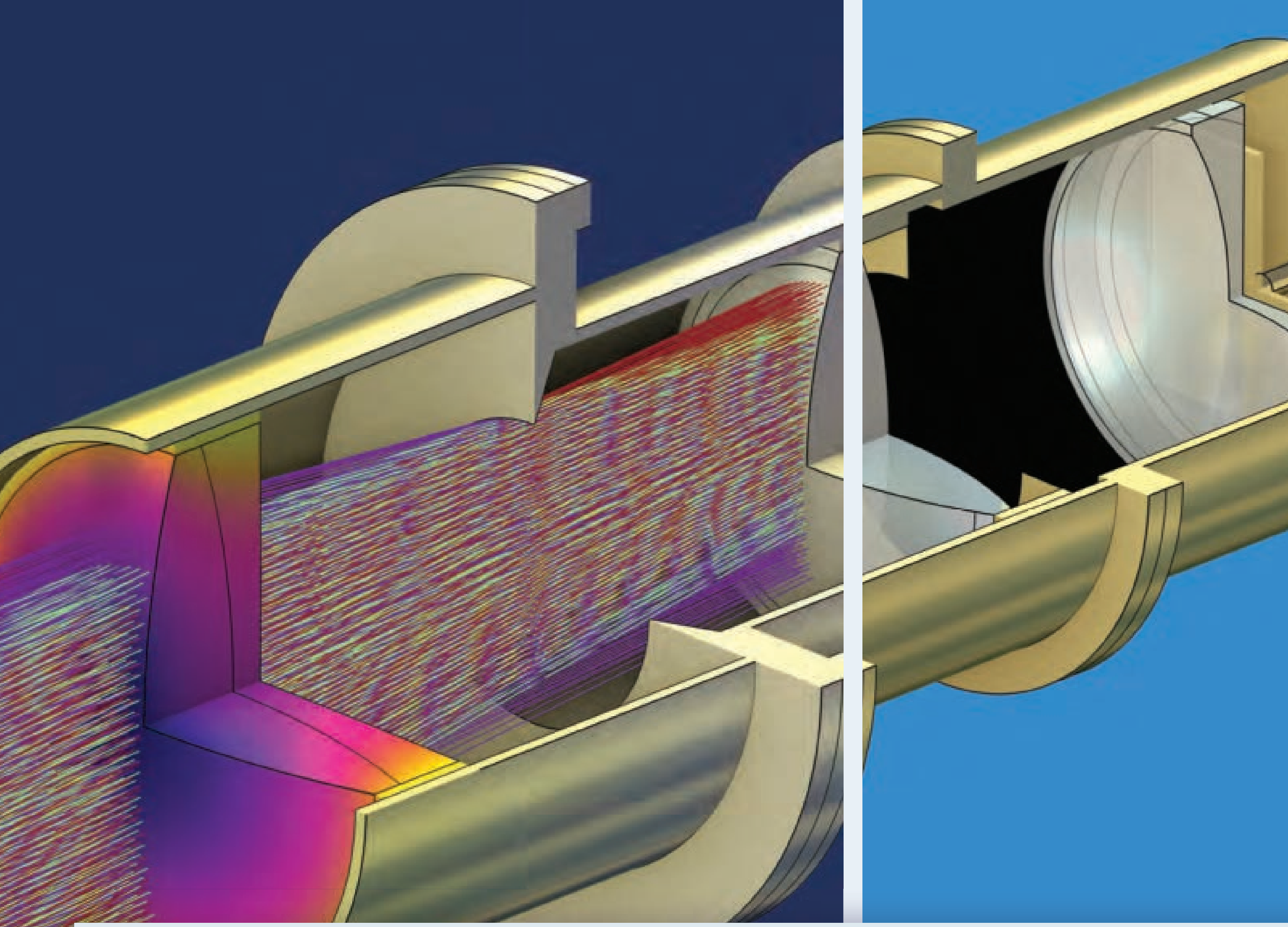
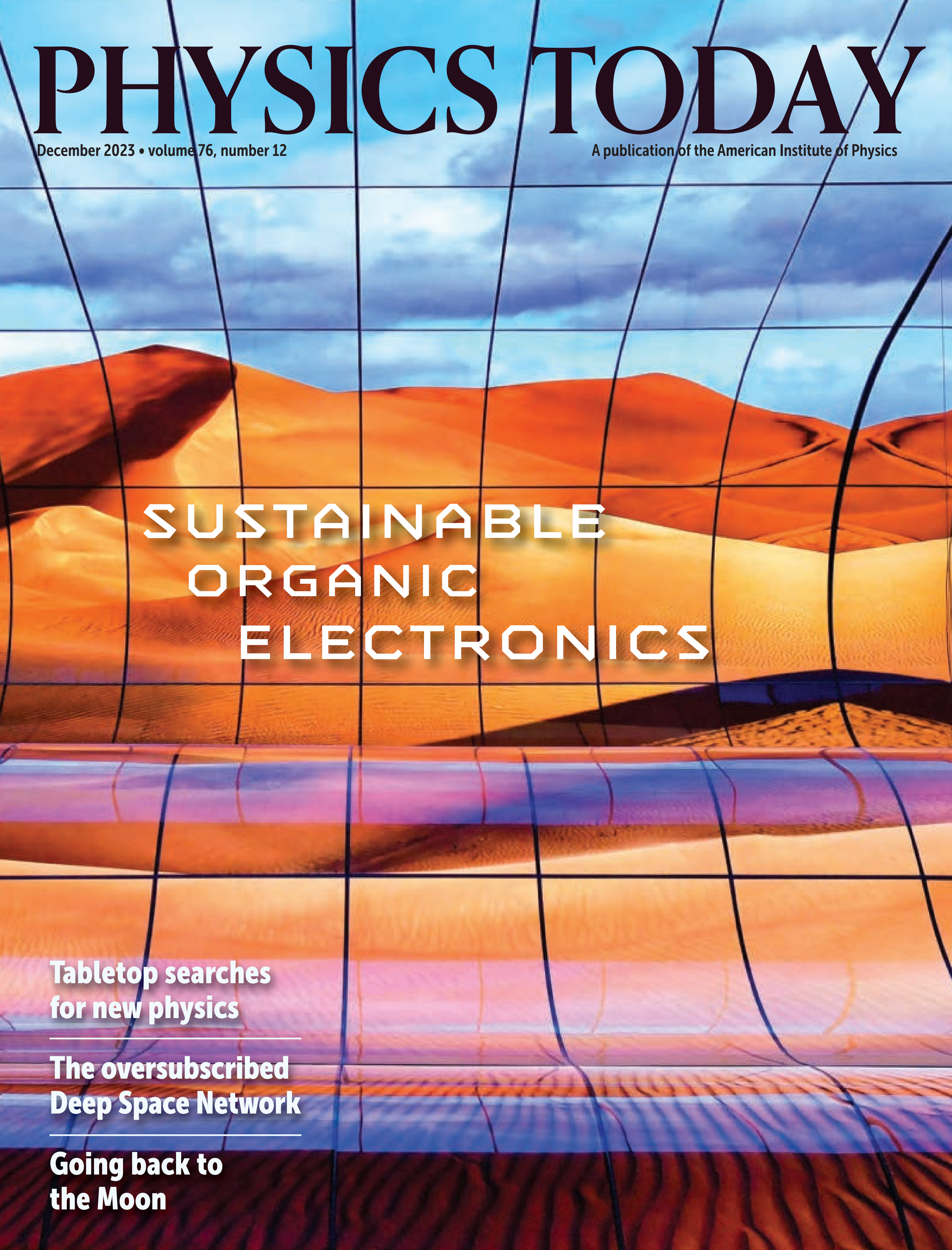


PHYSICS TODAY

December 2023 • volume 76, number 12

A publication of the American Institute of Physics

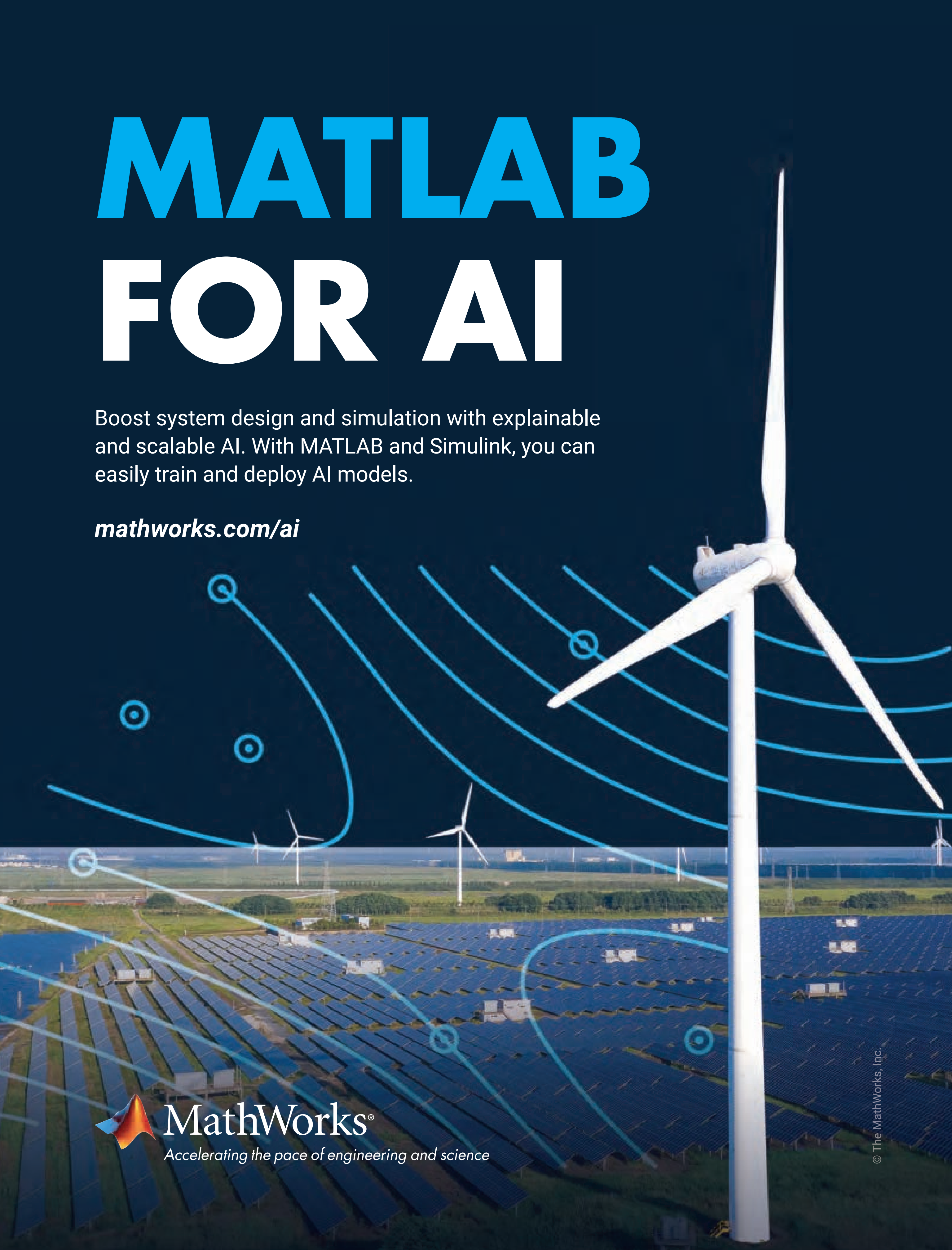


SUSTAINABLE ORGANIC ELECTRONICS

Tabletop searches for new physics

The oversubscribed Deep Space Network

Going back to the Moon



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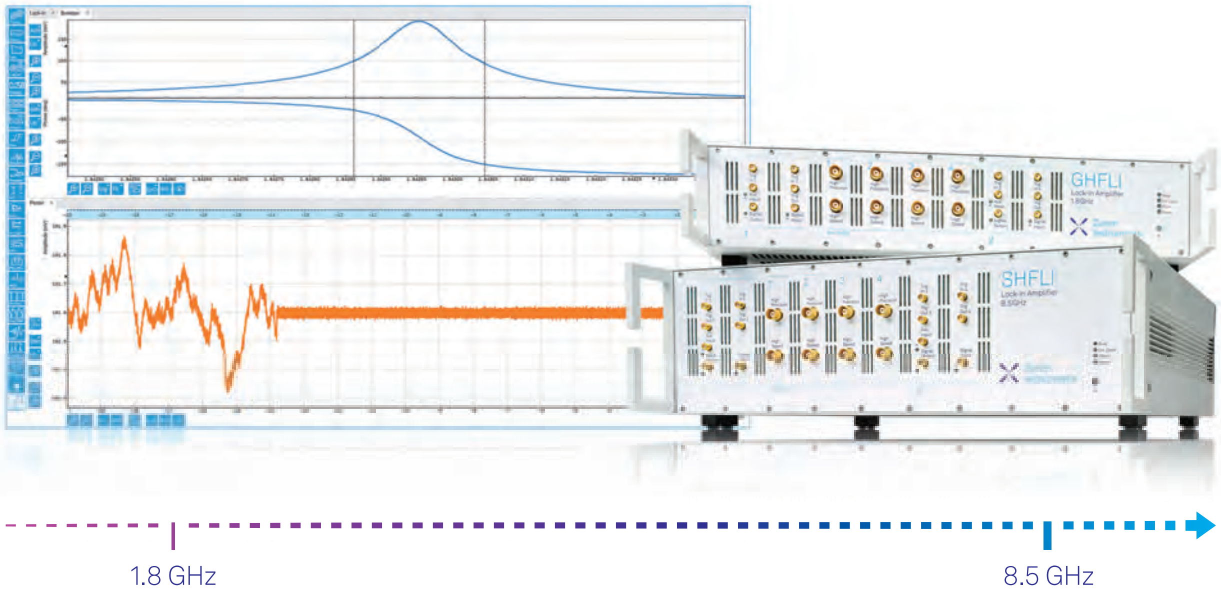
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FEATURES


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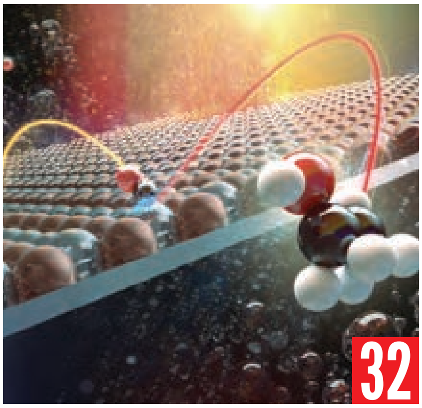
24 Sustainable fabrication of organic electronics

Simon Trudel

Amorphous materials are often an unwanted result of low-temperature thin-film deposition. Yet those disordered materials can be used with great effect for applications with stringent manufacturing requirements.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32 Artificial photosynthesis: A pathway to solar fuels

Harry A. Atwater

Taking inspiration from nature and from the success of photovoltaic solar conversion, scientists are developing foundations for sunlight-driven synthesis of fuels, chemicals, and materials.


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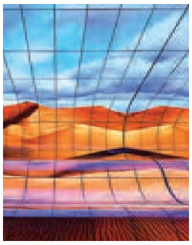
Michael J. Neufeld

Despite a lack of public enthusiasm, NASA's Artemis program will endure because human spaceflight has strong congressional support and signals great-power status.



ON THE COVER: Organic LED screens are becoming more prevalent, including in TVs and video game consoles. Those electronics aren't just better for creating large, curved screens to be shown off at trade shows; they are better for the environment. On **page 24**, Simon Trudel discusses how using amorphous materials for organic electronics can offer a pathway toward sustainable manufacturing. (Image by Schoening/Alamy Stock Photo.)

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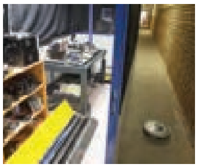
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Lab in a castle

Marissa Giustina and colleagues in Vienna needed a space with specific dimensions and sufficient utilities to perform a landmark quantum entanglement experiment. They ended up in the basement of the city's famous Hofburg palace. Giustina describes the unique lab setting and the challenges that came with it.

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Mars Sample Return

After receiving critical feedback from an independent review board, NASA is considering major changes to its planned late-2020s flagship mission to retrieve Martian rock and soil and bring them to Earth. The mission is facing delays, cost overruns, and a threat of cancellation from Congress.

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Dinos done in by dust?

Among the deadly consequences of the asteroid that struck Earth 66 million years ago was the suspension of aerosols in the atmosphere. New simulations suggest that microsized dust, rather than soot, was the most likely culprit for blocking sunlight and halting photosynthetic activity for an extended period.

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Physics Today (ISSN 0031-9228, coden PHTOAD) volume 76, number 12. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to Physics Today, American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300. Views expressed in Physics Today and on its website are those of the authors and not necessarily those of AIP or any of its member societies.

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

Art and production
Freddie A. Pagani, art director
Cynthia B. Cummings, photographer
Nathan Cromer
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Editors
Ryan Dahn *rdahn@aip.org*
Laura Fattaruso *lfattaruso@aip.org*
Toni Feder *tf@aip.org*
Abby Hunt *ahunt@aip.org*
David Kramer *dk@aip.org*
Alex Lopatka *alopatka@aip.org*
Johanna L. Miller *jlm@aip.org*
Gayle G. Parraway *ggp@aip.org*
Jennifer Sieben *jsieben@aip.org*
R. Mark Wilson *rmw@aip.org*

Online
Andrew Grant, editor *agrant@aip.org*
Greg Stasiewicz *gls@aip.org*

Assistant editor
Cynthia B. Cummings

Editorial assistant
Tonya Gary

Contributing editors
Karina Cooper
Andreas Mandelis
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Sales and marketing
Christina Unger Ramos, director *cunger@aip.org*
Bonnie Feldman
Unique Carter
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Address
American Institute of Physics
One Physics Ellipse
College Park, MD 20740-3842
+1 301 209-3100
pteditors@aip.org

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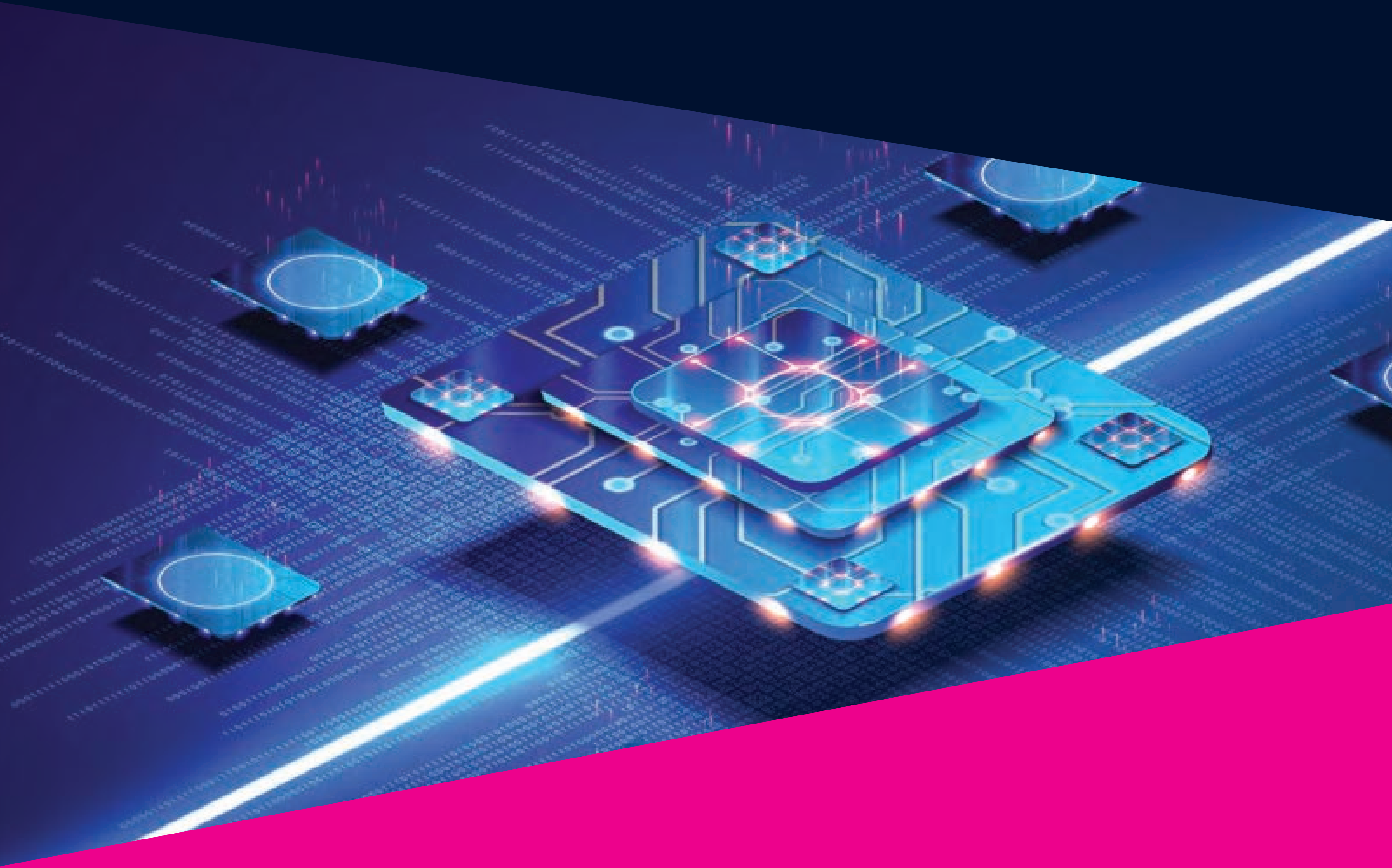

READERS' FORUM

Islam and women's education

Toni Feder's Q&A with Sola Mahfouz ("Physics was her ticket out of Afghanistan," PHYSICS TODAY online, 24 August 2023) made for a delightfully inspiring reading—so much so that I emailed it to my six nieces (two physicists, two doctors, and two dentists) and would have included my three sisters (a physicist, an accountant, and a banker, all retired) had they had email addresses. All are in a Muslim-majority developing country that has suffered for decades on account of wars and sanctions.

