: Physics is the objective, methodical study of matter and energy, which are devoid of life, let alone social and political actors. How can physics be biased?

But if you read Branson's interview, it's clear he was quite aware of the systemic obstacles faced half a century ago by Black students in science. Indeed, he campaigned to remove them. Black colleges and universities had—and still have—less funding than other universities. "We know how to make a first-rate school in America," Branson told his interviewer. "It's primarily a question of money."

When PHYSICS TODAY published its interview with Branson, the last of the five Civil Rights Acts of the 1950s and 1960s—the Fair Housing Act of 1968—was stalled in the Senate. Asked if his physics students were as active in civil rights as humanities students, Branson answered, "Perhaps embarrassingly so." Quite to his surprise, physics majors were among the student leaders in local civil rights movements. Some of them, he lamented, did not continue to pursue physics.

As members of a prominent Black university in the US, those "lost" students of Branson's who joined the struggle for civil rights were surely made welcome in the physics department. Sadly and reprehensibly, too many of today's Black physics majors and graduate students do not feel as though they belong. If you doubt that physics is unwelcoming to Black students, read the commentary by Charles D. Brown II, which was posted on PHYSICS TODAY's website on 20 July. Brown, who is a postdoc in atomic physics at the University of California, Berkeley, recounts a litany of racist slights and presumptions that he faced as a physics student.

Making physics more welcoming to Black people and other underrepresented groups will take effort, not least because a student's peers have a strong influence on whether a department is welcoming. Professors must lead by example. If you need advice on how to do that, read the report[1] from the TEAM-UP Task Force, which was organized by the American Institute of Physics (PHYSICS TODAY's publisher).

A recent briefing in the *Economist* identified three policy areas that, if addressed effectively, could improve the lives and opportunities of African Americans: segregation, education, and childhood poverty. Although tackling those and other systemic sources of disadvantage will be expensive and difficult, it needs to be done. And Branson recognized another challenge in his 1966 interview: "Suppose you take a 17-year-old from an indifferent intellectual and cultural background; what can you do to bring him into 20th-century science? It's not only a tough question for America but for the rest of the world as well."

Given the magnitude of the challenges, the individual physicist, including me, might be tempted to ask with exasperation, What can I do? We can listen to the personal experiences of Black physicists. We can work toward making our departments, labs, and teams more welcoming. And we can confront racism whenever we encounter or witness it. The killing of George Floyd on 25 May again brought into stark, painful view the anti-Black racism that endures in the US. The time is now to do what we can to eliminate it.

## Reference


1. 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). PT

# Animal communication in context

Megan McKenna's article "The sounds around us," dealing with animal communication (PHYSICS TODAY, January 2020, page 28), is an informative discussion of the role of sound in the natural world. A somewhat surprising omission is the role of Earth's two dominant fluid systems, the atmosphere and the oceans, in the propagation and detection of sound. Sounds in both depend on the fluid's state.

If the fluid is stratified with a stable vertical density distribution, sound can be trapped and transmitted over unusually long distances. The oceans characteristically exhibit such a layer, the thermocline, near the surface. Whales employ it to communicate over distances of hundreds, or even thousands, of kilometers. Those cetaceans—and multiple species, including dolphins and porpoises—use songs, whistles, and clicks to communicate, to sense their surroundings, and to locate prey through echolocation.[1]

Pervasive atmospheric nocturnal inversions, particularly in dry habitats such as Namibia's Etosha National Park, are used by elephants to communicate over distances of 10 km. Because of their low birth rate of less than one calf in five years, African elephants must use sound to survive. Their ability to find a mate in the dense rain forest where elephants evolved depends on their using long-wave (30 m), low-frequency (15 Hz) sound in an environment where the highest temperatures are at the tops of the trees and the lowest at the forest floor. Low-frequency calls trapped in such a forest inversion of temperature can be heard over an area of roughly 300 km$^2$, which would likely contain more than one adult male.

ALBATROSS/ALAMY STOCK PHOTO

Surprisingly, when the rain forests contracted some 20 million years ago and the elephants migrated to the savannas, similar atmospheric conditions prevailed during early evening and night. In the dry desert-like conditions, the surface cools rapidly just before and after sunset. A strong nocturnal temperature inversion 100 m deep forms rapidly. The inversion traps the elephants' low-frequency calls such that an estrous female may be heard by several male elephants ready to compete for her. Without such a choice, propagation of the species might be in question. Sound in the oceans and the atmosphere is a major part of the ecological story.[2]

## References


1. Whale and Dolphin Conservation Inc, webpage "How do dolphins communicate?" (2018); https://us.whales.org/whales-dolphins/how-do-dolphins-communicate.
2. M. Garstang, *Elephant Sense and Sensibility: Behavior and Cognition*, Academic Press (2015), chap. 9.



**Michael Garstang**
*(mxg@swa.com)*
*Simpson Weather Associates Inc*
*and University of Virginia*
*Charlottesville*


I read with interest the article "The sounds around us" by Megan McKenna (PHYSICS TODAY, January 2020, page 28). I wonder if anyone is studying the sounds of animals communicating while they are confined in slaughterhouses or in trucks transporting them to slaughterhouses. Are those sounds different from the ones they make as they join the assembly line during slaughter? And does anyone study the sound of a dairy cow as its newborn calf is taken away? She must communicate a lot.

My take is that communication among nonhuman animals is of no concern to humans when it comes to their taste buds or their pocketbooks.


**Richard J. Peppin**
*(peppinr@asme.org)*
*Rockville, Maryland*

# Putting noise in its place

Roland Wittje's informative article "Noise: From nuisance to research subject" (PHYSICS TODAY, February 2020, page 42) shows how the concept of noise in physical systems has evolved and proliferated, from its origins in 19th-century studies of acoustics, to a general notion of unwanted fluctuations across a swath of disciplines extending well beyond the borders of physics. The proverb "one person's noise may be someone else's signal" suggests a concise, general, and likewise proverbial definition: Noise is information out of place.

That formulation, of course, paraphrases a celebrated observation by William James,[1] about certain "elements of the universe" being "irrelevance and accident—so much 'dirt,' as it were, and matter out of place," which was explored in depth by Mary Douglas.[2]

## References


1. W. James, *The Varieties of Religious Experience: A Study in Human Nature*, Longmans, Green (1902), p. 133.
2. M. Douglas, *Purity and Danger: An Analysis of Concepts of Pollution and Taboo*, Routledge (1966).



**John Morgan**
*(morganjohn@earthlink.net)*
*La Cañada Flintridge, California*


In his article on the evolution and history of noise (PHYSICS TODAY, February 2020, page 42), Roland Wittje mentions in passing physicists, including Nobel laureates, involved in acoustics during World War I. What he did not mention was the essential work of James Lighthill (1924–98) during the 1950s. After Lord Rayleigh's monumental contributions in his two-volume work *The Theory of Sound*, Lighthill's development of aeroacoustics[1] is considered some of the most important work in the field; he defined the source of sound and especially illuminated the issue of noise reduction. (See Lighthill's obituary in PHYSICS TODAY, March 1999, page 104.)

## Reference


1. M. J. Lighthill, *Proc. R. Soc. London A* **211**, 564 (1952); M. J. Lighthill, *Proc. R. Soc. London A* **222**, 1 (1954).



**Julian Ting**
*(juhilian@gmail.com)*
*De-Font Research Institute*
*Taichung, Taiwan*


# Enchanted by a tiny swimmer

Rachel Berkowitz's Search and Discovery story "A tiny swimmer generates rapid, far-reaching signals in water" (PHYSICS TODAY, September 2019, page 22) was fascinating—that such rich physics and biology could be found in a little creature in a pond in Palo Alto, California. It started, as Berkowitz writes, with Manu Prakash noticing a funny little swimmer that could contract so quickly it seemed to disappear, and it ended with hydrodynamic modeling of trigger waves.[1]

This is the kind of investigation I think young scientists, myself included, dream about: We notice something in our environment and then seek to understand it. Our beautiful odyssey brings together ideas that range from spaghettification of black hole explorers to "the fractal nature of cellular connectivity near the critical point"[1] and demonstrates how interdisciplinary nature can be. It shows the richness of the world around us and reminds us that mysteries lie in the most unexpected places.

As I look out my window at the birds that will disappear with the advent of winter, I wonder how a Baltimore oriole can fly thousands of miles at night and find its way to the exact spot it was at a year ago. With my interest in quantum physics, I wonder, for example, if nature has developed an organism that uses quantum correlations akin to those characterizing entanglement for communication. With hundreds of millions of years of evolution, nature has many surprises. If it is possible and useful, nature has done it. It is up to us to explore.

## Reference


1. A. J. T. M. Mathijssen et al., *Nature* **571**, 560 (2019).



**G. Jordan Maclay**
*(jordanmaclay@quantumfields.com)*
*Quantum Fields LLC*
*St Charles, Illinois*


# Careers beyond the ivory tower

Thank you for the initial PHYSICS TODAY Annual Careers Issue in October 2019. As someone who earned a PhD in oceanography more than 20 years ago but chose to pursue a career outside the traditional academic track, I've long been an advocate of educating students at all levels about the myriad career options available to them other than professorships.

The issue features a range of professional opportunities such as those Elizabeth Frank mentions in her commentary (page 10) and physicists working at Boeing. I especially enjoyed the article "The road taken" (page 32), by Anne Marie Porter and Susan White and found its figure 4, showing movement between first and current job sectors, particularly interesting.

It's worth noting, though, that of 43 job postings in that issue, 31 were for tenure-track academic positions. Only eight were for the industrial sector: seven in a single large project (the Thirty Meter Telescope) and one at the American Institute of Physics itself, which publishes PHYSICS TODAY. The others were for government or graduate-student fellowships.

In a special issue devoted to careers in the physical sciences, perhaps AIP could have solicited more nontraditional job postings. It would be a great encouragement and help to those seeking nonacademic opportunities. Other than that, this was the most practical and useful issue of PHYSICS TODAY that I've read in quite some time.


**Karl Newyear**
*(karl.newyear@gmail.com)*
*Parker, Colorado*



**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.

# Teacher harassment and a loss of respect

Thirty-one years ago I retired from teaching physics. Much has changed since then, but on reading the commentary in the March 2020 issue of PHYSICS TODAY (page 10), I was appalled but not surprised to learn that one aspect of teaching has not changed—harassment of teachers. In my era everyone was more civilized than today, so harassment from whining and complaining students was verbal, not physical.

During my 20-year career, I found that the most virulent of the whiners and complainers were the premed and pre-engineering students. They tried to intimidate professors to get the high grades needed to be admitted to their respective professional schools. They implied that professors, not they, would be responsible for their careers.

At the beginning of every course, I explained that I do not give grades. I simply record the grades the students earn. Also, I set rules of classroom decorum and declared that students who remained in my class tacitly agreed to those conditions. Nevertheless, at grade time a few students begged for higher grades. I suspect that behavior has not changed.

One protocol I disliked was written student evaluations of professors (see PHYSICS TODAY, January 2020, page 24). To avoid having grades and those evaluations influence each other, students submitted their evaluations before they received their grades, and professors saw them afterward. I usually received high marks and favorable comments, but some students gave me low scores and wrote insulting remarks. I frequently observed a strong correlation: Students earning low grades often were the ones submitting unfavorable comments.

How can administrators eliminate or reduce harassment of professors? And why do students harass them? I am too far beyond my campus years, so I cannot answer the first part, except to guess that administrators are overly concerned with political correctness as applied to their sources of income—the students.

As to the second question, our society—students included—has suffered a general breakdown in courtesy. The students' part of that may be because the evolution of classroom attire from proper to casual to relaxed to sloppy promoted sloppy habits and attitudes. And from recent visits to campuses, I noted that many professors emulated their worst-attired students. When professors become too casual, allow or encourage informality with students, and relax discipline, they can lose dignity, prestige, and respect.

To stop harassment of professors, administrators surely should pay more attention to the welfare of their faculty, and professors should dress and act as though they deserve respect from students. That way, they will be more likely to get it.

**William J. Veigele**
*(wveigele@aol.com)*
*Santa Barbara, California* PT

# HEAD | DEPARTMENT OF PHYSICS AND ASTRONOMY, PURDUE UNIVERSITY

Purdue University's College of Science invites applications for the role of Head of the Department of Physics and Astronomy, with the possibility where suitable of an accompanying named and/or distinguished professorship. We seek a recognized researcher with a proven track record of leadership, scholarship, and mentoring. Following a very positive recent external visiting committee review and substantial investment in new hires and facilities, the successful candidate will have a clear plan to continue to increase the visibility, stature, and intellectual leadership of the Department and the College of Science, and will demonstrate a commitment to teaching excellence.

Physics and Astronomy is an interdisciplinary department with more than 50 faculty involved in research spanning most of the broad portfolio of the physics and astronomy subfields. Recent faculty hiring initiatives in atomic, molecular, and optical physics and in quantum information science have led to exciting new strengths in those areas, as well as the traditional areas of condensed matter, high energy, astrophysics, biological physics, nuclear physics, and physics education. Departmental faculty are also involved in University-wide multidisciplinary research in quantum photonics, nanoscience, and quantitative biosciences. Further information about the Department can be found at https://www.physics.purdue.edu/ and additional materials are available upon request.

The Department of Physics and Astronomy is one of seven departments in the College of Science, with involvement in numerous interdisciplinary programs and centers. Key initiatives of interest to a new head will include university priorities and centers in the data & computational sciences and quantum science & engineering as well as substantial recent investments in the geosciences, life sciences, environmental & atmospheric science, and space sciences & engineering. Further information on the College of Science is available on the website at www.science.purdue.edu.

Qualifications: The successful candidate will have a Ph.D. in Physics, Astronomy, or a related discipline, an outstanding record of scholarly achievement and a history of extramurally funded research commensurate with the rank of full professor at Purdue, exceptional and proven leadership abilities, a vision for the Department in the University, state, and nation, a commitment to excellence in undergraduate and graduate education, a record of teaching achievement, an enthusiasm for engagement, and a dedication to championing diversity, equity, and inclusion.

Applications: Interested candidates should submit a cover letter, curriculum vitae, a statement of research and teaching accomplishments, a vision statement for the future of research and education in the Department, and the names and email addresses of three references who might be contacted later (contingent upon approval of the candidate) after an initial short list of candidates is selected by the Committee. Applications should be submitted to https://career8.successfactors.com/sfcareer/jobreqcareer?jobId=10675&company=purdueuniv. Inquiries should be directed to Chris Greene, Chair of the Physics and Astronomy Head Search Committee, chgreene@purdue.edu. Review of applications will begin August 28, 2020, and will continue until the position is filled. A background check is required for employment in this position.

Purdue University's Department of Physics and Astronomy is committed to advancing diversity in all areas of faculty effort, including scholarship, instruction, and engagement. Candidates should address at least one of these areas in a separate Diversity and Inclusion Statement, indicating their past experiences, current interests or activities, and/or future goals to promote a climate that values diversity and inclusion.

# Near-IR nanosensors help blind mice see

When blindness sets in gradually, the patient's remaining vision can hinder prospective treatments. In a new experimental strategy, researchers turn to a different wavelength.

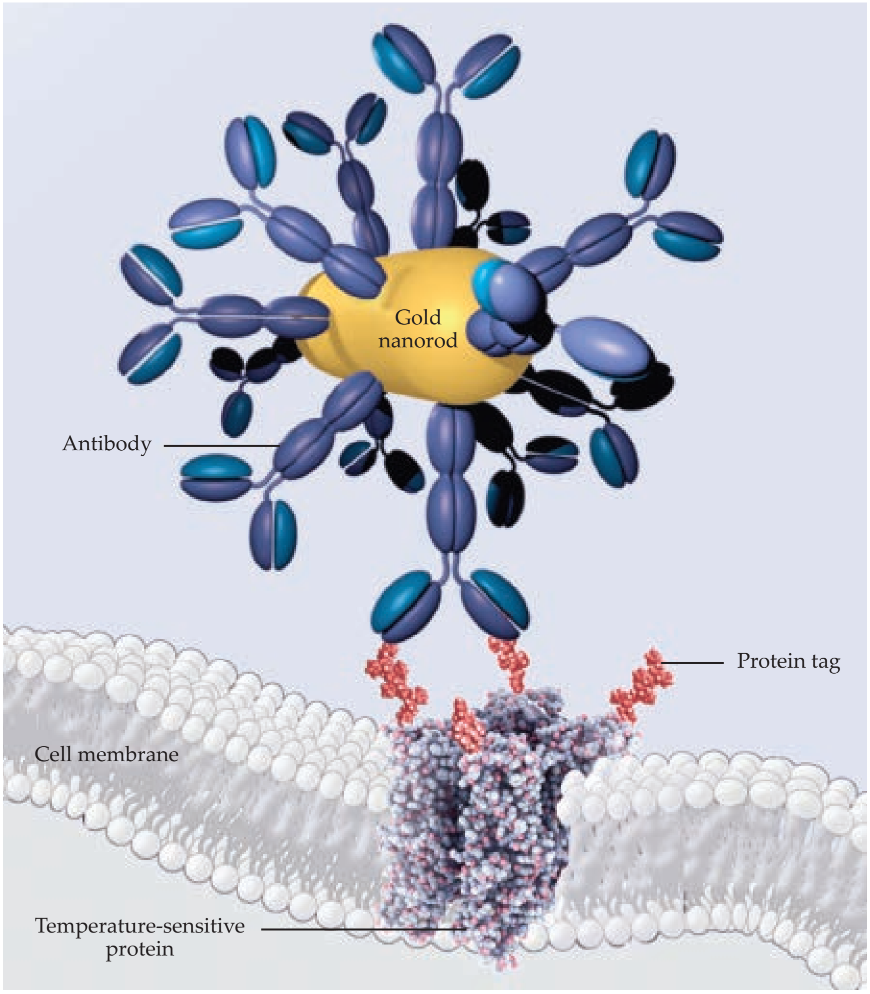



**FIGURE 1. HOW TO SEE IN THE NEAR-IR.** A gold nanorod strongly absorbs 915 nm light to produce heat, and a temperature-sensitive protein generates an electrical signal when heated. When the protein is embedded in a retinal cell membrane and linked to the nanoparticle via a protein tag and corresponding antibody, the retina becomes sensitive to near-IR light that most animals can't normally see. (Image by Veronique Juvin, SciArtWork.)

Even in the dark, rattlesnakes and their fellow pit vipers can strike accurately at small warm-blooded prey from a meter away. Those snakes, and a few others, can see in the IR—but not with their eyes. Rather, they have a pair of specialized sensory organs, called pit organs, located between their eyes and their nostrils and lined with nerve cells rich in temperature-sensitive proteins that cause the neurons to fire when heated.[1] The pits work like pinhole cameras to focus incoming thermal radiation onto their heat-sensitive back walls; the thermal images are then superimposed with visual images in the snake's brain.

Heat-responsive neurons are not unique to snakes. We have them over every inch of our skin, to feel objects warm to the touch, and on our tongues, to taste spicy food. But the snakes' ability to resolve the source of radiated heat at a distance is unusual.

Inspired by the snakes, Dasha Nelidova and her colleagues at the Institute of Molecular and Clinical Ophthalmology in Basel, Switzerland, are developing a new treatment for forms of blindness caused by the degeneration of retinal photoreceptors.[2] Using gene therapy, they endow remaining retinal cells with thermoresponsive proteins, thereby compensating for their lost light sensitivity with heat sensitivity. The proteins by themselves aren't sensitive enough to rival normal vision, so the researchers tether them to gold nanorods, as shown in figure 1. The 80-nm-long nanorods strongly absorb near-IR light at 915 nm and convey the concentrated heat to the attached proteins.

So far, the researchers have tested the protein–nanoparticle combination on blind mice and on donated postmortem human retinas. The results are promising: The mice could learn a behavioral response to a flash of near-IR light, and the human retinas, like the one shown in figure 2, produced a detectable electrical signal. But it will take years of additional work to turn the procedure into a safe and effective treatment for live humans.

## The eyes have it

From the cornea to the optic nerve, any component of the visual system can malfunction, and correspondingly, there are many types of blindness, some more treatable than others. Cataracts, the clouding of the normally transparent lenses, are routinely treated by surgically replacing the faulty lenses with artificial implants. If the cornea becomes cloudy or opaque, part or all of it can be replaced with a transplanted one. Although organ and tissue transplants are never easy, corneal transplants are among the most straightforward: The eyes are an immune-

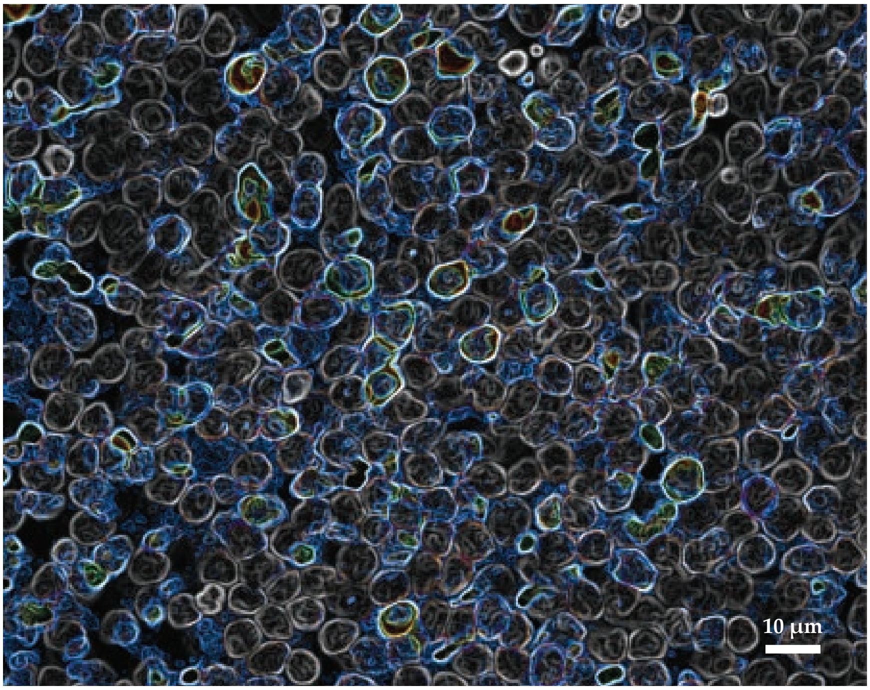



**FIGURE 2. DELIVERING A NEW GENE.** Retinal cells don't normally manufacture the thermoresponsive protein shown in figure 1, but they can be made to do so through gene therapy. Benign viruses, packed with the DNA that encodes the protein, inject their genetic material into the cells, which take up the gene and start expressing the protein. In this image of a treated postmortem human retina, the thermoresponsive protein is stained with a fluorescent dye. The cells shown in color are all producing the new protein; the cells shown in gray are not. (Courtesy of Dasha Nelidova.)

privileged site, meaning that the body is less likely to attack and reject the foreign tissue.

In the industrialized world, most vision loss is due to photoreceptor degeneration, a category that includes age-related macular degeneration—which affects millions of people in the US alone—and several less common inherited conditions. In each of them, the rods and cones in the retina gradually lose their light-sensitive parts (and may die off altogether) until vision is noticeably impaired and eventually lost. Treatments can slow the progress of macular degeneration, but none yet exist to reverse it.

For several years, Nelidova and her colleagues have been working to combat photoreceptor degeneration with optogenetics, a technique for controlling neurons with light by endowing them with genes for light-sensitive membrane proteins borrowed from bacteria or algae. Optogenetic methods are typically used for basic neuroscience research—optically switching neuronal activity on or off to figure out which neurons do what in the neural circuits in the brain. The researchers hope to restore lost vision by inserting the same light-sensitive proteins into cells in the retina: the photoreceptors themselves if they're still alive, or neurons in the next layer of retinal cells if they're not.

The eye is an advantageous target for gene therapy. It's small and compartmentalized, so the therapeutic gene can be selectively conveyed to the cells that need it. Its immune privilege means that the foreign genetic material is protected from attack and rejection. And researchers have developed a toolkit of gene-delivery vectors, called adeno-associated viruses, for targeting specific types of retinal cells. The viruses don't cause disease, and they reliably insert their genetic payload into the cells' genome in a way that doesn't interfere with normal cellular function. The viruses are introduced to the retina through subretinal injection, a surgical procedure.

In 2017 the FDA approved a gene therapy treatment for Lebers congenital amaurosis, a form of photoreceptor degeneration caused by a specific genetic mutation; the treatment isn't optogenetic but instead replaces the problematic gene. Optogenetic treatments, which can restore light sensitivity even when the cause of the degeneration is not known, are currently in clinical trials.

But optogenetic therapy suffers from a major unmet challenge. A healthy retina can detect light over eight orders of magnitude in brightness, from a faintly lit room to a sunny summer day. The microbial proteins used in optogenetics are sensitive only to the brightest end of that range. To see under dimmer conditions, an optogenetic patient must wear video goggles that image the visual scene and amplify its brightness. That strategy works well for someone who's totally blind, but photoreceptor degeneration is a progressive condition that's debilitating long before blindness is complete. For a patient with some remaining vision, the healthy photoreceptors would be overwhelmed by the goggles' bright light.

The new work aims to surmount that hurdle by creating vision at a wavelength that healthy rods and cones can't see. Because the world doesn't look the same in the near-IR as it does in the visible regime, patients would still need to wear goggles to convert incoming visible light to 915 nm. The remaining healthy photoreceptors can't help to process that image—but they also won't be overwhelmed.

## Engineering nanovision

Gold nanorods, an essential component of Nelidova and colleagues' near-IR sensors, are no newcomers to biomedical applications. Because of their surface plasmon resonances, metal nanoparticles are exceptionally good at absorbing light and converting it into heat (see the article by Mark Stockman in PHYSICS TODAY, February 2011, page 39), and they can be tuned through their size and shape to absorb at a particular desired wavelength. Among their uses is photothermal therapy for cancer, which involves targeting them to a tumor and zapping them with a laser to cook the tumor to death. Although the heat they give off can wreak selective havoc on tissues, the nanoparticles themselves appear to be safe and biocompatible. And they can be injected into the retina in the same surgery as the gene-carrying viruses.

Plasmonic nanorods aren't the only nanotechnological route to seeing in the near-IR. Last year, Tian Xue and colleagues of the University of Science and Technology of China showed that they could endow mice with near-IR vision using so-called upconversion nanoparticles, whose structure of a core wrapped in an outer shell allows them to absorb light at one wavelength and emit it at a shorter one.[3] (For more on upconversion nanoparticles, see the article by Marco Bettinelli, Luís Carlos, and Xiaogang Liu in PHYSICS TODAY, September 2015, page 38.) They chemically anchored their nanoparticles to retinal photoreceptors—the mice they used weren't blind—so that when the particles absorbed in the near-IR and emitted in the visible, the light was visually processed in the normal way.

Because Xue and colleagues' approach relies so heavily on the existing retinal structure, their mice could recognize and distinguish simple near-IR spatial patterns. Nelidova and colleagues, so far, have shown only that their mice can detect an undifferentiated near-IR flash. And in seeking to restore vision to degenerated human retinas, they face an additional challenge. The topology of neural connections in the retina is complicated, and it's not clear whether a lost photoreceptor cell can be adequately replaced by a neuron in the same location. As Nelidova notes, "Restoration of high-resolution vision is still many years away."

Another unknown is how long the treatment will last: Is a single injection of genes and nanoparticles good for a lifetime, or does its effectiveness eventually wane? The researchers are hoping for the former: A subretinal injection is a difficult surgery that's especially challenging to perform more than once in the same eye. Although gene therapy is still a young technology, the coming years will provide a clearer picture of its long-term outcomes in Lebers congenital amaurosis patients and the subjects of optogenetic clinical trials.

As for the nanoparticle half of the sensors, mature retinal cells don't divide, so a single procedure to dose the existing cells with nanoparticles should suffice. But if the particles aren't securely anchored in place, they could be cleared by the body and lost.

To solve those problems, the Basel researchers are working on optimizing their near-IR sensor by tinkering with its parts. Across the animal kingdom, there are many variants of the thermosensitive protein, each of them responsive to a slightly different temperature. Nanoparticles can be tuned in size and shape, and the protein tags and antibodies can also be reengineered. The researchers have tested several of the possible combinations so far, and they plan to explore further. Says Nelidova, "One reassuring thing shown by the experiments is that we can disconnect, reconnect, and exchange sensor components, with predictable final outcomes."

**Johanna Miller**

### References

1. E. O. Gracheva et al., *Nature* **464**, 1006 (2010).
2. D. Nelidova et al., *Science* **368**, 1108 (2020).
3. Y. Ma et al., *Cell* **177**, 243 (2019).

# Photoelectron spectra explain how ammonia solutions become metallic

The gradual emergence of delocalized electron states in lithium–ammonia solutions underlies their transition.

Dropping a chunk of sodium into water and watching it explode is a classic high-school chemistry demonstration. The violent reaction is caused by the alkali metal's dissociation into $Na^+$ ions and electrons when it enters $H_2O$. The electrons react with the water to liberate hydrogen atoms, and those quickly pair to form $H_2$ gas that is ignited by the exothermic reaction.

The same demonstration becomes less incendiary if $H_2O$ is replaced with liquid ammonia, because $NH_3$ is harder to break apart. Whereas about 1 in every $10^9$

$H_2O$ molecules self-dissociates (roughly $10^{-7}$ moles per liter), only about 1 in $10^{17}$ $NH_3$ molecules does. Free electrons' brief lifetimes in water—less than a microsecond—make them, and their effects on the molecules around them, difficult to observe. But in ammonia, the formation of $H_2$ gas is slow enough to form metastable alkali metal–$NH_3$ solutions. Ammonia solutions can therefore be used to study solvated electrons, which are highly reactive participants in many chemical reactions, including the Birch reduction that was critical for developing synthetic steroids and the first oral contraceptives.

Nuclear magnetic resonance and electron spin resonance have long been used to study alkali metal–$NH_3$ solutions,[1] but to directly probe their energetics, photoelectron spectroscopy (PES) is the favored technique. It entails bombarding a material with x rays or UV light to eject electrons; the electrons' kinetic energies are then measured to determine their binding energies. Unfortunately, applying PES to alkali metal–$NH_3$ solutions is difficult. The ultrahigh vacuum needed to give photoelectrons an unimpeded path to the spectrometer causes the volatile liquid ammonia to evaporate almost immediately. Samples must be kept below −33 °C, the temperature at which ammonia boils, and in a meticulously clean environment to avoid unwanted auxiliary reactions.

Now Tillmann Buttersack (then at IOCB Prague, Czech Academy of Sciences, now at the University of Southern California), Ryan McMullen (USC), Phil Mason (IOCB Prague, CAS), Christian Schewe (Fritz Haber Institute of the Max Planck Society), and coworkers have overcome those challenges by performing PES on alkali metal–$NH_3$ microjets using lithium, potassium, and sodium.[2]

Their measurements span a range of concentrations over which the solution's behavior transitions—from electrolytic, in which localized ions carry currents as in salt solutions, to metallic, with extended electron states that facilitate charge transport. The spectrum's evolution points to a gradual change in electronic structure as the dissolved metal concentration increases. Along with simulations, the results suggest that localized electrons coalesce into a system-spanning electron network to cause the metallic transition.

## A fine blue color

Alkali metal–$NH_3$ solutions have been studied for more than 200 years, and much is already known.[3] Humphry Davy

**FIGURE 1. ALKALI METAL–AMMONIA SOLUTIONS** are a deep blue color at concentrations below about 4 mol percent metal. At higher concentrations their electrons transition from localized to extended states, which causes the solutions to turn bronze and exhibit metallic behavior. (Courtesy of Philip Mason.)

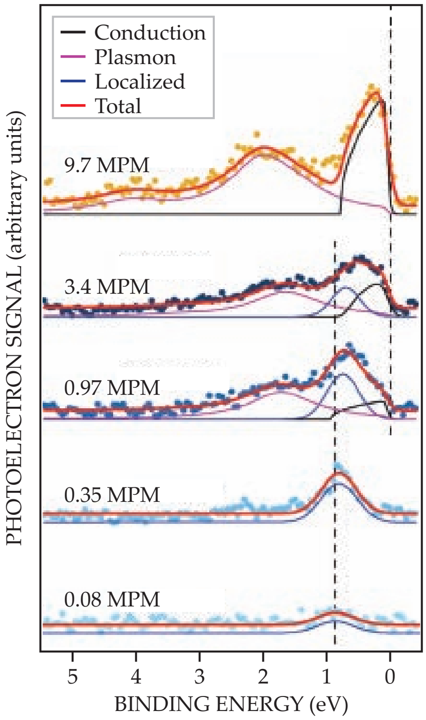



**FIGURE 2. PHOTOELECTRON SPECTRA OF LITHIUM–AMMONIA SOLUTIONS** show an evolution from electrolytic to metallic behavior. At low mol percent metal (MPM), dissociated electrons sit in localized cavities surrounded by $NH_3$ molecules. A single spectrum peak reflects the binding energy associated with those cavities. As the MPM increases, the electrons form extended wavefunctions like those found in metals. Models (solid lines) show that the increasing prevalence of a free-electron conduction band and collective oscillations, or plasmons, account for the spectrum's peaks. (Reprinted from ref. 2, with permission.)

first reported on them in 1807 while trying to prove that potassium was an element rather than a hydride of potash; he observed that the metal was dissolved by gaseous ammonia and produced a blue film. Ammonia having been liquefied in 1823 enabled further experiments, including the discovery of the solution's metal transition more than 50 years later.

Subsequent studies have filled in details. At low concentrations—below a mole fraction of about $10^{-5}$, or $10^{-3}$ mol percent metal (MPM)—electrons and cations from the dissolved metal are isolated in localized cavities surrounded by $NH_3$ molecules. A conductive electrolytic solution results. The solvated electrons absorb IR light, and in ammonia that absorption peak bleeds into the visible spectrum and produces the deep blue color shown in figure 1.

Increasing the metal concentration beyond $10^{-3}$ MPM results in pairing—first between electrons and cations, and then between opposite-spin electrons—which reduces the solution's conductance. By about 0.5 MPM the conductivity reaches a minimum, a feature also seen in simple salt solutions.

Above 1 MPM, however, the ammonia solution's conductivity increases, and around 4 MPM the solution turns bronze (see figure 1). Ammonia is unusual in that it can support high enough solvated electron concentrations to reach that transition. The metallic sheen reflects underlying behavior: Previously localized electrons inhabit extended states like those responsible for conduction in familiar metals; they screen the electric field of incoming visible light to produce a telltale reflectivity. When the solution reaches saturation around 20 MPM its conductance is about half that of mercury; that's noteworthy considering there are four nonconducting ammonia molecules for every solvated electron in the solution.

The research groups of long-standing collaborators Bernd Winter (Fritz Haber Institute of the Max Planck Society), Stephen Bradforth (USC), and Pavel Jungwirth (CAS), all authors on the paper, teamed up to study and help explain the mechanism behind the metallic transition. They collaborated remotely to design and perform PES measurements on metal–$NH_3$ solutions, with their experimental prototype being assembled in Jungwirth's lab in Prague. But before they could tackle the question at hand, they had to overcome a critical experimental hurdle: keeping the ammonia solutions liquid under experimental conditions for long enough to make measurements.

## Jet setters

The collaborators turned to a microjet technique that has been used to apply PES to water, simple alcohols, and even liquid nitrogen and argon. Fast-flowing jets refresh the liquid in the observation window quickly enough to compensate for evaporation. Ammonia is liquid between −77 °C and −33 °C at atmospheric pressure, so they cooled their samples and the surrounding equipment to −60 °C. But that's not so cold compared to argon, whose boiling point is −186 °C. The bigger challenge was making sure the apparatus was impeccably clean: Ammonia is reactive, and any insoluble products could clog the micronozzle. With conditions just right, the ammonia formed a stable liquid jet a few centimeters long.[4]

By the time the researchers reported on pure ammonia jets in 2019, they were already applying the technique to solutions with solvated electrons. As in their previous experiments, they bombarded microjets of the solutions with high-brilliance x rays from the BESSY II synchrotron radiation source.

Figure 2 shows the photoelectron spectra for lithium–ammonia samples at concentrations from 0.08 to 9.7 MPM, spanning the metallic transition. For the lowest concentrations, 0.08 and 0.35 MPM, a single peak corresponds to the energy needed to kick a solvated electron out of its ammonia cage. Then, around 1 MPM—the concentration at which conductivity starts increasing—the spectrum develops a more complicated form. The researchers showed that contributions from two electron populations, those in localized and extended states, explain the change. A Gaussian peak accounts for isolated electrons, and a free-electron gas model accounts for metallic ones. The free-electron gas model, commonly used to describe metals, contributes a conduction band and plasmon resonances.

The fraction of isolated electrons needed to account for the observed spectra decreases with increasing metal concentration. At the highest concentration, 9.7 MPM, the spectrum is entirely described by the free-electron gas model, and the conduction-band peak has the predicted sharp edge at the Fermi energy. A plasmon peak in the visible range accounts for the solution's bronze, rather than silver, appearance. The 9.7 MPM spectrum's shape closely mirrors that of 50–50 sodium–potassium, a more standard liquid metal that the researchers tested for comparison.

## Structural shifts

*Ab initio* molecular dynamics simulations performed by coauthor Ondřej Maršálek, an assistant professor at Charles University in Prague, paint a more detailed molecular picture. He found that

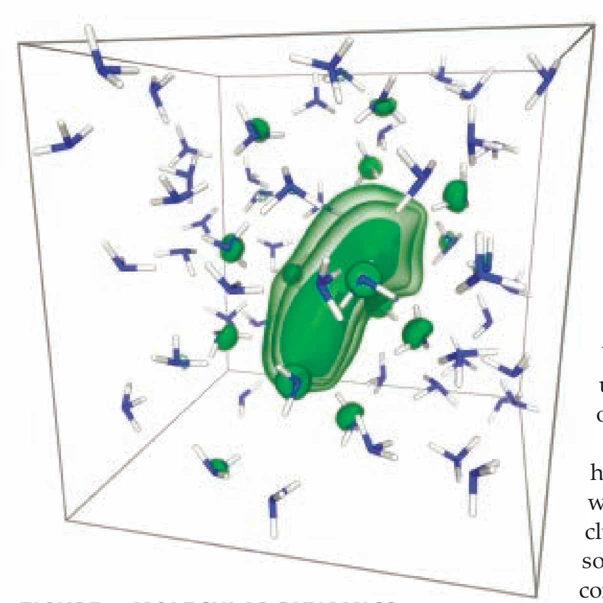


**FIGURE 3. MOLECULAR DYNAMICS SIMULATIONS** provide details about the size and structure of the cavities that house electrons solvated in ammonia. Spin-paired electrons, shown in green, are surrounded by approximately 12 ammonia molecules (blue and white). Those molecules form cavities about 4.4 Å across; the cavities around unpaired electrons are approximately 3.9 Å. (Courtesy of Tomáš Martinek and Ondřej Maršálek.)

both isolated and spin-paired electrons in solution are surrounded by a diffuse layer of approximately 12 ammonia molecules (see figure 3). The cavities confining solvated electrons in ammonia were about 3.9 Å in diameter for a single electron and 4.4 Å for paired electrons.

One simple explanation for the onset of metallic behavior is the Mott criterion, which says that metallic conduction should arise when the average distance between the diffuse solvated electrons is less than approximately four times their extent. At 1 MPM, that distance would be about 4 Å. But that picture is too simplistic—such a transition would be abrupt, whereas the Li–$NH_3$ spectrum evolves gradually. Unfortunately, there isn't another system with an analogous transition to guide the researchers' thinking. Based on their data, they suspect that coalescence of electron cavities into a continuous network underlies the transition to a metallic state. But at the moment that's just a guess.

Pinning down what's really happening in the transition will require improved simulations. Maršálek had already upgraded to a more accurate electron density functional and a more extensive set of basis functions compared with his earlier studies of water.[5] Both were necessary to reproduce the known bound state, which is more diffuse in ammonia than water, but they increased the simulation time by up to three orders of magnitude.

Extending simulations to higher metal concentrations will require Maršálek to include cations, which he reasonably neglected at low concentrations. The main challenge is that ammonia solutions are dynamic and disordered. Fully simulating the diffuse electrons, metal cations, and solvent molecules in all their possible configurations requires a lot of sampling, which makes the already expensive computation even more daunting.

Despite its challenges, the inclusion of cations is an important next step. At increasing metal concentrations, they're likely to be important to the formation, structure, and dynamics of an electron network. The researchers suspect that, like the atomic lattice in crystalline conductors, the cations provide the background potential for extended electron states.

Acquiring complementary experimental information on electronic structures throughout the metallic transition would require neutron or x-ray scattering, and the collaboration's experimentalists hope to attempt those measurements. But that doesn't mean they're done with PES; studies on highly concentrated electrons in water are already in the pipeline.

**Christine Middleton**

## References


1. P. P. Edwards, *J. Phys. Chem.* **88**, 3772 (1984).
2. T. Buttersack et al., *Science* **368**, 1086 (2020).
3. E. Zurek, P. P. Edwards, R. Hoffmann, *Angew. Chem. Int. Ed.* **48**, 8198 (2009).
4. T. Buttersack et al., *J. Am. Chem. Soc.* **141**, 1838 (2019).
5. F. Uhlig, O. Marsalek, P. Jungwirth, *J. Phys. Chem. Lett.* **3**, 3071 (2012).


PT

# Could hydrogen bail out nuclear power?

As nuclear-powered water electrolysis becomes cheaper, it could compete with the current, carbon-intensive hydrogen production process.

Struggling to defend its market share from lower-cost electricity produced from natural gas and renewables, the US nuclear industry is tentatively exploring a new revenue source: hydrogen production. The US Department of Energy is encouraging that potential repurposing by providing more than $84 million for improving electrolyzers that split water and for installation demonstrations at two commercial nuclear power plants.

The growth of low-cost wind and solar power and an abundance of cheap shale gas have made higher-cost nuclear power often unprofitable (see Physics Today, December 2018, page 26). “It doesn’t make sense to downwardly dispatch a perfectly running nuclear plant,” said Michael Green, general manager of nuclear policy at Pinnacle West Capital, the holding company for the utility Arizona Public Service. A hybrid plant producing hydrogen and electricity would provide an outlet for the nuclear power that is now sold at a loss.

In one DOE-backed project valued at $7.2 million, Exelon, the country’s largest nuclear plant operator, will install a 1 MW electrolyzer at one of its 21 reactors. DOE will split the cost with the utility giant. Exelon plans to complete the demonstration in April 2023 and will use the hydrogen it produces on-site. Hydrogen gas is commonly used to cool and provide a low-drag environment in electricity-generating turbines. Three national laboratories and Norway’s Nel Hydrogen are participating in the demonstration. Nel is one of several manufacturers of modular electrolyzers. Others include US-based Plug Power, Germany’s Siemens, and Canada’s Hydrogenics.

Scot Greenlee, Exelon’s senior vice president of engineering and technical industry support, said the company concluded after a two-year study that, second only to steam heat for greenhouses in the marijuana-growing industry, hydrogen production was the most lucrative alternative use for nuclear plants. Potential industrial uses of hydrogen include petroleum refining, steelmaking, chemical synthesis, and, in combination with carbon dioxide captured from corn ethanol production, synthetic fuels.

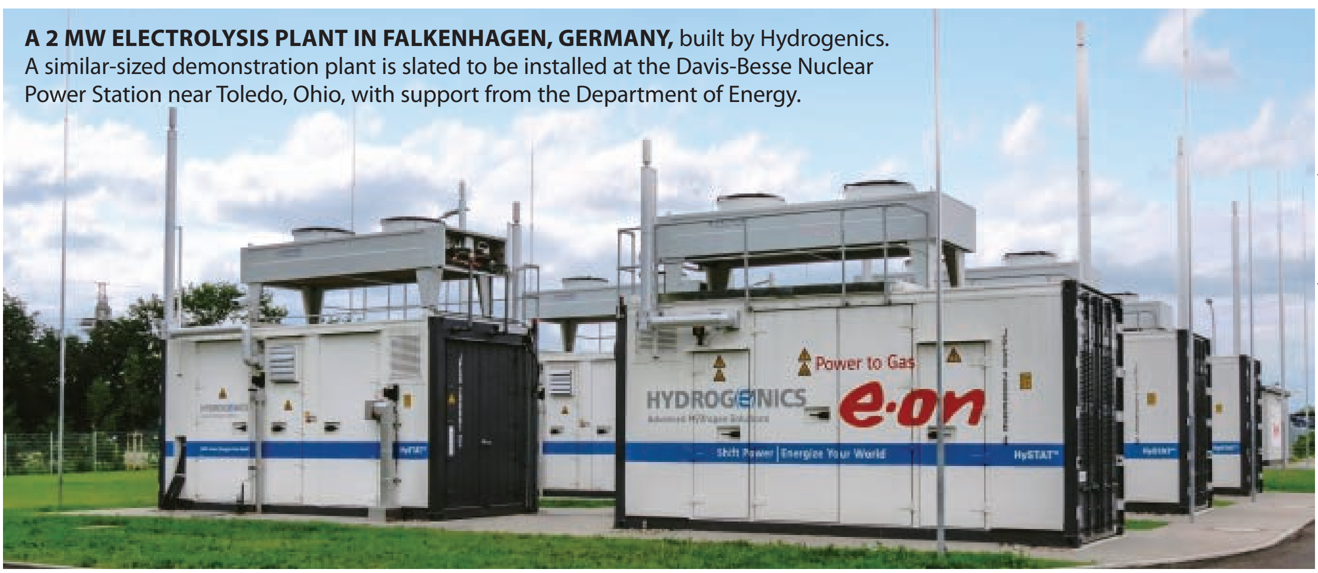
Separately, Energy Harbor, an Ohio utility company, is set to install a 2 MW electrolyzer at its Davis-Besse Nuclear Power Station near Toledo. Project manager Alan Scheanwald said the equipment will be installed during the plant’s next refueling outage in March 2022. Partners in the demonstration are Xcel Energy, which owns three reactors at two sites, and Arizona Public Service, which operates three reactors at the Palo Verde plant, the US nuclear industry’s largest installation. DOE is providing $9.2 million of the project’s $11.5 million cost. The hydrogen generated will be sold for off-site use.

Energy Harbor will operate its electrolyzer for six to eight months to determine whether there is a business case to scale up production. “We definitely see hydrogen as an emerging technology and a growing market,” Scheanwald said.

Green, Greenlee, and Scheanwald all spoke during an 8 June virtual conference sponsored by the American Nuclear Society (ANS).

## Nuclear industry woes

Nearly all US hydrogen is currently produced through a process called steam reforming, in which a nickel-catalyzed reaction between methane and steam at 700–1100 °C generates hydrogen and $CO_2$. According to the International Energy Agency (IEA), the cost of steam reforming in the US was around $1/kg in 2018. Last August Idaho National Laboratory published a study titled *Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest*. In it, the lab reported that an unidentified




**A 2 MW ELECTROLYSIS PLANT IN FALKENHAGEN, GERMANY,** built by Hydrogenics. A similar-sized demonstration plant is slated to be installed at the Davis-Besse Nuclear Power Station near Toledo, Ohio, with support from the Department of Energy.

reactor in the Midwest could produce hydrogen by electrolysis at a cost of \$1.50/kg—well below the \$2/kg target for carbon-free production set by DOE for 2020. But the lab's estimate was highly qualified; it assumed that states would grant clean-energy credits to nuclear plants and that the cost of electrolyzers would decrease substantially. Several states, including Illinois, New Jersey, and New York, already provide clean-energy credits to some of the nation's 96 reactors to help them compete in the wholesale electric markets.

The current capital cost of electrolyzers is \$1000 to \$1500 per kilowatt, according to industry and IEA reports. The IEA and DOE have projected that capital cost can be lowered to \$400/kW, a point at which continuous but not intermittent electrolysis could be economically competitive with steam reforming, says Sunita Satyapal, director of DOE's hydrogen and fuel cell technologies office. Reaching that lowered cost will require increasing electrolyzers' efficiency to 70% from the current 60% and improving their durability.

Because nuclear-powered electrolyzers would be operated nearly continuously, their levelized cost of production—the lifetime cost divided by hydrogen output, a standard measure for comparing production methods—should be much lower than that for electrolysis powered by intermittent wind and solar energy.

On 22 June DOE announced a five-year, \$50 million initiative on electrolyzer R&D that will be carried out by a consortium of national laboratories. The scope includes basic and applied research on materials, materials integration, and manufacturability. Industry and academia are expected to partner with the labs and bring in additional funding, Satyapal says.

US hydrogen production is forecast to nearly double to 25 million tons a year by 2030, according to Greenlee. The 13 million tons produced annually now would require power plants having a total capacity of 74 GW of electricity if it were generated by electrolysis, Greenlee said. A typical nuclear reactor has a capacity of around 1 GW.

A DOE request for proposals that closed 30 June offered \$64 million for R&D on a variety of hydrogen topics, including \$15 million for improving high-volume manufacturing of megawatt- and gigawatt-scale electrolyzers. Winners will be selected in the next several months.

The efficiency of electrolysis is boosted considerably at elevated temperatures, and nuclear reactors could supply the heat. Today's light-water reactors can provide steam at up to 300 °C, according to the World Nuclear Association. Operation at 800 °C or higher can raise efficiency above 90%, Satyapal says. Advanced reactors, if they become a commercial reality, could supply such temperatures.

Xcel Energy, a partner in the Energy Harbor project, is proposing to demonstrate a high-temperature electrolyzer, most likely at its Prairie Island nuclear plant, said Patrick Burke, the company's vice president of nuclear strategy. "We are big believers in generating hydrogen from nuclear power, but we have to prove it can be supplied at utility scale."