In defying restrictions on the education of young girls, Mahfouz follows in the footsteps of education activist Malala Yousafzai, the youngest Nobel Prize recipient. Mahfouz is from Afghanistan, where girls 12 and up have been barred from returning to school since September 2021 and women have been forbidden from attending universities since December 2022. The restrictions are a regression after two decades of progress—the number of women and girls enrolled in Afghan schools, for example, had increased tenfold between 2001 and 2018.[1]

THE UNIVERSITY OF AL-QARAWIYYIN is the oldest continually operating educational institution in the world. Fatima al-Fihri, a Muslim woman, established the school in Fès, Morocco, in the ninth century AD. (Photo by waleedyousef/Shutterstock.com.)

I would like to point out, though, that the Afghan authorities' attitude toward the education of women is not indicative of the teachings of Islam and gives the faith an undeservedly bad name.

Let us start with the Muslim scripture, the Koran. The book does not contain any text, explicit or implicit, that limits learning to a specific gender. It does include general statements pertaining to education, such as that "knowledge is light" and "those who know are not the same as those who do not know." Indeed, the prophet Muhammad (c. AD 570–632), the founder of the faith, emphasized the importance of education, explicitly stating, "The pursuit of knowledge is a duty of every Muslim, man and woman."

Next, let us look at Muslim-majority countries. The current prime minister of Bangladesh, Sheikh Hasina Wazed, is a Muslim woman and was named one of the 100 most influential people in the world by *Time* in 2018. Afghanistan's neighbor, Pakistan, had an Oxford University–educated woman, the late Benazir Bhutto, as its prime minister in 1988–90 and again in 1993–96. Save for Afghanistan, no other country—and therefore no Muslim-majority country—limits education to a particular gender.

Women have also long been welcomed into learning at the institutional level. Al-Azhar University, a well-known center of Islamic learning in Cairo, Egypt, is open to women. The oldest continually operating university in the world—the University of Al-Qarawiyyin in Fès, Morocco—was established by a Muslim woman, Fatima al-Fihri, in AD 859.[2] Al-Fihri used her inheritance from her father to establish the venerable educational institution, when many people would have used such newfound wealth for themselves. Among the school's alumni are the philosopher Maimonides (1135–1204), the historian Ibn-Khaldūn (1332–1406), the philosopher Averroës (1126–1198), and Pope Sylvester II (c. 940–1003).

All societies, especially those in developing countries, must use their resources to advance and improve the standard of living of their citizens, and education is the best way to do that. Women are roughly half the population. Excluding them from the educational system means ending up with half a society. An apt reminder is found in lines written by the Egyptian and Muslim poet Ḥāfiẓ Ibrāhīm (c. AD 1871–1932): "The mother is a school / If established well, she establishes a noble people." That is consistent with the well-known expression, "If you educate a man, you educate one person. If you educate a woman, you educate a nation."

In time, it will become clear that placing barriers on education is a futile effort. But in the meantime, what can be done to help young girls in Afghanistan and elsewhere to gain an education? One option is to use modern technology. Young people worldwide are adept at using the internet and social media, and those channels can be used to provide them with free educational resources.

Indeed, the BBC has been running an educational program for girls in Afghanistan via the web, TV, and radio. The program is called *Dars*, which means "lesson" in Dari and Pashto, the country's official languages. It has been used in "secret schools" and was commended as a "learning lifeline" by the United Nations.[3] The member societies of the American Institute of Physics should consider working with organizations such as UNESCO and UNICEF to create additional learning lifelines.

Such initiatives would be consistent with 21st-century thinking surrounding equity, diversity, and inclusion—at large and in the sciences in particular. They would require concerted effort and patience, but they would be bound to succeed in the end. You cannot underestimate the resolve of younger generations to aspire to a better life for themselves and their families. In time, it will become clear to those who place barriers on education that their efforts are futile.

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Muthana Al-Ghazi
(malghazi@uci.edu)
Tustin, California

The insufficient word in Physics Today's first issue

When Physics Today debuted in May 1948, its first editor, David Katcher, wrote the following in an editorial introducing the magazine.

> Physics Today is for the physicist, to inform him in comfortable, everyday language, of what goes on and why and who goes where. But it is also for the chemist, the biologist, and the engineer, to tell them of the science towards which they are driven by so many of their investigations; it is for the student, the teacher, the lawyer, the doctor, and all who are curious about physics; it is for administrative officials who deal with research; it is for editors and writers whose profession puts them midway between what is done and how it should be reported; it is for you, whatever reason brought you to this page.

In his engaging article "Physics Today turns 75," (Physics Today, May 2023, page 42) current editor-in-chief Richard Fitzgerald comments on that editorial, saying, "One part of Katcher's description above is notably out of date, though. Physics Today has evolved into more than a magazine and can be found well beyond the printed page. We have a website, email newsletters, social media, and webinars, and we'll continue to seek out and engage with our audiences wherever they may be."

I feel that Fitzgerald's feature missed an important opportunity to discuss an even glaringly more out-of-date part of Katcher's description, in the first sentence: the use of the pronoun "him"—which makes the introduction to both the magazine, and thus Fitzgerald's article, explicitly gendered.

Given, as Fitzgerald puts it, that Physics Today strives "to be a reminder of our

commonalities as scientists," the magazine's 75th anniversary presents an opportunity to reflect on the contributions that women have made during the lifetime of the publication and in the discipline it covers.

Perhaps a starting point could be to observe that the only mentions of "women" or "girls" in the article are literally in small print in two of the figures: the 1992 ad for Hubble Postdoctoral Fellowships and the word clouds.

Andrew G. White
(andrew.white@uq.edu.au)
University of Queensland
Brisbane, Australia

Expand STEM education for older adults

The US would greatly benefit from expanding educational opportunities in STEM (science, technology, engineering, and mathematics) for people of age 60 and up. By 2060 about 30% of the US population will be above the age of 60—and the percentage of adults between 18 and 64 will have declined.[1] That raises questions about how society can sustain the workforce and current retirement systems. People of age 60 and up could be a resource, on either a paid or volunteer basis, that counterbalances the increasing shortage of younger people in the labor force. But to do that, we will need to place more emphasis on teaching and training for older adults.[2]

Older adults in the US who participate in formal educational offerings can choose from formats and programs at various types of places, including higher-education institutions, religious institutions, community organizations, nonprofit groups, and self-organized initiatives.

Studies have shown that learning at older ages has a positive impact on physical health, self-confidence, social inclusion, independence, and cognitive ability.[3] In addition, STEM education could help older adults keep up to date with technological and scientific advancements. That is important not only because society needs older adults to continue participating in the workforce after retirement, but also because studies have shown that older adults score lower on science knowledge tests than younger generations. Meanwhile, science misinformation—and its potential to mislead voters—has only continued to spread. Given that older generations are more likely to vote, society would benefit from older generations having more STEM education.[4]

Policymakers and researchers need to pay more attention to the topic of participation, educational behaviors, and interests of older adults in education. The little existing research indicates that multiple factors, such as social class and gender, affect the likelihood of whether adults take part in lifelong learning in older age. Initial studies suggest that older adults participating in education tend to be white people with financial security.[5] It is important to expand opportunities for population groups that are underrepresented for reasons beyond the individuals' control.

Recently we conducted a dedicated interdisciplinary workshop on STEM education for ages 60 and up. The event brought together experts and decision-makers from different disciplines (https://indico.phys.hawaii.edu/e/stem60plus). Based on the discussions, we suggest the following action items:

- Increase research efforts focused on implementing lifelong STEM education effectively and develop tailored programs for different population groups.
- Expand STEM education programs for older generations.
- Make lifelong-learning opportunities widely accessible, especially to groups with low prior educational attainment.

The member societies of the American Institute of Physics can play a crucial role in facilitating discussion with politicians and the other STEM disciplines about investing resources into educating older adults.

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Sandra von Doetinchem
(sandravd@eduworks.com)
Eduworks Corporation
Corvallis, Oregon
Philip von Doetinchem
(philipvd@hawaii.edu)
University of Hawaii at Manoa
Honolulu
Paul Mantsch
(mantsch@fnal.gov)
Fermi National Accelerator Laboratory
Batavia, IL

Correction

September 2023, page 20—The original story misstated the name of cryogen-free instrument manufacturer Bluefors. PT

Attosecond pioneers win physics Nobel

Through advances in atomic and optical physics, the laureates broke new ground in the measurement of time.

In one second, light travels 300 000 km, most of the way from Earth to the Moon. In one nanosecond, a billionth of a second, it travels 30 cm, the length of a sheet of paper. In one attosecond, a billionth of a nanosecond, it travels 3 angstroms, about the length of a water molecule.

Attoseconds—or more precisely, tens to hundreds of attoseconds—are the natural time scale of the motion of electrons. Whereas atoms and molecules typically move on the scale of tens to hundreds of femtoseconds, electrons are about three orders of magnitude lighter and faster. Their motions include processes, such as tunneling and photoionization, that were once thought to be instantaneous, or at least too fast ever to be measured.

But the attosecond regime is now measurable, thanks to decades of theoretical and experimental work by dozens of scientists. For this year's Nobel Prize in Physics, the Royal Swedish Academy of Sciences has chosen three researchers who made groundbreaking experimental contributions to the creation of the first attosecond-scale pulses of light: Anne L'Huillier of Lund University in Sweden; Pierre Agostini of the Ohio State University in Columbus; and Ferenc Krausz of the Max Planck Institute of Quantum Optics in Garching, Germany. L'Huillier's one-third share of the prize is the largest ever to be awarded to a woman in physics.

High harmonics

The femtosecond-scale pulses that are used to observe the motions of atoms and molecules are an extension of conventional laser technology (see Physics Today, December 1982, page 19). The 1999 Nobel Prize in Chemistry went to Ahmed Zewail for his work on femtosecond studies of molecules. (See Physics Today, December 1999, page 19.) But Zewail's contribution was discovering how to use the ultrashort laser pulses, not how to create them.

Attosecond-scale pulses require a fundamentally new approach. Visible light has a wavelength range of 400–700 nm, corresponding to periods of 1.3–2.3 fs. The duration of a light pulse can't usually be shorter than a single wave period, so attosecond pulses can't be produced simply by chopping visible-light waves shorter and shorter. Breaking into the attosecond regime is more readily accomplished with wavelengths of tens of nanometers, well into the extreme ultraviolet (XUV).

Lasers can operate in the UV. But because the operating power scales with the fifth power of the frequency, there's a practical limit to how short their wavelengths can go. On the other hand, XUV radiation is made in abundance at sources such as synchrotrons, but it lacks the temporal coherence to be shaped into ultrashort pulses.

Nonlinear optics offers a route to short-wavelength light with laser-like coherence. In 1961, only a year after the invention of the laser, it was discovered that 694 nm laser light, focused into a quartz crystal, could generate a small amount of light at 347 nm, the second harmonic.

Harmonic generation is normally a perturbative process: The third harmonic is much weaker than the second, the fourth is much weaker than the third, and so on. So one might naturally assume that the easiest route to XUV harmonics starts with the shortest-wavelength laser light. Indeed, when several groups in the 1980s experimented with pushing the limits of harmonic generation, most started with 250–350 nm lasers. Some of the resulting harmonics extended into the XUV. But their intensities, as expected, diminished quickly.

It was a stroke of serendipity, then, when in 1987 L'Huillier (then at the CEA Saclay in France) and colleagues started with intense 1064 nm laser light instead and fired it into jets of noble-gas atoms.[1] "We weren't even looking for harmonics," says L'Huillier. "We were trying to see fluorescence. And we used 1064 nm because that was the laser that we had."


Anne L'Huillier

BBVA FOUNDATION


Pierre Agostini

KRYSTAL KENNEY


Ferenc Krausz

DANIEL GERST

Not only did they see harmonics, though, but the harmonics wouldn't quit. In xenon, they saw up to the 21st harmonic; in krypton, the 29th; and in argon—as shown in figure 1—the 33rd. (For symmetry reasons, only odd-numbered harmonics are produced by the atomic gases.) And instead of dropping off quickly, the harmonic intensity plateaued, with several harmonics in a row being almost equally bright.

The high-harmonic generation (HHG) "was completely unexpected," says Eva Lindroth, a theorist at Stockholm

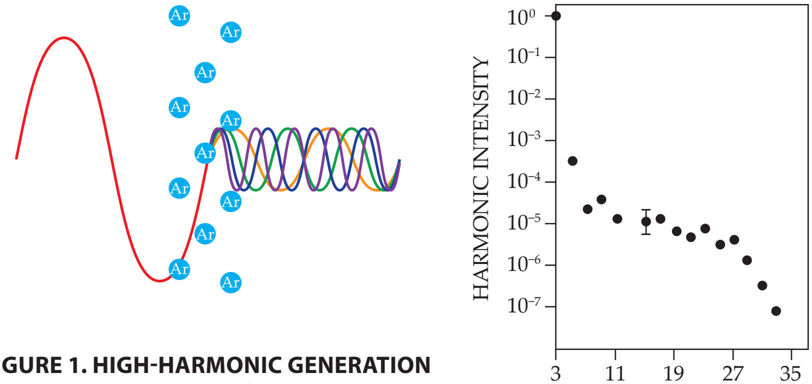

FIGURE 1. HIGH-HARMONIC GENERATION converts long-wavelength light (red) into a superposition of shorter-wavelength harmonics (orange, green, blue, and purple) by means of a jet of noble-gas atoms (here argon). Anne L'Huillier and colleagues discovered that, as shown in the graph on the right, the harmonic intensity plateaus instead of falling off steeply. The equal-intensity harmonics could—and in fact do—combine coherently to produce a train of attosecond-scale pulses. (Figure by Freddie Pagani and Lorien Williams; graph adapted from ref. 1.)

University and a long-time collaborator of L'Huillier's. "Nobody thought that when you increased the intensity of the light, you'd get a plateau of harmonics. It was a completely new thing—but it's very robust."

Electron three-step

"Having a femtosecond XUV laser-like source was already a major advance," says Pascal Salières of CEA Saclay, who earned his PhD under L'Huillier in the 1990s. But the potential further implications soon became clear. It was well known, both mathematically and experimentally, that when many waves of equal amplitude and equally spaced frequencies are added together, the sum is a series of short pulses equally spaced in time. That phenomenon is the basis for the optical frequency comb, recognized by the 2005 physics Nobel (see Physics Today, December 2005, page 19). If L'Huillier and colleagues' high harmonics added together coherently, the resulting pulses would be just hundreds of attoseconds long.

But did the harmonics add together coherently? That part wasn't yet known, and it wasn't safe to assume. After all, the HHG output was the product of a vast number of individual atoms. Without a better understanding of the process, there was no way to know how coordinated their responses would be.

During the early 1990s, L'Huillier and others made great strides in understanding the physics of HHG at both the single-atom and ensemble levels. But perhaps the biggest leap in conceptual understanding came from a three-step recollision model, presented independently in 1993 by Lawrence Livermore National Laboratory's Kenneth Kulander and colleagues and by Paul Corkum of the National Research Council Canada.[2]

According to the model, HHG is initiated when the laser light's electric field is strong enough to temporarily rip an electron away from its atom. When the field reverses direction, it slingshots the electron back from whence it came. Finally, the electron drops back into the empty orbital it left behind, and its accumulated energy is released as a high-harmonic photon. That simple picture is semi-classical, but the full quantum mechanical description gives similar results. (See the article by Paul Corkum, Physics Today, March 2011, page 36.)

The model explains why a 1064 nm laser produces a high-harmonic plateau but a 300 nm laser does not: In the latter case, the electric field oscillates too quickly for the liberated electrons to pick up much energy. And it suggests that the atom's responses should be synchronized well but not perfectly: Electrons can be pulled from their atoms only at certain points during the optical cycle. But depending on how much energy they gain, they don't all recollide at exactly the same time.

The model also points the way to at least two routes to generating attosecond pulses one at a time rather than in a series. One way is to start with an ultrashort laser pulse in which only a single optical cycle is intense enough to initiate HHG (see Physics Today, April 2003, page 27). Another way is to vary the polarization. Recollision requires linearly polarized light: With circular or elliptical polarization, the electrons are led around in spirals rather than back toward their atoms. So if a pulse's polarization varies in time from circular to linear to circular, it initiates HHG only at the instant of linear polarization.

By the late 1990s, then, the stage was set for attosecond physics. Researchers were probably already making plenty of attosecond-scale pulses—but they were unable to prove that they were. They were faced with a conundrum: How do you calibrate an attosecond-scale stopwatch if you don't already have an attosecond-scale stopwatch to calibrate it against?

How short?

In 2001 Agostini (then at CEA Saclay) and Krausz (then at the Technical University

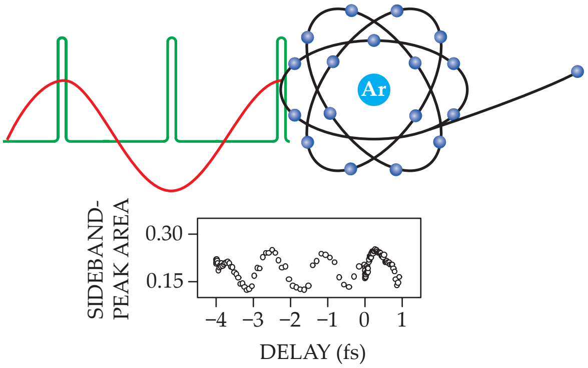

FIGURE 2. RABBIT (reconstruction of attosecond beating by interference of two-photon transitions) is a technique developed by Pierre Agostini and colleagues to measure the length of the pulses in a high-harmonic pulse train. The pulse train (green) and IR fundamental (red) can interfere constructively or destructively to ionize an atom (here argon). The interference is observable in the intensity of several sidebands, one of which is plotted here. By analyzing the sideband areas as a function of the delay between the two waves, Agostini and colleagues proved that the pulses were on the attosecond scale. (Figure by Freddie Pagani and Lorien Williams; graph adapted from ref. 3.)