In Minnesota, where Xcel's reactors are located, potential regional markets for hydrogen include oil refineries and producers of ammonia and fertilizer, Burke said. Companies that operate large data centers are also interested in buying cleanly sourced electricity. Blending hydrogen into the natural gas supply system would lower that fuel's $CO_2$ footprint. And hydrogen can replace coal for reducing iron ore, an essential step in steelmaking. But companies will have to meet the challenges of safely storing hydrogen, create a distribution network, and deal with regulatory, siting, and licensing issues before deploying electrolysis on an industrial scale, Burke noted.

Greenlee cautioned at the ANS conference that the US nuclear industry shouldn't count on hydrogen to solve its economic crisis. "The big challenge is working with the states to get them interested in making the plants viable so we can exist long enough to see [a hydrogen economy] become a reality." It's not enough that Exelon has received state clean-energy credits for two plants in Illinois and one in New York, he said. In the region where Exelon operates, "the market construct is broken and needs to be fixed."

## Big plans abroad

Outside the US, electrolysis as a carbon-free source of hydrogen has been mainly associated with renewable energy. In March a 10 MW electrolyzer began operating in Namie, northeastern Japan, using power from renewables. Hydrogenics in Canada is building what will be the world's largest proton exchange membrane (PEM) electrolyzer for Air Liquide in Bécancour, Quebec. Nearly all of that province's power comes from renewables.

In April the Australian Renewable Energy Agency launched a renewable hydrogen production project and offered AU\$70 million (\$44 million) for green electrolysis at commercial scale. The agency aims to support deployment of two or more advanced electrolyzers with a minimum capacity of 5 MW and preferably at least 10 MW. Each electrolyzer must be powered by renewable electricity, either directly or through renewable-power purchase agreements. Australia's national hydrogen strategy, unveiled in November 2019, sets a goal of AU\$2/kg for green hydrogen (see PHYSICS TODAY, May 2019, page 28). Australia has no nuclear power.

French nuclear giant EDF formed a new subsidiary, Hynamics, in 2019; the move signaled the utility company's intent to become a major player in green electrolysis for industrial and transportation applications. A study commissioned by EDF last year confirmed the feasibility of installing two 1 MW electrolyzers at one of the eight nuclear power stations the company operates in the UK. The two electrolyzers would employ different approaches: PEM cells and the more common alkaline technology.

The European Union (EU) released a hydrogen strategy on 8 July that calls for 1 million tons of hydrogen to be produced from green electrolyzers by 2024, with that figure increasing to 10 million tons in 2030. The plan does not mention a role for nuclear power, but proposes "hydrogen valleys" where electrolyzers would be directly powered by local renewable sources. The EU currently produces about 10 million tons of hydrogen annually, almost all from natural gas. Notably, the EU plan acknowledges that methane reforming will continue to supply part of Europe's hydrogen demand, but those plants will be required to capture and store their $CO_2$ emissions.

Germany has its own national green hydrogen initiative, funded at €7 billion (\$7.9 billion). Nuclear power won't be included: The last of Germany's nuclear plants is to be closed by 2022. The plan calls for 5 GW of domestic hydrogen production from renewable sources to demonstrate feasibility at scale, but beyond that, Germany will count on other parts of the globe to provide the massive amounts of renewable energy it will need to satisfy its hydrogen goals.

**David Kramer**

# New 5G exemption may jam GPS devices

Opposition in the public and private sectors is growing against a US telecommunications plan that would allow one company to use its satellite communications radio spectrum for terrestrial applications.

A unanimous decision on 19 April by the Federal Communications Commission (FCC) allows Ligado Networks to use its radio spectrum in the 1500–1700 MHz frequency range to develop a ground-based 5G network for smartphones, driverless vehicles, and other internet-connected devices. The FCC approval is unusual and unprecedented: Ligado's portion of that spectrum range has usually been designated for satellite applications only, and various GPS receivers are likely to malfunction as a result of the decision.

Representatives from many communities—airline companies, federal departments, surveyor associations, weather forecasting, and the defense industry, among others—oppose the decision, and many have petitioned the FCC to reconsider. The 30-day period to submit a petition has passed, and FCC rules stipulate that petitions must be responded to within 90 days. But as PHYSICS TODAY went to press, the FCC had made no public response. On 22 April, the chairs and ranking members of the Senate and House Armed Services Committees warned that if the FCC approval stands, "it will be up to Congress to clean up this mess."

Ligado had been trying for a decade to obtain FCC approval to use its satellite spectrum for terrestrial applications. In 2010 the telecommunications company, which was then known as LightSquared and was acquired by a private hedge fund, initially applied to the FCC to repurpose its satellite spectrum holdings. But the GPS community, which includes geophysicists and meteorologists, aired concerns about adjacent-band interference.

Radio-spectrum applications each operate in a certain frequency band, and


**AIRLINE COMPANIES MAY BE FORCED TO PAY** for costly upgrades to their GPS hardware because of a new telecommunications rule that would introduce more radio interference.

GPS users argued that the terrestrial signals would disrupt receivers tracking GPS satellites in the nearby band. After the FCC denied the request, LightSquared filed for bankruptcy in 2012. Then three private equity firms bought the company and renamed it Ligado Networks, tweaked the spectrum plan by lowering the power of transmitter emissions, and resubmitted a spectrum proposal in 2015.

Despite the recent green light for its proposal, Ligado faces financial challenges. The company's website says that it has been partnering with Nokia and Ericsson to develop a 5G telecommunications network, but whether those efforts would continue should the FCC reverse its decision is unclear. Ligado and the other telecommunications companies declined to comment on the matter.

## Out of bounds

The Ligado holdings—the 1526–1536 MHz, 1627.5–1637.5 MHz, and 1646.5–1656.5 MHz bands—lie in the so-called L-band frequency range, 1–2 GHz. Radio regulations set by the United Nations International Telecommunication Union stipulate that activity in that range be reserved for mobile satellite services or communications between mobile Earth stations and space stations. Frequency bands allocated for terrestrial use typically don't overlap bands for satellite use. But the new FCC order grants Ligado permission to use its spectrum for a 5G network and other terrestrial applications in the US.

GPS satellites transmit signals in the L-band in three frequency bands; the one closest to Ligado's spectrum is centered at 1575 MHz with a bandwidth of about 30 MHz. The power of any radio signal weakens with the distance squared from the transmitter, and satellites are at least 20 000 km from the GPS receivers on Earth. But Ligado's proposed transmitters would be only tens or hundreds of

SOUTHWEST AIRLINES

meters away from those receivers, which weren't designed to filter such a powerful signal.

In April 2018 the Department of Transportation published an assessment that considered how GPS receivers would be affected by a cellular base station emitting at 1530 MHz, which lies in Ligado's spectrum. Ligado's proposed cellular base stations, per the FCC decision, may emit no more than 9.8 dBW, which is lower than the 32 dBW of typical cellular base stations. Although the report concludes that smartphones can still operate without loss of functionality, it determines that a GPS receiver used for high-precision work, general location and navigation, or timing would "become unpredictable in its ability to meet the accuracy, availability, and integrity requirements of its intended application."

Besides the potential for GPS interference, the FCC decision may have downwind ramifications for US weather forecasting. Dan DePodwin, the forecasting manager for AccuWeather in State College, Pennsylvania, says that if the FCC's decision holds, "the next [spectrum] piece will be 1675 to 1680 megahertz." In 2019 the FCC announced its intention to reallocate that band for federal and private shared use. Ligado currently leases the adjacent 1670–1675 MHz band. If the spectrum is repurposed for terrestrial use, the change would likely interfere with the joint NOAA–NASA *Geostationary Operational Environmental Satellites*, which transmit meteorological and hydrological data relied on by weather forecasters, researchers, and emergency managers.

## Sparring over spectrum

Telecommunications interest groups and the Department of Justice support the FCC decision. For example, the CEO of the Wireless Infrastructure Association, Jonathan Adelstein, said in a 20 April press release that the FCC's approval of Ligado's L-band plan "is even more critical now during these unprecedented circumstances as mobile connectivity is increasingly relied upon." In a statement about maintaining US economic and technological advantages compared with China, Attorney General William Barr said, "I applaud FCC Chairman [Ajit] Pai's proposal to make available L-band spectrum."

Many organizations across government and industry oppose the FCC decision, however. The Department of Homeland Security said in a statement on 21 April that the FCC should have denied the Ligado license because it would hamper the collection and use of "precise and uninterrupted Positioning, Navigation and Timing (PNT) data from the Global Positioning System."

Sixty-eight organizations—including the airlines Southwest and United, professional scientific associations like the American Meteorological Society and the American Geophysical Union, defense and technology companies like Lockheed Martin, and delivery companies such as UPS and FedEx—filed a statement on 6 May in response to the Senate Armed Services Committee hearing on how the FCC authorization for Ligado's spectrum would affect national security, public safety, and the economy. To avoid powerful interference, GPS users would need to upgrade their hardware with stronger RF filters, according to the statement. It also says that replacing current GPS and satellite equipment would cost taxpayers billions of dollars.

Several federal and private organizations, including the National Telecommunications and Information Administration and Trimble—a California-based company that develops GPS receivers and software for agriculture, construction, transportation, and other industries—filed petitions asking the FCC to revoke the approval. But, says Tim Farrar, a telecommunications analyst and president of TMF Associates in Menlo Park, California, "I don't believe any new compelling evidence was presented in the petitions for reconsideration that were filed. It appears unlikely that the FCC will reverse its decision unless forced to by Congress."

The House Armed Services Committee wrote a letter on 7 May to the FCC asking it to provide a more thorough rationale for the Ligado decision. On 15 May, a bipartisan group of 32 senators wrote a letter to Pai and the other four commissioners urging them "to immediately stay and reconsider their Order on this matter, more fully consider the technical concerns raised by numerous federal agencies and private sector stakeholders, and outline a path forward that adequately addresses these concerns."

On 11 June the Senate Armed Services Committee approved 25–2 its fiscal year 2021 National Defense Authorization Act. Among other things, the bill seeks to protect the public's access to GPS and satellite communications infrastructure. Under the terms of the FCC order, the Department of Defense would be required to identify vulnerable GPS receivers and work with Ligado to repair or replace them. The bill instructs DOD to ignore the FCC order until the secretary determines the total cost of GPS interference and an independent technical analysis is completed by the National Academies of Sciences, Engineering, and Medicine.

More opponents have joined the fight against the FCC's order. On 23 June, five professional associations, representing equipment manufacturers, farmers, pilots, boaters, and transportation builders,

US SENATE PHOTOGRAPHIC STUDIO/RENEE BOUCHARD

**US SENATOR TAMMY DUCKWORTH (D-IL)**, a veteran and member of the Armed Services Committee, is part of a bipartisan group of 32 senators that urged the Federal Communications Commission in a 15 May letter to address the technical risks that may arise from its decision to grant an exemption to the telecommunications company Ligado.

established the Keep GPS Working Coalition, which supports the bipartisan legislation proposed by the Senate Armed Services Committee.

Farrar says Ligado faces financial pressure because of an agreement with Inmarsat, a satellite communications company based in London. Inmarsat has leased some of its L-band spectrum to Ligado and agreed to allow Ligado to defer its 2019 payments. Having obtained FCC approval, Ligado must now pay Inmarsat $136 million per year, according to an Inmarsat press release.

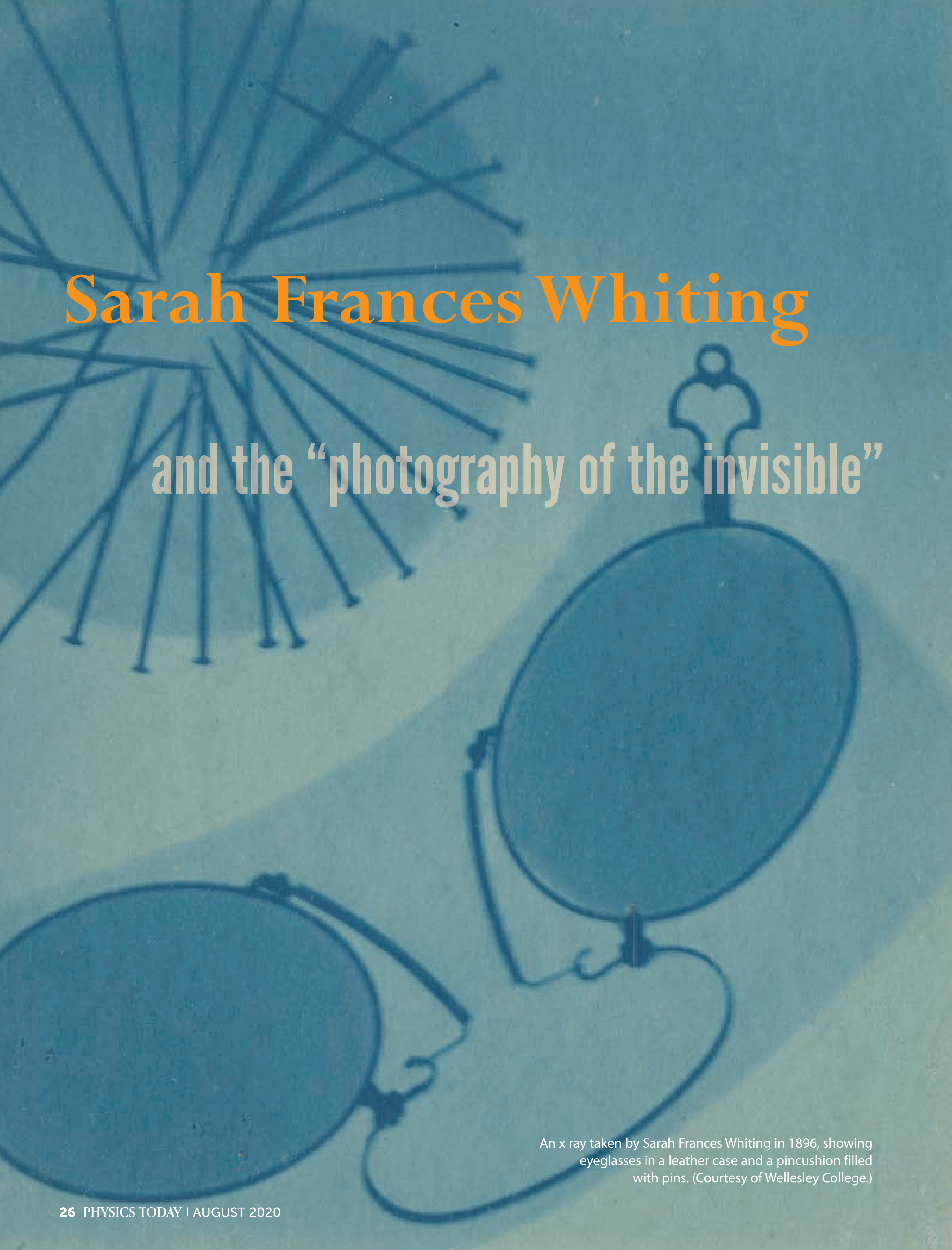
If Ligado can't pay those debts, its spectrum may sit idle, according to Farrar, and the potential for GPS interference may disappear. But he and other telecommunications analysts say that if Ligado strikes an agreement with Verizon, it may be able to pay Inmarsat and even make a profit. Like the other large telecommunications companies, Verizon is working to develop its own 5G network, though Farrar thinks it needs to buy additional spectrum. Ligado has suggested that for Verizon to improve its 5G network, it could use Ligado's L-band spectrum in conjunction with midrange spectrum in the 3700–4200 MHz band.

A new auction for that midrange spectrum is scheduled for 8 December. In a letter to the White House dated 8 April, one of the five FCC commissioners, Mike O'Rielly, urged President Trump to "free the necessary spectrum bands to provide our wireless providers the means to succeed." Farrar says that "to give Verizon time to prepare for the auction, they [Ligado] probably need to do a deal in September or October. If nothing happens, it's likely that Ligado will have to file for bankruptcy at the end of the year."

**Alex Lopatka** PT

# Sarah Frances Whiting

## and the “photography of the invisible”



An x ray taken by Sarah Frances Whiting in 1896, showing eyeglasses in a leather case and a pincushion filled with pins. (Courtesy of Wellesley College.)

**John S. Cameron** is an emeritus professor of biological sciences and **Jacqueline Marie Musacchio** is a professor of art history at Wellesley College in Massachusetts.

John S. Cameron and Jacqueline Marie Musacchio

**A team of women working in the physics laboratory at Wellesley College carried out some of the first successful x-ray experiments in the US.**

In February 1896 Sarah Frances Whiting, founder of the physics and astronomy departments at Wellesley College, conducted a series of x-ray experiments. She was working only a few weeks after the public announcement of Wilhelm Röntgen's discovery of the rays, and she was not alone; amateur and professional scientists at colleges, universities, and medical centers across the US were attempting to replicate and extend Röntgen's results. But Whiting (see figure 1), who enlisted the assistance of a Wellesley colleague and several students, was among the first to do so successfully. Even more importantly, Whiting was the first woman—and almost certainly the first person, male or female—to do so in an undergraduate laboratory. Her original glass plates from the experiments do not survive, but 15 photographs printed from them (see the opening image of one such photo) were recently rediscovered in a campus building slated for demolition. They provide a vivid reminder of Whiting's success.

The x-ray experiments were only one instance in which Whiting drew on her keen engagement with contemporary scientific advances to offer her students an experience available to few undergraduates at the time, and to almost no women. Throughout her long career, Whiting introduced thousands of women to physics and astronomy, both fields then associated almost entirely with men. Her pedagogical efforts led many of her female students to pursue their own careers in the sciences.

## Wellesley, Whiting, and a new science pedagogy

Philanthropists Pauline Fowle Durant and Henry Fowle Durant founded Wellesley College in 1870 as an educational experiment. At that time there were few options for women to pursue higher education in the US, and the Durants decided to use their significant wealth to provide women students and faculty with the same opportunities available to men.[1] Finding faculty, however, was a challenge. With few exceptions, the first generations of Wellesley faculty were female, single, and characterized as spinsters in the parlance of that time. It was a common belief that married women had obligations at home that should keep them out of academia. Even Wellesley's popular second president, Alice Freeman, had to step down when she married in 1887. Faculty lived on or near campus, often with their mothers or sisters; Whiting, for instance, lived with her sister Elizabeth, who was also on the Wellesley staff. In some cases, Wellesley faculty lived with other women in mutually beneficial relationships, some platonic and some not, that Henry James and others in the late 19th century called Boston marriages.

As one of only a few institutions of higher learning in the

**FIGURE 1. SARAH FRANCES WHITING (1847–1927) USING A FLUOROSCOPE** to examine the bones in her hand in Wellesley College's physics laboratory, circa 1896. On the table in front of her is a Crookes tube mounted on a stand and an induction coil to modulate the voltage. (Courtesy of Wellesley College.)

US that both employed and educated women, Wellesley quickly became a haven for progressive female intellectuals. Faculty were engaged in all aspects of college life and worked together to establish a rigorous curriculum like those taught at contemporary men's colleges. But there was also a conscious attempt to set Wellesley apart from other educational institutions. Henry Durant was quoted as saying, "If we were like other colleges we should not be what we ought to be."[2]

But establishing a successful college for women wasn't easy. Most female students in that era came to higher education with less training than their male counterparts, and significant numbers of them withdrew before earning their degrees, whether to marry or due to other social pressures. Although 246 women matriculated in Wellesley's first class in 1875, only 18 graduated four years later. To combat attrition, the Durants established a preparatory school to ready students for college-level work. They also expanded the curriculum to encompass a wider range of subjects, providing employment opportunities for scholarly women in numerous disciplines. From 1875 through at least 1921, for example, Wellesley employed far more female scientists than any other institution of higher education in the country.[3]

One of the most prominent Wellesley scientists was Whiting, who was hired to teach physics in 1876. We know a great deal about Whiting from her own writings and from obituaries written by her most famous student, astronomer Annie Jump Cannon, class of 1884.[4] Whiting had been interested in science from an early age, in part due to the influence and encouragement of her father, a teacher himself. After earning a BA in 1864 from Ingham University in Le Roy, New York, she began teaching mathematics and classics at a girls' secondary school in Brooklyn. Whiting had no graduate training in the sciences—relatively few of her Wellesley colleagues did in those early years—but she attended lectures to further her education and made enough of an impression on the educational community to attract the Durants' attention. They offered her a position at Wellesley and arranged for her to spend her first two years visiting colleges and universities in and around New England.

During those years, Whiting became the first woman to attend Edward Pickering's physics classes at MIT. Pickering's novel, hands-on method of laboratory instruction made a strong impression on the Durants and on Whiting, and Whiting used it as a model to devise her own physics curriculum. Like Pickering, Whiting required her students to design and conduct laboratory experiments. That practice aligned well with Wellesley's efforts to encourage students to be actively engaged in their own learning, and it spread quickly to other disciplines. The college developed the first undergraduate laboratory for comparative anatomy in the US, and under the leadership of Alice Van Vechten Brown, art history students learned and practiced historical artistic techniques. Brown's approach made such an impression on other educators that it became known as the Wellesley method when it was adopted elsewhere.[5]

## Facilities at Wellesley

The hands-on method of teaching physics required an extensive collection of scientific equipment. Whiting established just the second undergraduate physics laboratory in the country, after MIT, and the first for women. There were few commercial manufacturers of scientific equipment in the US, but with generous funding from the Durants and advice from Pickering, Charles Barker—who Whiting later referred to as her "scientific father"[6]—of the University of Pennsylvania, and others, Whiting secured what she needed. She selected some instruments from the displays of European manufacturers at the 1876 Centennial Exhibition in Philadelphia and commissioned the manufacture of others by providing exacting specifications to New England artisans. When Whiting taught her first physics classes in fall 1878, her laboratories were extraordinarily well equipped with instruments to study sound, heat, electricity, and mechanics (see the box on this page). She also had a full selection of photographic apparatus and sophisticated optical instruments, including a wide range of spectroscopes (see figure 2).

Whiting proved to be a dedicated teacher. She wrote an astronomy textbook—*Daytime and Evening Exercises in Astronomy for Schools and Colleges* (1912)—and multiple articles on science pedagogy, all part of her efforts to train the next generation of female scientists. She also kept abreast of new developments in order to introduce them to her students. She met Thomas Edison and gave a demonstration of his incandescent bulbs to the Wellesley community to persuade trustees to invest in his new technology. She attended classes at the universities of Berlin and Edinburgh and interacted with a wide range of scientists in the US and Europe, both in person and via correspondence. Her travels and meetings with other scientists were a point of pride for Whiting; she later recalled,

> I was at a meeting of the British Association in 1881 when Langley's heat spectrum was announced, in 1888 when Section A was discussing the discoveries of Hertz, and again in 1896 when the Xrays [sic] of Roentgen were to the fore and Ramsey gave me a tube of the Helium he had just discovered. At the American Association in 1900 I was present when Nichols announced the verification of Maxwell's prediction that light exerted pressure. . . . In 1896 I was invited, by exception, to visit the laboratories of Dewar at the Royal Institution in London and see the apparatus in action which liquified air. In 1896 also I visited the laboratories of Onnes of Leyden the very week he liquified Helium.[7]

Unfortunately, as women working in what was then very much a man's field, Whiting and other female scientists had to deal with considerable prejudice and limited opportunities.[8] Near the end of her career, she reflected on "the somewhat nerve-wearing experience of constantly being in places where a woman was not expected to be, and doing what women did not conventionally do."[6] Some scientists took an enlightened approach to the presence of women in their ranks. In London, Whiting met Lord Kelvin; in a 1924 article for *Science*, she recalled being impressed when he was "neither surprised nor alarmed" by her gender.[9] But others were concerned about what might happen to their comfortable worlds if more women entered their fields. When Whiting met William Crookes in 1888, he reportedly mused, "What would become of the buttons and the breakfasts if all the ladies should know so much about spectroscopes?"[10]

### PHYSICS FACILITIES AT WELLESLEY COLLEGE

The *Wellesley College Calendar for 1877–8* (page 39) boasted that the physics department had

> a convenient lecture-room, with lantern and porte lumiere constantly in place for the illustration of lectures, or the projection upon the screen of minute experiments. Water, wires from the battery, oxygen and hydrogen and illuminating gas, are furnished at the lecturer's desk. The costly apparatus for this department has been selected with great care from the best makers in England, France, Germany, and this country. . . . This is arranged in eight separate rooms and alcoves. One dark room is supplied with a Bunsen's Photometer for measuring the candle power of gases, and with apparatus for Spectrum Analysis, etc. Another room is fitted up for an Electrical Laboratory, and supplied with a Wheatstone's Bridge and Resistance Coils, Thomson's Mirror Galvanometer and Lamp Stand, made by Elliot of London, and other apparatus necessary for Electrical measurements. There is also a battery room and a room for photography.