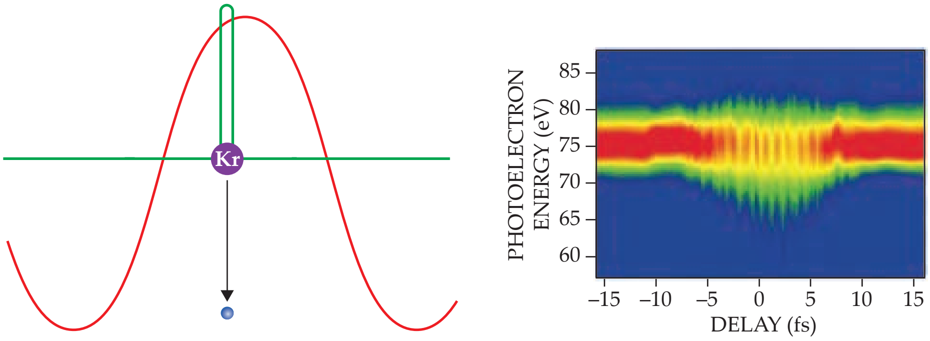

FIGURE 3. ATTOSECOND STREAKING was used by Ferenc Krausz and colleagues to measure the duration of a single attosecond-scale pulse. The pulse (green) ionizes an atom (here krypton), and the liberated electron (blue) is accelerated in the electric field of a strong IR wave (red). The graph shows the wobbles in the electron energy as a function of the pulse–IR delay; from them, Krausz and colleagues concluded that the pulse was 650 attoseconds long. (Figure by Freddie Pagani and Lorien Williams; graph adapted from ref. 4.)

of Vienna) independently published their solutions. Their experiments, although different, were based on the same two principles. First, optical delay lines make it possible to control the relative timing of two light pulses with subfemtosecond precision. Second, the shape of a light wave can be used to measure times much shorter than the full wave period.

Agostini's approach, now known as RABBIT (reconstruction of attosecond beating by interference of two-photon transitions) is shown schematically in figure 2. It superposes the HHG output—assumed, but not yet proven, to be a series of attosecond pulses—and the IR fundamental wave that produced it.[3] The combination of the two waves photoionizes an atom (argon, in this case). From the kinetic energy of the liberated electron, one can infer how much energy the atom absorbed.

The HHG spectrum consists of odd multiples of the IR fundamental energy. But the even multiples, called sidebands, show up in the photoelectron spectrum too. They can arise in two ways: through the combined absorption of one HHG photon and one IR photon or through HHG absorption followed by stimulated IR emission. Those processes can interfere either constructively or destructively, depending on the relative phase of the two waves.

Agostini looked at the sideband intensities as a function of the delay between the HHG and IR waves. If the HHG isn't actually a series of attosecond pulses but rather an incoherent XUV emission smeared out over the whole IR wave period, then adjusting the delay wouldn't make any difference—the sideband intensities would always be the same. Because, instead, the sideband intensities oscillated, Agostini inferred that the HHG is organized into a series of discrete pulses. By analyzing the oscillations quantitatively, he concluded that the pulses were 250 attoseconds long.

Krausz's approach, called attosecond streaking, is illustrated in figure 3. It uses a single HHG pulse, superposed on an IR wave, to ionize an atom.[4] Instead of two-photon transitions, Krausz looked at how the liberated electron was accelerated in the IR wave's electric field. If the ionization happened during a crest in the IR wave, the electron was accelerated downward (because electrons are negatively charged); during an IR trough, it would be accelerated upward.

As Agostini did with RABBIT, Krausz varied the delay between the IR and HHG pulses and looked for a change in the electron signal. If the HHG pulse is long compared with the IR period, there would be no change. By analyzing the wobbles that he observed, Krausz concluded that the pulse had a duration of 650 attoseconds.

Photoionization and beyond

Now that the world had access to attosecond pulses, what was it to do with them? The beauty of both RABBIT and attosecond streaking is that they can probe not just the time scale of the HHG pulses, but also the time scale of photoionization. Absolute timing measurements are unfortunately not possible—there's no way to determine what time delay is truly "zero"—but relative measurements are. If two different photoionization channels are measured simultaneously, and if one is a bit slower than the other, the difference shows up as an offset in the RABBIT or streaking oscillations.

In 2010 Krausz and colleagues made just such a measurement on neon by using attosecond streaking.[5] Neon can eject an electron from either the 2*s* orbital or a 2*p* orbital, and the researchers found that the latter was 21 attoseconds slower than the former. (HHG pulses by that point had shrunk to some 200 attoseconds, which was sufficient to measure such a difference.) It was the first clear experimental evidence that photoionization is not instantaneous—at least, not always.

Theory, however, predicted a time difference only half as large. And when L'Huillier and colleagues revisited the problem in 2017, using RABBIT, they resolved the discrepancy: The 2*s* channel was concealing another, even faster ionization channel, making it appear some 10 attoseconds faster than it really was.[6] Streaking couldn't resolve them, but RABBIT could. (See Physics Today, January 2018, page 18.)

Importantly, notes Krausz, the experimenters had theory to guide them along the way. It's not easy to calculate the dynamics of neon's 10 electrons, but it's possible—and in the end, the calculations were right. "We didn't really discover anything new," he says. "We already understood the physics pretty well, we just hadn't observed the process evolving in time. It's proof that the technology works."

Attosecond-pulse technology was discovered by atomic physicists, so it was naturally first applied to problems in atomic physics. But its more significant contributions are likely to be made in other fields where theoretical answers are not yet known. The physical chemistry of small molecules is a natural next step, especially in the thorny regime where nuclei and electrons move on the same time scale and conventional approximations break down. (See Physics Today, June 2018, page 20, and August 2021, page 14.)

Further afield, there are potential applications to problems in large-molecule chemistry, solid-state physics, and even biology. Electrons are everywhere, and their motion underlies phenomena in a wide range of fields.

Expanding attosecond science beyond atomic physics means making attosecond measurements available to researchers who aren't experts in that field. That's happening in two ways. "For groups that are capable of using ultrafast lasers, they can buy attosecond sources commercially," says Francesca Calegari with the German Electron Synchrotron, "but normally, nonexperts would apply for beam time in a laser lab." Such attosecond user facilities are springing up around the world. Among them are ELI-ALPS (Extreme Light Infrastructure Attosecond Light Pulse Source) in Szeged, Hungary, which has been open to users since 2018, and the NSF NeXUS (National Extreme Ultrafast Science) facility at Ohio State, scheduled to open next year. Although they're not based on HHG, free-electron lasers such as the Linac Coherent Light Source at SLAC are also making attosecond pulses available to users.

The interdisciplinary connections are already bearing fruit. "At the 2022 ATTO conference, I was blown away by how diverse the field has become," says Jon Marangos of Imperial College London. "Attosecond physics has really transformed into a broader attosecond science."

At the same time, the full potential of attosecond measurements may yet be discovered. "When you find something in nature that's completely new, then in the beginning you don't know what it can be used for," says Lindroth. "When the laser was invented, for a long time people just used it to look at energy levels in atoms, but now laser applications are everywhere. So I think we need to be a little bit patient."

Johanna Miller

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Makers of quantum dots share Nobel Prize in Chemistry

By confining electrons to nanoscale spaces, the laureates created crystals that emit light at specific wavelengths. That behavior has been harnessed for displays and other technologies.

An LED's color depends on the semiconductor material it's made of. When current flows through an LED, an excited electron crosses the semiconductor bandgap. It can then relax and recombine with a hole in the valence band, resulting in the emission of a photon. The light's color, therefore, varies with the energy required to cross the bandgap. (To learn more about blue LEDs, see Physics Today, December 2014, page 14.)

But new behavior emerges when a semiconductor shrinks to a few nanometers in size. When electrons in nanocrystals get excited, the emitted photons can have only certain allowed energies. And as the space that an electron can occupy shrinks, so too do the allowed values of its wavelength, according to the particle-in-a-box model in quantum mechanics, and the bandgap of the semiconductor widens.

Semiconductor nanocrystals are often called quantum dots, and the wavelengths they shine at depend only on their size: Bigger quantum dots emit red and orange light, and smaller ones shine green and blue. (See the article by Dan Gammon and Duncan Steel, Physics Today, October 2002, page 36.)

For discovering quantum dots and for developing a reliable, high-quality method to manufacture them, Aleksey Yekimov of Nanocrystals Technology Inc. in New York, Louis Brus of Columbia University, and Moungi Bawendi of MIT were awarded this year's Nobel Prize in Chemistry. Their contributions to the field have helped lead to all sorts of technological applications, such as quantum-dot-based TVs available for purchase today, medical-imaging technology, and highly efficient IR detectors.

Frozen in glass

Since medieval times, glassmakers have known that adding small amounts of powdered metal-oxide impurities to a molten mixture of sand and ash would yield various colors of glass when cooled. But what wasn't known was why it worked. Hundreds of years later emerged the interdisciplinary field of colloid science, which focuses on the study of small solid or liquid particles

Aleksey Yekimov

NEXDOT

Louis Brus

COLUMBIA UNIVERSITY

Moungi Bawendi

JUSTIN KNIGHT/MIT

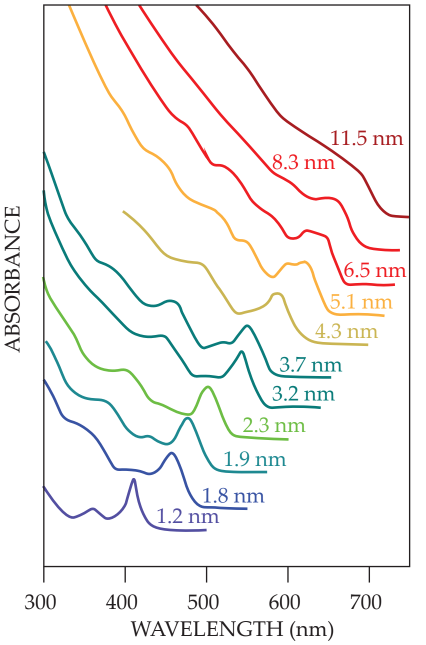

FIGURE 1. CADMIUM SELENIDE NANOCRYSTALS absorb and emit differently colored light depending solely on the semiconductor's size. Moungi Bawendi and his then graduate students Christopher Murray and David Norris developed a synthesis technique in 1993 to make defect-free semiconductor nanocrystals with narrow size distributions. (Adapted from ref. 3.)

mixed and suspended in a solution. But the exact mechanism that produces color in stained glass remained uncertain until the early 1980s.

Yekimov wanted to learn more about the growth of colloids in stained glass, so he began studying them at the S. I. Vavilov State Optical Institute in Leningrad in the Soviet Union. He and his PhD mentee, Alexei Onushchenko, tinted silicate glass with a single type of semiconductor colloid—in their case, a little bit of copper chloride—and measured the glass's optical absorption.

Based on the absorption measurements, they inferred that small CuCl crystals were forming in the molten glass solution. Variations in temperature regulated the size of the CuCl crystals, and subsequent x-ray scattering measurements showed that the crystals ranged from just a few nanometers to tens of nanometers in size. Yekimov and Onushchenko also observed that the smaller nanocrystals emit shorter wavelengths of light, whereas larger ones have longer wavelengths.[1]

Yekimov correctly identified in 1981 that quantum confinement effects are responsible for the changing wavelengths of light. Sufficiently energetic electrons can jump across the material's bandgap to the conduction band. When the electrons are electrostatically attracted to the holes left in the valence band, they combine. In doing so, they emit photons at a specific wavelength, and for nanocrystals, that wavelength is limited by the 3D confinement of the electrons.

Shortly after Yekimov's discovery, he began collaborating with a theoretician named Alexander Efros, who was based at the Ioffe Institute in Leningrad and is now at the US Naval Research Laboratory. They further studied the size-dependent optical and electronic properties of various semiconductor nanocrystals, but they faced a challenge. The nanocrystals were frozen in glass, so the researchers had limited opportunities to manipulate or change them further.

"One day I was called into the special department of the Ioffe Institute," says Efros, "where the chief of the department said, 'Do you know Louis Brus? Who is Louis Brus?' He gave me an open envelope, which was a preprint of a journal that the Ioffe Institute didn't have." Inside was a copy of a 1983 paper that Brus had recently published.[2] (He had found a translated copy of Yekimov's first paper and was intrigued.) "We learned that some people on the other edge of the world are working on the same topic," says Efros, "and it was very exciting for us."

In liquid

The Cold War had prevented most exchanges between Soviet and US scientists. So unbeknownst to Yekimov and Efros, Brus had also been researching quantum dots, at Bell Labs in Murray Hill, New Jersey. He was preparing nanometer-sized cadmium sulfide crystals by precipitating them out of a liquid that was injected with precursor ions. He observed that over time, the CdS crystals dissolved and then recrystallized to larger sizes, with the aged ones reaching a diameter of up to 12 nm.

"The initial observation was accidental," says Brus. "I tried to figure out what it meant, and it took a while to sort through possibilities." After ruling out a suspected electromagnetic effect, Brus slowed down the reaction that formed the CdS nanocrystals and got smaller samples. Using absorption spectroscopy, he and his colleagues found that the older, larger particles had a spectrum similar to that of bulk CdS, but the younger, smaller particles exhibited a shift to shorter wavelengths.[2] Yekimov had observed the same effect a year earlier.

"I realized that what I was dealing with was relevant to the future of microelectronics," says Brus. "As the size in transistors became smaller all the time, eventually we would enter a regime where silicon and the transistor would no longer behave like bulk silicon." He presented the initial findings to his managers at Bell Labs. "They were quite happy for me to go ahead and pursue this subject systematically," Brus says.

With an interdisciplinary group of scientists working with him, Brus investigated other chemical methods to make the nanocrystals in the mid 1980s. By adding the reagents more slowly, the researchers found that they could control the reaction better and grow existing nanocrystals without nucleating as many new ones.[3]

Brus credits his research success, in part, to the reliable funding of Bell Labs, which didn't require regular grant proposals from him or others working there. "I don't think it could have been done in a university," says Brus. "Under the way the NSF and the DOD work, it would have been hard to get funding."

Fewer flaws

Brus brought several young chemists to Bell Labs as postdocs in the 1980s, including Moungi Bawendi. Under the guidance of Brus, Bawendi worked there in 1988–90 trying to improve the synthesis of the colloidal nanocrystals, which had variations in size, shape, crystal structure, and surface states. All those heterogeneities made it difficult to isolate the size-dependent effects Brus first saw a few years earlier.

Bawendi left Bell Labs at the end of the decade for MIT. Although he had ideas for improvement, he didn't have an established protocol yet. Three graduate students—Christopher Murray, Manoj Nirmal, and David Norris—joined Bawendi at MIT to tackle the problem in his first year there.

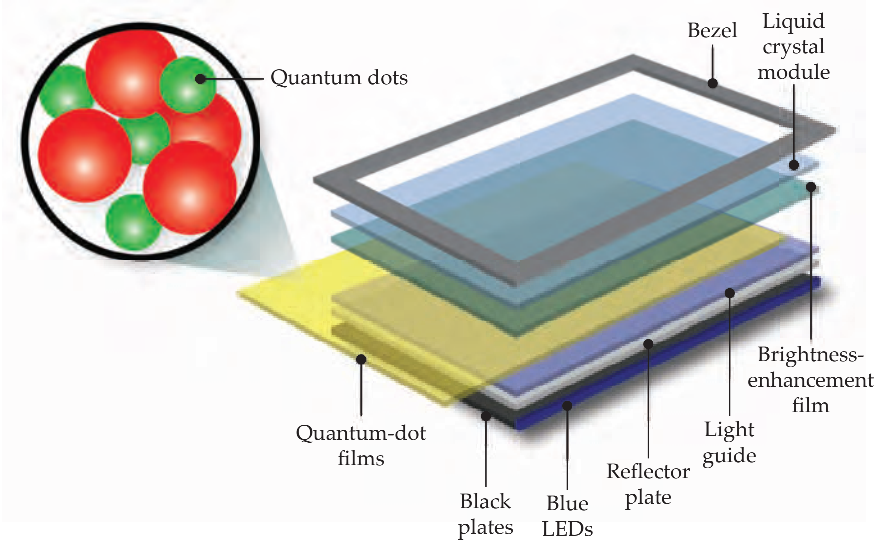

FIGURE 2. QUANTUM DOTS are used in some new TVs and other displays. A blue LED backlight illuminates a thin film of quantum dots, which in their excited state emit brighter light than an LCD screen. Quantum-dot TVs also have larger color ranges, require less power, and can be incorporated into bigger and more-flexible displays. (Jyurek/Wikimedia Commons/CC BY-SA 3.0.)

"Moungi had a vision of what he wanted to do and created a really exciting environment for us," says Norris. "We each had our own research areas, and Chris Murray's project was to focus on synthesizing better nanocrystals." Bawendi initially directed Murray to continue down the path he had found promising while at Bell Labs, in which salts are mixed into a liquid solution, initially at low temperature to encourage the crystallization of nanometer-sized semiconductors.

Most samples made with that method were rife with defects, but Bawendi reasoned that if the nanocrystals were heated up after the synthesis, the defects could be removed and the samples' optical properties improved. So Murray began making semiconductor nanocrystals and then trying to remove the defects. But, he says, "I found it very difficult for all the reasons that they did at Bell Labs before. So I thought maybe it would be better to avoid the nucleation of the defects in the first place."

Looking for a solution, Murray went to the basement of one of MIT's libraries and started reading about colloid science and chemical-vapor deposition, which places volatile precursors onto a reactive substrate to produce high-quality thin films. Based on the literature, Bawendi and Murray decided to abandon room-temperature synthesis and grow the nanocrystals at about 300 °C. After tweaking the solvents so that they had a higher boiling point, Murray says, "the pieces started coming together."

By injecting the precursor materials into a heated solvent and then carefully controlling the temperature, Bawendi and his students succeeded in growing nanocrystals of specific sizes. The resulting quantum dots were nearly free of defects, their sizes could be precisely tuned, and the method was adaptable to all sorts of semiconductors.[4] Figure 1 shows how the peak wavelength of light absorbed by the synthesized cadmium selenide nanocrystals depends critically on their size.

Detectors and displays

Shortly before publishing the 1993 paper, Bawendi's three graduate students—Murray, Nirmal, and Norris—went to their first conference to present the results. "And I still remember," says Norris, "nobody was interested in our posters. All three of us were just completely depressed after that."

Nirmal and Norris graduated from MIT in the mid 1990s and pursued other research, unsure if nanocrystals were a good topic to continue with in their careers. Only after a few years of the community tinkering with the new synthesis method with other materials did the possible applications become apparent.

Today some research groups are working on IR detectors based on quantum dots. Similar to how they can emit specific wavelengths of light in the visible range, quantum dots can be tuned for different IR wavelengths and then spread across a substrate. The layer could be incorporated into a highly sensitive camera. On a car, for example, such a detector could more clearly illuminate people and pets not visible from the road.

Quantum-dot-based detectors in the near-IR work, but the technology gets worse at the mid-IR and at longer wavelengths. "We're using photon detectors, which can do high-speed observations, but they have to be cooled with liquid nitrogen, and they are super expensive, around $50 000 each," says University of Chicago's Philippe Guyot-Sionnest.

More basic research needs to be done before an IR detector based on quantum dots is a commercial possibility. But if the remaining challenges can be surmounted, Guyot-Sionnest says, "in principle, this would lead to very, very low cost infrared images that would slash the cost down by a factor of 1000."

Now you don't need to be a synthetic chemist to work with quantum dots. They're for sale in various sizes at scientific supply retailers and are capable of emitting specific wavelengths to suit all sorts of requirements. And they're already available in some consumer products too.

The "Q" in Samsung's QLED TVs, for example, stands for the monolayer of quantum dots that's included in the screen, shown in figure 2. That technology was made possible by the development of highly luminescent zinc selenide nanocrystals by Guyot-Sionnest and former graduate student Margaret Hines.[5] Guyot-Sionnest says, "All the applications today are using this bright fluorescence."

Alex Lopatka

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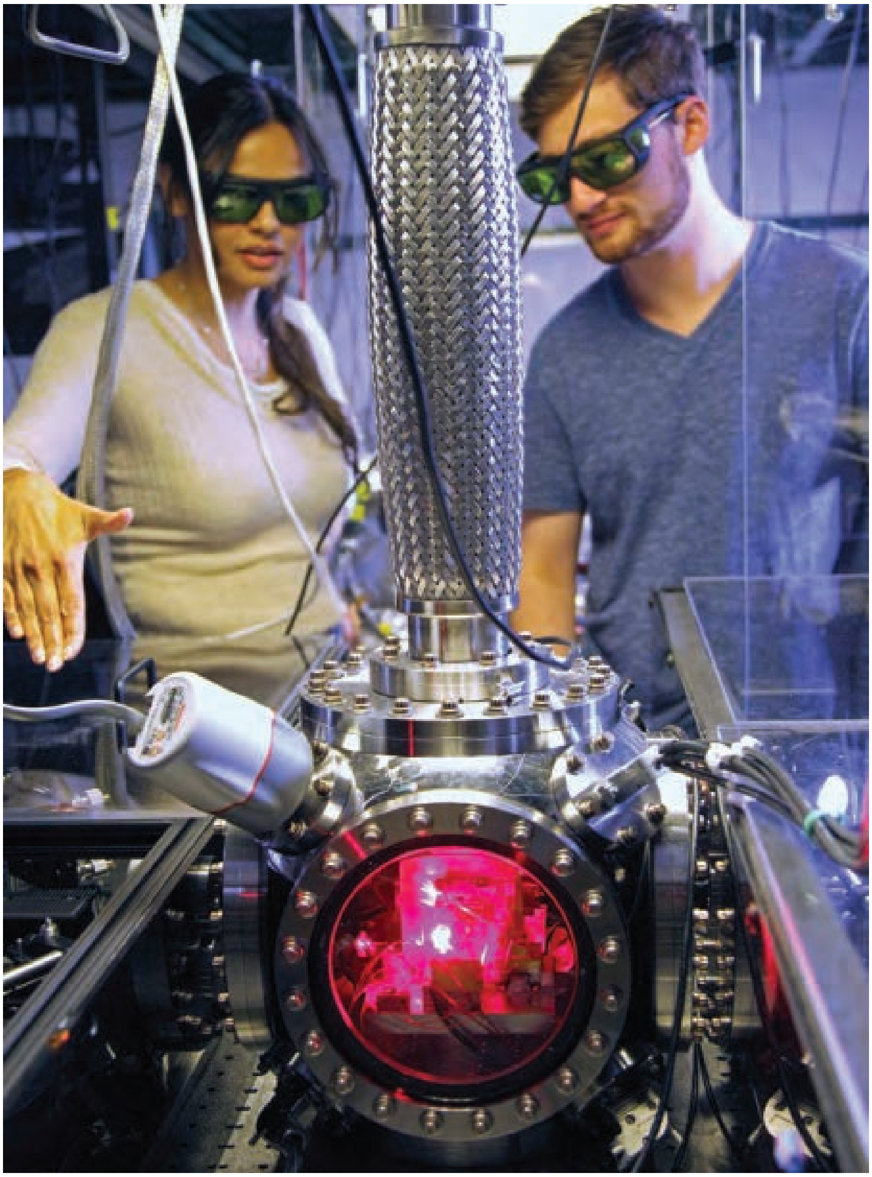
Precision measurements bring the search for new physics to the table

Targeted small-scale experiments look to find smoking guns—or at least to rule out possibilities.

Practitioners of atomic, molecular, and optical (AMO) physics are increasingly applying their tools to the search for physics beyond the standard model, thanks largely to advances in precision-measurement techniques. Particle colliders have dominated the search for new physics in recent decades. But the growth in small-scale studies coincides with two realities: the Large Hadron Collider (LHC) has not found hoped-for new physics and a higher-energy particle collider is likely to be far in the future.

Much evidence exists that the standard model is insufficient in explaining the universe. The preponderance of dark matter and dark energy, which make up roughly 95% of the universe but remain unidentified, is a prime example. Others include the excess of matter over antimatter, the fact that neutrinos have mass, the unexpectedly low mass of the Higgs boson, and the relationship between gravity and the other fundamental forces.

Whereas colliders can detect a wide range of particles and events, tabletop experiments are typically designed to target specific interactions. “You pick what you want to look for and then design the experiment accordingly,” says Daniel Carney, a theoretical physicist at Lawrence Berkeley National Laboratory. The search could be for evidence of dark matter, a fifth force, or changing values of fundamental constants. “The space of possible experiments is vast and unexplored,” says Carney, who started working on tabletop searches for new physics when he “got obsessed with the idea of testing quantum gravity. Tabletop searches are the Wild West.”


TOM PENNY/YALE WRIGHT LABORATORY

MOLLY WATTS AND BEN SIEGEL, graduate students at Yale University, with a vacuum chamber containing trapped microparticles. They use the apparatus to look for recoils of the microparticles when an implanted nucleus decays. It is sensitive to forces as small as zeptonewtons (10^{-21}N).

“We don’t know how close we are to finding new physics, because we don’t know where it is,” says David DeMille of the University of Chicago. He is one of three principal investigators on ACME, an experiment that seeks to measure the electron’s electric dipole moment using beams of molecules. (See “Diatomic molecules, a window onto fundamental physics,” by David DeMille, Physics Today, December 2015, page 34, and “The implications of a precise electron measurement,” by Yuichiro Nakai

MIRA LITTMANN

A VAN transports the Broadband Reflector Experiment for Axion Detection from the University of Chicago to its new home inside a large magnet at Argonne National Laboratory, roughly 45 kilometers away.

and Matthew Reece, Physics Today online, 14 November 2018.)

Cool tools

Over the past 15 or so years, experimenters in AMO physics have advanced techniques to cool, trap, and quantum control systems—from atoms to electrical circuits to macroscopic objects. Many of the advances were made to improve atomic clocks. More recently, "spectroscopic tricks" that were developed for atoms have been extended to molecules, notes Eric Cornell at JILA, a joint institute of NIST and the University of Colorado Boulder.

Cornell is a principal investigator on a trapped-ion experiment that currently puts the tightest constraint on the electron's electric dipole moment. The constraint is about seven orders of magnitude greater than the standard model prediction; a dipole moment larger than predicted by the standard model would be new physics. "If you want to see the electron wobble, you want to apply the biggest honking electric field possible," says Cornell. "Where is that? Inside molecules! They are like a mini high-field physics lab, but with long coherence times that you would not find in a high-energy collision."

Once a new technique exists, says Cornell, people look around and wonder, "I have this cool tool, what can I use it for?" Atomic clocks can be accurate to 18 digits, he says. It's natural to ask, "How can I turn that precision in timekeeping into precision for physical measurements?"

Amar Vutha is trying a different approach to measure the electron's electric dipole moment in his lab at the University of Toronto: He freezes molecules into neon ice. The ice orients the molecules, says Vutha. "Then you apply a magnetic field and look for anomalous spin precession that depends on the orientation of the electron relative to the axis of the molecules."

The approach could search a wide range of parameter space, Vutha says. Any "smoking gun" signals could be followed up with colliders or other experiments, he says. Null results could rule out theories.

At Columbia University, Tanya Zelevinsky and her group are studying transitions between vibrational levels in molecules to learn about interatomic forces; they have characterized a transition in the strontium dimer to parts in 10^{14}. "What does gravity look like at the nanometer scale?" she asks. "If a force is found that modifies the Newtonian gravitational force, it would be a signature of a new physics."

Dark matter could exist over a huge parameter space, covering tens of orders of magnitude. GNOME, the Global Network of Optical Magnetometers to Search for Exotic Physics, is one of many dark-matter searches. It consists of a dozen widely separated stations that collect time-synchronized data on atomic spins to look for transient effects induced by dark-matter collisions or other exotic interactions. And many groups are looking for axions, a proposed ultralight dark-matter particle. Theorists cooked up axions to explain a lack of observed violation of *CP* (combined charge conjugation and parity) symmetry in strong interactions, but axions double as a dark-matter candidate.

Gerald Gabrielse has been working on small-scale precision measurements for 30 years. Until a decade or so ago, he says, "it was lonely." His focus—looking for magnetic and electric dipole moments of electrons, protons, and neutrons—was not mainstream. Now the field is abuzz. After three decades at Harvard University, Gabrielse was wooed by Northwestern University to found and run a center devoted to tabletop precision measurements—where "tabletops" come in various sizes. The ACME experiment, for example, fills a room there. Similar centers, including one created last year at Caltech, are popping up around the world.

Experimental cultures

AMO experiments are typically small, involving just a few people, a few years, and a few hundred thousand to a few million dollars. They may be done by a single group or a small collaboration on a professor's startup funds or grant. And scientists can try things and take risks that would be impossible with an expensive, 20-year high-energy program. The style of work is different, says Zelevinsky. "In AMO culture, experiments are flexible. A couple of students can redesign an experiment to try something new."

Some tabletop precision experiments expand to larger scales. For example, Zelevinsky, DeMille, and collaborators recently moved their apparatus for measuring the proton's electric dipole moment to Argonne National Laboratory. A permanent electric dipole moment would violate time-reversal symmetry and could give hints about the asymmetry of matter and antimatter, says Zelevinsky.

A tabletop experiment that measures nuclear recoil during beta decay to look for sterile neutrinos—hypothetical particles that interact only via gravity—has led to a follow-on, the Superconducting Array for Low-Energy Radiation. SALER, which is setting up shop at the Facility for Rare Isotope Beams at Michigan State University (see Physics Today, June 2023, page 21), expands the use of rare-isotope-doped superconductors to search for a wide range of exotic new physics, says Kyle Leach, a nuclear physicist at the Colorado School of Mines.

David Miller, a physicist at the University of Chicago, is a member of the 3000-strong ATLAS experiment on the LHC at CERN and also works on the tabletop Broadband Reflector Experiment for Axion Detection (BREAD). He interacts on a daily basis with about 10 ATLAS colleagues, he says. A large collaboration like ATLAS requires different subgroups to coordinate with each other and to have formalized procedures in a way that a small collaboration doesn't need. Another difference, says Miller, is that contributions from any one individual tend to be more "end-to-end" in a small collaboration and more specialized in a large one.

For precision measurements that grow in scale, says JILA's Cornell, "some of the skills of people who manage big collaborations could be merged with atomic physics."

Interplay of approaches

Should collider physicists feel threatened by the low-cost approaches to seeking new physics? Might those approaches be seen as a better investment than a next-generation collider, which would come with a multibillion-dollar price tag? The consensus seems to be no.

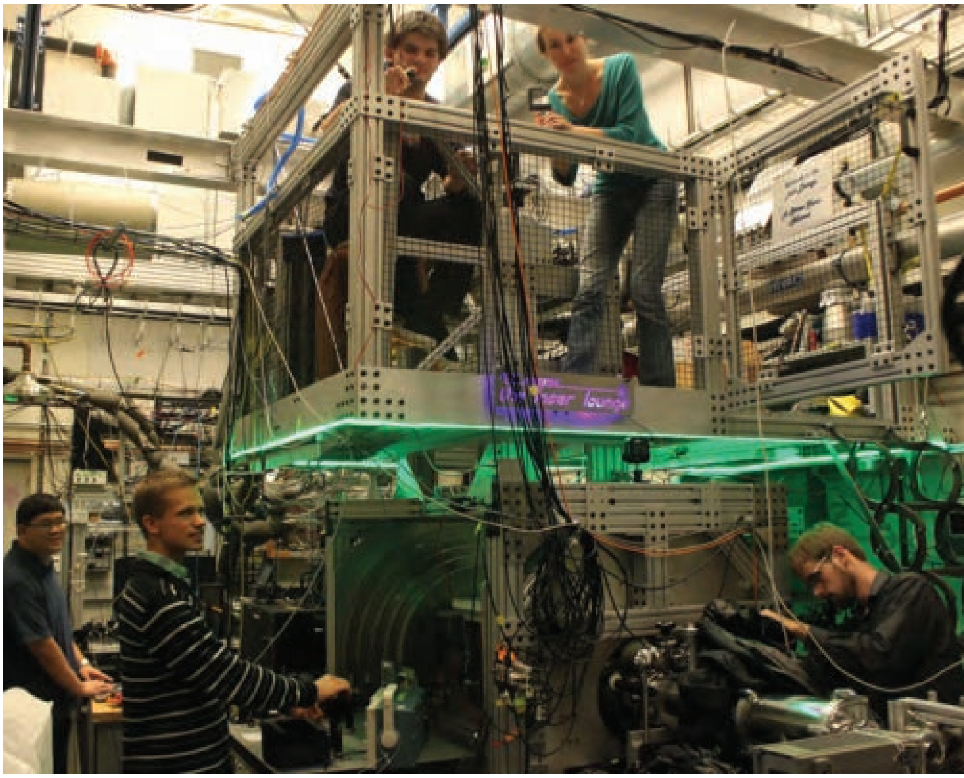
"Collider people debate which collider. The rest of us debate, 'Is a collider worth it?' " quips Berkeley Lab's Carney. "But the search for new physics needs a broad approach."

Precision measurements and high-energy experiments are not in direct competition, says Andrew Geraci, an experimental physicist at Northwestern. If a fifth force is observed, there will be an associated boson, "and you can go look for it with a collider." The discovery of an electron electric dipole moment "would motivate the high-energy-physics strategy," says Gabrielse. "The size of a magnetic moment that we see, or fail to see, places limits on where new physics could be discovered. There is interplay."

For the field as a whole it's good to have studies of different sizes and time scales, says Juan Estrada, a scientist at Fermilab who works on dark-matter and dark-energy experiments. The shorter time scales and lower costs of tabletop experiments "can be attractive for young people to get results," he says, and can provide an opportunity for graduate students to learn instrument building.

"I see colliders and precision measurements as complementary," says DeMille. The LHC is a general-purpose machine, he says. "It's capable of seeing directly—or sometimes indirectly—many different types of particles and fields." In contrast, the electric-dipole-moment experiments, for example, are sensitive only to particles and forces that violate *CP* symmetry, and there is no guarantee that new particles will have that property.

ADAM WEST



ACME IS AN EXPERIMENT to set limits on the electron's electric dipole moment. Here, collaboration members work on an earlier incarnation of the room-sized apparatus when it was housed at Harvard University. The current generation of the experiment is at Northwestern University.

What's most exciting, says DeMille, is that electric-dipole-moment experiments are probing mass scales higher than the LHC will ever be able to do. "If we see clear evidence for an electron electric dipole moment, that would set an upper limit on the mass at which new particles have to appear. That would be healthy for collider physics."

Or, if precision measurements discover axions, says Miller, then it would be "perfectly reasonable" to hypothesize the existence of related particles. "We could detect fundamental properties at BREAD and constrain the parameter space, which could help the LHC look for evidence of particle cousins, like the supersymmetric axino."

"It's an open question as to whether anyone will build the next collider," says Holger Müller, a University of California, Berkeley, physicist who uses atom interferometry to measure the fine-structure constant. "If the LHC had delivered a large number of physics discoveries," he says, "there would be no question. It didn't, so I think it's unclear what will happen. But if the next collider isn't built, it won't be because of precision physics."

Toni Feder

The Deep Space Network: Overburdened and underfunded

NASA's worldwide antenna array is bursting at the seams as new missions head into space.


NASA/JPL-CALTECH

ANTENNAS stationed at NASA's Deep Space Network Goldstone Complex work with two other complexes around the world to communicate with over 40 space missions.

Oversubscription of the Deep Space Network (DSN) has officials concerned about data loss by space science missions. The radio antenna array, operated and managed by the Jet Propulsion Laboratory, is designed to command, track, monitor, and conduct experiments with spacecraft; it currently juggles communications with over 40 space missions from nearly 30 countries. (See "The Deep Space Network at 50," by Joseph Lazio and Les Deutsch, Physics Today, December 2014, page 31.)

Without the DSN, rovers couldn't roam on Mars and *James Webb Space Telescope* (*JWST*) images would never leave the observatory. The network is up to 40% oversubscribed, leaving many missions unserviced at a time when the rate of new launches is increasing. By the 2030s, excess demand on the DSN is expected to reach 50%, according to an audit that NASA's inspector general released in July. Even as demand increases, the DSN budget has decreased by tens of millions of dollars over the past decade.

The DSN consists of three deep-space-communications facilities evenly spaced over the globe to provide around-the-clock communication. They are located in Goldstone, California; Madrid, Spain; and near Canberra, Australia. Each site has a 70-meter antenna that can track spacecraft tens of billions of kilometers away and varying numbers of 34-meter antennas, for a total of 14. The smaller antennas can be combined to strengthen weak signal reception and increase data rates.

As Earth rotates and a craft rises above the horizon at a site, a mission can begin its scheduled communication pass with a DSN antenna. During a pass, operators can receive telemetry, perform radio science experiments, and track and monitor the craft. They also downlink data to Earth. If a spacecraft is still communicating with the DSN when it sets on the horizon at one complex, an antenna at another one will pick up the signal. When the mission has completed its pass, another mission will hop on the antenna. Typically, an antenna can talk to one spacecraft at a time. But a technique called multiple spacecraft per aperture has been applied to communicate simultaneously with a few Mars missions.

The DSN talks to craft that range in distance from 16 000 kilometers away to beyond the solar system. The network still communicates with *Voyager 1*, the farthest spacecraft from Earth. *Voyager 1* was launched in 1977 and is currently more than 38 billion kilometers out. The farther away a craft is, the larger the antenna it needs.

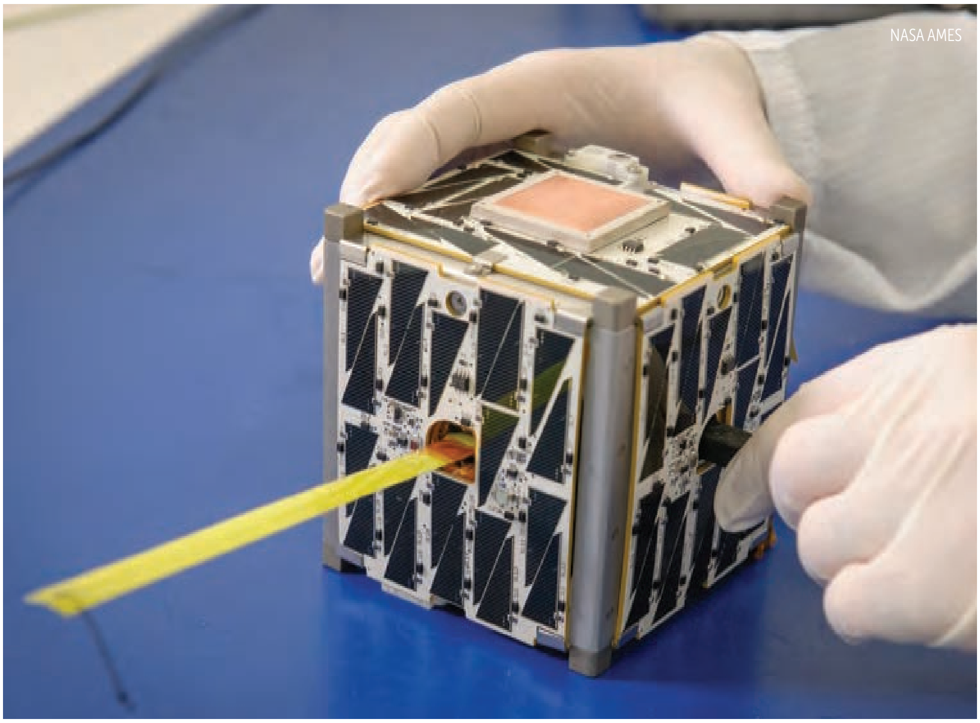
Glen Nagle, the education and public outreach manager at the Canberra site, says the DSN schedule looks like an airport departure board, with its many missions scheduled far in advance and down to the minute. Mission planners at the Space Telescope Science Institute, the Jet Propulsion Laboratory, and the DSN complexes work together to schedule each craft up to a year beforehand. The schedule gets locked in about a month in advance, but can be changed in emergencies. Some spacecraft, such as the *JWST*, have a few passes a day, ranging from two to six hours, says lead mission planner Kari Bosley.

Of the 77 000 hours the DSN supplied to NASA and international partners in 2022, 6732 were devoted to the *JWST*, according to the DSN audit. With 5309 hours, the *Solar and Heliospheric Observatory*, a European Space Agency and NASA spacecraft, was the second largest user. "Recent large missions like the *James Webb Space Telescope* and Artemis have added a significant demand on the DSN as the prime communication link," says Philip Baldwin, acting director of NASA's network services division.

Artemis 1 was a lunar test flight launched on 16 November 2022 that lasted less than a month, splashing down on 11 December 2022. Despite the short flight, it used 1774 DSN hours. One reason the mission consumed so much time on the DSN comes in a Rubik's Cube–sized package: CubeSats. A standard CubeSat measures 10 centimeters on each side and weighs around one kilogram, and up to 24 can be grouped together. They cost tens of thousands of dollars apiece, and that low price tag makes them appealing to universities. CubeSats typically carry out just one or two functions. They might take images of Earth or perform small science experiments, such as measuring Earth's magnetic field.