**FIGURE 2. A ROOM IN WELLESLEY'S PHYSICS LABORATORY, CIRCA 1893.** The instrumentation includes various electrostatic generators, or Wimshurst machines, Leyden jars, induction coils, and a galvanometer. It was only the second undergraduate physics laboratory in the country, and the first for female students. (Courtesy of Wellesley College Archives, Library & Technology Services.)

FIGURE 3. **SARAH FRANCES WHITING'S COLLEAGUE MABEL CHASE PLACES HER HAND ON A GLASS PHOTOGRAPHIC PLATE**, below a Crookes tube, to take a radiograph of the bones of her hand in Wellesley's physics laboratory, circa 1896. (Courtesy of Wellesley College Archives, Library & Technology Services.)

Whiting must have found Crookes's comment amusing, since she did in fact know a great deal about spectroscopes. She guided her students' laboratory experiments on solar spectroscopy, emission spectra of various metals, absorption spectra of chlorophyll, and, in her Physical Astronomy course, the classification of stellar spectra.[11] That knowledge, along with her emphasis on experimentation, led to her success with x rays.

## Röntgen and x rays

In November 1895, while observing the spectra created by beams of electrons in a shielded cathode-ray tube, German physicist Wilhelm Conrad Röntgen made a remarkable discovery. An unidentified form of radiation from the tube was passing through solid materials and leaving images—what we would now call a radiograph—on prepared glass photographic plates. After fixing the images with a chemical bath, he used the plates as negatives to make paper photographs that could then be reproduced and circulated. Although other scientists had noticed similar phenomena, Röntgen was the first to explore the physical properties of that radiation, which he named x rays after the mathematical symbol of an unknown quantity. Röntgen published his findings in *Sitzungsberichte der Würzburger Physikalischen-Medicinischen Gesellschaft* (*Proceedings of the Würzburg Physico-Medical Society*) later that year; the editor decided to forgo the customary prepublication lecture as an acknowledgment of its importance.

Although Röntgen wrote in German in a journal with limited circulation, he sent copies of the article and his photographs to colleagues. News of his discovery reached English-language newspapers by 7 January 1896. Additional accounts quickly followed, culminating with translations of Röntgen's paper in both *Nature* on 23 January and *Science* on 14 February. A photograph of the hand of Röntgen's wife, Anna Bertha Ludwig, her wedding ring on her third finger, was a particular sensation.

The ability to render the invisible visible captured the popular imagination in a way few previous scientific announcements had, prompting songs, poems, books, and public demonstrations. (It was not until later, of course, that scientists and physicians realized the risks associated with x-ray exposure.[12]) Prominent physicists all over the world, along with quite a few amateur scientists, rushed to replicate Röntgen's experiments. In 1926 a graduate of Davidson College claimed that he and his classmates had secretly conducted a successful x-ray experiment on 12 January 1896; that claim, however, cannot be corroborated.[13] The first confirmed successes in the US had the backing of major research universities: Arthur Wright at Yale University on 27 January, John Trowbridge at Harvard University by 29 January, Edwin Frost at Dartmouth College on 3 February, Mihajlo Pupin at Columbia University on 4 February, Arthur Goodspeed at the University of Pennsylvania on 5 February, and William Magie at Princeton University on 6 February.[14]

## Whiting's x-ray experiments

On 7 February Whiting joined that elite group. It seems likely that Whiting first heard about the discovery from an article in the *Boston Daily Advertiser* on 14 January. The article described Röntgen's equipment—a Crookes tube, an induction coil, and a battery—all of which were readily available in Wellesley's laboratory, along with glass plates, holders, and photographic chemicals.

Whiting was assisted by a colleague, physics instructor Mabel Augusta Chase, who went on to a long career at Mount Holyoke College (see figure 3). In accordance with Wellesley's laboratory teaching methods, the two instructors were joined by at least two students: Cannon, who had returned to take additional classes before continuing her astronomy studies at Radcliffe College and Harvard, and Grace Evangeline Davis, class of 1898, who became a noted meteorologist and taught physics at Wellesley from 1899 to 1936. Together the women experimented with several variables—different objects, equipment, and timings—to produce at least 15 "shadow photographs," as Whiting described the x-ray images left on the glass plates.

Other than annotations on the reverse of some of the photographs made from those plates, Whiting left no written documentation of her x-ray experiments. However, someone alerted the *Boston Daily Advertiser*, who reported it on 8 February. The *Advertiser* also interviewed Whiting for a longer article that appeared on 11 February. In that piece, she described the results of her experiments at length, explaining her use of different power sources, exposure times, and materials to improve the quality of her images and investigate the degree to which the rays would penetrate materials of different density.

Additional information about their first experiment comes from a letter Cannon wrote to her cousin Ned Jump. On the reverse of torn sheets of mimeographed lecture notes, Cannon described their efforts in detail:

> We took – a photograph this morning by the so-called Röntgen process, or by the Cathode rays. It is not a brilliant negative, but it is there, that's the point. . . . Miss Whiting has been intending to try it, and so concluded to do it immediately. We arranged it very simply thus. A current from four cells was passed through a Ruhmkorff coil, and connected to a Crook's tube. On the table where they were all placed, right under the cathode of the tube, we laid a plate holder horizontally, [glass] slide in. On top of the slide, we placed a pair of pincers, a picture hook, a key. We started the current, and left them all in position one hour and a quarter. Miss Chase + I then proceeded to the dark room to develop. Little did I think there would be anything there to develop! I was somewhat excited, you may imagine. At first, there did not seem to be anything. I covered the plate tight, to beware of fog. The next time I looked, lo and behold there was a light streak, "It's the picture-hook," we both exclaimed, and so it was, clear and unmistakable. The pincers came out too, but the key did not.[15]

Whiting annotated a photograph of the experiment with her name and that of Chase and the following description: "A picture hook + pincers in a wooden box. First attempt. Under-exposed but showed that success was attainable with apparatus in use viz a crooks tube [here she inserted a sketch of the tube] made to show molecular shadows. Executed with 6 in coil." That last phrase refers to the six-inch-diameter induction coil visible on Whiting's work bench in figure 1.

Even underexposed, it was a thrilling outcome and gave the women a better sense of how to proceed. Cannon's letter outlined their next steps: "While I am writing to you, we have another [glass] plate, shall I say, exposed. It's the queerest looking exposure you ever saw. A dark paste-board box, with various metallic objects inside is tied onto a plate-holder, [glass] slide in—all standing up before the Crook's tube, while the current is sizzing away. We are going to give it two hours."[15]

A few hours later, an exhausted Cannon added another page to her letter. She revealed, "I stayed up to develop the second one + have a good negative. Everything inside the box is good, but there's no sign of the box, no sign of the [glass] slide. I am tired + can not write more."[15]

The women made a photograph from that negative too. The objects—a ring, a hook, and two unidentifiable shapes—appeared blurry, but the image was nevertheless an improvement over their first. Whiting's annotation reads, "Metal objects taken in a wooden box. The second picture taken just after newspaper accounts of xray discovery." Whiting and Chase then conducted a third experiment, this time exposing blocks of different materials, including glass, quartz, gum, alum, spar, and salt, to assess their relative transparency to x rays. The different materials made it difficult to determine exposure time; the image showed little variation between the blocks, and Whiting noted on the reverse: "A bad print."

Whiting's annotations demonstrate that she was keen to keep track of and perfect her experiments. She used the knowledge gained from the first three attempts to make additional images. In a number of them she used laboratory objects, such as screwdrivers, placed inside containers that seemed to miraculously disappear when exposed to radiation. In one case, she used an assortment of metal jewelry (see figure 4), presumably her own or that of her colleagues, a striking contrast to the objects her male counterparts employed. Other images featured a pince-nez and a round pincushion filled with pins (see the opening image), tools, and hands with and without rings.

## Whiting's legacy

Whiting's achievement was celebrated in newspaper articles in Boston and beyond alongside the work of her male colleagues.

**FIGURE 4. WHITING'S X-RAY PHOTOGRAPH OF OBJECTS IN A LEATHER POUCH.** Most of Whiting's experiments used objects common to physics laboratories or even the average desk drawer. In this example, however, she used a group of decidedly female accessories—a ring, a brooch, a heart-shaped pendant on a chain, and an intricately fashioned link necklace or bracelet—and a tiny key. (Courtesy of Wellesley College.)

But some commentators could not resist referring to her gender in patronizing terms. On 16 February, the *Boston Daily Globe* quoted an unidentified professor as saying, "Perhaps the women at Wellesley will discover an entirely new kind of ray—a feminine ray, or something like that. Or they may find that the Roentgen ray is composed of two parts, male and female. Although no great scientific discoveries have ever been made by a woman, it does not follow that none will ever be, and every student of science is glad to see the women interested."

But Whiting knew what her x-ray experiments meant for women's education. In the 11 February *Advertiser* article, she stated that "the colleges for women are quite as much interested and as intelligent in the matter as those for men." Accounts in Boston area newspapers, and in the *New York Tribune*, indicate that she delivered several lectures about x rays on the Wellesley campus in February, March, and April.

Like other Wellesley faculty, Whiting was active in Boston's intersecting circles of women intellectuals, writers, artists, abolitionists, suffragists, and reformers. Her work with Röntgen's rays made her a celebrity among those women. Letters in the Wellesley College Archives indicate that the reformer Mary Livermore invited Whiting to speak to Boston's Fortnightly Club, a group of women engaged in social justice issues who regularly gathered for lectures on various topics. On 14 March, the Fortnightly Club's newspaper, *The Woman's Column*, reported on the great success of the lecture: "The rooms were crowded to hear Prof. Whiting, of Wellesley, on the 'Photography of the Invisible' (Roentgen's Rays). Many were unable even to get standing room."

Whiting's x-ray experiments immediately became part of the physics curriculum taught by Wellesley faculty. While Whiting was on sabbatical during the 1896–97 academic year, her replacement taught the topic; in her notes, now in the Wellesley College Archives, Florence Crofut, class of 1897, included multiple references to "Röntgen rays." Years later Lucy Wilson, a 1909 graduate who in 1945 became the first holder of Wellesley's Sarah Frances Whiting Professorship of Physics, remembered that Whiting "gave two of us a never-forgotten experience when she provided the apparatus by which we repeated Roentgen's discovery of X rays. The equipment we used was exactly like that described by Roentgen . . . and we obtained clear photographs of the shadows of our own bones."[16]

Whiting looked back fondly on the collective female effort that went into her experiments. In a Christmas card to Cannon, written sometime between 1914 and 1926, Whiting inscribed a series of reminiscences about her relationship with her former student, including a reference to their work with x rays.[17] Cannon must have felt the same; in her 4 November 1927 obituary for Whiting in *Science*, she commented, "The advanced students in physics of those days will always remember the zeal with which Miss Whiting immediately set up an old Crookes' tube and the delight when she actually obtained some of the very first photographs taken in this country of coins within a purse and bones within the flesh."

Whiting retired in 1916, though she remained engaged with life at Wellesley until her death in 1927. Although her x-ray experiments were cited in Cannon's obituaries and in some modern scholarship, the details and the photographic evidence have not been published before. As almost certainly the first successful x-ray experiments in an undergraduate college, they were made possible by Whiting's dedication to the laboratory method of instruction and her awareness of advances in scientific knowledge. As the first such experiments by female faculty and students, they exemplify the role of both Whiting and Wellesley at the forefront of the teaching of science, and the dissemination of knowledge more broadly, to women in the US. It was a legacy that extended to Whiting's students, who in addition to Cannon, Davis, and Wilson include Isabelle Stone, class of 1890, the first American woman to earn a PhD in physics, and Louise Sherwood McDowell, class of 1898, the first American woman to work at the National Bureau of Standards, now NIST. From her laboratories at Wellesley College, Whiting helped to shape the role of women in the sciences for decades to come.

ON THE WEB:
PHOTO GALLERY OF
Whiting's x rays
VISIT
physicstoday.org/Whiting

## REFERENCES

1. J. Glasscock, ed., *Wellesley College 1875–1975: A Century of Women*, Wellesley College (1975); H. L. Horowitz, *Alma Mater: Design and Experience in the Women's Colleges from Their Nineteenth-Century Beginnings to the 1930s*, Knopf (1984); P. A. Palmieri, *In Adamless Eden: The Community of Women Faculty at Wellesley*, Yale U. Press (1995).
2. S. F. Whiting, "Department of physics," *Wellesley College News*, 22 February 1911, p. 6.
3. M. W. Rossiter, *Women Scientists in America: Struggles and Strategies to 1940*, Johns Hopkins U. Press (1982), pp. 25–26.
4. Ref. 2; S. F. Whiting, "The experiences of a woman physicist," *Wellesley College News*, 9 January 1913, p. 1; S. F. Whiting, "History of the Physics Department of Wellesley College from 1878 to 1912," box 2, Physics Department Papers, Wellesley College Archives; A. J. Cannon, *Pop. Astron.* **35**, 539 (1927); A. J. Cannon, *Science* **66**, 417 (1927); F. A. Stahl, *Am. J. Phys.* **73**, 1009 (2005).
5. K. Hentschel, *Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching*, Oxford U. Press (2002); M. R. S. Creese, *Ladies in the Laboratory? American and British Women in Science, 1800–1900: A Survey of Their Contributions to Research*, Scarecrow Press (1998); C. R. Sherman, in *The Early Years of Art History in the United States: Notes and Essays on Departments, Teaching, and Scholars*, C. H. Smyth, P. M. Lukehart, eds., Princeton U. Press (1993), p. 151.
6. Ref. 4, S. F. Whiting, "The experiences of a woman physicist," p. 3.
7. Ref. 4, S. F. Whiting, "History of the Physics Department of Wellesley College from 1878 to 1912."
8. M. W. Rossiter, in *The Cambridge History of Science*, vol. 5, M. J. Nye, ed., Cambridge U. Press (2002), p. 54.
9. S. F. Whiting, *Science* **60**, 149 (1924), p. 150.
10. Ref. 4, S. F. Whiting, "The experiences of a woman physicist," p. 4.
11. Ref. 5, K. Hentschel, p. 385.
12. R. Herzig, *Am. Q.* **53**, 563 (2001).
13. W. H. Sprunt III, *N. C. Med. J.* **18**, 269 (1957); "X-Ray: Davidson College, 1896–1939 and 1940–2010," Davidsoniana file, Davidson College Archives.
14. R. Brecher, E. Brecher, *The Rays: A History of Radiology in the United States and Canada*, Robert E. Krieger (1969); P. K. Spiegel, *Am. J. Roentgenol.* **164**, 241 (1995).
15. A. J. Cannon to N. Jump (7 February 1896), box 1, Personal Correspondence, Papers of Annie Jump Cannon, 1863–1978, Harvard University Archives.
16. S. S. Hinerfeld, ed., *Wellesley After-Images*, Wellesley College Club of Los Angeles (1974), p. 4.
17. S. F. Whiting to A. J. Cannon (no date), Cannon papers, in ref. 15.

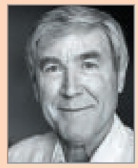
PT

# DOES NEW PHYSICS LURK INSIDE LIVING MATTER?

Paul Davies

Courtesy of Kaitlin M. Baudier, Arizona State University.

**Paul Davies** is a Regents' Professor in the physics department at Arizona State University in Tempe and the director of the university's Beyond Center for Fundamental Concepts in Science.



**The link between information and physics has been implicit since James Clerk Maxwell introduced his famous demon. Information is now emerging as a key concept to bridge physics and biology.**

To a physicist, life looks like magic. Living things accomplish feats so dazzling, so enigmatic, that it's easy to forget they are made of ordinary atoms. But if the secret of life is not the stuff of which living things are made, then what is it? What gives organisms that distinctive élan that sets them apart as remarkable and special? That was the question posed by Erwin Schrödinger in a famous series of lectures delivered in Dublin, Ireland, in 1943, and published the following year as an influential book titled *What Is Life?*[1]

Schrödinger was a giant of theoretical physics and one of the founders of quantum mechanics, the most successful scientific theory ever conceived, both in terms of applications and accuracy. For example, when applied to the electromagnetic field, it correctly predicts the anomalous magnetic moment of the electron to better than 10 significant figures. Almost at a stroke, quantum mechanics explained the nature of inanimate matter, from subatomic particles, through atoms and molecules, to stars. But, frustratingly, it didn't explain living matter. And despite spectacular advances in biology in the intervening decades, life remains a mystery. Nobody can say for sure what it is or how it began.[2]

Asked whether physics can explain life, most physicists would answer yes.

The more pertinent question, however, is whether known physics is up to the job, or whether something fundamentally new is required. In the 1930s many of the architects of quantum mechanics—most notably Niels Bohr, Eugene Wigner, and Werner Heisenberg—had a hunch that there is indeed something new and different in the physics of living matter. Schrödinger was undecided, but open to the possibility. "One must be prepared to find a new kind of physical law prevailing in it," he conjectured.[1] But he didn't say what that might be.

Those questions go beyond mere academic interest. A central goal of astrobiology is to seek traces of life beyond Earth, but without a definition of life it is hard to know precisely what to look for. For example, NASA is planning a mission to fly through the plume of material spewing from fissures in the icy crust of Enceladus, a moon of Saturn known to contain organic molecules (see the article by John Spencer, PHYSICS TODAY, November 2011, page 38). What would convince a skeptic that the material includes life, or the detritus of once-living organisms, as opposed to some form of pre-life? Unlike the measurement of, say, a magnetic field, scientists lack any sort of life meter that can quantify the progress of a chemical mixture toward known life—still less an alien form of life.

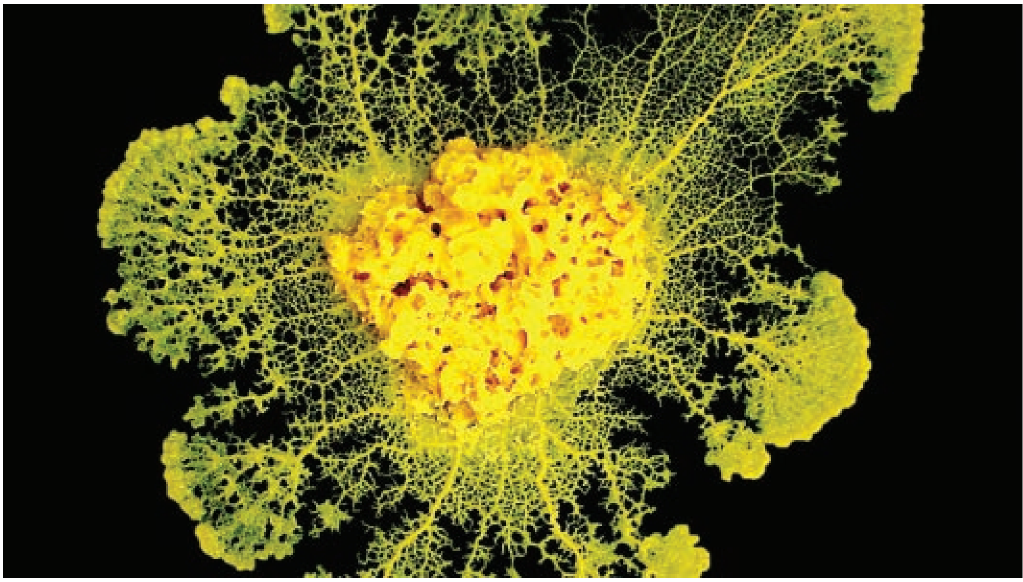


**FIGURE 1. SLIME MOLD.** Sometimes collections of free, single cells form cooperatives and behave like a single organism with a common agenda. (Courtesy of Audrey Dussutour, CNRS.)

Most astrobiologists focus on signatures of life as we know it. For example, NASA's Viking mission to Mars in the 1970s sought signs of carbon metabolism using a broth of nutrients palatable to terrestrial organisms. Another much-discussed biosignature is homochirality—the presence of only one enantiomer. Although the laws of physics are indifferent to left–right inversion, known life uses left-handed amino acids and right-handed sugars. But inorganic soil chemistry can mimic metabolism, and homochirality can be generated by iterated chemical cycles without life being involved, so those putative biosignatures are not definitive.

Farther afield, the problem of identifying life is doubly hard. Astrobiologists have pinned their hopes on detecting oxygen in the atmospheres of extrasolar planets, but again, atmospheric oxygen is not an unambiguous signature of photosynthesis, because nonbiological processes can also create oxygenated atmospheres. What we lack is any general definition of "living" independent of the biochemical substrate in which life is instantiated. Are there any deep, universal principles that would manifest identifiable biosignatures, even of life as we don't know it?

## The two cultures

The gulf between physics and biology is more than a matter of complexity; a fundamental difference in conceptual framework exists. Physicists study life using concepts such as energy, entropy, molecular forces, and reaction rates. Biologists offer a very different narrative, with terms such as signals, codes, transcription, and translation—the language of information. A striking illustration of that view is the amazing new CRISPR technology that allows scientists to edit the codebook of life (see the article by Giulia Palermo, Clarisse G. Ricci, and J. Andrew McCammon, PHYSICS TODAY, April 2019, page 30). The burgeoning field of biophysics seeks to bridge the conceptual gulf by, for example, modeling patterns of information flow and storage in various biological control networks.

Life is invested in information storage and processing at all levels, not just in DNA. Genes—DNA sequences that serve as encrypted instruction sets—can switch other genes on or off using chemical messengers, and they often form complex networks. Those chemical circuits resemble electronic or computing components, sometimes constituting modules or gates that enact logical operations.[3]

At the cellular level, a variety of physical mechanisms permit signaling and can lead to cooperative behavior. Slime molds, like the one shown in figure 1, provide a striking example. They are aggregations of single cells that can self-organize into striking shapes and sometimes behave coherently as if they were a single organism. Likewise, social insects such as ants and bees exchange complex information and engage in collective decision making (see the Quick Study by Orit Peleg, PHYSICS TODAY, April 2019, page 66). And human brains are information processing systems of staggering complexity.

The informational basis of life has led some scientists to pronounce the informal dictum, Life = Matter + Information. For that linking equation to acquire real explanatory and predictive power, however, a formal theoretical framework is necessary that couples information to matter. The first hint of such a link came in 1867. In a letter to a friend, Scottish physicist James Clerk Maxwell imagined a tiny being that could perceive individual molecules in a box of gas as they rushed around. By manipulating a screen and shutter, the demon, as the diminutive being soon came to be known, could direct all the fast molecules to the left of the box and the slow ones to the right, as illustrated in the box on page 37.

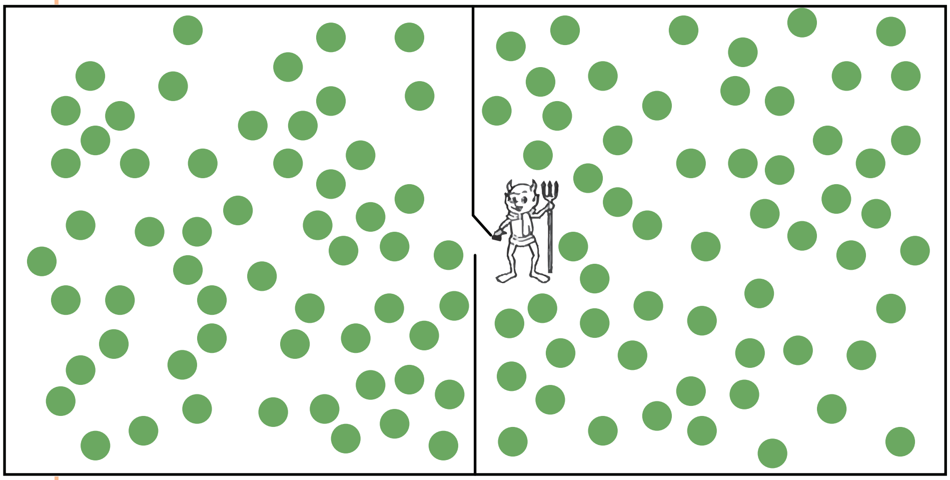
Because molecular speed is a measure of temperature, the

## MAXWELL'S DEMON

The figure here shows a box of gas divided into two chambers by a screen with a small aperture through which molecules (green) may pass one by one. The aperture is blocked by a shutter. It's controlled by the 1867 brainchild of James Clerk Maxwell: a tiny demon who observes the randomly moving molecules and can open and close the shutter to allow fast molecules to travel from the right-hand chamber to the left, and slow molecules to travel in the opposite direction. The mechanism could then be used to convert disorganized molecular motion into directed mechanical motion.

The demon lay like an inconvenient truth at the heart of physics for decades, mostly dismissed as a mere theoretical puzzle. A century after Maxwell envisaged the thought experiment, a real demon was made in a laboratory in Edinburgh, the city of Maxwell's birth. The experiment consisted of a molecular ring that could slide back and forth on a rod with stoppers at the end. In the middle of the rod sat another molecule that could exist in two conformations—one that blocks the ring and one that allows it to pass. The molecule thus serves as a gate, akin to Maxwell's original conception of a movable shutter.[17]

Following that lead, a cottage industry in demonic devices emerged, including an information-powered refrigerator built by Jukka Pekola's nanoscience group at Finland's Aalto University and Dmitri Averin of Stony Brook University.[18] In the refrigerator, the role of the gas molecule is played by a single electron confined to a two-sided nanoscale box that is coupled to a heat bath. The cooling cycle exploits the existence of two degenerate box states for a certain electron energy. The cycle begins with the electron in a definite, nondegenerate state. An external electric field raises the electron energy to the degenerate level, where the electron can reside with equal probability in either of the two states.



That introduction of uncertainty represents an increase in the entropy of the electron and a corresponding decrease in the entropy, and thus the temperature, of the bath. At this point the demon—played by another single-electron box coupled to the first—detects which of the two states the electron is in and autonomously feeds the information to the driving field, which uses it to rapidly return the electron to its initial nondegenerate state and complete the cooling cycle. The researchers found that the creation of one bit of information per cycle—which state the electron is in—could extract heat from the bath with an average efficiency of about 75%. Maxwell was right: Information really can serve as a type of fuel.

demon would, in effect, use information about molecules to create a heat gradient inside the box. An engineer could then tap that gradient to extract energy and perform useful work. On the face of it, Maxwell had designed a perpetual motion machine, powered by pure information, in defiance of the second law of thermodynamics (see the article by Eric Lutz and Sergio Ciliberto, PHYSICS TODAY, September 2015, page 30).

To resolve the paradox, information must be quantified and formally incorporated into the laws of thermodynamics. The basis for modern information theory[4] was laid down by Claude Shannon in the late 1940s. Shannon defined information as reduction in uncertainty—for example, by inspecting the outcome of a coin toss. The familiar binary digit, or bit, is the information gained by determining heads or tails from flipping a coin. The synthesis of Shannon's information theory and thermodynamics led to the identification of information as negative entropy. Any information acquired by the demon to gain a thermodynamic advantage must therefore be paid for by a rise in entropy at some stage—for example, when the demon's memory store is erased and reset so the demon can repeat the cycle.

Maxwell conceived of his demon as a thought experiment, but advances in nanotechnology now permit experimental realizations of the basic idea (see the box). Yet life has been making and using varieties of demons for billions of years. Our bodies are replete with them.[5] Molecular machines that copy DNA, transport cargo along fibers, or pump protons through cell membranes operate very close to the ideal thermodynamic limit. They play the margins of the second law to gain an energy advantage.[6,7] The human brain uses in its wiring a type of demon—voltage-gated ion channels—to propagate electrical signals. Those ion channels enable the brain to run on the energy equivalent of a dim light bulb even though it has the power of a megawatt supercomputer.[8]

### The contextual nature of biological information

Demonics is merely the tip of life's informational iceberg. Biological information goes far beyond optimizing the energy budget; it often acts as a type of manager. Consider the way an embryo (figure 2) develops from a fertilized egg. It's supervised at every stage by information networks finely tuned to a multitude of physical and chemical processes, all arranged so that the complex final form emerges with the right architecture and morphology.

Attempts to model embryogenesis using information flow in gene regulatory networks have been remarkably successful. Eric Davidson and his coworkers at Caltech worked out the entire wiring diagram, chemically speaking, for the gene network that regulates the sea urchin's early-stage development. By tracking the information flow, the group programmed a computer to simulate the network dynamics step by step. At each stage they compared the computer model of the state of the circuit with the observed stage of the sea urchin's development and obtained an impressive match. The researchers also considered the effects of chemically silencing specific genes in the computer model to predict what would happen to the mutant embryo; again, their modeling matched the experimental observations.[9]

A group led by Thomas Gregor and William Bialek at Princeton University has been investigating the early stages of fruit fly development—in particular, how distinctive morphological features first appear. During development, cells need to know their location relative to other cells in three-dimensional space. How do they obtain that positional information? It has long been known that cells exhibit a type of GPS based on chemical gradients that are, in turn, regulated by the expression levels of specific genes. The Princeton group recently zeroed in on four so-called gap genes that lay the foundations for patterning the embryo by creating gaps, or bands, in the body plan. They found that cells were extracting optimal positional information from the gene expression levels by exploiting Bayesian probabilities, and thereby achieving an astonishing 1% accuracy. The researchers were able to apply a Bayesian optimization model to mutant strains and correctly predict their modified morphology too.[10]

Those analyses raise a crucial philosophical question that goes to the heart of the conceptual mismatch between physics and biology. Studies of gene regulatory networks and the application of Bayesian algorithms are currently treated as phenomenological models in which "information" is a convenient surrogate or label for generating a lifelike simulation of a real organism. But the lesson of Maxwell's demon is that information is actually a physical quantity that can profoundly affect the way that matter behaves. Information, as defined by Shannon, is more than an informal parameter; it is a fundamental physical variable that has a defined place in the laws of thermodynamics.

Shannon stressed that his information theory dealt purely with the efficiency and capacity of information flow; it said nothing about the meaning of the information communicated. But in biology, meaning or context is critical. How might one capture mathematically that property of instructional or supervisory or contextual information? Here's one approach: Molecular biology's so-called central dogma—a term coined by Francis Crick a decade or so after he and James Watson deduced the double helix structure of DNA—is that information flows in one direction, from DNA to the machinery that makes proteins and thence to the organism. One might term that a "bottom-up" flow.

Today, information transfer in biology is known to be a two-way process, involving feedback loops and top-down information flow. (See the article by George Ellis, PHYSICS TODAY, July 2005, page 49.) For example, if cells cultured to grow in a Petri dish get too crowded, they stop dividing, a phenomenon known as contact inhibition. And experiments with microbes on the International Space Station have shown that bacteria may express different genes in a zero-gravity environment than they do on Earth. Evidently, system-level physical forces affect gene expression operating at the molecular level.

The work of Michael Levin and his colleagues at Tufts University's Allen Discovery Center provides an arresting example of top-down information flow. Levin's group is exploring how

ANATOMYUMFTM©2012

**FIGURE 2. A HUMAN EMBRYO**, 38 mm long, 8–9 weeks. (Adapted from photo by Anatomist90, Wikimedia Commons, CC BY-SA 3.0.)

system-wide electrical patterning can be as important as mechanical forces or chemical patterning in controlling the growth and morphology of some organisms. Healthy cells are electrically polarized: They maintain a potential difference of a few tens or hundreds of millivolts across the cell walls by pumping out ions. Cancer cells, by contrast, tend to be depolarized.

Levin's group has found that in multicellular organisms, cell polarization patterns across tissues play a key role in growth and development, wound healing, and organ regeneration. By disrupting those electrical patterns chemically, the group can produce novel morphologies to order.[11] A species of planaria flatworm provides a convenient experimental subject. If a normal worm is chopped in two, the head grows a new tail and the tail grows a new head, making two complete worms. But by modifying the electrical polarization state near the wound, one can make two-headed or two-tailed worms, as shown in figure 3. (See PHYSICS TODAY, March 2013, page 16.)

Amazingly, if those monsters are in turn chopped in two, they do not revert to the normal phenotype. Rather, the two-headed worms make more two-headed worms, and likewise with two-tailed worms. Despite all having identical DNA, the worms look like different species. The system's morphological information must be getting stored in a distributed way in the truncated tissue and guiding the appropriate regeneration at the gene level. But how does that happen? Does an encrypted electrical code operate alongside the genetic code?

The term epigenetics refers to the phenotype-determining factors, such as gross physical forces, that lie beyond the genes. Very little is known about the mechanisms of epigenetic information storage, processing, and propagation, but their role in biology is critical. To make progress, we need to discover how different types of informational patterns—electrical, chemical, and genetic—interact to produce a regulatory framework that manages the organization of living matter and translates it into specific phenotypes.

Thinking about the physics of living matter in informational terms rather than purely molecular terms is analogous to the difference between software and hardware in computing. Just as a full understanding of a particular computer application—PowerPoint, for example—requires a grasp of the principles of software engineering as much as the physics of computer circuitry, so life can only be understood when the principles of biological information dynamics are fully elucidated.

## A new concept of dynamics

Since the time of Isaac Newton, a fundamental dualism has pervaded physics. Although physical states evolve with time, the underlying laws of physics are normally regarded as immutable. That assumption underlies Hamiltonian dynamics, trajectory integrability, and ergodicity. But immutable laws are a poor fit for biological systems, in which dynamical patterns of information couple to time-dependent chemical networks and where expressed information—for example, the switching on of genes—can depend on global or systemic physical forces as well as local chemical signaling.

Biological evolution, with its open-ended variety, novelty, and lack of predictability, also stands in stark contrast to the way that nonliving systems change over time. Yet biology is not chaos: Many examples of rules at work can be found. Take the universal genetic code. The nucleotide triplet CGT, for example, codes for the amino acid arginine. Although no known exceptions to that rule exist, it would be wrong to think of it as a law of nature—like the fixed law of gravity. Almost certainly, the CGT-to-arginine assignment emerged, millions of years ago, from some earlier and simpler rule. Biology is full of cases like that.

A more realistic description of change in biosystems would be the variation in the dynamical rules as a function of the state of a system.[2,12] State-dependent dynamics opens up a rich landscape of novel behavior, but it is far from a formal mathematical theory. To appreciate what it might entail, consider the analogy to a game of chess. In standard chess, the system is closed and the rules are fixed. From the conventional initial state, chess players are free to explore a state that, while vast, is nevertheless constrained by immutable rules to be but a tiny subset of all possible configurations of pieces on the board. Although an enormous number of patterns are possible, an even greater number of patterns are not permitted—for example, having all bishops occupy squares of the same color.

Now imagine a modified game of chess in which the rules can change according to the overall state of play—a system-level, or top-down, criterion. To take a somewhat silly example, if white is winning, then black might be permitted to move pawns backward as well as forward. In that extended version of chess, the system is open, and states of play will arise that are simply impossible using the fixed rules of standard chess. That imaginary game is reminiscent of biology, in which organisms are also open systems, able to accomplish things that are seemingly impossible for nonliving systems.

To explore the consequences of state-dependent dynamics in a simple model that captures top-down information flow, my research group at Arizona State University has used a modification of a 1D cellular automaton (CA). A standard CA is a row of cells—squares or pixels—that are either empty or filled (white and black, respectively, for example); a fixed rule is then used to update the state of each cell according to the existing state and that of its nearest neighbors. The system has 256 possible update rules.[13]

To play the CA game, one picks an initial cell pattern—conveniently represented as a sequence of bits, either 0 or 1—and then applies the chosen update rule repeatedly to evolve the system. Many update rules lead to dull outcomes, but a few produce elaborate patterns of evolving complexity. To implement a modified, state-dependent CA, my colleagues Alyssa Adams and Sara Walker computationally coupled two standard CAs. One represented the organism; the other, the environment.[14]

**FIGURE 3. THIS TWO-HEADED WORM** was created by manipulating electrical polarity. The worm reproduces other two-headed worms when bisected, as if it is a different species, even though it has the same DNA as normal one-headed worms. Somehow the information about the global body plan is passed on to the progeny epigenetically. (Adapted from T. Nogi et al., *PLOS Negl. Trop. Dis.* **3**, e464, 2009.)

Then the two researchers allowed the update rule for the organism to change at each iteration. To determine which of the 256 rules to apply at any given step, they bundled the organism CA cells into adjacent triplets—000, 010, 110, and so forth—and compared the relative frequencies of each triplet with the same patterns in the environment CAs. Such an arrangement changes the update rule as a function of both the state of the organism, making it self-referential, and the state of the environment, making an open system.

Adams and Walker ran thousands of case studies on a computer to look for interesting patterns. They wanted to identify evolutionary behavior that is both open-ended—the organism does not soon cycle back to its starting state—and innovative. In this context, innovation means that the observed sequence of organism states could never occur in any of the 256 possible fixed-rule CAs from any starting state. It's analogous to having four bishops end up on the same color squares in the modified game of chess. Although such open, innovative behavior turned out to be rare, some clear-cut examples emerged. It took a lot of computing time, but Adams and Walker discovered enough to be convinced that even in their simple model, state-dependent dynamics provide novel pathways to complexity and variety. Their work illustrates that merely processing the bits of information isn't sufficient. To capture the full richness of biology, the information-processing rules themselves must evolve.

## Life on the quantum edge

If biology deploys new physics, such as state-dependent dynamical rules, then at what point between simple molecules and living cells does it emerge? CA models may be instructive, but they are cartoons, not physics; they tell us nothing about where to look for new emergent phenomena. As it happens, standard physics already contains a familiar example of state-dependent dynamics: quantum mechanics.

Left in isolation, a pure quantum state described by a coherent wavefunction evolves predictably according to a well-understood mathematical prescription known as unitary evolution. But when a measurement is made, the state changes abruptly—a phenomenon often called the collapse of the wavefunction. In an ideal measurement, the jump projects the system into one possible eigenstate corresponding to the observable being measured. For that step, the unitary evolution rule is replaced by the Born rule, which predicts the relative probabilities of the measurement outcomes and introduces into quantum mechanics the element of indeterminism or uncertainty. That marks the transition from the quantum to the classical domain. Could quantum mechanics therefore point us to what makes life tick?

In his famous Dublin lectures, Schrödinger appealed to quantum mechanics to explain the stability of genetic-information storage. Before Crick and Watson had elucidated the structure of DNA, Schrödinger deduced that the information must be stored at the molecular level in what he termed "an aperiodic crystal," a perceptive description of what nucleic acid polymers turned out to be. Left open, though, was the possibility that quantum phenomena might play a more pervasive role in living organisms.

In the intervening decades, a general assumption prevailed that in the warm, noisy environment of living matter, quantum phenomena would be smothered and classical ball-and-stick chemistry would suffice to explain life. In the past decade or so, however, interest has grown in the possibility that non-trivial quantum phenomena, such as superposition, entanglement, and tunneling, might be important for life after all. Although considerable skepticism remains, the new field of quantum biology is now under intensive investigation.[15] Research has focused on topics as diverse as coherent energy transport in photosynthesis, the avian magnetic compass, and the olfactory response of flies.

Investigating the quantum properties of living matter on the nanoscale presents significant challenges. Systems that are critical to the operation of life may involve few degrees of freedom, are far from thermodynamic equilibrium, and are strongly coupled to their thermal environment. But it is here, in the field of nonequilibrium quantum statistical mechanics, that the emergence of new physics might be expected.

One set of experiments of possible relevance is the measurement of electron conductance through organic molecules. Recently, Gábor Vattay and colleagues have claimed that many biologically important molecules, such as sucrose and vitamin D3, have unique electron-conductance properties associated with the critical transition point between an insulator and a disordered metal conductor. Vattay and colleagues wrote, "The findings point to the existence of a universal mechanism of charge transport in living matter."[16] While their findings fall short of showing that quantum weirdness explains life, they do hint that the realm of quantum-tuned large molecules is where one might spot the emergence of the new physics that Schrödinger and his contemporaries suspected.

## Clash of ideas

Theoretical physicist John Archibald Wheeler used to say that major progress in science stems more from the clash of ideas than from the steady accumulation of facts. Biophysics lies at the intersection of two great domains of science: the physical sciences and the life sciences. Each domain comes with its own vocabulary, but also with its own distinctive conceptual framework, the former being rooted in mechanical concepts, the latter in informational concepts. The ensuing clash presages a new frontier of science in which information, now understood formally as a physical quantity—or rather a set of quantities—occupies a central role and thereby serves to unify physics and biology.[2]

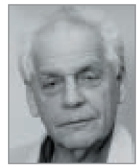
The huge advances in molecular biology of the past few decades may be largely attributed to the application of mechanical concepts to biosystems—that is, to physics infiltrating biology. Curiously, the reverse is now happening. Many physicists, particularly those working on foundational questions in quantum mechanics, advocate placing information at the heart of physics, while others conjecture that new physics lurks in the remarkable and baffling world of biological organisms. Biology is shaping up to be the next great frontier of physics.

## REFERENCES


1. E. Schrödinger, *What Is Life? The Physical Aspect of the Living Cell*, Cambridge U. Press (1944).
2. P. Davies, *The Demon in the Machine*: *How Hidden Webs of Information Are Solving the Mystery of Life*, U. Chicago Press (2019).
3. U. Alon, *An Introduction to Systems Biology: Design Principles of Biological Circuits*, Chapman & Hall/CRC Press (2006).
4. J. Soni, R. Goodman, *A Mind at Play: How Claude Shannon Invented the Information Age*, Simon & Schuster (2017).
5. P. Hoffman, *Life's Ratchet: How Molecular Machines Extract Order from Chaos*, Basic Books (2012).
6. P. M. Binder, A. Danchin, *Eur. Mol. Biol. Org. Rep.* **12**, 495 (2011).
7. P. Ball, "Bacteria replicate close to the physical limit of efficiency," *Nature* (20 September 2012).
8. W. Loewenstein, *The Touchstone of Life: Molecular Information, Cell Communication, and the Foundations of Life*, Oxford U. Press (1999), p. 227.
9. J. Smith, E. Davidson, *Proc. Natl. Acad. Sci. USA* **105**, 20089 (2008).
10. M. D. Petkova et al., *Cell* **176**, 844 (2019).
11. M. Levin, *Regen. Med.* **6**, 667 (2011).
12. N. Goldenfeld, C. Woese, *Annu. Rev. Cond. Mat. Phys.* **2**, 375 (2011).
13. S. Wolfram, *A New Kind of Science*, Wolfram Media (2002).
14. A. Adams et al., *Sci. Rep.* **7**, 997 (2017).
15. J. McFadden, J. Al-Khalili, *Life on the Edge: The Coming of Age of Quantum Biology*, Broadway Books (2014).
16. G. Vattay et al., *J. Phys.: Conf. Ser.* **626**, 012023 (2015).
17. V. Serreli et al., *Nature* **445**, 523 (2007).
18. J. V. Koski et al., *Proc. Natl. Acad. Sci. USA* **111**, 13786 (2014). PT

# NANOTUBES
## from layered transition metal dichalcogenides

**Jan Musfeldt** is Ziegler Professor of chemistry and professor of physics at the University of Tennessee in Knoxville. **Yoshihiro Iwasa** is professor in the Quantum Phase Electronics Center and the department of applied physics at the University of Tokyo and a team leader at the RIKEN Center for Emergent Matter Science in Japan. **Reshef Tenne** is research professor emeritus at the Weizmann Institute of Science in Rehovot, Israel.



Janice L. Musfeldt, Yoshihiro Iwasa, and Reshef Tenne

**The two-dimensional materials form one- and zero-dimensional hollow structures with a host of promising mechanical, optical, and electrical properties.**

Following the synthesis and characterization of carbon nanotubes by Sumio Iijima in 1991, researchers have been interested in synthesizing nanotubes from other single and multilayered materials besides graphene. As early as 1992, one of our groups (Tenne's) and, later on, others succeeded using boron nitride and the transition metal dichalcogenide (TMDC) compounds tungsten disulfide and molybdenum disulfide.[1] In the past two decades, nanotubes have extended to 2D materials composed of two elements—such as metal chalcogenides, halides, and oxides—and three- or four-element misfit layered compounds.[2] Misfit compounds comprise alternating slabs of rock-salt structures, such as lead sulfide, and hexagonal layered compounds, such as tantalum disulfide. Given the many materials that form nanotubes in practice and in computer models, the nanostructures seem to be a genuinely stable phase of 2D materials in the nanoscale range.

ROI LEVI AND OHAD HERCHES, WEIZMANN INSTITUTE

A material's properties change dramatically as its dimensions are reduced. The favorable changes from bulk to two dimensions have driven interest in graphene, monolayer $MoS_2$, and other 2D materials over the past decade. Likewise, the quasi-1D structure of nanotubes endows them with behavior that is, in some cases, entirely different from the bulk or even 2D nanostructures. A prototypical example is the $WS_2$ nanotube, which has enhanced properties, such as increased strength, photoluminescence, electron mobility, and tribological and mechanical properties. Those properties packed into nanoscale make it well suited for applications such as reinforcing polymer nanocomposites and nanoscale field-effect transistors.

Nanotubes form from inorganic 2D materials because the atoms at the edge of the material are abundant. Those edge atoms have a higher energy, and since the surface-to-volume ratio increases dramatically for nanoparticles smaller than 100 nm, it pays for the 2D nanoparticle to fold on itself and seam into a nanotubular structure or a hollow closed-cage nanoparticle, similar to fullerene. But the elastic energy per atom for folding a $MoS_2$ or $WS_2$ layer is about an order of magnitude larger than that for a carbon nanotube with the same diameter. To compensate energetically, $MoS_2$ nanotubes often adopt a multiwall structure, with concentric nanotubes stabilized by van der Waals interactions. Single-wall nanotubes can thus be tricky to produce from 2D compounds.

Different strategies have been developed to synthesize inorganic nanotubes; many of them rely on high-temperature chemical syntheses. But low-temperature techniques, such as hydrothermal synthesis, have proven useful for obtaining nanotubes from many 2D materials. Only some nanotubes—for example $WS_2$, $MoS_2$, and BN—are produced in usable quantities. As a result, researchers have studied them, in particular $WS_2$ nanotubes, comprehensively for their unique physical properties and possible applications.

Multiwall nanotubes are complex structures. Each layer in a tube has a different diameter, number of atoms, and potentially different chirality—the lattice's orientation relative to the tube's axis. Furthermore, multiwall nanotubes in the same synthesis batch are of various diameters and lengths. That variability, and the corresponding variability in material properties, makes the study of individual tubes essential.

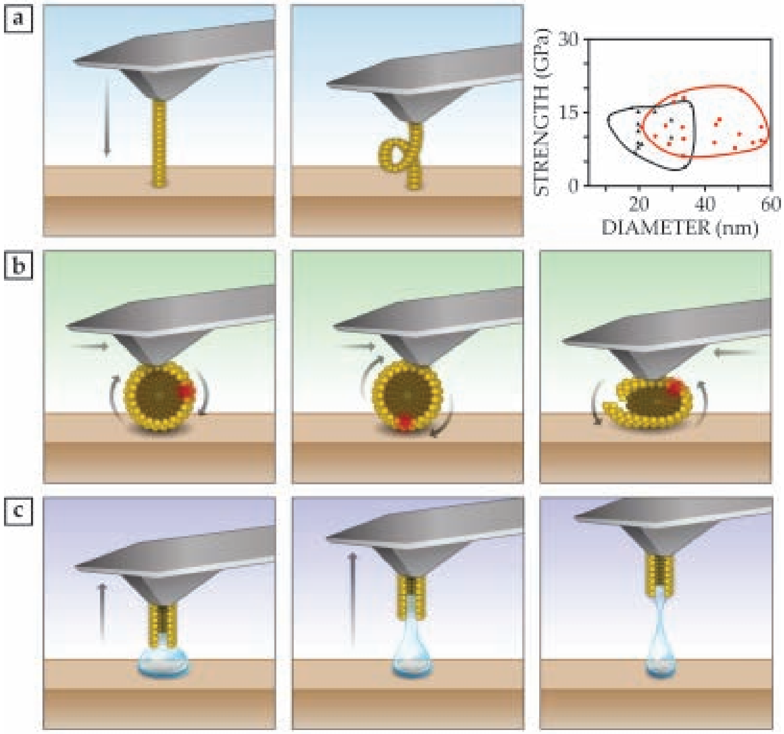



**FIGURE 1. MULTIWALL TUNGSTEN DISULFIDE NANOTUBE STANDS UP TO STRESS. (a)** A nanotube glued to a cantilever (left) bends when compressed (center) without any atomic deformation. The breaking point of a nanotube depends on its diameter (right), either narrow (black triangles) or larger diameter (red dots). (Adapted from ref. 3.) **(b)** When compressed and sheared, a nanotube rolls (left and center) until the load is high enough to cause exfoliation (right).[4] **(c)** Because of strong capillary forces, inserting (left) an open-ended nanotube into the surface of a water droplet and (center) removing it draws the water into the hollow core despite the nanotube's hydrophobic surface. Even after separation (right), some water remains inside the nanotube.[6] (Courtesy of Noa David, Weizmann Institute.)

## Pushed to the breaking point

Individual $WS_2$ and $MoS_2$ nanotubes are mechanically strong. In an early experiment, $WS_2$ nanotubes were compressed and stretched with different stresses,[3] as shown in figure 1a for the case of compression. A nanotube glued to a cantilever (left) would bend rather than break under severe compressive stress (center). In higher compression cases it buckled, but the nanotube still returned to its original shape when the pressure was removed. Under a large tensile stress, the nanotube's behavior depended on its diameter. $WS_2$ nanotubes with small diameter, less than 40 nm, withstood up to 16 GPa (black triangles in the figure 1a graph). They finally broke according to the "sword in a sheath" model, in which only the outmost layer breaks and reveals the unharmed inner tubes. On the other hand, nanotubes with larger diameter (red dots) were stronger and broke only under more than 20 GPa tensile stress. Their breakdown was through a different mechanism known as layer-by-layer, in which multiple layers share the stress and thus all break. The mechanism is possible because crystalline imperfections in larger-diameter tubes interlock the walls and allow them to share the load.