Artemis 1 launched 10 CubeSats to complete various science experiments. More than half of them lost contact with Earth, and the large DSN antennas were recruited to help find the CubeSats' low-powered transmitters. The CubeSats are "all very experimental in terms of their ability to handle the conditions of deep space," says Nagle. Nearly half of the total DSN hours *Artemis 1* ended up using were to track the lost CubeSats.

Artemis 1 was a test flight, but it garnered priority on the DSN to assess equipment that will be used to ensure the safety of astronauts on upcoming crewed Artemis missions, including the Orion capsule that will carry the crew. "For *Artemis 1*, the DSN provided the only communication link to the Orion capsule as it ventured around the Moon," says Baldwin. "The same will be true for future Artemis missions." Future lunar missions will likely siphon away DSN time from the *JWST* and other missions, and could prevent them from meeting their scientific aims, the DSN audit says.


NASA AMES

CUBESATS, mini-satellites that typically measure 10 centimeters on a side and are often used by students for science experiments, have proved a nuisance for NASA's Deep Space Network. Many of those carried by *Artemis 1* in late 2022 got lost, requiring nearly half of the mission's DSN hours just to track them down.

Even before *Artemis 1* launched, missions had been losing time on the DSN because of excessive demand. Over the last five years, the *Mars Odyssey*, *Voyager 2*, and *New Horizons* each received between 8500 and 15 000 fewer tracking hours than needed. That squeeze has already had a significant impact on NASA's science missions, according to the audit. The missions have faced data loss and at times were unable to send commands, pushing their plans behind schedule.

Fixes falling behind

NASA initiated the Deep Space Network Aperture Enhancement Program in 2010 to accommodate more missions. As of the end of 2022, four of six planned new 34-meter antennas had been constructed. The audit notes that the project is nearly five years behind schedule, and the cost has jumped to $706 million from the original estimate of $419 million. That's apart from the overall DSN budget for operations and maintenance, which shrank from $250 million in 2010 to $213.5 million in 2024. Some aspects of the enhancement project are not expected to be finished until 2029, over a decade behind schedule.

A potential efficiency would be to use higher-frequency signals to increase data downlink rates: What would take days could be reduced to hours with higher frequencies. With data transfers expected to increase 10 000-fold moving into the 2030s, says Nagle, shifting frequencies will help. But more high-power transmitters will be necessary to access those frequencies; the plan to install two 80-kilowatt transmitters contributes $18.1 million to the upgrade's price hike.

NASA is exploring other ways to reduce the DSN load, including expanding the use of tracking multiple spacecraft with single antennas and applying artificial intelligence. Machine learning and AI are already used to help determine when maintenance tasks need to be performed, says Baldwin.

Meanwhile NASA is working with international partners to identify existing antennas that might provide support to the DSN. The agency is designing and building three smaller antennas specifically to assist in the upcoming Artemis missions, and is attempting to procure commercial antenna services to support future Artemis missions, says Baldwin.

Space-communications networks in other countries do not face the same strain as the DSN because they support only their own missions. But a few networks rely on the DSN for their projects. When the Indian Space Research Organisation launched its *Mars Orbiter Mission* in 2013, it used the DSN because India's network only has the capability for lunar distances. The European Space Agency's Estrack network has single antennas in three locations around the world and sometimes leans on the DSN for support.

In sum, says Nagle, the DSN is "a victim of its own success." The communications network has done its job for six decades, he says, but "the strain is showing."

Hannah H. Means PT

Sustainable fabrication of

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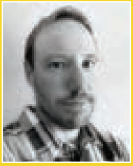
Simon Trudel is a professor of physical chemistry and the director of the nanoscience program at the University of Calgary in Alberta, Canada. He enjoys deciphering the complex structure–property relationships in amorphous materials and creating spin-off technology based on his research.



Amorphous materials are often an unwanted result of low-temperature thin-film deposition. Yet those disordered materials can be used with great effect for applications with stringent manufacturing requirements.

Simon Trudel

organic electronics

Industrial manufacturing is responsible for a great deal of harm to the environment. To help undo the damage, the United Nations has included mitigating the ongoing harm in its "industry, innovation, and infrastructure" sustainable development goal, one of 17 such goals.[1] Several can be tackled through innovation in materials design, engineering, and production. The deliverables are multifold: Simplified, low-cost manufacturing methods enable a more widespread, rapid, and equitable deployment of new technologies. When those technologies are themselves means to harness renewable energy, or to make better use of the energy already available, the benefits are compounded. In addition to being low cost and low energy, manufacturing should also be nimbler and easily implemented.

Manufacturers who follow tenets of green chemistry in an effort to be less wasteful and who forgo using or generating harmful chemicals are crucial.[2] Those tasks may seem daunting, but many of the objectives can be achieved with solution-based processing, which refrains from using high temperatures, high vacuum, and associated, complicated infrastructure and energy requirements.

Solution-based processing technologies can make a big difference in the creation of organic electronics,[2] including organic photovoltaics (PVs) and organic LEDs (OLEDs). As illustrated in figure 1, they are thin-film devices that contain several layers, each of which plays a key functional role.

The active layer carries out the device's function: light absorption in a PV cell, or light emission in an OLED. On both sides of the active layer are charge-transport layers, which selectively move positive or negative charges to and from the active layer. Electrical contact is completed through conducting materials on both sides. In optoelectronic devices, at least one of the contacts, usually a conducting oxide, must be transparent. The device resides on a substrate, such as glass or a flexible plastic. In a fully organic device, all layers would be based on organic small molecules or polymers, but it is common for at least one of the layers to be an inorganic material, such as a metal oxide.

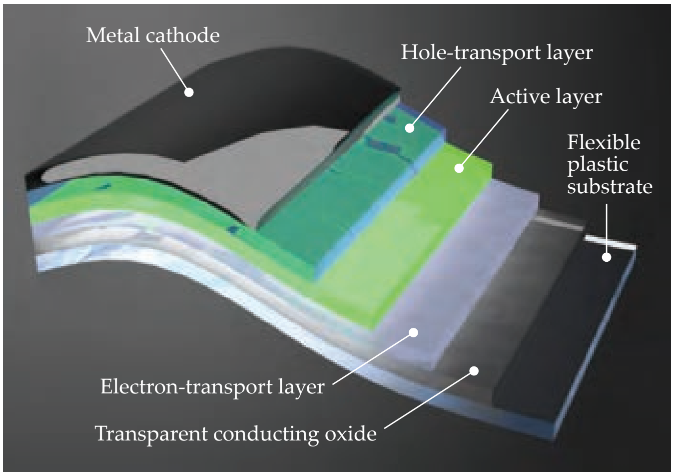


FIGURE 1. ORGANIC LED ARCHITECTURE, showing the multiple layers used to carry charges to the active layer responsible for light emission. The charge-transport layers are the electron-transport layer, the hole-transport layer, and the conductive transparent oxide. The layers can be made more eco-friendly by using metal oxide thin films.

In both organic PVs and OLEDs, charges must flow in a single direction. That is facilitated by the charge-transport layers, which selectively allow the transit of negative charges (electrons) or positive charges (holes). The unidirectional flow of charge is essential to device performance.

Organic semiconductors have been extensively studied as potential charge-transport layers. Organic materials, however, can become unstable when they react with moisture in the air or with the adjoining active layer. Furthermore, their thermal stability imposes a maximum temperature, or thermal budget, that must not be exceeded during device fabrication.

As an alternative, metal oxide thin films, which are touted for having a high chemical and thermal stability, can be used as charge-transport layers. For efficient layers, transition metal oxides can be used; examples include tin oxide and zinc oxide for electron-transport layers, nickel oxide and molybdenum oxide for hole-transport layers, and zinc indium tin oxide and zinc indium gallium oxide for conductive transparent oxides. To improve the commercial viability without compromising the efficiency of the finished device, room-temperature, solution-phase processing techniques to form metal oxides need to be adopted.

Typical metal oxide synthesis

The classic recipes for synthesizing metal oxides are hardly considered sustainable. The ubiquitous shake-and-bake approach relies on mixing metal oxides or salt powders, milling those starting materials to a fine powder, and firing them at high temperatures, often as high as 1000 °C, over periods of hours to days.[3] That process often needs to be repeated more than once for the reaction to go to completion. The approach provides a straightforward means to produce well-crystallized, single-phase functional metal oxides in bulk quantities, but it is slow and energy-intensive. The high temperature and long reaction times are indicative of the processes involved: namely, the calcination of the starting materials to separate components and remove impurities, the solid-state diffusion of the ions that is required to form a homogeneous material, and the formation of the thermodynamic product of choice—a crystallized oxide of the desired phase. The large crystals that are formed are not amenable to integration in thin-film devices.

So how are metal oxide thin films typically formed? The table on page 27 compares thin-film deposition methods.[4] One family of methods uses metal oxides as starting materials. While binary metal oxides can be procured from commercial vendors, custom complex oxides containing two or more distinct metals will typically be formed through the solid-state shake-and-bake process previously described. Those metal oxides are then vaporized and allowed to condense on the surface of a cooler substrate, thus depositing a thin film. For metal oxides with a low enough boiling point, vaporization can be achieved by simply heating the source metal oxide in a crucible. The heating is carried out in a vacuum chamber, which adds to the technical requirements of an otherwise simple approach. Such solid-state synthesis methods are used to form molybdenum oxide thin films that are used as hole-transport layers in PV devices.

Other methods, such as sputtering and pulsed laser ablation, can be used to vaporize the metal oxide. In those cases, the energy required to eject material from the source target is gained from collisions with ions, high-energy electrons, laser pulses, or a plasma. Such physical deposition methods can yield high-quality films but are rarely amenable to large-scale synthesis because of the large vacuum chambers that would be required. Metal oxide layers in thin-film devices are typically fabricated through sputtering, whose requirements pose a challenge to large-scale sustainable commercialization. For example, currently available transparent conducting oxide layers, such as tin-doped indium oxide, are prepared by high-vacuum techniques and represent a further inefficiency in device manufacturing.

To form large-scale, uniform thin films, fabricators use methods that typically rely on gas-phase chemistry, including chemical vapor deposition and atomic layer deposition. In those cases, a volatile metal-bearing precursor will be decomposed on or near the substrate's surface to yield the metal oxide. Again, the methodology relies on complex instrumentation, controlled atmospheres, elevated temperatures, and the handling of hazardous reactants. Some precursors are highly toxic and must be rigorously contained to avoid accidental release.

Researchers have developed solution-based methods to decrease both the energy and complexity of metal oxide thin-film deposition. One such method relies on sol-gel chemistry: Metal-containing precursors are mixed with chemicals that lead to the formation of the sol, a colloidal suspension that then reacts to form a gel, a semisolid material with a bonded network in three dimensions.[3] The solution can then be delivered onto a substrate. Subsequent heating leads to the calcination of the film, which turns into a solid metal oxide.

Technically, it is a much-simplified approach because the reaction occurs at low temperature and can happen in everyday glassware. One advantage of using solution processing rather than solid-state diffusion is that the intimate mixing of

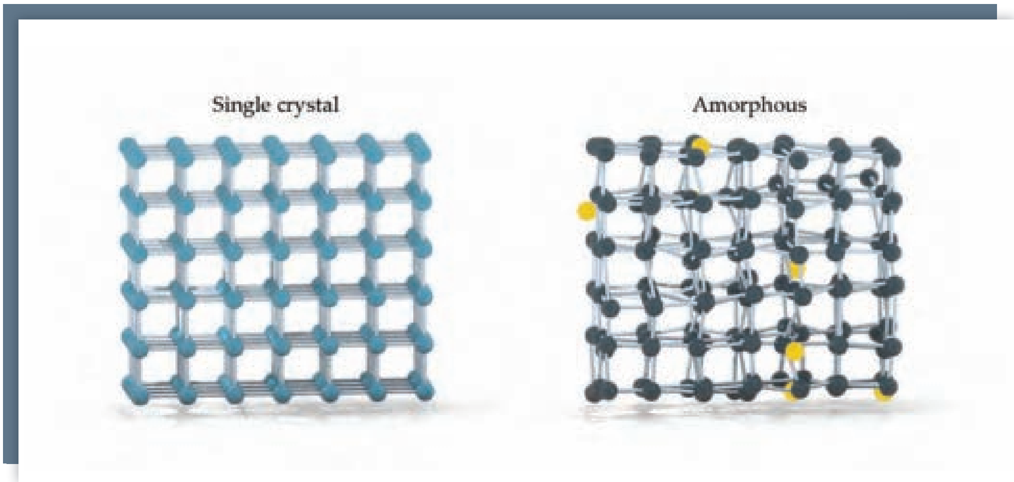


FIGURE 2. MATERIALS ARE ORDERED OR AMORPHOUS. When researchers know the position of a single atom in a single-crystalline material (left), they can position the other atoms in all directions. By contrast, they cannot do that in an amorphous material (right) because it lacks a regular arrangement of the atoms. The bond distances between next nearest neighbors are not well defined, and neither is the symmetry around each atom. Several defects, such as vacancies (shown as yellow spheres), are also present.

atoms necessary for the formation of a homogenous material is greatly simplified. Such mixing ensures that the process does not spend a large portion of the device's thermal budget. Temperatures ranging from 400 °C to 600 °C are still required to convert the gel into the metal oxide.

While sol-gel synthesis is a step in the right direction, the temperature range is still too high to be compatible with many organic optoelectronic devices. At those temperatures, organic functional materials are likely to melt, react, or altogether decompose. Doped indium oxide, for example, is a ubiquitous transparent conducting oxide used in myriad optoelectronic devices where light must be transmitted through a substrate. That transparency is crucial in PV devices so that the light can reach the light-absorbing layer and in LEDs so that the light is efficiently transmitted. Unfortunately, tin-doped indium oxide is unstable above temperatures of approximately 250 °C;[5] heating it above that temperature greatly decreases its conductivity and thus limits its use and the thermal budget of any device incorporating it.

An advantage of organic electronics is the prospect of using them on a flexible plastic substrate, such as polyethylene terephthalate. Coincidentally, polyethylene terephthalate starts melting in the same 250–260 °C range. As such, keeping the thermal budget to below 250 °C has been a longstanding goal.

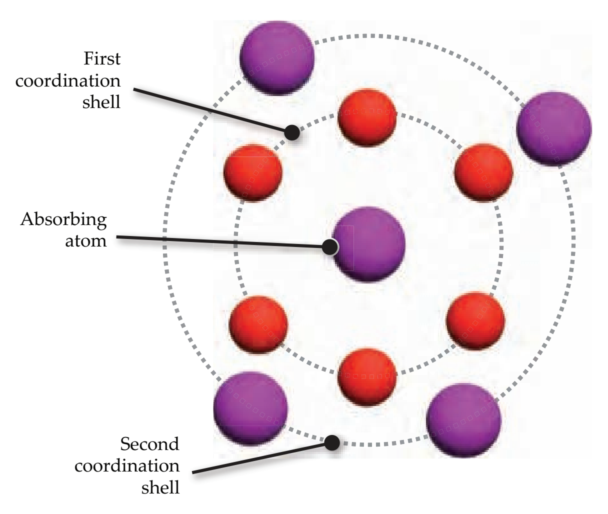
Amorphous materials

If the thermal input during material formation is reduced, the atoms do not get to move and sample various arrangements with their nearest neighboring atoms to achieve the thermodynamically preferred configuration. As such, there is an increased probability that they form an amorphous material (see figure 2). Importantly, the amorphous state is a metastable one, meaning the atoms are frozen in a kinetically trapped arrangement.[6] Given the chance, an amorphous material will irreversibly crystallize into a well-ordered material when sufficient energy, such as a high temperature, is provided. Amorphous materials are notoriously difficult to characterize.[3] Instead of long-range atomic ordering, they have only short-range order, typically just a few shells of neighboring atoms. Even in those small regions of localized order, bond distances and angles will display discrepancies from atomic site to atomic site.

Thin-film deposition methods

✗ Not a component or benefit of the method
▬ Sometimes a component or benefit of the method
✓ A component or benefit of the method

Method	Solution process	Ambient atmosphere	Simple equipment	Low temperature	Large-area films
Solid-state synthesis	✗	✓	✗ high-*T* furnace	✗	✗
Physical deposition sputtering, pulsed laser ablation	✗	✗ vacuum chambers	✗ vacuum chambers	✗	▬
Chemical deposition chemical vapor deposition, atomic layer deposition	✗	✗	✗	✗	✓
Sol-gel	✓	✓	✓	▬	✓
Combustion	✓	✓	✓	✓	✓
Photodeposition	✓	✓	✓	✓	✓



X-ray absorption spectroscopy

Deciphering structure–property relationships in disordered, amorphous materials is as challenging as it is necessary in order to drive the design of new materials with customized and optimized properties. The golden method to achieve that is based on a quantitative analysis of the absorption of x-ray photons.

In x-ray absorption spectroscopy, the energy of the incident photons is typically 1000–10 000 times as much as the energy of the photons used in UV–visible spectroscopy. Upon absorption of the high-energy x-ray photons, electrons from deep-lying energy levels (such as a 1*s* orbital in what's termed *K*-edge spectroscopy) are excited to vacant energy levels or, when sufficient energy is provided, photoemitted into the vacuum. That family of methods provides element-specific information about an atom's oxidation state, coordination geometry, and local structural arrangement.

Photoelectrons created from the absorption of x-ray photons will propagate as an outgoing wave. As that wave travels through the material, it will scatter off neighboring atoms. Scattering will produce interference in that outgoing wave, resulting in an absorption spectrum that varies with the energy of the incident x rays. The oscillations observed in the absorption spectrum are called the extended x-ray absorption fine structure.

By analyzing that pattern, one can determine the type, occurrence, and distance of atoms around the atom that initially absorbed the x-ray photon. Although the analysis does not provide a direct atomic structure of the material, it does give the distances between the absorbing atom and its neighboring atoms, from which details about the atoms' coordination and bonding can be inferred. That information is available irrespective of the crystallinity of the material, making x-ray absorption spectroscopy a tool of choice to study amorphous materials, for which diffraction-based methods are ineffective.[7] Until recently, x-ray absorption spectroscopy experiments were possible at only synchrotron light sources. Newly available commercial, lab-scaled instruments will accelerate the use of the method in materials science.

Diffraction methods, such as x-ray and electron diffraction, that rely on well-ordered periodic arrangements of atoms will return featureless patterns for amorphous materials. That makes identifying the local structure in amorphous materials challenging. Given the localized regions of order, methods that can probe the short-range atomic arrangement are necessary to elucidate that structure. A prominent family of methods uses synchrotron-based analysis, such as extended x-ray absorption spectroscopy[7] (see the box at left) and the atomic pair distribution function technique. The latter method analyzes the diffuse scattering of x rays that occurs in disordered materials. Such an analysis yields the likelihood that a pair of atoms are separated by a given distance. Although the methods are quite different, both ultimately yield insight into the structure in disordered materials.

Nanobeam electron diffraction, carried out in a transmission electron microscope, is another approach to structurally characterize amorphous materials.[6] A highly focused electron beam is directed toward a suitably thin (less than 100 nm) sample. The microscope focuses the beam to an approximately 0.1 nm spot size to ensure that the beam interacts and scatters from only a few atoms at a time. The scattered electron beam forms a diffraction pattern on the detector. Instead of sharp diffraction spots characteristic of crystals, amorphous materials typically produce ring-like diffraction patterns in nanobeam diffraction. The radius and intensity of the rings can be analyzed by pair distribution function analysis to reveal information about nearest-neighbor distances, coordination numbers, and short-range order in the amorphous structure.

The difficulties involved in characterizing disordered materials lead to conflicting reports of their physical properties. Unlike crystalline materials with well-defined structural features that can be easily identified and cataloged, not all amorphous materials are created equal. That idea, called "polyamorphism," proposes that multiple structural instances of a given composition may exist in amorphous states. For example, a material may be densified through annealing but remain amorphous.

In addition to the inherent challenge in elucidating their structural characteristics, the electronic properties of amorphous materials can be difficult to understand. The lack of well-defined, or well-characterized, structure restricts the utility of computational methods. The myriad atomic configurations present in amorphous materials are difficult to capture in simulations, which typically rely on so-called melt-and-quench molecular dynamics methods. Because the properties of amorphous materials are known to be highly dependent on the preparation method, it is difficult to ensure that a simulated amorphous structure bears relevance to the laboratory sample.[8] The same diversity of atomic configurations leads to a smearing of the electronic energy levels and the creation of new electronic bands and defect sites.[6] Those defect sites tend to be deeper in amorphous materials, meaning that charge carriers that get trapped in such defects will require more energy to be able to escape from them.