$MoS_2$ and $WS_2$ microparticles (platelets) have served as solid lubricants for almost 100 years. Applications include two-stroke engines, ski waxes, and bullet coatings. When the platelets are between two metal surfaces that slide past each other, the weak van der Waals interactions between the TMDC layers facilitate easy shearing of the platelets' layers and render the friction between the metal surfaces very low. In ultrahigh-vacuum conditions, $MoS_2$ even displays vanishing friction, or superlubricity (see the article by Jean Michel Martin and Ali Erdemir, PHYSICS TODAY, April 2018, page 40). But shearing is prohibited for interlocked layers in a nanotube or fullerene-like nanoparticle, as confirmed by the absence of the low-frequency shearing Raman mode typical in bulk flakes of $WS_2$ and $MoS_2$.

As shown in figure 1b (left and center), rolling the entire nanotube or fullerene-like nanoparticle can produce ultra-small friction coefficients, less than 0.03, even under sizable loads.[4] And although the friction is comparable to that of platelets, the nanotubes last longer. For loads beyond about 0.5 GPa, the nanotube layers start flaking off (right). Those mechanically exfoliated layers settle on the metal surface, where they reduce the friction between the cantilever and the surface. Although the exact behavior in real systems is more complex, exfoliation is also the dominant failure mechanism for TMDC nanoparticles[5] under loads greater than 0.5 GPa but not under loads below 1 MPa, which are typical for lubricants in medical devices, such as endoscopes or catheters (see the article by Sabrina Jahn and Jacob Klein, PHYSICS TODAY, April 2018, page 48). Because of their low friction, fullerene-like $WS_2$ nanoparticles have already been used in the heavy metal industry, mining, and heavy-duty machines as solid-state lubricants and in metal working fluids.

How $WS_2$ nanotubes interact with different gases and liquids is important for applications currently under development, including artificial membranes, sensors, and polymer nanocomposites. To study those interactions, researchers dipped a single nanotube attached to a cantilever tip in and out of water,[6] as shown in figure 1c. Because the W–S bonds are highly covalent and therefore highly nonpolar, the bottom rim of the nanotube is hydrophobic, and that provides a small force, which drives only a few water molecules on the tube's outer surface. Despite the minimal wetting of the outside, environmental scanning electron microscopy, atomic force microscopy experiments, and molecular dynamic calculations revealed that a receding nanotube pulls the water up with it. Capillarity forces elicit strong interactions between the water droplet and the open-ended nanotube. The nanotube's withdrawal from the water surface leads to the formation of a meniscus (figure 1c center) and subsequent necking of the water (right). On the other hand, closed-end $WS_2$ nanotubes, which usually have diameters larger than 60 nm, were barely wetted and interacted only weakly with the water surface.[6]

## Vibrational insight

Raman modes, such as the one shown in figure 2a, provide additional understanding of the breakdown process of nanotubes.[7] When a nanotube is compressed, all its vibrational modes increase in frequency as the surrounding pressure increases (see figure 2b). However, one mode, the $A_{1g}$, blueshifts at twice the rate of the others. It is an out-of-plane vibration of the chalcogen atoms (yellow spheres), and in a nanotube, the $A_{1g}$ is a radial vibration. The mode's sensitivity to the tube's breakdown suggests that the strain passes between the tube walls through their expanding and contracting against each other. That $A_{1g}$-mediated breakdown mechanism explains why fractures are generally perpendicular to the tube's axis, as shown in the transmission electron microscopy (TEM) images of the tubes before and after compression in figure 2c.[7]

Strained $WS_2$ nanotubes show the opposite trend. Raman scattering on a stretched nanotube embedded in polymer fibers revealed redshifting of the mode frequencies, which indicated load transfer.[8,9] In the future, using tip-enhanced spectroscopic techniques, researchers should be able to employ that systematic frequency shift to test for local strain in isolated $WS_2$ tubes under a load.

Raman scattering is a useful tool for uncovering the properties of TMDCs in general. In the 1970s the breathing and shear vibrations of entire layers were an early indication of the 2D layered structure of bulk TMDCs,[10] and various Raman-active modes are used today to quantify a crystal's quality and the thickness of exfoliated few- and single-layer flakes. Recent theoretical work suggests that, just as in TMDC flakes, the

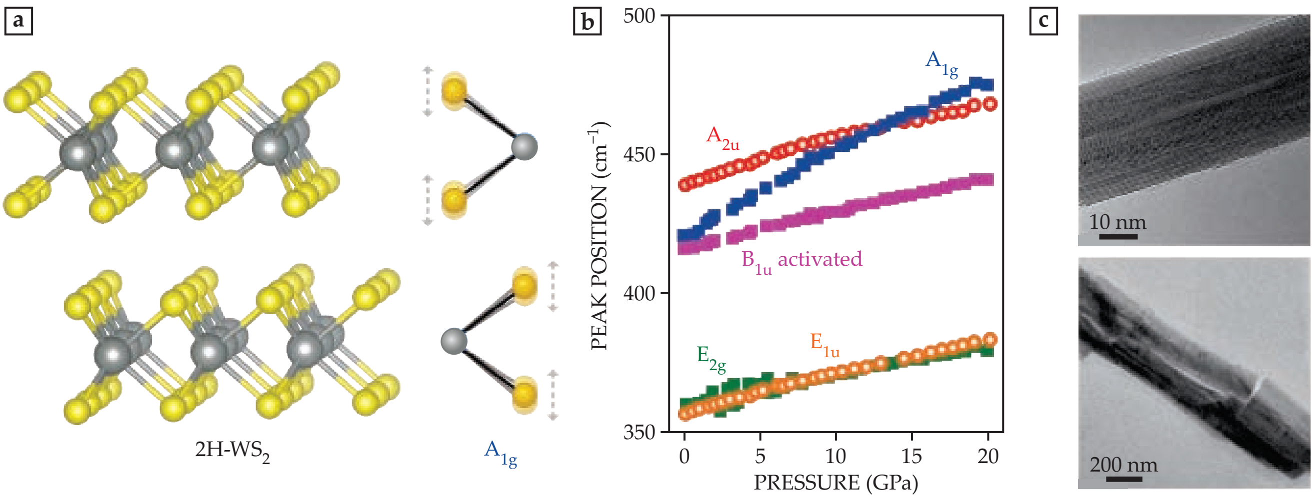



**FIGURE 2. THE VIBRATIONAL PROPERTIES OF MULTIWALL NANOTUBES** change under compression. **(a)** Each layer of tungsten disulfide has a layer of W (gray spheres) sandwiched between two layers of S (yellow). One of the possible Raman modes, $A_{1g}$, is an out-of-plane vibration of the S atoms and a radial motion in the nanotube. **(b)** All of the nanotube's vibrational modes ($A_{1g}$, $A_{2u}$, $B_{1u}$, $E_{2g}$, and $E_{1u}$) increase in frequency (peak position) as the pressure increases. The $A_{1g}$ mode is more sensitive to compression, and it blueshifts at twice the rate of the others. **(c)** A pristine nanotube, shown in the upper transmission electron microscopy image, is damaged (lower image) after compression at 20 GPa. The tube fractures perpendicular to its axis, and the outer layer exfoliates. (Adapted from ref. 7.)

vibrations of $MoS_2$ tubes—that is, their phonons—can be a sensitive probe of crystallinity and morphology.[10] Raman and IR mode frequencies, symmetries, and selection rules may distinguish the tube diameter and chirality, such as zigzag or armchair chiralities.[11]

Phonons can also be in resonance with electronic excitations. Nanotubes have different bound states of electrons and holes, or excitons, and Raman modes with certain symmetries exchange energy with certain excitons. For example, the odd-symmetry $B_{1u}$ mode, which is activated by disorder,[12] resonates with what is known as the A exciton, whereas only the $A_{1g}$ mode resonates with a different exciton known as the B exciton.

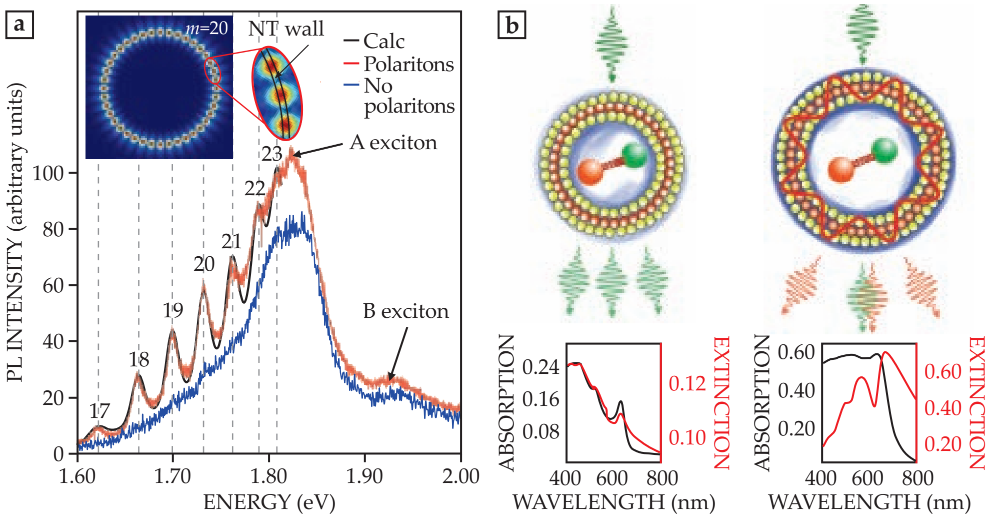



**FIGURE 3. EXCITONS AND POLARITONS DICTATE A NANOTUBE'S OPTICAL PROPERTIES. (a)** Molybdenum disulfide nanotubes host whispering gallery modes, as shown as a simulation in the inset. Those modes have angular momentum characterized by quantum number *m*. The tube's excitons can couple with optical modes to form polaritons, and those polaritons introduce a series of peaks present in the photoluminescence (PL), as shown in experimental results (red) and calculations (black), but absent in a typical PL spectrum (blue). The peaks correspond to different values of *m*. (Adapted from ref. 14.) **(b)** A small (< 60 nm, left) and a large (> 80 nm, right) nanotube respond differently to optical excitation. Narrow tubes display simple excitonic absorption (green wavy arrows) that results in almost matching absorbance (black) and extinction (red) graphs. The polaritons in large-diameter tubes strongly scatter light (red wavy arrows) alongside the weaker excitonic absorption. The resulting extinction and net absorption spectra are quite different from each other. (Courtesy of Sudarson S. Sinha; adapted from ref. 15.)

## Mind the gap

Bulk TMDCs, such as $MoS_2$ and $WS_2$, are indirect gap semiconductors, which means a charge carrier moving from the valence to the conduction band requires phonon assistance. When reduced to a monolayer, $MoS_2$ acquires a direct gap, and thus strong photoluminescence, and a peak in the photoconductivity near 1.84 eV. The peak corresponds to the A exciton, which is the lowest energy exciton in monolayers. The A and higher-energy B excitons are excited at a direct transition from a valence band split into two branches by spin–orbit coupling. The direct-to-indirect gap evolution is evident from the quenching of the photoluminescence for films thicker than a monolayer. The first electronic structure calculations on $MoS_2$ nanotubes predicted bandgap trends, strain and curvature, and other signatures of chirality.[13] Those calculations and subsequent experiments have shown that the exciton energies lie below those of the corresponding bulk material, and the A exciton shifts with tube diameter because of the changing strain. Single wall $MoS_2$ and $WS_2$ nanotubes with zigzag structure exhibit direct gap transitions, whereas tubes with armchair structure have an indirect transition.[13]

But unlike their flake counterparts, multilayer $MoS_2$ tubes emit light.[14] Their emission includes photoluminescence (PL) from both direct and indirect excitons and is induced by various symmetry-breaking effects. In PL measurements on multiwall $MoS_2$ tubes, the A exciton energy is below that of a flake, and its shape and intensity depend on whether the tube has a circular cross section or is somewhat flattened. Additionally, optical whispering gallery modes travel around the rim of a nanotube, as shown in the inset of figure 3a. Excitons couple with those modes to form quasiparticles known as polaritons. Those polaritons lead to a series of peaks on the low-energy side of the A exciton's PL, as shown in figure 3a for experiment and simulations. Each peak corresponds to a polariton formed by an optical mode with a different angular-momentum quantum number, which is indicated over the peak.

The strength of the interaction between the exciton and optical mode is described by a quantity known as Rabi splitting. In the strong coupling limit with Rabi splitting of 400 meV, the exciton splits the polariton mode into upper and lower branches with an energy difference given by the splitting. Complementary work on $WS_2$ tubes demonstrates coupling with Rabi splitting of 270–330 meV,[15] much larger than III–V compounds such as gallium arsenide.

The optical extinction and absorption of $WS_2$ nanotubes with different average diameters show that only some nanotubes host polaritons. A centrifuge tube loaded with pristine powder and run at different speeds produced batches of nanotubes with different average diameter between 30 nm and 150 nm.[16] $WS_2$ nanotubes with diameter smaller than 60 nm cannot confine the light, and as a result, they display purely excitonic absorption and extinction, as shown on the left side of figure 3b. However, nanotubes of diameter 80 nm and larger exhibit strong coupling of the A and B excitons with the optical cavity modes confined in the nanotube. That coupling leads to dips in the extinction spectra at energies very close to the position of the A and B excitons.

Additional evidence for polaritonic behavior comes from transient absorption and extinction spectra.[15] For large-diameter $WS_2$ tubes, two dips in the transmission at 1.88 eV and 2.25 eV appear, which are blueshifted by 40 meV during the first 30 ps.

**The higher efficiency offered by nanotubes' 1D character and nanoscale dimensions could prove useful for photovoltaic and nanophotonics devices, field-effect transistors, and optical resonators with *Q*-factors on the order of several hundred, to name a few.**

For the shortest delay, the energies of the photobleaching dips almost coincide with the first and second polaritonic peaks of the extinction spectrum. For small-diameter nanotubes, the photobleaching dips nearly align with the A and B exciton peaks and reveal a relatively small 10 meV blueshift—more like TMDC flakes, which don't blueshift. Previously, strong coupling effects appeared mostly in hybrid nanomaterials—for example, plasmonic light-scattering from a cadmium selenide quantum dot fused to a gold nanoparticle. The strong coupling in $WS_2$ nanotubes is a manifestation of their quasi-1D character and high refraction coefficient, which can confine the optical cavity modes required for polariton formation.

## Superconductivity

$WS_2$ nanotubes are ordinarily semiconducting, but when highly doped with electrons, they turn metallic and even superconducting. In an ionic-gating device, the nanotube's doping is controlled by the voltage applied to a droplet of potassium perchlorate/polyethylene glycol electrolyte,[17] as shown in figure 4a. The voltage drives potassium to intercalate in the nanotube, where the ions donate electrons until a heavily doped semiconducting nanotube becomes highly metallic. When that nanotube is cooled to cryogenic temperatures, it becomes superconducting, with critical temperature of 5.8 K.

A large-enough magnetic field applied parallel to the tube axis suppresses the superconductivity, and the normal-state resistance is restored. On the way back to the normal state, the resistance shows small oscillations as a function of magnetic field. Figure 4b shows the extracted signals, which are known as Little–Parks oscillations of the supercurrent. The phenomenon is exclusive to cylindrical superconductors, and the oscillation period is related to the effective tube diameter—in the current case estimated at 80 nm, which is consistent with that obtained from atomic force microscopy measurements.

How does the chiral structure of a $WS_2$ nanotube influence transport phenomena? Rightward and leftward currents differ by 1–2% under a magnetic field parallel to the tube's axis. That directional dependence, called nonreciprocity, arises from the interaction of the magnetic field produced by the current and the applied magnetic field. When the current is fed through a chiral object, it consists of three components: parallel to the tube, along the circumference, and chiral. The chiral component produces a magnetic field parallel to the tube. When an external magnetic field is applied parallel to the tube, the magnetic field produced by the current is either parallel or antiparallel to the external magnetic field. The result is nonreciprocity in the resistance.

The nonreciprocal signal is sensitively detected by alternating-current resistance measurements. When a current with frequency $\omega$ is applied to a nanotube, the output voltage alters with frequency $\omega$ and also $2\omega$. The $2\omega$ component $\tilde{V}^{2\omega}$ is a measure of the nonreciprocity, and that response is dramatically enhanced in the superconducting state. The Little–Parks effect appears also in the second harmonic resistance signal. The simultaneous observation of the Little–Parks oscillations and nonreciprocal responses provides additional, unambiguous evidence that superconductivity occurs in the chiral tubes rather than in impurities or residual objects inside the tubes.

An 80 nm $WS_2$ tube, which is much thicker than a single-walled carbon nanotube, isn't expected to have quantized energy levels. And the system's low electrical mobility hinders the observation of chirality effects in the normal state. But once superconductivity sets in, phenomena arising from the intrinsic structure of the chiral tubes become visible because of the high coherence of the current flow. For example, another study found that the critical temperature decreased with decreasing tube diameter.[17]

## Bulk photovoltaic effect

$WS_2$ nanotubes have a structural feature that is absent in carbon nanotubes: polarity, which emerges because two of the mirror symmetries in 2D $WS_2$ are lost when it's rolled up. That polar nature leads to photovoltaic properties without the usual *p-n* or Schottky junctions. In the normal photovoltaic effect, shown schematically in figure 5a, light generates electron–hole pairs, which are driven away from each other by the local electric field at a junction. The resulting electricity is the basis for com-

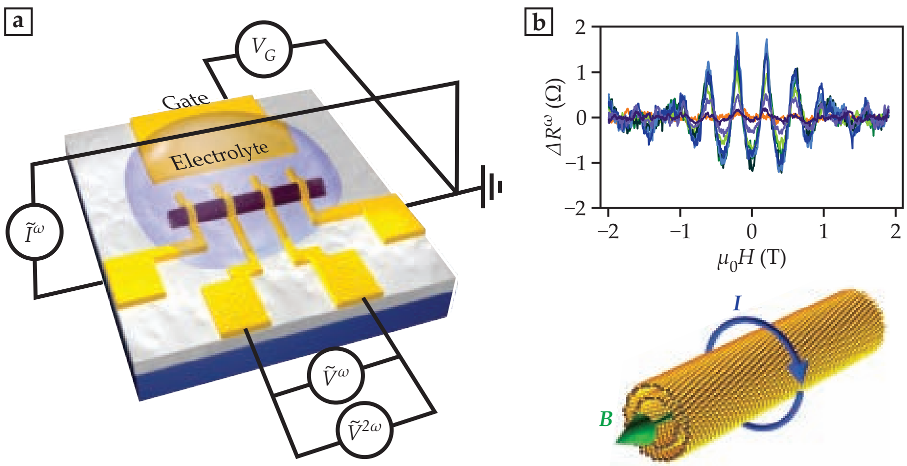



**FIGURE 4. HIGHLY DOPED NANOTUBES BECOME SUPERCONDUCTING. (a)** In a device, a nanotube (purple cylinder) is doped by a voltage $V_G$ applied to an electrolyte droplet. The current $\tilde{I}^\omega$ and the output voltage components with frequency $\omega$ ($\tilde{V}^\omega$) and $2\omega$ ($\tilde{V}^{2\omega}$) are probed by gold contacts (yellow). At high doping and at a temperature below 5.8 K, the nanotube becomes superconducting. **(b)** Under an applied magnetic field *B* with a radial current *I*, a nanotube's differential resistance $\Delta R^\omega$ fluctuates with the auxiliary field *H*. That response, known as Little–Parks oscillations, arises from the tube's cylindrical shape and is related to its diameter. (Adapted from ref. 17.)

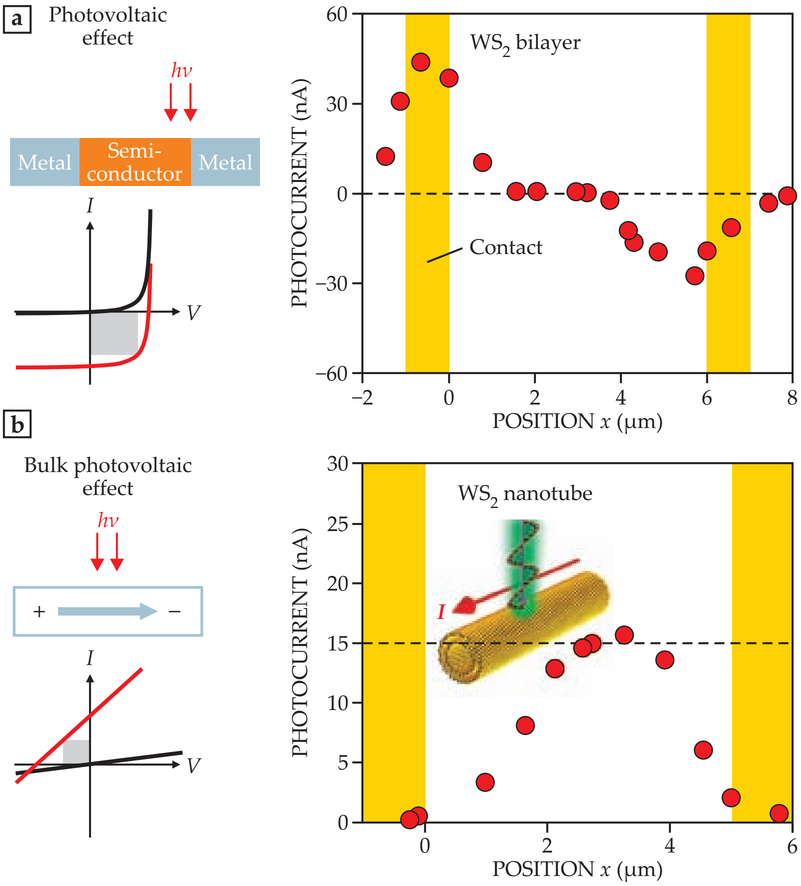



**FIGURE 5. THE PHOTOVOLTAIC EFFECT, CONVENTIONAL AND BULK. (a)** In the photovoltaic effect, light with energy *hν*, in terms of Planck's constant *h* and frequency *ν*, excites a semiconductor with two metal contacts (left). Photoexcited carriers are separated by the electric field at the junction between the metal and semiconductor. The black and red *I*–*V* curves are for a single Schottky junction in the dark and under light, respectively, and the area of the gray box represents the power produced. In a bilayer $WS_2$-based device, the photocurrent becomes nonzero only when the laser spot, at position *x*, is on the gold contacts, as expected for the photovoltaic effect. **(b)** A polar material usually exhibits a nearly linear *I*–*V* curve (black, on left), whereas it shows photocurrent (red) when irradiated by a laser. As a result, a polar $WS_2$ nanotube device, shown on the right, has a photocurrent at zero bias that reaches a maximum when the laser spot illuminates the center of the device away from the contacts. (Adapted from ref. 18.)

mercial solar cells. But materials with broken inversion symmetry can have the photovoltaic effect without a junction. A conventional interpretation of the effect, known as the bulk photovoltaic effect, is that photoexcited electrons and holes are separated by the internal electric field in polar materials, including ferroelectrics. Many experimental observations contradict such a simple view, so a new mechanism, shift current, has been proposed. The bulk photovoltaic effect is also expected in 2D monolayers of the $WS_2$ polymorph that has broken inversion symmetry.

To compare the photovoltaic effect and the bulk photovoltaic effect, bilayer $WS_2$ and $WS_2$ nanotubes are both irradiated by a laser spot, which scans the sample. The $WS_2$ bilayer (see figure 5a) has a photocurrent signal with opposite signs when the laser hits the two gold–$WS_2$ contacts. In contrast, the photocurrent in the $WS_2$ nanotubes peaks when the laser is between the gold contacts, as shown in figure 5b, and that indicates the bulk photovoltaic effect.[18] The photocurrent's dependence on the light intensity supports the recently proposed shift-current mechanism, which is the result of the real-space shift of the photoexcited conduction and valence Bloch electrons by a topological quantity, the Berry phase.

The photocurrent density generated in $WS_2$ nanotubes is several orders of magnitude larger than that of bulk ferroelectric materials. A large photocurrent response that doesn't require an energy-sapping electric field makes nanotubes promising for applications such as IR sensors. The higher efficiency offered by their 1D character and nanoscale dimensions could also prove useful for photovoltaic and nanophotonics devices, field-effect transistors, *p*-*n* junctions, thermoelectric generators, and optical resonators with *Q*-factors on the order of several hundred, to name a few. Furthermore, the strong catalytic activity of bulk $MoS_2$ and $WS_2$ suggests that their nanotube counterparts could work in nanocatalysis and advanced hydrogen storage platforms.

Nanotubes are also a platform for more fundamental exploration of physical properties in 1D without the issue of dangling bonds and defects common in nanowires. Those applications, studies, and more will become practical as new synthesis techniques work to produce $MoS_2$ and $WS_2$ nanotubes in both high quality and substantial amounts, beyond the current maximum rate of 100 g/day.

## REFERENCES

1. R. Tenne et al., *Nature* **360**, 444 (1992); Y. Feldman et al., *Science* **267**, 222 (1995); N. G. Chopra et al., *Science* **269**, 966 (1995).
2. L. S. Panchakarla et al., *J. Phys. Chem. Lett.* **5**, 3724 (2014).
3. I. Kaplan-Ashiri et al., *Proc. Natl. Acad. Sci. USA* **103**, 523 (2006); D.-M. Tang et al., *Nano Lett.* **13**, 1034 (2013).
4. O. Tevet et al., *Proc. Natl. Acad. Sci. USA* **108**, 19901 (2011); I. Lahouij et al., *Tribol. Lett.* **42**, 133 (2011); D. Maharaj, B. Bhushan, *Tribol. Lett.* **49**, 323 (2013).
5. F. Dassenoy, *Tribol. Online* **14**, 237 (2019).
6. O. Goldbart et al., *Proc. Natl. Acad. Sci. USA* **113**, 13624 (2016).
7. K. R. O'Neal et al., *Nano Lett.* **16**, 993 (2016).
8. M. Ghorbani-Asl et al., *Sci. Rep.* **3**, 2961 (2013).
9. O. Grinberg et al., *Phys. Chem. Chem. Phys.* **19**, 18443 (2017).
10. J. L. Verble, T. J. Wietling, P. R. Reed, *Solid State Commun.* **11**, 941 (1972).
11. J.-W. Jiang, B.-S. Wang, T. Rabczuk, *Nanotechnology* **25**, 105706 (2014).
12. M. Staiger et al., *Phys. Rev. B* **86**, 165423 (2012).
13. G. Seifert et al., *Phys. Rev. Lett.* **85**, 146 (2000).
14. D. R. Kazanov et al., *Appl. Phys. Lett.* **113**, 101106 (2018); Y. J. Zhang et al., *2D Mater.* **5**, 035002 (2018).
15. L. Yadgarov et al., *Phys. Chem. Chem. Phys.* **20**, 20812 (2018); S. S. Sinha et al., *Small* **16**, 1904390 (2020).
16. Y. Yomogida et al., *ACS Omega* **3**, 8932 (2018).
17. F. Qin et al., *Nat. Commun.* **8**, 14465 (2017); F. Qin et al., *Nano Lett.* **18**, 6789 (2018).
18. Y. J. Zhang et al., *Nature* **570**, 349 (2019).

PT

ISTOCK.COM/SLOBODAN MILJEVIC

# Experimental expectations versus realities


**Measuring Nothing, Repeatedly**
**Null Experiments in Physics**

**Allan Franklin and Ronald Laymon**
Morgan & Claypool, 2019. $69.95 (paper)

Physicists typically think they know more about experiments than they do. One main culprit is physics textbooks, which often present homework exercises as if they were straightforward descriptions of experiments rather than idealized situations designed to teach calculational techniques. As a result of such oversimplifications, the conceptual and theoretical analysis of experiments—that is, analysis of the evidence that is actually produced and the limitations of the conclusions that scientists can properly draw from that evidence—has not been given anywhere near the attention it deserves.

Fortunately, experts in the theory of experimental procedure and the history of experimentation have been filling that gap. *Measuring Nothing, Repeatedly: Null Experiments in Physics* by Allan Franklin and Ronald Laymon is a splendid example. Franklin is an emeritus high-energy experimentalist who has turned his attention to the theory of experiment, and Laymon is an emeritus philosopher and historian of science. As the title indicates, Franklin and Laymon focus on two issues: why we should be interested in null experiments and why experimentalists sometimes decide that it is worth their while to repeat experiments that have already been done before. As it turns out, the term "null experiment" has two quite different meanings. In one sense, a null experiment compares two systems, or the same system in two configurations, and finds no difference in observable behavior. In another, it finds no statistically significant deviation from the null hypothesis—that is, that a possible causal factor does not exist or has no influence.

Franklin and Laymon start with a discussion of Galileo's famous (and possibly apocryphal) experiment at the Tower of Pisa, in which he dropped from a high floor two bodies of the same substance but different weight. The relevant null result is the two objects hitting the ground at the same time. Galileo reports in *Discourse on Two New Sciences* that "you find, on making the experiment, that the larger anticipates the smaller by two inches." That counts as hitting the ground together within the margin of error, and Galileo certainly takes the result as a refutation of Aristotle's theory that heavier objects fall faster.

From there, Franklin and Laymon provide additional examples of null experiments: Galileo's observations of pendula, Newton's experiments with pendula, the famous Eötvös experiments on the proportionality of inertial and gravitational mass, and the searches for a "fifth force" and for a southern deviation of falling bodies. In each case the experimental protocols, theory, and analysis of data exhibit subtleties and problems, and the scientists made multiple attempts to repeat the experiments. "Repetitions" typically involved changes to the apparatus rather than attempts at pure replication. Only a careful consideration of possible systematic errors explains why the changes in procedure were considered improvements.

The book's second section focuses on the Michelson–Morley experiment, a late-19th-century attempt to detect a substance called ether that was thought to be the medium through which light waves traveled. The experiment has become a favorite anecdote in physics textbooks, but the comparison between those idealized accounts and the actual issues confronting experimentalists is eye-opening. For example, differences in temperature of merely 1/500 of a degree between the arms of the experimental apparatus might produce misleading results, but attempts to shield the arms from such variations might theoretically also interfere with the ether wind that the experiment was meant to measure.

In the first two sections, the experiments discussed are null in the sense that they show no difference between the behaviors of two systems or of the same system in different situations. The last section discusses searches for new particles or novel decays in high-energy experiments at the Large Hadron Collider. Its experiments are of critical importance for physicists investigating the possible limitations or omissions of the standard model. Null results are outcomes that agree with the null hypothesis; they can be accounted for by the standard model and mean that the experiment does not point to novel physics.

Physicists and physics students will likely be familiar with many of those experiments, but not with the detailed history behind them or the technical and conceptual challenges that confronted the experimenters. *Measuring Nothing, Repeatedly* is written as a textbook and would be ideal for a course that offers a broad survey of the challenges and limits of experimentation and data analysis.

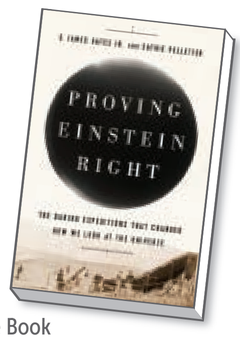
Apart from its potential as a textbook, *Measuring Nothing, Repeatedly* will be valuable to anyone interested in either the history of physics or the general problems of conducting experiments and evaluating their outcomes. There is a wide and variegated gap between idealized visions of scientific experiments that can be easily analyzed and the messy real-world experiments that scientists actually perform. Experimentalists must try to account for random errors, known sources of systematic error, and, most challenging of all, unknown sources of systematic error. Experimental designs that mitigate one sort of problem may amplify another. Even theorists who have neither the inclination nor the expertise to do experimental work can benefit from a finer appreciation of the problems that experimentalists confront and the sources of doubt that must accompany all empirical tests of physical theories.

**Tim Maudlin**
*New York University*
*New York City*



**A GROUP PHOTO OF THE OBSERVERS FOR THE 1918** Lick Observatory eclipse expedition. (Courtesy Special Collections, University Library, University of California, Santa Cruz, Lick Observatory Collection.)

# A social history of eclipse expeditions




**Proving Einstein Right**
**The Daring Expeditions that Changed How We Look at the Universe**
**S. James Gates Jr and Cathie Pelletier**
PublicAffairs/Hachette Book Group, 2019. $30.00

Written by a theoretical physicist and a novelist, *Proving Einstein Right: The Daring Expeditions that Changed How We Look at the Universe* is a wonderful social history of attempts to test the general theory of relativity by photographing stars during eclipses. The best-known efforts were the British expeditions to Africa and South America during the eclipse of 1919, which generated popular acclaim for Albert Einstein and his theory. But several expeditions had tried to obtain such images during previous eclipses; only one, from Lick Observatory in 1918, succeeded, and its results were never published. The book's account of those earlier expeditions is especially valuable because there is no comparable history of those unsuccessful attempts.

In *Proving Einstein Right*, S. James Gates Jr and Cathie Pelletier give extensive details on each venture, including brief biographies of the scientists involved. They also provide accounts of the travels, entertainments, and lodgings of the expeditioners, down to who ate lunch with whom and the origins of the steamship company that carried British astronomers to Brazil in 1919. The authors describe the social conditions in the host countries, including the conditions of workers on rubber plantations in Brazil and the lives of the enslaved workers forced to farm cocoa in Príncipe, the island off the west coast of Africa where Arthur Eddington's 1919 expedition landed. They even digress to a British report of murders by slavers in Angola.

It's a good read. All that's missing is one failed expedition and almost all the science.

Einstein's theories of gravitation, which he developed from 1911 to 1915, predicted a shift in the spectrum of sunlight compared with the absorption spectra from terrestrial sources. That shift, which had not been found by astronomers in the US or in Europe, is described in the book as a "Doppler effect," which it is not. The authors also do not touch on how the failures of the redshift measurements were eventually reconciled with the general theory of relativity.

Einstein's 1911 theory predicted a difference in angle of 0.83 arcseconds between light from a star passing at the limb of the Sun and light from the same star when the Sun was further away, a value essentially the same as the Newtonian prediction. The 1915 theory doubled it. *Proving Einstein Right* treats that change as simply a corrected calculation. It was not; the theory of 1911 and the generally covariant theory of 1915 were quite different. The 1915 theory also implied an explanation of the advance of the perihelion of Mercury—described here as a "wobble"—one of the key pieces of data that Newtonian theory could not account for.

Equally absent is a narrative of the difficulties that astronomers faced in analyzing the data for both the redshift and the light deflection. Estimating the gravitational deflection required clamping together two glass photographic plates, one depicting an eclipse and the other depicting the same field of stars during another season when the Sun was not in the field, and then using a micrometer to measure the distance between the two images of each star. The displacements were assumed to be a linear combination of several factors—for example, the slight misalignments of the clamped plates and the gravitational displacement. The coefficient estimates can be obtained by least squares if there are enough star images.

Unfortunately, the Eddington photographs that showed the best agreement with Einstein's 1915 prediction did not contain enough stars. Eddington had to do some finagling. Meanwhile, in Brazil, one telescope gave a result matching the Newtonian prediction, and the other gave a value more than a standard deviation higher than Einstein's prediction. Readers of *Proving Einstein Right* will not learn about those results, or how they were reconciled with Einstein's theory, or the controversies over the claim by Astronomer Royal Frank Dyson and Eddington that the results of the British expeditions confirmed Einstein's theory.

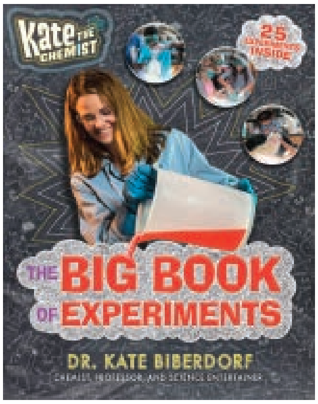
Nor will they find the fascinating reason why the Lick Observatory results from 1918 were never published. Lick director William Wallace Campbell presented the results to the Royal Astronomical Society as a preliminary refutation of Einstein's 1915 prediction; his colleague Heber Curtis made a similar presentation to the Astronomical Society of the Pacific. But Adelaide Hobe, a Carnegie assistant at Lick, remeasured the eclipse images against a new image of the comparison star field and obtained different numbers. Campbell decided the results were too uncertain to publish and that Curtis, who made the original calculations, was incompetent. Somewhat unjustly, Curtis soon was appointed the director of the Allegheny Observatory in Pittsburgh, Pennsylvania, while Hobe remained an assistant at Lick.

Other scientific questions are treated dismissively. Before his general theory was published, Einstein went to Göttingen, Germany, to visit David Hilbert, who was also working on a relativistic field theory of gravitation and gave a public report on it. Hilbert published his theory shortly after Einstein's appeared. Who owed what to whom is a subject of some historical debate, especially since the critical field equation had been cut out of Hilbert's manuscript. But *Proving Einstein Right* dismisses the matter in a couple of sentences.

Despite the dearth of scientific detail, this is a marvelous book that should be read by anyone interested in eclipse expeditions. For the history of the science, however, readers will have to look elsewhere.

**Clark Glymour**
*Carnegie Mellon University*
*Pittsburgh, Pennsylvania*

# NEW BOOKS & MEDIA

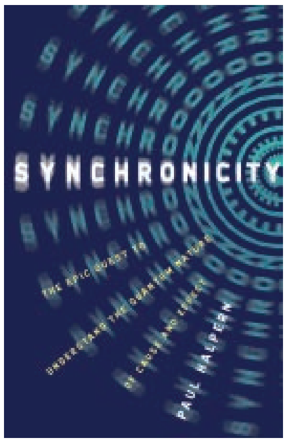



## Kate the Chemist
### The Big Book of Experiments

**Kate Biberdorf**
**Philomel Books/Penguin Random House, 2020. $17.99**

Kate Biberdorf, a chemistry professor at the University of Texas at Austin, combines her chemical know-how and science communication skills in this book of experiments aimed at kids ages 8–12. The step-by-step instructions, with accompanying photos, guide young chemists through making edible snot, a bubble snake, dancing raisins, and the perennial favorite, a soda volcano. Biberdorf also includes explanations of why the experiments work and the chemical and physical principles at play. Parents will appreciate that most experiments don't require exotic ingredients and that every experiment is labeled with a messiness level to help them plan for the cleanup afterwards. —MB

## Synchronicity
### The Epic Quest to Understand the Quantum Nature of Cause and Effect




**Paul Halpern**
**Basic Books, 2020. $30.00**

In *Synchronicity*, physicist Paul Halpern tackles the complex topic of quantum mechanics through a history of physics, from the ancient Greeks to the present day. Using anecdotes and biographical sketches of such scientists as Empedocles, Johannes Kepler, and Isaac Newton, he discusses the development of classical mechanics and goes on to cover key advances in physics, like the concept of causality, the wave and particle natures of light, and Einstein's theory of relativity. Halpern shows that the discovery of quantum theory in the early 20th century brought about a sea change in our understanding of how the world works. The book's title refers to a concept developed by psychologist Carl Jung and adapted by physicist Wolfgang Pauli to describe the meaningful coincidences, or acausality, of quantum phenomena. –CC

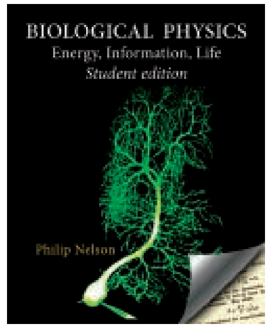

## Smarter Every Day

**Destin Sandlin**
**YouTube, 2007–present**

Want to take the first-ever online tour of the United Launch Alliance rocket factory? Learn about bird flocking behavior? Watch US Marines train to escape a sinking helicopter? *Smarter Every Day* is a series of videos on those and other topics. Series creator Destin Sandlin, who has degrees in both mechanical and aerospace engineering, says his goal is to explore the world using science and share with others what he learns. From the physics of riding a bicycle, to the kinetics of a golf swing, to the optics of laser tattoo removal, Sandlin focuses on the science of everyday things and explains them for a lay audience. –CC

## Biological Physics Student Edition
### Energy, Information, Life

**Philip Nelson**
**Chiliagon Science, 2020.**
**$27.00 (paper)**




Biophysicist Philip Nelson has updated figures, references, and some of the text to create this affordable edition of his 2004 textbook *Biological Physics*. The book is aimed at students in physics and the life sciences and requires prior knowledge of calculus. Nelson's clear explanations and attractive, instructive figures help guide readers through some potentially tricky material. Students and instructors who prefer ebooks can purchase it for $9.99 on Amazon Kindle. —MB

## NASA TV

**YouTube, 2008–present**

Available for free on YouTube, NASA TV provides a variety of educational and public relations programming and live streaming of such events as the 30 May launch of two NASA astronauts on SpaceX's *Crew Dragon* destined for the International Space Station. In addition to the main channel, there are individual channels for NASA research centers, including Ames, Goddard, and the Jet Propulsion Laboratory. Via #AskNASA, viewers can send agency experts questions about anything having to do with space exploration, science, and aeronautics. –CC PT

# Focus on lasers, imaging, nanoscience, and nanotechnology

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.

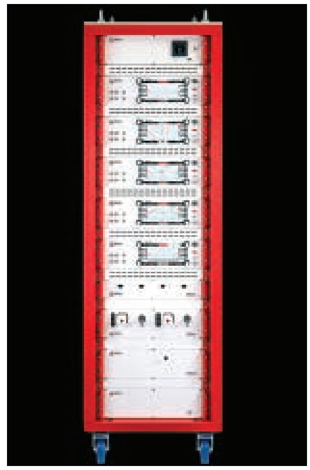
**Andreas Mandelis**

## Pulsed and CW laser diode drivers

Lumina Power has introduced the second generation of its precision pulsed laser diode drivers. The two models of the LDP series provide the option of either 1000 W or 2000 W average output. Both incorporate new technology that increases reliability and enhances pulsed performance while reducing circuit complexity and system size. Pulse widths of 50 μs through CW operation and 10 μs rise/fall time can now be achieved at repetition rates to 5 kHz, with higher rates optional. The LDP drivers feature output currents to 400 A, output power to 80 kW peak, and compliance voltages to 200 V with universal input voltage and an auxiliary ±15 V output. ***Lumina Power Inc***, *26 Ward Hill Ave, Bradford, MA 01835, https://luminapower.com*

## Versatile benchtop electron microscope

The LVEM 5 low-voltage electron microscope from DeLong Instruments combines four imaging functionalities into one benchtop apparatus suitable for use in life and materials sciences. With the click of a button, users can switch among modes to image the same sample region of interest. The LVEM 5 microscopes can be equipped with a CCD or scientific CMOS camera for transmission electron microscope (TEM) imaging of nanoparticles and thin sections. According to the company, the LVEM 5 is the only available benchtop TEM. Users can add a scanning detector to the TEM to obtain transmission images from denser materials. A backscatter electron detector offers a stereoscopic view of the sample; the scanning electron microscopy mode can be used to view the same area for topographical information. The electron diffraction mode provides structural characterization of crystalline materials. With its 5 kV electron source, the LVEM 5 can provide high contrast of organic and other soft materials without the need for heavy-metal staining. ***Delong America***, *4020 Rue St-Ambroise, Ste 473, Montreal, QC H4C 2C7, Canada, www.lv-em.com*



## Laser rack systems

Laser modules suitable for quantum technologies are now available from Toptica in a footprint appropriate for industrial rack integration. The novel product family includes narrow-linewidth tunable diode lasers, amplified and frequency-converted diode lasers, frequency combs, and related accessories. The T-Rack—Toptica's rugged 19-inch cabinet with a modular power-entry unit, professional cable, and heat management system—can house multiple modules. The laser modules consist of a laser head with fiber-coupled optical output from 330 nm to 1625 nm. They are equipped with the company's DLC pro digital laser controller. They can be remotely controlled and, according to Toptica, offer convenient, reliable operation and high performance that previously was only possible in research-grade laboratories on optical tables. Applications include quantum computing and simulation; quantum metrology and optical clocks; and quantum sensing, optics research, and communications. ***Toptica Photonics Inc***, *5847 County Rd 41, Farmington, NY 14425, www.toptica.com*

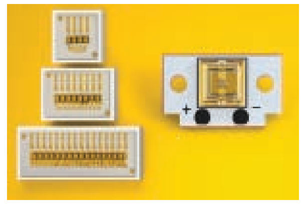
## Deeply penetrating optical coherence tomography

At 1310 nm, Lumedica's OQ StrataScope penetrates about twice as deep as the company's 840 nm optical coherence tomography imager, the OQ LabScope. With a depth resolution of 14 μm in air and 10 μm in tissue, the OQ StrataScope also produces more imaging data from industrial samples, such as silicon, and from tissue, such as skin, bone, and teeth. It can be used to precisely examine, monitor, and measure tissue structures and to gauge product integrity. The flexible instrument features horizontal, vertical, radial, and circle scan options. Size can be set for all scan types. Volume images (C-scans) range from 64 × 64 voxels to 512 × 512 voxels. The mechanical scan ranges are 7 mm linear and 5 × 5 mm volume. The compact OQ StrataScope is quick to set up, simple to operate, and easy to connect to user networks via built-in Wi-Fi. ***Lumedica***, *701 W Main St, Ste 200, Durham, NC 27701, www.lumedicasystems.com*

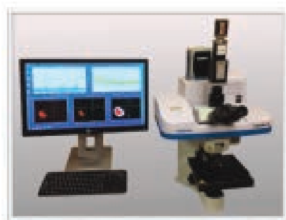

## Laser source for photoacoustics

EKSPLA now offers a high-energy laser source that features a large sample imaging depth and resolution for photoacoustic imaging applications. The PhotoSonus+ consists of a high-energy Q-switched laser, parametric oscillator, power supply, and cooling unit, all integrated in a single robust cart-type housing. It delivers up to 250 mJ of pulse energy at a 10 Hz repetition rate. With the fast switching option, consecutive laser pulses can be generated at different wavelengths within the entire signal or idler range, at any step, and in any order. That feature, which combines a high pulse energy of up to 250 mJ and a wide wavelength tuning range of 660–2300 nm, makes the PhotoSonus+ a suitable imaging source for photoacoustic systems. For user convenience, the output of the PhotoSonus+ laser can be outfitted with various types of customized fiber bundles. ***EKSPLA**, Savanoriu Ave 237, LT-02300 Vilnius, Lithuania, https://ekspla.com*

## Lasers with short rise times



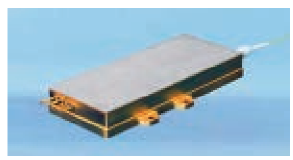
Laser Components has enlarged its vertical-cavity surface-emitting laser (VCSEL) product line to include emitters with 850 nm and 940 nm in power classes between 200 mW and 50 W. In VCSELs, light is emitted perpendicular to the chip's surface and can therefore be easily collimated. The compact multimode lasers' high power and short pulse sequences ensure extended range and higher resolution and make them suitable for lidar applications, among others. The products are characterized by extremely short rise times and thus support pulse trains in the low nanosecond range and below. The semiconductor structure enables the emission wavelength to remain nearly constant, even with temperature fluctuations. That allows narrow bandpass filters to be used on the detector side. The laser diodes are also available as powerful arrays. ***Laser Components USA Inc**, 116 S River Rd, Bldg C, Bedford, NH 03110, www.lasercomponents.com*



## Raman nanoparticle analysis

Horiba Scientific has announced products that combine its Raman microscopes with CytoViva's hyperspectral imaging microscopy module and enhanced dark-field (EDF) illumination. They are designed to make Raman analysis faster and more powerful and may advance applications related to nanomaterials research, drug delivery, nanotoxicology studies, and surface-enhanced Raman spectroscopy nanoparticle characterization. Hyperspectral microscopy allows rapid imaging with high sensitivity across the sample. The patented CytoViva EDF illumination improves the signal-to-noise ratio up to 10 times over standard dark-field microscopes and permits visualization of nanoparticles as small as 10 nm when isolated. Users can rapidly view the sample, target regions of interest, and leverage Raman measurements from the identical field of view to provide and confirm the chemical identification of nanoparticles and other sample elements. ***Horiba Scientific Division of Horiba Instruments Inc**, 20 Knightsbridge Rd, Piscataway, NJ 08854, www.horiba.com/scientific*

## Wavelength-stabilized diode laser



PhotonTec Berlin has added a high-power diode to its wavelength-stabilized product family. The new pumping source for fiber lasers and amplifiers emits up to 200 W through a 200 μm core with a fiber of numerical aperture 0.22 at 976 nm and of length 1 m or 2 m. The laser uses a volume grating to stabilize the emission wavelength at 976 nm, making it insensitive to current and to the operating temperature, up to a maximum of 45 °C. The new diode features a narrow linewidth of 1030–1100 nm and feedback protection for the fiber laser. It comes in a compact package with a thermistor and photodiode. ***PhotonTec Berlin GmbH**, Max-Planck-Strasse 3, D-12489 Berlin, Germany, www.photontec-berlin.com*

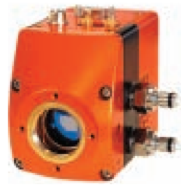
## Fast, ultrasensitive, back-illuminated camera

Andor, an Oxford Instruments company, has expanded its Marana scientific CMOS (sCMOS) physical sciences camera platform. According to the company, the Marana 4.2B-6's low read noise and innovative UltraVac vacuum cooling make it the most sensitive back-illuminated sCMOS platform available. It features 95% quantum efficiency and vacuum cooling down to −45 °C. Because the Marana 4.2B-6 delivers up to 74 fps, it is suitable for dynamic imaging and such spectroscopic applications as wavefront sensing, quantum gas dynamics, and lucky, speckle, and hyperspectral imaging. It has a 4.2 MP array format with 6.5 μm pixels. The smaller pixel is well suited for matching the resolution of many laboratory optical imaging configurations and for high-resolution echelle spectroscopy. ***Andor Technology Ltd**, 7 Millennium Way, Springvale Business Park, Belfast BT12 7AL, UK, https://andor.oxinst.com*