Despite the paucity of information available in the literature, amorphous materials have found important applications in many technological devices. Two contemporary examples of preparation methods for amorphous materials are combustion[9,10] and photochemical deposition.[11]

Combustion method

The combustion method remains a thermal decomposition approach, with the exception that the temperature is locally delivered through a highly exothermic reaction. Combustion requires three elements: an oxidizer, a fuel, and an ignition source. Combining an oxidizer, such as a metal nitrate, and a fuel, such as urea or acetylacetone, provides two of the elements needed to form metal oxides; myriad fuels and oxidizer combinations have been demonstrated. Under ideal conditions, the combustion reaction could reach temperatures of up to 700 °C and be ignited at temperatures as low as 200 °C. The process is efficient: Not only does the reaction occur rapidly, it runs cleanly, removing any impurities in the process. The temperatures are compatible with organic materials on flexible plastic substrates.

The oxidizer and fuel mixture can be delivered by various methods, including spin coating, inkjet printing, and blade coating. That makes the combustion method amenable to large-scale area deposition.

As expected, the low temperatures can lead to amorphous materials. A particularly successful family of amorphous oxide semiconductors is based on post-transition metal oxides.[9] (The post-transition metals, which include aluminum, indium, and tin, are located between the transition metals on the left and nonmetals on the right in the periodic table.) For example, amorphous indium gallium zinc oxide[12] has been successfully commercialized in displays, where they are part of thin-film transistors.[9] The success of post-transition metal oxides lies in their electronic structure. The conduction path in covalent semiconductors such as silicon relies on highly directional sp^3 orbitals responsible for the tetrahedral geometry around the atoms. In the amorphous state, the fluctuation in bond distances and angles between atoms disrupts the bonding overlap, thus reducing conductivity. Indeed, the electron mobility in amorphous silicon is approximately 1/200 that in single-crystal silicon. In post-transition metal oxide semiconductors, the electrons can travel through diffuse and spherical *s* orbitals.

The lack of strong directionality means that bonding and conductivity are not as sensitive to structural disorder.[13] As such, the electron mobility in amorphous indium gallium zinc oxide exceeds that of amorphous silicon by an order of magnitude, making the oxide a useful semiconductor in consumer devices.

Photochemical deposition

A different means of delivering the required energy to convert a precursor to the desired metal oxide is to use photons rather than heat. That method is called photodeposition, depicted in figure 3. One way a light-sensitive precursor is applied as a solid-state thin film is by spin-coating a solution containing the precursor. A suitable metal-containing precursor first needs to be identified. To be solution-processable, the precursor must be soluble, which is accomplished by choosing an appropriate molecular group, called a ligand, that binds to the metal center. For example, metal centers that are bound to carboxylate and β-diketonate ligands become light-sensitive precursors.

The film is then exposed to UV light, which triggers a ligand-to-metal charge-transfer excitation and ultimately leads to precursor decomposition and the formation of a metal oxide. The process is conducted entirely in air. The precursors are soluble in various organic solvents and can be delivered onto the substrate by a wide complement of methods, including spin coating, dip coating, spray coating, and printing. Photodeposition has been shown to be extremely versatile, compatible with essentially all the transition metals, the alkali and alkaline-earth metals, and the lanthanides and several elements from groups 13 and 14 as well as post-transition metals.

Additionally, the composition of the metal oxide obtained through photodeposition is easily controlled through the ratio of metal precursors in the initial precursor solution; that control allows easy access to binary, ternary, and more complex oxides. Because there is no thermal input, the atoms in the formed film do not have the necessary thermal motion required to sample various configurations and form a stabilized

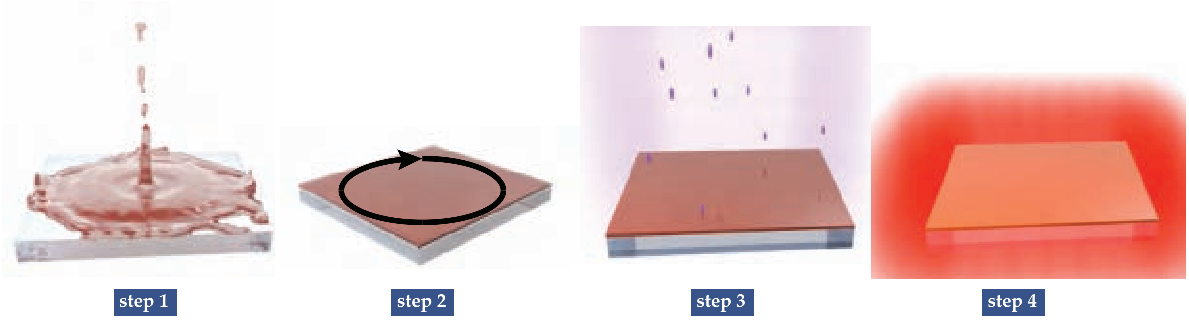


FIGURE 3. THE PROCESS OF PHOTODEPOSITION, which includes coating a substrate with a light-sensitive, metal-containing precursor, involves three primary steps and one optional treatment. It begins with spin coating: the precursor material is applied (step 1) and the sample spun quickly (step 2) to spread a thin film across the material evenly. Next, the precursor thin film is irradiated with UV photons (step 3) to trigger charge-transfer excitation. Annealing (step 4) is an optional low-temperature step to further tune the material. Photodeposition does not require the high temperature of other methods and can be applied across a large area.

crystalline material; instead, they form a kinetically trapped amorphous material. The metal oxides can be further tuned via an optional low-temperature annealing step.

When it comes to device fabrication, photodeposition can be used to directly pattern the metal oxide without the need for photoresists, thus streamlining the process and reducing waste. The precursor thin film is exposed through a photomask, which provides a template for which areas of the film are converted to the metal oxide. So-called negative- and positive-tone direct-write photolithography and electron-beam lithography have all been shown to work in a breadth of applications compatible with most semiconductor manufacturing techniques.

Photodeposition has been used to fabricate both organic PV cells and LEDs.[13,14] Previous work demonstrated that photodeposited metal oxides could supplant PEDOT:PSS—an organic polymer often used as a hole-transport layer in organic devices. That polymer benefits from being easily processed in solution, but its strong acidity can lead to the degradation of adjoining organic layers and of semiconductor device performance, so researchers are currently looking for an alternative to the polymer.[15]

One replacement candidate being explored for the hole-transport layer is copper oxide. In one set of experiments, a series of copper oxide thin films were photodeposited and then annealed in air to moderate temperatures (below 250 °C, constrained by the stability of indium tin oxide described above).[14] An initial x-ray diffraction study showed that all samples were amorphous—their diffractograms didn't show any features. Organic PV device performance told a different story. The as-prepared copper oxide thin films rendered barely functional devices. The behavior was maintained until an annealing temperature of 150 °C was reached. A drastic change in performance occurred at 200 °C and above, where the devices became fully functional.

Based on the drastic changes in the copper *K*-edge x-ray absorption spectra, the change in behavior was ascribed to a rarely observed amorphous-to-amorphous phase transition. Those spectra are characteristic of both the local atomic geometry and the oxidation state of the copper atoms. The low-temperature nonfunctional copper oxide was identified as Cu_2O, which oxidizes to CuO between 150 °C and 200 °C. Identifying such amorphous-to-amorphous phase transitions is challenging without the use of x-ray absorption spectra.

While the photodeposited amorphous copper oxide is a good step in the direction of identifying a replacement for PEDOT:PSS, it still requires a thermal treatment, albeit at temperatures that are fairly low. To decrease—or even completely remove—the thermal input, vanadium oxide thin films were used as hole-transport layers.[15] The as-deposited films were amorphous; they crystallized to form nanocrystalline V_2O_5 at 250 °C. No significant benefit was found for thin films created with annealed vanadium oxide instead of the unheated, room-temperature material.

Scaling up

In 2007, OLEDs were commercialized in Sony televisions.[16] With a market size of up to $25 billion, organic electronics are poised to see an ever-increasing share of day-to-day devices. Yet the organic PV market is still facing challenges toward successful commercialization.[17]

Of the materials and methods discussed here, both the combustion and photodeposition methods are rapid, scalable, and compatible with current thin-film fabrication and printing methods. As such, they offer enormous advantages over conventional oxide deposition techniques. Manufacturing opportunities can arise as new amorphous, metastable materials, which may not be thermodynamically stable, are formed. Amorphous materials open up a new parameter space for material discovery, and they are well suited to high-throughput screening. In particular, high-entropy oxides, which contain several (typically five) metals, present a new emerging field of highly tunable materials properties.[18] With their demonstrated ability to form multimetallic oxides, both combustion and photodeposition are poised to change the future of the field.

Several necessary steps are available to sustainably implement those fabrication methods. Full life-cycle analyses would likely shed light on areas where improvements need to be made. While reducing the thermal input is a step in the right direction, other aspects must be critically analyzed, such as the use of green solvents. The speed of the process should also be improved. That is especially important for making processes high-throughput, particularly when such approaches as roll-to-roll manufacturing are considered. The slowest step will dictate the speed of the process. Reducing the exposure time in photodeposition will have a huge impact on its commercial applicability.

The observation of amorphous-to-amorphous phase transition poses a new challenge. Researchers need to recognize that those transitions can have a determining influence on the functional properties while also presenting new opportunities and avenues for research. The advent of commercial turnkey x-ray absorption spectroscopy will catalyze such research and remove the need for synchrotron facilities to elucidate structure–property relationships in amorphous materials.

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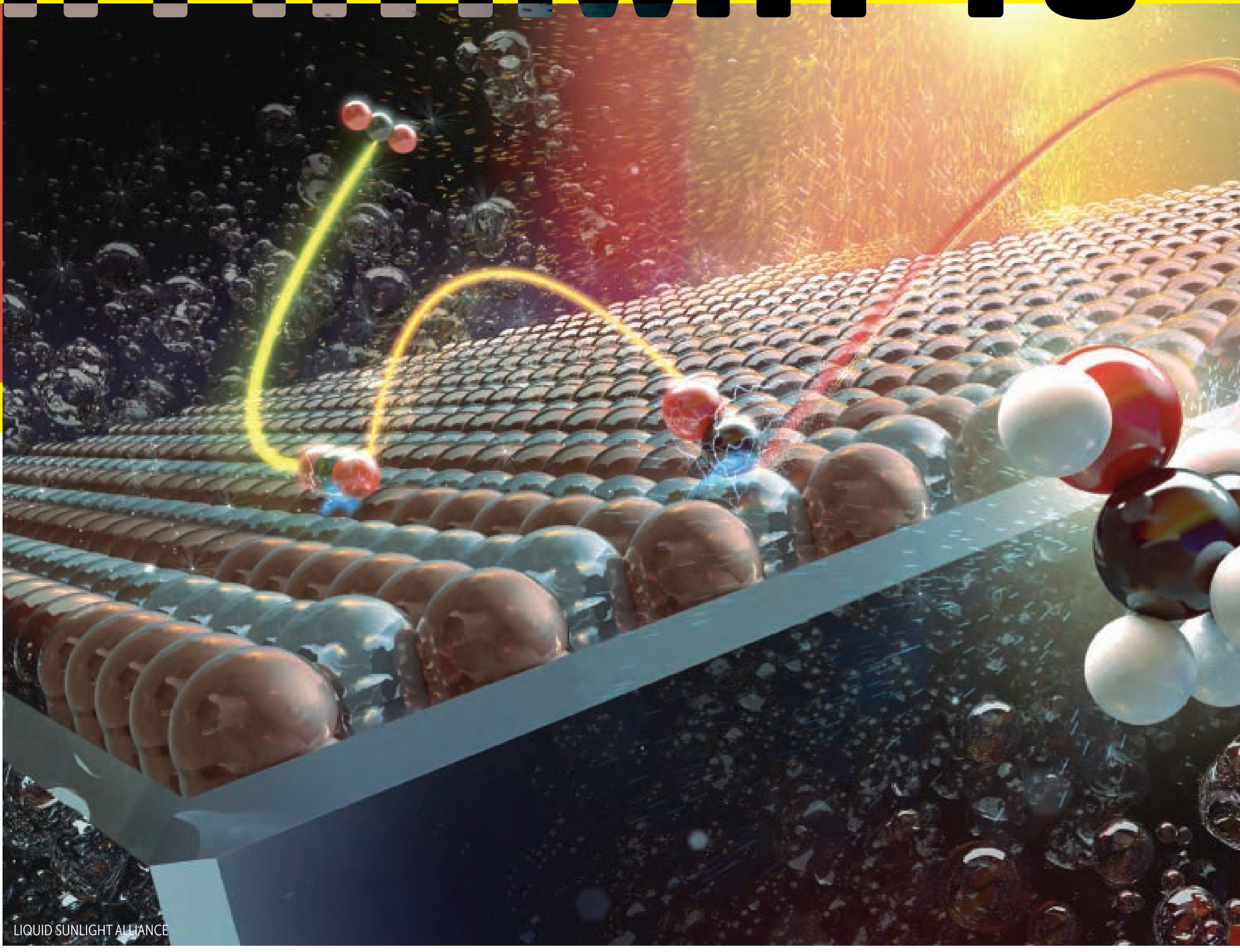
For full consideration, application materials should be submitted by Nov. 27, 2023. Early applications are encouraged. Offers for this appointment are contingent on the successful completion of a background screening. Candidates must meet all degree requirements before the start date of the position. The University of Michigan is supportive of the needs of dual-career couples and is an Affirmative Action/Equal Opportunity Employer. Women and members of minority groups are encouraged to apply.

ARTIFICIAL PHOTOSYNTHESIS: A PATHWAY TO



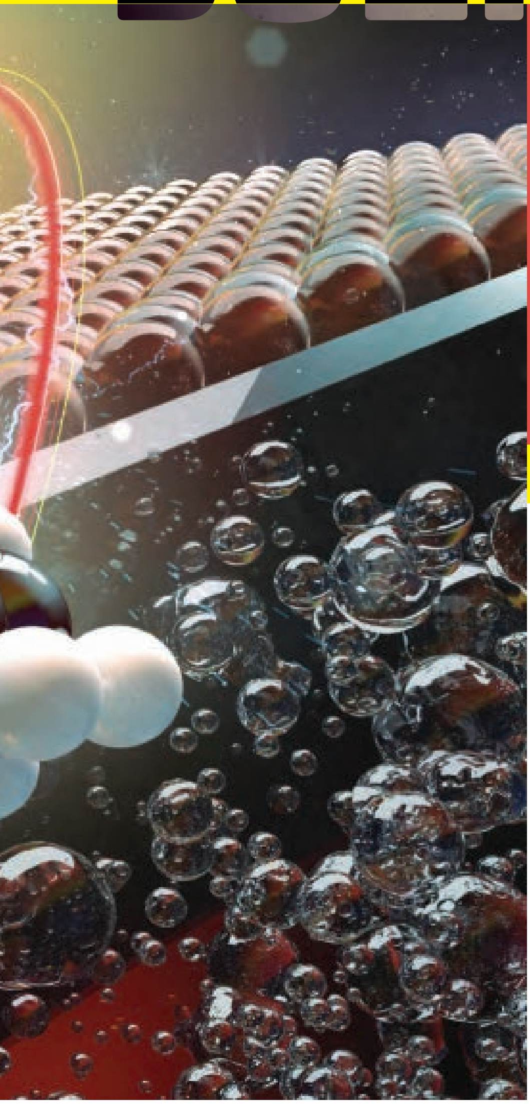
LIQUID SUNLIGHT ALLIANCE

Harry Atwater is the Howard Hughes Professor of Applied Physics and Materials Science and director of the Liquid Sunlight Alliance, a Department of Energy solar-fuels hub project, at Caltech in Pasadena, California.

SOLAR FUELS

Harry A. Atwater

Taking inspiration from nature and from the success of photovoltaic solar conversion, scientists are developing foundations for sunlight-driven synthesis of fuels, chemicals, and materials.



The urgent need to address climate change has motivated an international effort to rapidly decarbonize our world's energy systems. In its most recent report,[1] the Intergovernmental Panel on Climate Change outlined the challenges we face. It articulates a two-part strategy: First, move away from reliance on fossil fuels as soon as possible, primarily by the electrification of large sectors of our economy. Second, capture carbon from the atmosphere to mitigate the warming associated with greenhouse gas emissions. During that effort, large sectors of the economy will likely remain difficult to decarbonize. For example, future long-haul aviation will continue to require hydrocarbon fuel.[2] For such sectors, a circular carbon economy will need to be established, in which the use of hydrocarbon fuels is balanced by carbon capture and conversion.

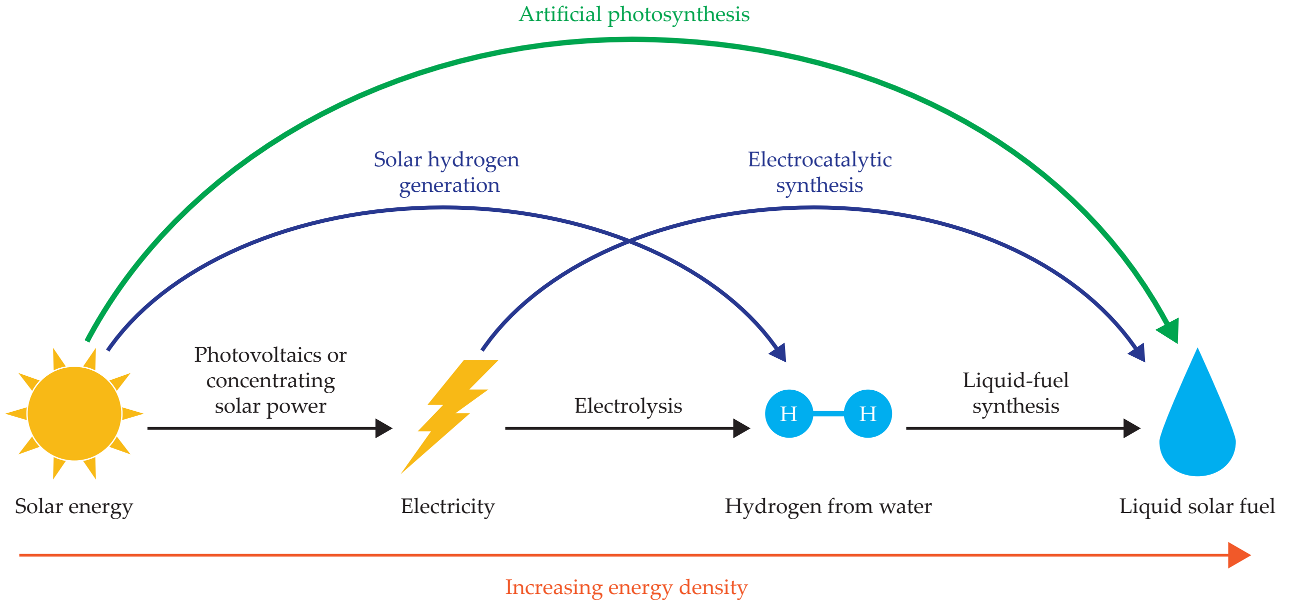


FIGURE 1. PATHWAYS for sunlight-driven chemical transformations of water and carbon dioxide into fuels. The green arrow indicating a direct pathway via artificial photosynthesis represents a single-step process for generating liquid-hydrocarbon and oxygenated fuels. The blue arrows indicate indirect pathways that can be combined to achieve liquid fuels. The processes include photoelectrochemical hydrogen generation, solar thermochemical hydrogen generation, photovoltaic or concentrating solar power for electricity production, electrolysis of water to make hydrogen, electrocatalytic synthesis of fuels using electricity, and liquid-fuel synthesis by chemically combining hydrogen and CO_2. (Courtesy of Liquid Sunlight Alliance.)

Nature is remarkably adept at carbon capture and conversion through the photosynthesis of plants, algae, plankton, and other organisms that make up the biosphere. As scientists investigate new mechanisms for large-scale conversion processes to meet the needs of our energy transition, an important pathway to explore is that of artificial photosynthesis, which seeks to emulate nature's example by using engineered photoelectrochemical systems to synthesize solar fuels, chemicals, fertilizers, and other materials. Artificial photosynthesis thus has the exciting potential to create most of the chemical products required by our industrial civilization through using the ultimate source of abundant, renewable energy—our sun.