## High-pulse-energy femtosecond amplifier

The Astrella HE one-box femtosecond amplifier from Coherent delivers up to 9 mJ at a repetition rate of 1 kHz. According to the company, that is the highest pulse energy commercially available from a water-cooled, single-stage, kilohertz regenerative amplifier. The compact Astrella HE delivers beam quality of $M^2 \leq 1.25$ and comes with 35 fs or 100 fs pulse widths. It can be used to pump several tunable optical parametric amplifiers to run multiple experiments simultaneously or single experiments that need numerous independently tunable wavelengths. The company claims the Astrella HE can lower the entry barrier to applications—for example, extreme-UV generation approaching the water window or laser plasma acceleration—that to date have been enabled only by complex, costly, multibox ultrafast amplifiers. ***Coherent Inc***, *5100 Patrick Henry Dr, Santa Clara, CA 95054, www.coherent.com*

## Short-wave-IR camera



Raptor Photonics has released the next generation of its Ninox 640 camera, which can image the wavelengths between visible and short-wave IR (SWIR). With an ultralow typical readout root-mean-square (rms) noise of 18 $e^-$ and a typical dark current reading of < 750 $e^-$ at −15 °C, the Ninox 640 II improves on its predecessor's noise performance. It has a superior mechanical design and is significantly more compact than the Ninox 640; according to the company, the Ninox 640 II is one of the smallest and lightest SWIR cameras available. The cooled digital camera uses a 640 pixel × 512 pixel indium gallium arsenide sensor to perform high-sensitivity imaging from 0.4 µm to 1.7 µm. The 15 µm × 15 µm pixel pitch delivers high resolution, and the low readout rms noise enables the highest SWIR detection limit. Available with a 14-bit Camera Link output, the Ninox 640 II will run up to 120 Hz, which enables high-speed digital video with intelligent automated gain control. ***Raptor Photonics Ltd***, *Willowbank Business Park, Larne, Co Antrim BT40 2SF, Northern Ireland, www.raptorphotonics.com*

## Extreme-UV photodetector

Opto Diode Corp, an Illinois Tool Works company, has unveiled its SXUV5 extreme-UV (EUV) photodiode with a circular active area of 2.5 mm diameter. It has high responsivity in the 1–190 nm wavelength region and is designed to remain stable for long periods of time when exposed to high-intensity EUV energy. The SXUV5 is housed in a windowless, TO-5 package to allow for responsivity at wavelengths shorter than 150 nm. It features a minimum shunt resistance of 20 MΩ and a reverse breakdown voltage of 5–20 V. Capacitance is 500–1500 pF, and response time is 1–2 ns. Storage and operating temperatures range from −10 °C to 40 °C in ambient environments and from −20 °C to 80 °C in nitrogen or vacuum environments. The lead soldering temperature is 260 °C. ***Opto Diode Corporation***, *1260 Calle Suerte, Camarillo, CA 93012, www.optodiode.com*

## Scientific CMOS camera for astronomy

IDEX Health & Science has launched its Finger Lakes Instrumentation (FLI) Kepler KL6060 scientific CMOS (sCMOS) camera for space debris detection and space situational awareness applications. The large-format 37.7-MP cooled camera can capture images at up to 19 fps using the optional quad small-form-factor pluggable fiber interface. The KL6060 camera is available with a high-quantum-efficiency back-illuminated sensor or with an economical front-illuminated sensor. It delivers a high-dynamic-range 16-bit image using FLI's proprietary algorithms, which ensure the end product is highly linear. The new sCMOS camera is suitable for imaging wide fields of view at high frame rates. ***IDEX Health & Science LLC***, *619 Oak St, Oak Harbor, WA 98277, www.idex-hs.com* PT

# OBITUARIES

## John Theodore Houghton

Atmospheric physicist John Theodore Houghton died of complications of COVID-19 on 15 April 2020 following a long illness. He was born on 20 December 1931 in Dyserth in North Wales, not too far from his final retirement home in Tywyn, a village by the sea on the edge of the Snowdonia National Park.

Something of a child prodigy, at age 16 John won a scholarship to study physics at Oxford University and went on to be first in his class of 1951. His lecturers included luminaries such as Sydney Chapman and Gordon Dobson; they inspired him to stay on to study for a doctorate with Alan Brewer, who led a small meteorology group in Oxford's Clarendon Laboratory. There John learned to make delicate IR radiometric measurements in the atmosphere the hard way—on a noisy and uncomfortable Mosquito aircraft left over from World War II.

After some years at the Royal Aircraft Establishment at Farnborough, where he continued his aircraft measurements in lieu of active military service, John returned to Oxford in 1962 to take over the meteorology group when Brewer moved to Toronto. He and Des Smith discussed how superior radiation measurements could be made from the new generation of Earth satellites coming on line. They devised a selective chopper radiometer, which used cells containing carbon dioxide to filter the upwelling flux from the atmosphere and measure its intensity, and they flew a version of it on a high-altitude balloon into the stratosphere.

Lewis Kaplan took a year's leave from NASA's Jet Propulsion Laboratory (JPL) to work with John's group in Oxford. Together, he and John showed that the radiation measurements could be inverted to obtain meteorologically useful vertical temperature profiles. John and Smith then boldly proposed to NASA that it fly their British instrument on one of the US experimental weather satellites and thus extend the capability to the global atmosphere. *Nimbus 4*, with the instrument on board, launched in April 1970; subsequent *Nimbus* satellites carried improved versions. The instrument on *Nimbus 7*, which launched in 1978, added composition measurements, including water vapor and nitrogen oxides, to the temperature profiles.

In developing the space instruments, John had worked with two big government science laboratories, named after Edward Appleton and Ernest Rutherford. Taking leave from the university in 1969 to become director of Appleton, John was instrumental in merging the two labs into the Rutherford Appleton Laboratory, which is today the UK's lead center for space technology.

Having honed his skills as a manager and motivator, John could not resist an invitation to become director general of the UK Meteorological Office when the position became available in 1983. "I must be mad," he told me after I returned from a 10-year stint at JPL and prepared to take over his Oxford department. Being leader of the Met Office was not an altogether smooth ride for John. The nadir came in October 1986, when a violent storm hit southern England and caused massive damage and loss of life, with no timely warning from the Met Office. Parliament members called for John's resignation. The crisis blew over, however, and John went on not only to be an outstanding leader of the office, for which he earned a knighthood, but also to extend its purview in 1990 into longer-term forecasting by establishing the Hadley Centre for Climate Prediction and Research.

The Hadley Centre has become a cornerstone of the work of the Intergovernmental Panel on Climate Change (IPCC). Despite its modest name, it is far more than a panel, with thousands of scientists and others involved in writing, under the auspices of the United Nations, regular reports that assess and warn world governments about the probability and likely impact of climate change. The IPCC was created in 1988, with John as a leading light; he chaired the scientific assessment body and was lead author for several key publications. The job was no sinecure; the agreement of more than 100 diverse national groups had to be secured in the face of powerful opposition from lobby groups. John hated going to the meetings and sometimes came back shattered, but he persevered, driven by his strong religious faith and his conviction that he had a duty to apply his knowledge of climate physics to help the world avert what he saw as potential doom. With corecipient Al Gore, John and several other scientists accepted the 2007 Nobel Peace Prize on behalf of the IPCC.

FRED TAYLOR

John Theodore Houghton

**Fredric W. Taylor**
*Clarendon Laboratory*
*Oxford, UK*

**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.**

### RECENTLY POSTED NOTICES AT www.physicstoday.org/obituaries

Alexey Soluyanov
20 October 1983 – 26 October 2019

Thomas Trueman
24 September 1935 – 30 August 2019

Arthur Joseph Epstein
2 June 1945 – 25 August 2019

Nikolai Kardashev
25 April 1932 – 3 August 2019

Keith Marlow
14 November 1928 – 1 July 2019

Marcus T. McEllistrem
19 April 1926 – 14 June 2019

Robert H. Silsbee
24 February 1929 – 23 May 2019

Edward James Ludwig
13 April 1937 – 7 September 2018

# INDEX TO ADVERTISERS


| COMPANY | PAGE NO. |
|---|---|
| AIP Publishing | 41 |
| Bartington Instruments Ltd | 55 |
| Cobolt AB | 24 |
| COMSOL Inc | C3 |
| Cremat | 55 |
| Janis Research LLC | 51 |
| Mad City Labs Inc | 12 |
| Mathworks Inc | 1 |
| Nanomagnetics Instruments | 2 |
| National Reconnaissance Office | 9 |
| Nor-Cal Products | C4 |
| Oxford Instruments | 7 |
| Pearl Companies | C2 |
| Purdue University | 13 |
| Stanford Research Systems | 3, 15, 17, 19 |
| The National Academies of Sciences, Engineering & Medicine | 12 |
| Zurich Instruments AG | 4 |



## ADVERTISING SALES MANAGEMENT

**American Institute of Physics**
One Physics Ellipse
College Park, MD 20740
+1 301.209.3393
www.physicstoday.org/advertising

**Sales and Marketing Manager**
Christina Unger Ramos • cunger@aip.org

**Recruitment Advertising**
ptjobs@aip.org

**Ad Traffic Coordinator**
Unique Carter • ucarter@aip.org

## ADVERTISING SALES CONSULTANTS

**USA and CANADA**

**AL, AK, AZ, AR, CO, HI, ID, IL, IN, IA, KS, KY, LA, MI, MN, MS, MO, MT, NE, NV, NM, ND, OH, OK, SD, TN, UT, WV, WI, WY**
CEL Associates II
Merrie Lynch
+1 617.594.4943
merrie.lynch@celassociates2.com

**CA, CT, DE, FL, GA, ME, MD, MA, NH, NJ, NY, NC, OR, PA, RI, SC, VT, VA, WA, and Canada**
CEL Associates II
Jody Estabrook
p: +1 774.283.4528
m: +1 978.835.2013
jodyestabrook@comcast.net

**INTERNATIONAL**

**Northern and Western Europe**
John Gold
+44 208.641.7717
johnfgold@gmail.com

**Central and Eastern Europe**
Leo Ploner
+49 172.8231.062
leo@ploner.de

**Asia/Pacific**
Jake Wilson
+61(0)413 949 644
jwilson@imraust.com.au

PHYSICS TODAY

www.physicstoday.org/advertising

**Lee Miller** is a senior scientist at Atmospheric and Environmental Research in Lexington, Massachusetts.

# The warmth of wind power

**Lee Miller**

As wind turbines harvest energy, they redistribute heat in the lower atmosphere. Farmers have been exploiting the effect for decades.

This past year, the US generated 300 billion kilowatt-hours from wind turbines. That's 7.3% of the country's electricity demand, more power than is produced by any other renewable technology, including hydroelectricity. Although the turbines don't pollute the air with greenhouse gases, many recent studies conclude that they nonetheless warm the lower atmosphere near the ground—albeit temporarily and at night.

Wind turbines now reach heights of 300 m, with each blade 50 m in length—half a football field. The US has about 60 000 turbines and that number will increase as they are deployed in clusters up to thousands per county to reach future power targets. As they harvest kinetic energy, those turbines reduce wind speeds and introduce wake turbulence, which in turn alters the exchange of heat, moisture, and momentum between Earth's surface and the lower atmosphere. Curiously, the effects don't appear limited to the turbines' immediate vicinity; they are detectable tens of kilometers downwind. Understanding wind turbines' effects on the environment is important as they become increasingly common fixtures in our landscape.

## Power from the wind

Differences in solar heating between Earth's equator and its poles give rise to pressure gradients that produce the planet's wind currents. Friction with the surface slows them. Those balancing effects help maintain our climate. The influence of friction is particularly strong in the lowest 1–3 km, where about half of all turbulent atmospheric dissipation occurs. Wind turbines are therefore contained in a column of air that naturally dissipates atmospheric power at an average rate of about 1 W/m$^2$.

Let's put that average input power in context. In 2018 the US electricity consumption rate was about 0.07 W/m$^2$. Wind power could meet a substantial fraction of that rate, but doing so would require covering a significant portion of the nation's land surface with turbines. Operational US wind farms currently occupy less than 1% of the country's land area and generate electricity at rates between 0.5 and 1.5 W/m$^2$. (The rate has a wide spread because of several factors, including the farms' sizes, turbine density, and how windy different areas are.) Still, the comparability of the dissipation and generation rates is striking and evidence of the farms' efficiency at extracting energy from the wind.

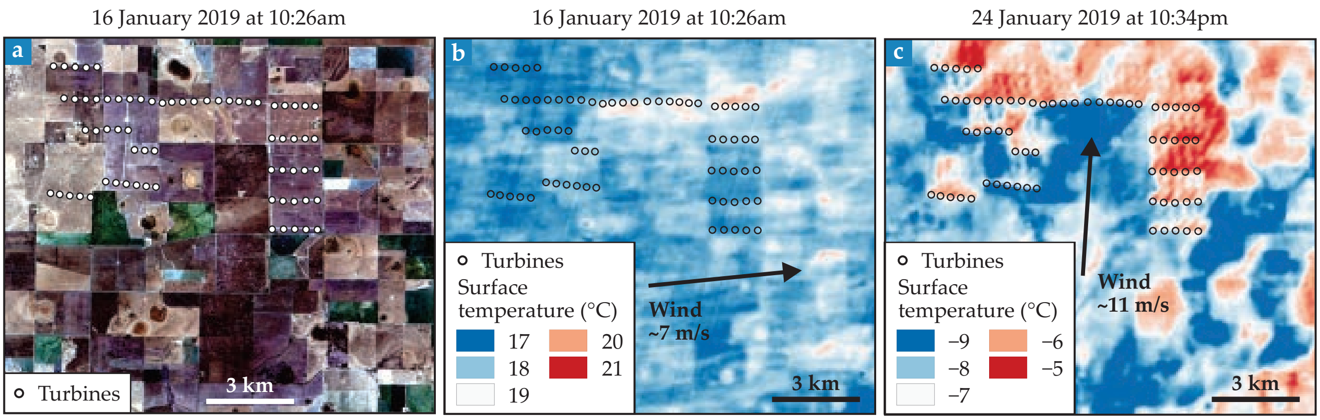
## Redistributing heat

Wind turbines alter the climate through atmospheric mixing—by redistributing heat in the lower atmosphere, which is completely unrelated to the mechanisms of climate change. The natural differences in atmospheric mixing between day and night strongly influence the turbines' effect on the downwind climate. During the day, solar radiation heats the ground surface, which drives convection from the ground. The process homogenizes wind speeds, air temperature, and humidity to heights of 1–3 km, well above the physical extent of the turbines. The upshot is that wind turbines operating during the day are enveloped in an already well-mixed column of air and have little effect on the surface temperature.

At night, in the absence of solar-driven convection, the atmosphere is typically not well mixed above 50–150 m. That thin layer of calm air buffers the atmosphere from surface friction and allows vertical gradients in wind speed, temperature, and humidity to develop. Those nighttime conditions are well known in meteorology. As wind power is roughly proportional to the cube of the wind speed, there are clear advantages to utilizing longer blades, taller towers, and elevated topography to reach the faster winds aloft. Engineered to extract kinetic energy rather than redirect the winds around them—like the canopy of a tree—the slowing of the wind steepens the vertical wind-speed gradient, dramatically increasing the vertical mixing rates of higher-altitude air with air near the surface. Other factors, such as the turbines' orientation in rows and the wind farm's area, can influence the extent and magnitude of the changes. When that typically warmer, drier air from aloft is carried downward and mixed in with the surface air, surface temperatures increase.

More substantial climatic effects are therefore expected at night than during the day, even from the same turbines at the same location with the same incoming wind speeds. Day–night differences have been discussed in nearly a dozen studies using surface- or space-based observations over Texas, Iowa, Illinois, and California. Directly attributed to turbine–atmosphere interactions, the effects include differences in temperature, turbulence, and evaporation rates. Also measured abroad, the effects included slower wind speeds and increased turbulence extending 50–75 km downwind of Germany's offshore wind plants.

The recent release of several free public data sets now makes assessing wind power's surface warming relatively straightfor-




**NASA'S *LANDSAT 8* SATELLITE** measured the surface warming effect from wind power over a northern Texas location (34.77° N, −102.05° E) in the winter of 2019. **(a)** The daytime image (16 January, 10:26am) shows how the 100 $km^2$ region would appear from above to the human eye. **(b)** A coincident surface-temperature map is shown of the area at the same time. **(c)** One week later (24 January, 10:34pm), the satellite measured night surface temperatures in the region. (Data from Lee Miller.)

ward. The US Geological Survey maintains the US Wind Turbine Database, which includes geospatial data and technical specifications on about 60 000 operational US wind turbines. Data from NASA's *Landsat 8* satellite is also free and publicly available. Although primarily used for monitoring vegetation, *Landsat 8* also measures ground surface temperatures—or, more specifically, emissivity in the IR—at a spatial resolution of 8100 square meters.

## Imaging local heat

Over the past seven years, *Landsat 8* has acquired 306 daytime images and 32 nighttime images over northern Texas. After filtering the data of cloudy conditions when the surface is invisible to the satellite, I examined images taken during the winter of 2019. The two 16 January 2019 daytime images, shown in the figure's panels a and b, are typical: No warming effect is visible in that day's temperature map (panel b). A nighttime warming effect, however, is apparent in panel c. That image was captured at 10:34pm on 24 January—the earliest nighttime snapshot of the region since 16 January.

With below-freezing temperatures and northward winds moving at 11 m/s at the height of the turbines, the 2–4 °C warming extended several kilometers downwind of the turbines and became more spatially extensive with successive downwind rows. That downward entraining of warmer air does not likely occur every night downwind of every turbine, though. (Indeed, no warming effect was evident in the nighttime image on 9 January 2019, a week earlier.)

The precise conditions required to create the warming effect are unclear, so I am uncertain how routine or widespread they are in Texas or elsewhere, especially given the limited availability of nighttime *Landsat 8* observations. The effect is also likely dependent on near-surface turbulence and wind speed. Nonetheless, other observational studies using coarser (1 × 1 $km^2$) resolution satellite data over a different Texas wind farm estimated an annual nighttime warming effect of 0.3 °C. A modeling study estimated that effect closer to 0.6 °C, on average.

Although the link between wind power and warmer surface temperatures may come as a surprise, avocado, citrus, and apple farmers have operated airplane-like propellers on towers since the 1940s to minimize frost damage to their crops. A validation study in 1970 concluded that a "wind machine" warmed surface temperatures during spring nights by about 2 °C over an area of 20 acres. Other climatic effects, such as changes in evaporation and heat fluxes, may also occur downwind, but they are difficult to measure with satellite sensors.

All renewable technologies affect the climate insofar as they redistribute heat, momentum, and moisture to generate electricity. The warming effects of wind power should not be cause for immediate alarm. They will continue to occur—predominantly inside the wind-farm area—only for as long as the demand for turbine-based electricity exists. And scientific research on the topic is still in its infancy.

Wind power's relevance to climate goes beyond surface warming. The turbines also likely affect precipitation, as warm, dry air from above displaces cooler, more moist air at the surface and increases the rate of evaporation. But that issue is beyond the scope of this Quick Study. Few would question that 20 years from now, wind turbines will be much more pervasive than they now are in the central US—their number is currently growing by about 3000 each year. The opportunity for researchers is to understand the turbines' admittedly intermittent effects today to inform our land-use policies and environmental expectations in a wind-powered future.

## Additional resources

▶ E. M. Bates, "Temperature inversion and freeze protection by wind machine," *Agric. Meteorol.* **9**, 335 (1971/1972).

▶ L. M. Miller, D. W. Keith, "Climatic impacts of wind power," *Joule* **2**, 2618 (2018).

▶ L. M. Miller, D. W. Keith, "Observation-based solar and wind power capacity factors and power densities," *Env. Res. Lett.* **13**, 104008 (2018).

▶ A. Platis et al., "First *in situ* evidence of wakes in the far field behind offshore wind farms," *Sci. Rep.* **8**, 2163 (2018).

▶ S. B. Roy, J. Traiteur, "Impacts of wind farms on surface air temperatures," *Proc. Natl. Acad. Sci. USA* **107**, 17899 (2010).

▶ L. Zhou et al., "Impacts of wind farms on land surface temperature," *Nat. Climate Change* **2**, 539 (2012). PT

# Restraining respiratory droplets

Wearing face masks to reduce the spread of COVID-19 has become a part of many people's daily routine. But not all coverings are created equal. To better visualize a mask's effectiveness, Siddhartha Verma, Manhar Dhanak, and John Frankenfield from Florida Atlantic University in Boca Raton positioned a masked mannequin in front of a camera and pumped bursts of a vaporized liquid mixture through its mouth from a fog machine. They directed a beam from a green laser pointer through a glass rod to create a plane vertical sheet to more easily picture the droplets.

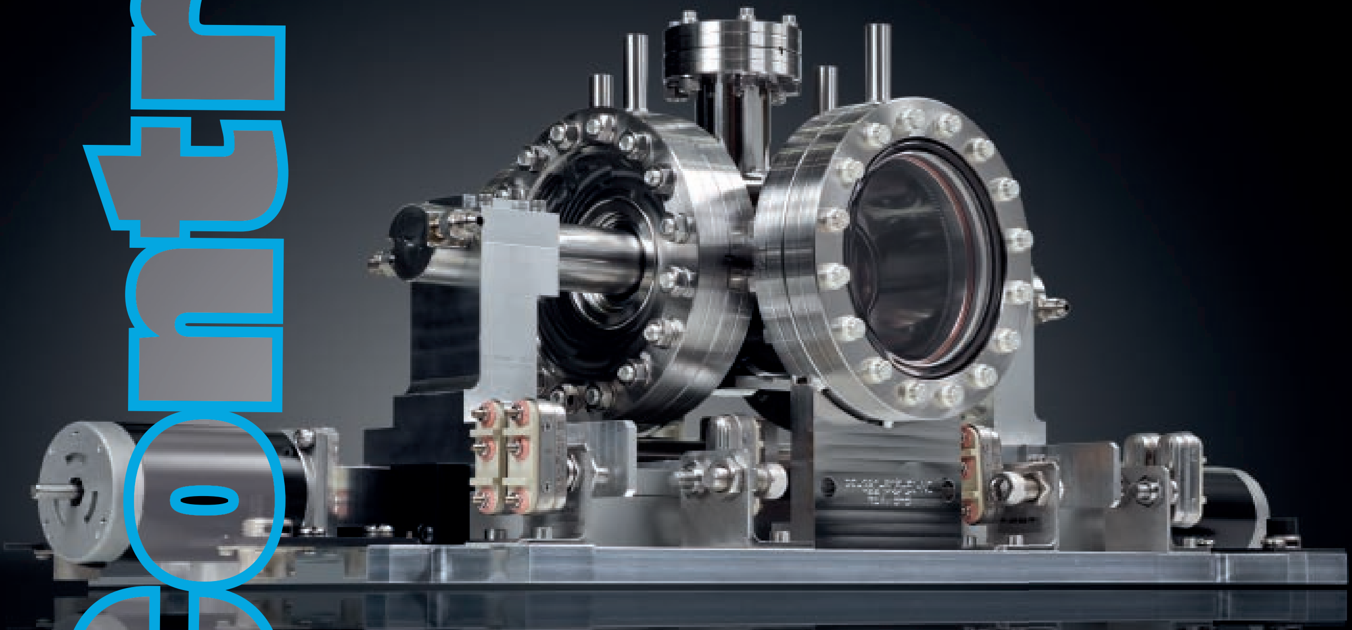
This image shows a mannequin head wearing a stitched mask made of two layers of cotton quilting fabric. The droplets from the simulated cough travel an average distance of 2.5 inches. With a mask made from a single-layer bandana of elastic T-shirt material, droplets travel about 3.5 feet away. More worrisome is the result from the uncovered mouth. In that case, the respiratory droplets travel 2 feet farther on average than the minimum recommended social-distancing guideline of 6 feet. (S. Verma, M. Dhanak, J. Frankenfield, *Phys. Fluids* **32**, 061708, 2020; picture courtesy of Siddhartha Verma.)

—AL

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

## N-Control

## *Improve UHV system integrity with our highly configured vacuum solutions*



Adjustable-gap collimators eliminate undesirable electrons, thus avoiding excessive radiation due to beam loss in sensitive areas, and reducing activation of accelerator components.

Allow Nor-Cal Products' vacuum engineers the opportunity to apply their expertise in the design and manufacturing of your next beamline project. *Let's talk.*

**Nor-Cal Products**

**NC**

**by PFEIFFER VACUUM**

- Full service engineering
- Precision manufacturing
- Global sales and technical support
- Over 6000 standard components

**www.n-c.com | 800.824.4166 | ncsales@n-c.com**

International Organization of Standardization ISO 9001:2015 Registered