Energy-conversion landscape

Solar-fuel systems use photoexcitation, chemical transformation, and transport processes to produce fuel.[3] A typical system includes light absorbers integrated with oxidation and reduction catalysts, membrane separators, and water-based electrolytes. Three central chemical reactions are involved in the artificial photosynthesis of carbon-containing products: the oxygen-evolution reaction, the hydrogen-evolution reaction, and the carbon dioxide–reduction reaction, as described in the box on page 35.

Each component must be designed so that the system efficiently uses the sunlight's energy to cause a reaction of water and CO_2 that produces fuel. The two primary types of solar-fuel systems are those generating H_2 as the fuel[4] and those reducing CO_2 to gaseous, liquid, or oxygenated hydrocarbons, such as ethanol,[5] as depicted by the green path in figure 1. Although they share common features, the two types have distinct advantages and challenges. The H_2-generating system consumes only water and produces a single fuel (H_2), but it requires corrosive electrolytes to achieve high efficiency.

In natural photosynthesis, plants use sunlight to convert water and CO_2 into sugars and carbohydrates. That process, however, is not efficient: Plants convert only about 1% of sunlight energy into stored fuel as plant biomass. Plants can also propagate themselves and use low CO_2 levels in the atmosphere. To be viable alternatives, nonbiological systems must achieve an efficiency of at least 10% by directly producing useful fuels rather than bulky biomass, because they cannot repair or replicate themselves.

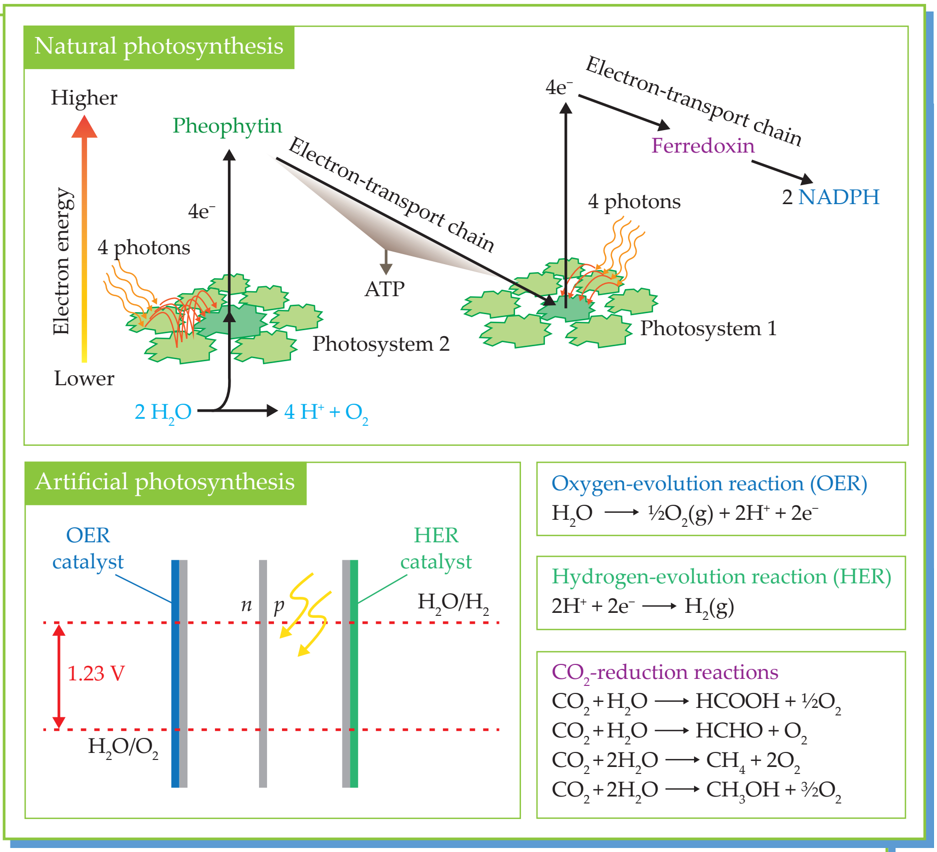
Solar-fuel systems must be capable of operating outdoors for years, which requires that their active components be durable and withstand daily temperature and seasonal weather changes. Corrosion at the liquid–solid interface can be a problem caused by the acidic or basic conditions inherent in the electrolyte or generated by reactions at the electrode. Potential-dependent corrosion of the catalyst or light absorber can also occur.

The water-splitting process—the production of hydrogen gas from the decomposition of water—which is crucial for the systems, demands two catalysts: one for oxygen evolution, which produces O_2 molecules and protons, and another for hydrogen evolution, which assembles H_2 molecules from protons. Oxygen evolution usually occurs in either acidic or basic environments, but catalysts for the process tend to be unstable in highly acidic environments, except for those based on the rare precious metals iridium and ruthenium.

Storage and distribution of H_2 are challenging, because it must be carefully separated from the byproduct oxygen (O_2) gas to avoid forming an explosive mixture. On the other hand, CO_2-consuming generators can operate with less-corrosive electrolytes and produce a fuel much like existing fossil fuels, such as natural gas and petroleum. That advantage allows engineers to leverage existing energy storage, distribution, and utilization infrastructure.

The reaction of CO_2 with water results in a mixture of different products and has low energy-conversion efficiency be-

Energy conversion in natural and artificial photosynthesis



Natural photosynthetic systems, such as chlorophyll, use two light-harvesting centers, photosystem 1 and photosystem 2, in a tandem configuration to create the chemical energy needed to produce adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH), two key sources of energy used by life at the cellular level. By analogy, efficient artificial photosynthetic systems like the one shown here can also use a tandem light-absorbing system consisting of two series-connected semiconductor photoelectrodes. The absorptions of photons (yellow) produce the photovoltage needed to drive the fuel-forming reactions—either water splitting (the production of hydrogen by the decomposition of water) or carbon dioxide reduction.

Alternatively, one can design a simpler but less efficient system (not pictured here) that uses a single semiconductor photoelectrode with a wider energy gap to absorb sunlight and produce the 1.23 V potential required for water splitting. Artificial photosynthetic systems also use either heterogeneous or molecular catalysts integrated onto the photoanode and photocathode surfaces to perform the oxidation and reduction reactions, respectively, needed for fuel formation. Although photoelectrochemical water splitting has only two fuel-forming reactions, various pathways exist to produce fuel in CO_2 reduction, thanks to the richness of carbon chemistry.

Copper is the most important heterogeneous catalyst for CO_2 reduction because of its ability to produce multicarbon products. It typically produces them with little chemical selectivity, though. Thus a key challenge in solar-fuel systems designed for CO_2 reduction is achieving the required chemical selectivity to produce a single product with high yield rather than many products.

cause of low reactant concentrations and the complexity of the reaction mechanisms. The main technical challenges lie in achieving either high solar-to-fuel efficiency with multiyear durability or high product selectivity using CO_2.

Electrochemical conversion reactions can be coupled to sunlight indirectly—for example, by combining photovoltaics and electrolysis[6]—which optimizes the light-harvesting and catalytic processes that produce liquid fuels. They can also be directly coupled using integrated artificial photosynthetic systems, with the advantages those systems offer for integrated design, chemical control, and direct use of energy from sunlight.[7]

In many direct solar-fuel systems, bulk semiconductors absorb light and generate the photovoltage needed to drive fuel-forming electrochemical reactions. The photovoltage required to split water or drive the CO_2-reduction reactions at high (greater than 10%) solar-to-fuel efficiencies can be achieved using multiple photoabsorbers in a series-connected tandem configuration.[8] With their exceptionally high photovoltages, multijunction III–V semiconductors have been a popular choice for more than two decades. Silicon, which is dominant in the microelectronics and photovoltaic industries, has also found extensive use. Some of the earliest work on photoelectrochemical systems involved metal chalcogenides and chalcopyrite- and kesterite-type semiconductors because of their tunable bandgaps, which are ideal for solar-fuel generation.[9]

Computation, high-throughput synthesis, and data mining have accelerated the discovery and development of new semiconductor materials for solar fuels.[10] Those semiconductors, however, still suffer from excessive corrosion in aqueous electrolytes when they're used as photocathodes, and that corrosion limits their durability.[11] Semiconductor photoelectrodes can be protected using inert overlayers such as titanium dioxide,[12] though flaws in the coatings can reduce their efficacy. The fundamental science underlying photocorrosion reactions and kinetics—and how to control them—is an important research area for artificial photosynthesis because of the need for durable materials, as I'll discuss later.

Water splitting

The first demonstration of direct solar-driven synthesis of fuels was reported in 1972 by Akira Fujishima and Kenichi Honda, who generated hydrogen by photoelectrochemical water splitting using a TiO_2 crystal as a semiconductor absorber.[13] Their device also oxidized water on the TiO_2 surface and generated hydrogen gas with a separately wired platinum electrode. In 1983 Melvin Calvin, a chemistry professor at the University of California, Berkeley, published a groundbreaking paper establishing conceptual links between natural and artificial photosynthesis. In that work, he likened the components of a solar-fuel system to the components of biological systems containing micelles and vesicles.[14]

Over the past 15 years, researchers have made tremendous progress designing the architecture for photoelectrochemical, water-splitting solar-fuel generators. Modeling of solar-fuel prototypes has also been critical for guiding materials development because it defines the operational conditions and constraints for various cell designs. Researchers have used chemically selective membranes to develop strategies for stabilizing systems while ensuring greater than 10% solar-to-hydrogen conversion efficiency. The durability of photoelectrodes—in particular, their resistance to photo-induced degradation processes—was enhanced by the development of interfacial protection layers and hybrid composite coatings to prevent corrosion in acidic or basic electrolyte environments.

The advances in each of those areas, together with predictive models for design, have enabled researchers to make rapid progress increasing the efficiency of photoelectrochemical water-splitting devices. Figure 2 illustrates the result of that research: a device with a demonstrated 19% solar-to-hydrogen efficiency.[15]

Advanced water-splitting prototypes combine photonic design, transparent-catalyst synthesis, semiconductor band engineering, and protective antireflective coatings. Tailored multifunctional crystalline TiO_2 interphase layers provide corrosion protection, with favorable band alignment between the semiconductor conduction band and the energy level for water reduction, which facilitates electron transport at the cathode–electrolyte interface. Under a standardized level of simulated solar irradiation, solar-to-hydrogen efficiencies of 19.3% and 18.5% were obtained in acidic and neutral electrolytes, respectively. Such systems can now reach a value of 85% of the theoretical limit for photoelectrochemical water splitting.

CO_2 reduction

The architecture of the solar-fuel generator directly affects the product selectivity and activity for CO_2-reduction catalysis. In a water-splitting cell, the concentration of water is 55 molar; the reactant concentration thus poses no limitation on the reaction rate. But the low solubility of CO_2 in liquid-water-based electrolytes (30–40 millimolar, typically) constrains the reaction rate in a reduction system. Thus solar-fuel generators for CO_2 reduction typically use vapor-phase environments rather than liquid-electrolyte ones. Gas-diffusion-electrode (GDE) and membrane-electrode-assembly (MEA) architectures feature porous conductive membrane architectures like the one shown in figure 3; they can overcome not only the CO_2 solubility issue but also the inherent ohmic losses associated with liquid layers.[16]

Cells with liquid between the electrodes are labeled as diagnostic in figure 3 because they allow researchers to explore specific physical phenomena in laboratory experiments. To reach higher current densities and exploit the other benefits of vapor feed—for example, low water concentrations and the use of CO as an alternative reactant feed gas—high-efficiency cells are advantageous. Typically, MEA and GDE cells use a copper or silver heterogeneous catalyst, and the CO_2-reduction reaction occurs at a gas-solid-liquid interface in the membrane layer. Such CO_2 conversion devices have been able to produce chemical products that are dominated by dicarbon-containing molecules, such as ethylene and ethanol, and high current densities are possible at relatively low cell potentials.

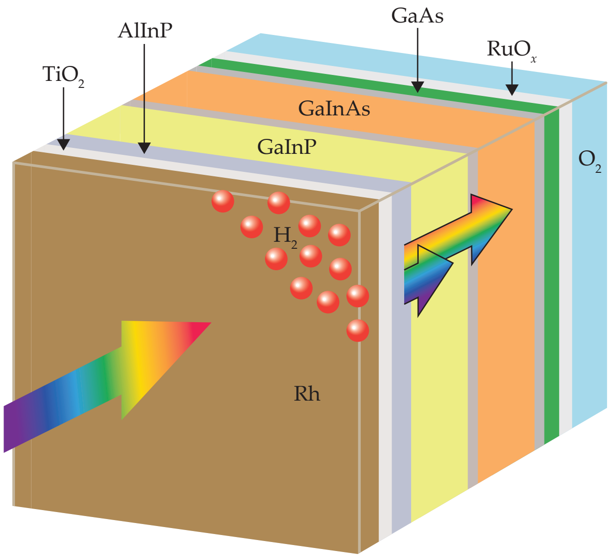


FIGURE 2. A SOLAR-FUEL GENERATOR splits water to produce hydrogen gas from sunlight at an efficiency that exceeds 19%. Sunlight strikes a front-facing tandem GaInP/GaAs photoelectrode that is functionalized with a rhodium catalyst to trigger the hydrogen-evolution reaction and with a ruthenium oxide catalyst to trigger the oxygen-evolution reaction. A titanium dioxide coating on the GaInP photocathode serves as a chemical protective layer and antireflection coating. The blue–green part of the solar spectrum is absorbed in the GaInP photoelectrode and the red-IR portion of the spectrum is absorbed in the GaAs photoelectrode. (Figure adapted from ref. 15.)

Integration of all those components in a structure as complex as a GDE can introduce significant variations in the electrode's activity, selectivity, and durability, even for well-studied catalysts such as copper. Mass-transfer effects and the local environment can lead to changes in the product distribution that could be incorrectly attributed to catalyst deactivation—a common concern in such studies. Further progress in developing next-generation architectures will likely require a combination of multiphysics modeling and measurements of local pH and reactant species under reaction conditions. Such modeling and experimental studies reveal the importance of the local chemical environment.

The voltage efficiency of a solar-driven electrochemical cell depends on the physical properties of its components—namely, catalysts, the electrolyte, and the membrane; operating conditions, which are the CO_2's flow rate and pressure and the current density; and the cell's physical dimensions. To make progress designing complex reactors, scientists have developed multidimensional models for GDE and MEA electrochemical CO_2-reduction cells—more specifically, for cells that simulate electrocatalysis for CO_2 reduction and oxygen evolution, ionic transport, and chemical acid–base reactions in liquid- or ion-conducting polymer electrolyte layers.

The ion-transporting membranes in such devices are situated close to the gas–solid interface. Thus hydrating the membrane with liquid water is an important concern because the liquid- and ion-containing exchange solutions help to lower the cell voltage. An important area for future research is to assess and evaluate the CO_2 utilization efficiency in those complex chemical environments. It can be low in the exchange solutions because of CO_2 pumping across the anion-conducting membrane.

Making liquid solar fuels from CO_2

Compared with water splitting, CO_2 reduction requires addressing a much more complex set of issues related to the transport and interfacial reactivity of reactants, intermediates, and products. When the solar-fuel community was primarily focused on water splitting, the appropriate scientific approach was to address mechanistic questions related to processes, such as reactions around a catalytic center or charge-carrier generation and transport. And researchers largely focused on processes occurring in a single sunlight-driven microenvironment, such as a photoabsorber-catalyst cathode interface.

Such approaches generated small-molecule gaseous fuel products, such as molecular hydrogen or carbon monoxide, for which small numbers of electron and proton transfers are needed. Most of the effort in the solar-fuels arena has previously addressed conditions in which concentrated feedstocks are present. They include liquid water as a source for generating hydrogen or pure CO_2 as a source for generating related products of CO_2.

The ultimate goal of direct solar generation of liquid fuels, such as multicarbon reduced products of CO_2 using dilute sources, however, is a far greater challenge that requires a conceptually different approach. To control the complex interplay of sequential or coupled transfers of multiple electrons, protons, and photons needed for liquid solar fuels requires a rethinking of the microenvironments that bring reactants to the reaction center.

Designing solar-fuel systems as assemblies of microenvironments is a new paradigm. Previous advances in solar fuels have led to success in building single microenvironments suited to water splitting and CO_2 reduction to two-electron products on the one hand and electrocatalysis to multicarbon products on the other. Until recently, though, the design of microenvironments for direct, efficient, and selective sunlight-driven generation of multicarbon or nitrogen-containing fuel products has been out of reach.

A new focus for solar-fuels research is to couple multiple microenvironments with an integrated or cascaded format—that is, to directly use sunlight to create liquid multicarbon fuel products in a precisely tailored manner and over a broad range of scales and ambient operating conditions. The microenvironment assemblies include photocatalysts, CO_2 capture media, membrane and porous media for ion and molecular transport, media for proton and cation management, and molecular and inorganic photo- and electrochemical reaction centers.

An example of such a coupled microenvironment architecture is illustrated in figure 4, which shows a tandem cascade of a photoelectrochemical reactor for CO_2 reduction to ethylene, coupled with a sunlight-driven thermochemical reactor that synthesizes ethylene-based fuel products. The mixture has a carbon concentration in the C_4 to C_{17} range, which resembles the typical molecular weight distribution of jet fuel.

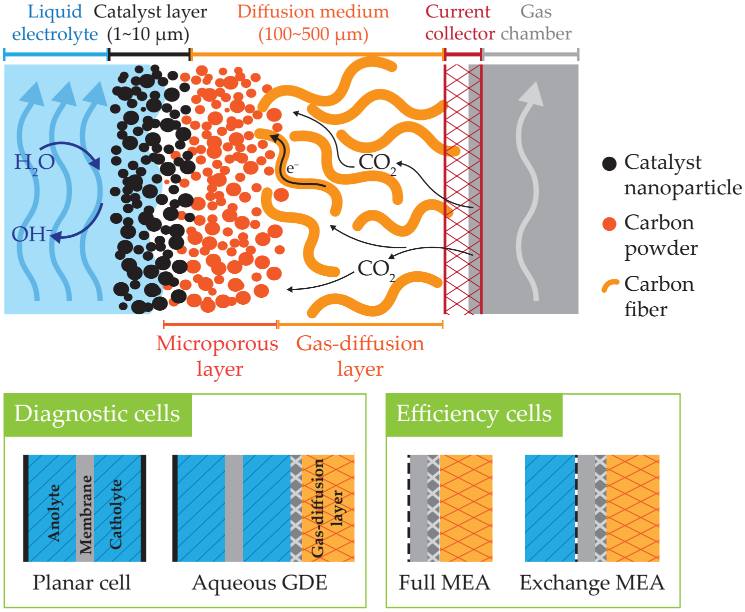


FIGURE 3. A GAS-DIFFUSION ELECTRODE (GDE) with different membrane-electrode-assembly (MEA) cell designs. The top panel depicts an aqueous liquid electrolyte that supplies protons to the catalyst, which is in contact with a porous gas-diffusion medium that facilitates the transport of carbon dioxide gas to the catalyst layer. The bottom panels illustrate (at left) a liquid electrolyte (planar) cell and a GDE used to characterize the voltage in the cell. At right are membrane-electrode assemblies, whose layer thicknesses and configurations are tailored to optimize the device efficiency. (Adapted from L. -C. Weng, A. T. Bell, A. Z. Weber, *Phys. Chem. Chem. Phys.* **20**, 16973, 2018.)

The goal is to demonstrate how the coupling of photoelectrochemical and photothermal reactors produces a liquid fuel from sunlight, CO_2, and water vapor. To date, that coupled microenvironment reactor has synthesized butene and hexene with high efficiency.

Selective synthesis of multicarbon products

A key requirement for complex product synthesis in solar-fuel systems is the precise synthesis of a single product with high selectivity and the suppression of minor or undesired products. Achieving that catalytic selectivity could in principle eliminate the need for separations, which is one of the costliest steps in any chemical synthesis process. A key advance in the past few years has been to apply molecular additive layers and ionomer coatings during the synthesis in order to tune the product distribution. The tuning is achieved, in turn, by controlling the availability of CO_2 and water at the reaction interface. Fortunately, molecular additives, such as pyridinium and Nafion ionomer coatings, can control the chemical microenvironment at the CO_2-reduction cathode interface.

Mechanistic studies are helping researchers understand how nitrogen-substituted pyridinium films can tune the rich profile of CO_2-reduction products on copper and silver electrodes. Silver surfaces catalyze primarily the CO_2-to-CO conversion in aqueous electrolytes, with the concomitant production of H_2 and a small amount of formate (HCOOH), depending on the potential that's applied. Whereas copper produces multicarbon products, silver typically produces only CO and H_2 in

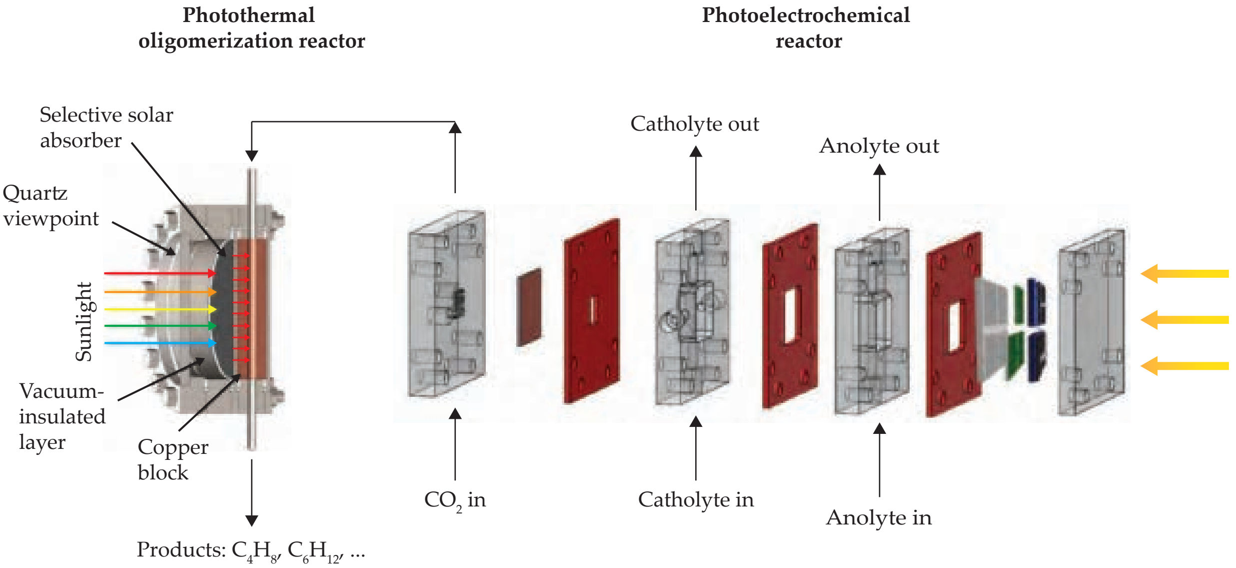


FIGURE 4. REACTORS IN TANDEM synthesize liquid fuel. This microenvironment features two reactors situated in a cascaded configuration: A photoelectrochemical reactor (at right) takes in sunlight to electrochemically reduce carbon dioxide to ethylene, and then a solar photothermal reactor (at left) uses harvested sunlight to heat a thermal heterogeneous catalyst, which then transforms the ethylene into alkene products. (Courtesy of Liquid Sunlight Alliance.)

electrocatalysis of CO_2 reduction. Silver thus offers a simpler system for understanding chemical processes.

Certain nitrogen-substituted pyridinium additives on silver foils produce CO with extremely high selectivity by inhibiting proton reduction—that is, hydrogen evolution—but not CO reduction. The data from electrokinetic studies suggest that hydrogen production was selectively inhibited by the growth of hydrophobic organic layers on the silver surface that limits proton transport but not CO_2 transport. Although the situation is more complex for CO_2 reduction on copper, researchers have found that selected pyridinium molecular additive films suppress hydrogen evolution and certain CO_2-reduction products, such as methane, and favor the formation of ethylene and ethanol instead. The data point to proton transfer as the rate-determining step in catalysis instead of the commonly observed electron-transfer step, for example, in the case of planar silver electrodes.

Durability

The performance demands for generating liquid solar fuels are significant. They require that generators operate efficiently and stably for up to 100 000 hours under real-world conditions. Despite substantial research on artificial photosynthesis over the past several decades, a major bottleneck in designing long-lasting systems for liquid solar fuels is the durability of components. Corrosion is well recognized as a failure mechanism, but little is understood about the myriad other processes that can influence the photocatalyst or reaction-center microenvironment and thus drive changes in performance over time.

Researchers need to understand the fundamental chemical and physical mechanisms that cause degradation and compromise the function of photocatalysts, membranes, and coatings. If such an understanding could be achieved, a set of tools would likely emerge for designing components for both stability and performance in photo-driven microenvironments. Knowing the corrosion mechanisms, the operational limits of durability, and details about the evolution of catalyst shapes will provide feedback for such models and enable predictive design of future systems.

Several approaches have been taken to understand and control corrosion in solar-fuel systems. Quantitative methods for studying corrosion rates were developed by detecting degradation products in the electrolyte or by measuring the mass loss of the component. *In situ* observation of corrosion processes by scanning probe techniques is also possible, and when combined with theory, it can reveal underlying mechanisms. Many anode and cathode materials are metastable under water-splitting or CO_2-reduction conditions, and their resistance to corrosion can be incorporated as a selection criterion in computational and experimental searches for new materials for CO_2-reduction photocathodes.

Photocorrosion is not the only process that can lead to performance loss. Photocathodes that drive CO_2 reduction usually incorporate a cocatalyst that favors CO_2 reduction over hydrogen evolution and controls product selectivity. Often the cocatalysts are metal nanoparticles; copper is used in many studies because it is the only metal catalyst that facilitates the C–C coupling reactions necessary to form C_{2+} products.

It is well known that nanocrystalline, copper-based CO_2-reduction catalysts can change shape or sinter during operation and lose their selectivity. Identifying the mechanisms responsible for that performance degradation might allow researchers to design systems resistant to those effects. The corrosion mechanism involves coupled charge and atom transfer from a solid interface into solution. Theories have been extended to include proton-coupled electron transfer, which is central to water oxidation. They do not, however, address the processes that initiate corrosion in the first place or help identify corrosion-resistant materials.

Another major gap in the science of solar fuels and electrochemical systems is understanding the rare events that cause material instability or passivation. During macroscopic corrosion, the rare events occur orders of magnitude faster than researchers can observe them. To correct that problem, researchers are starting to explore model systems with *in situ* time-resolved experiments.

A path to scaling up

Engineers have now developed photovoltaic energy systems up to the terawatt scale, and their manufacture is supported by comprehensive supply chains, distribution networks, and a worldwide infrastructure. An important question is whether solar fuels can follow a similar trajectory to large-scale production. Most conceptual work on the scalability of solar-fuel systems has focused on water splitting. To date, solar-fuel researchers have developed prototype systems at the 100 m^2 scale[17] and produced a detailed description of a hypothetical 1 GW hydrogen plant that generates 220 000 metric tons of H_2 per year with a photoelectrochemical generator design.[18]

Materials, initial energy requirements, and estimates of the annual net energy for the plant came from an initial study. A key finding was that the most significant factors affecting the energy returned on energy invested are the solar-to-hydrogen efficiency and panel lifetime. That study and similar ones point to the importance of ensuring high efficiency and a long lifetime for sustainable photoelectrochemical hydrogen production.

Significant advances have been made in solar-fuel research in the past decade for both water splitting and CO_2 reduction. Although no manufacturing industry currently exists, solar fuels have the potential to contribute to a sustainable circular carbon economy in a climate-stable world. Researchers in the field can take inspiration from the example of photovoltaics, which has undergone a millionfold expansion in production capacity over the past 30 years. If many of the same manufacturing methods and infrastructure resources that are now available for photovoltaics can be reused for solar fuels, they may offer a pathway for rapid acceleration of this important renewable-energy technology.

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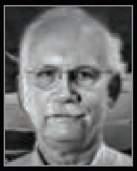
Back to the Moon

The Moon and Earth as seen from the Orion spacecraft during the *Artemis 1* mission. (Courtesy of NASA.)

Michael J. Neufeld retired in 2023 as a senior curator at the Smithsonian's National Air and Space Museum in Washington, DC. He is the author or editor of nine books, including *Von Braun: Dreamer of Space, Engineer of War* (2007) and *Spaceflight: A Concise History* (2018).



. . . to stay?

Michael J. Neufeld

Despite a lack of public enthusiasm, NASA's Artemis program will endure because human spaceflight has strong congressional support and signals great-power status.

NASA's April 2023 introduction of the members of the *Artemis 2* crew—the first humans scheduled to go to the Moon in over half a century—is a sign that the US and its international partners are serious about human lunar exploration. That is new. Two presidents—the Bushes—gave major speeches announcing that astronauts would return to the Moon and venture on to Mars. But no lasting program emerged from either pronouncement. Humans have not been more than 650 kilometers from Earth since the *Apollo 17* astronauts splashed down in December 1972.

It was not until November 2022 that NASA finally managed to launch the Space Launch System booster and the Orion crew vehicle on the uncrewed *Artemis 1*, at least five years later than originally scheduled. The spacecraft orbited the Moon and returned safely to Earth in December, capping a highly successful test. But will the program last, or will it be like Apollo: a magnificent technical and scientific success that was politically unsustainable? The US sent nine expeditions to the Moon between 1968 and 1972, six of which landed astronauts on the lunar surface. And then the Apollo program came to an end. Will it be different this time?

Despite weak public support for human lunar exploration, I believe it will be sustained this time because of three reinforcing political factors: an entrenched human spaceflight–industrial

THE *APOLLO 17* COMMAND MODULE approaches splashdown in the South Pacific Ocean on 19 December 1972. (Courtesy of NASA.)

complex with strong support in Congress, the signaling of great-power status that results from flying astronauts, and growing space competition from China, notably surrounding the Moon. But to understand that in historical context, one must follow the meandering course of US space policy since Apollo to grasp why it took 50 years for another such program to emerge. It's also necessary to examine what changed in the later 2010s and the political factors that now seem to make an expensive human lunar program more sustainable.

Questions, of course, remain. Does human exploration make any sense when robotic spacecraft are getting more and more capable, efficient, and cheap? And are humans suited to deep-space exploration given the hostile radiation environment beyond the protective shield of Earth's magnetosphere? Regardless, it appears likely that Artemis will last at least into the 2030s and probably beyond. If China lands astronauts on the Moon around 2030, as a Chinese official asserted in 2021,[1] then it is even more likely to endure.

The legacies of Apollo

In hindsight, Apollo's unsustainability was foreordained. Although the program was wrapped in rhetoric of science and exploration, President John F. Kennedy set its core purpose in May 1961: to beat the Soviet Union to a human landing on the Moon or at least be competitive with it. Once the race was won, it was going to be harder to argue for a continuation, especially after the Soviets failed to send cosmonauts to the Moon.

Moreover, as the former NASA chief historian Roger Launius has shown, public support for spending billions of dollars on Apollo was always weaker than space enthusiasts want to remember. Only two 1960s public opinion polls, one of them at the time of the July 1969 *Apollo 11* landing, showed a slight majority in favor. Not long after Neil Armstrong, Michael Collins, and Buzz Aldrin returned to Earth, support plummeted.[2] By the time *Apollo 12* launched in November 1969, a large fraction of the US public was asking what the point was: We beat the Soviets, so why were we doing it again? With the Vietnam War, riots in the cities, urban decay, and a growing sense of environmental crisis, why were we still spending billions on Apollo?[3]

Because of the program's remaining momentum, NASA managed to carry out five more landings out of six attempts. Those expeditions shifted decisively toward science; the program produced a priceless haul of samples and data from different regions of the Moon. The result was a greatly increased understanding of the violent early history of the solar system, which set a baseline for the development of planetary science thereafter. But the public and the politicians cared little about that. Every Apollo lunar landing cost over $400 million (the equivalent of several billion dollars today). Congress had already begun cutting NASA's budget in 1967, and the freefall continued into the early 1970s.

Richard Nixon and his administration in 1971 seriously discussed canceling the last two Apollo missions and not funding NASA's proposed space shuttle. The agency's plans for a large space station, let alone Moon and Mars programs, were already dead. That the president did not end human spaceflight was in no small part because of a 12 August 1971 memorandum from Caspar Weinberger, then deputy director of the Office of Management and Budget (OMB). He argued that no US astronauts in space would confirm the impression of many at home and abroad "that our best years are behind us, that we are turning inward, reducing our defense commitments, and voluntarily starting to give up our super-power status."[4]

In short, the US would no longer look like a great power if it lacked a human space program. In the end, Nixon approved the space shuttle on the agency's promise that it would drastically lower launch costs, but also because it promised aerospace jobs in California at a time when he was thinking about the 1972 campaign.

The shuttle became the lifeline for another Apollo legacy:

NASA's massively expanded human spaceflight infrastructure, mostly located in the Deep South, plus the giant aerospace corporations that depended on it. Apollo and other large space and military programs had taught the lesson that spreading federal spending to as many states as possible ensured congressional support. The agency became a self-perpetuating system of large engineering centers and military–industrial contractors, each supported by politicians determined to protect the jobs created by spaceflight in their districts.

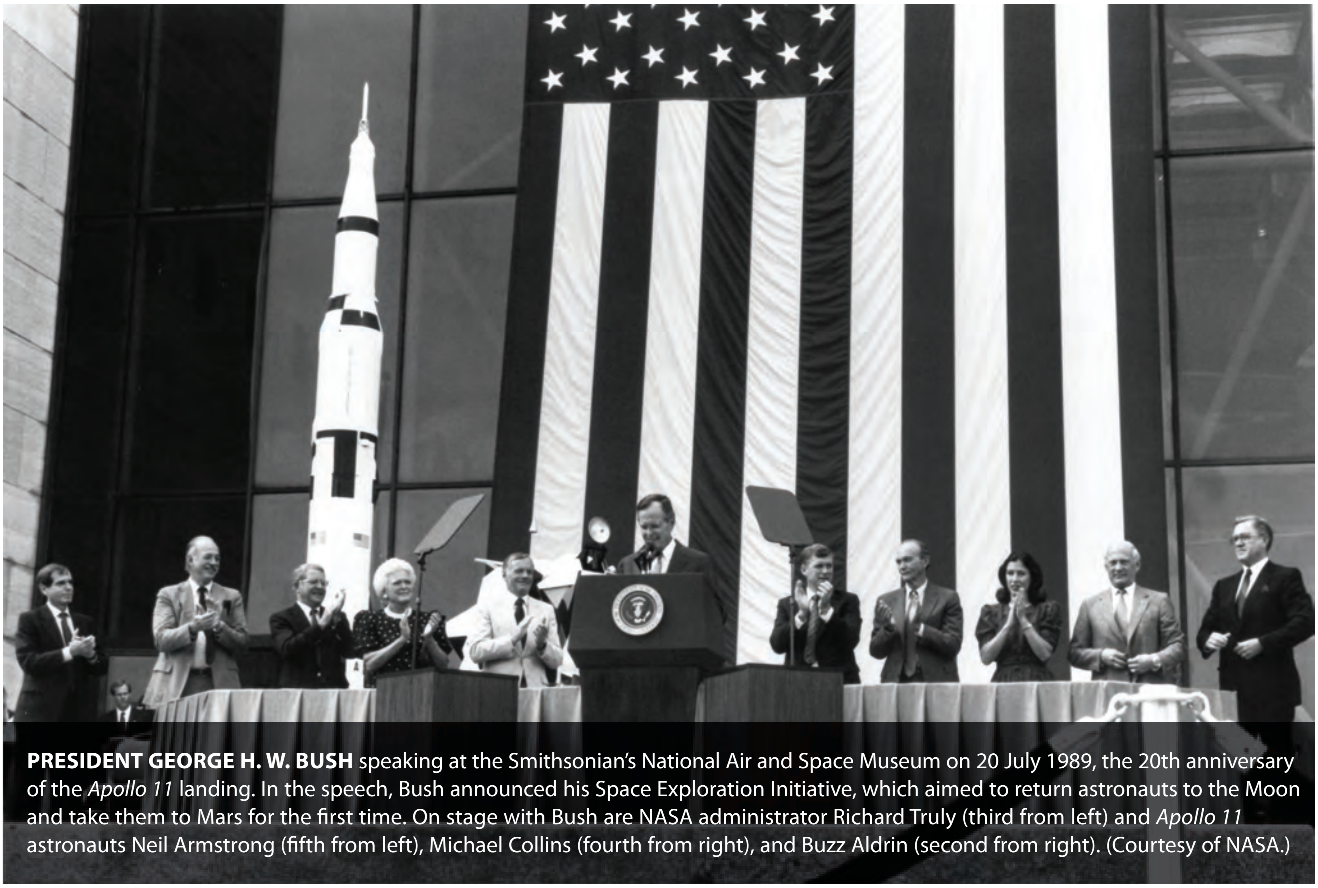
Through lean times, better times, and two fatal accidents, the shuttle remained the space agency's foundation, notwithstanding the vehicle's failure to deliver on NASA's promises of frequent launches and greatly lowered costs. The shuttle did many remarkable things, like broadening access to space to diverse crews, launching and then refurbishing the *Hubble Space Telescope*, and building the International Space Station (ISS). But it remained NASA's core program largely because it was entrenched in its infrastructure and political economy. As long as another use for it could be found, it was hard to terminate: Several attempts to develop a successor went nowhere. The result was that when it was finally retired in 2011 after 30 years of flights, the US had to depend on Russia to send astronauts to the ISS.

Going to the Moon and Mars—or not

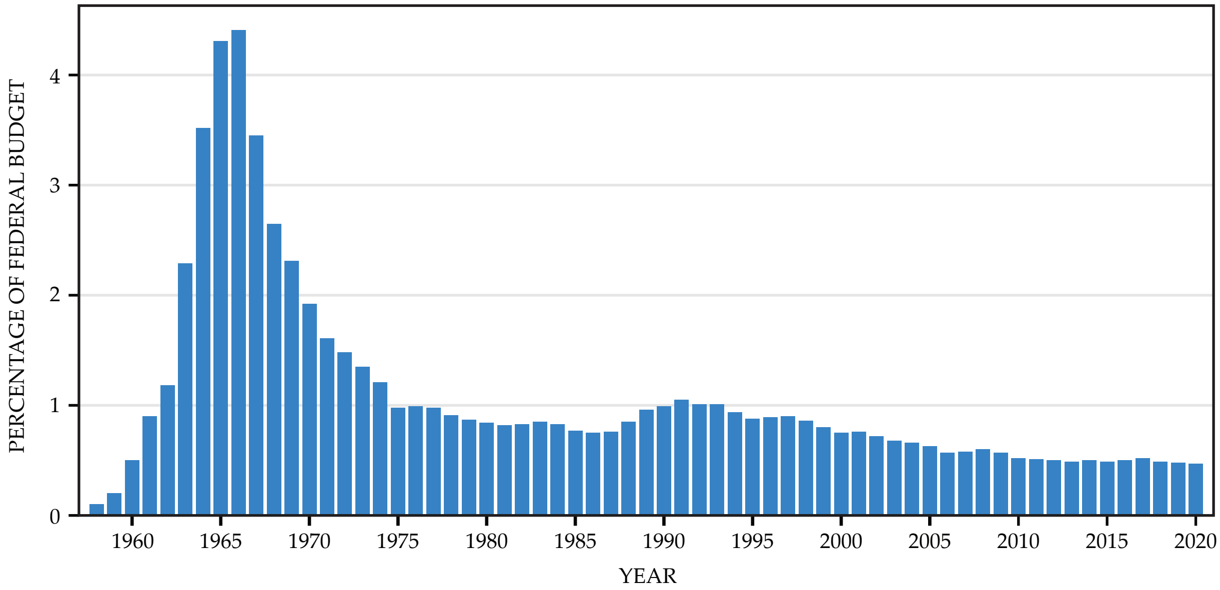
The two fatal accidents, those of *Challenger* in 1986 and *Columbia* in 2003, did produce soul-searching. Both failures sparked reconsiderations of US civil space policy that led two presidents—George H. W. Bush and George W. Bush—to propose striking out for the Moon and Mars. Both felt they needed to articulate a bold vision for space that ultimately meant sending astronauts to the red planet. Both proposals failed because of weak public and political support.

The origin of the senior Bush's 1989 Space Exploration Initiative (SEI) was the aftermath of the January 1986 *Challenger* disaster, which caused significant changes to space policy. President Ronald Reagan ended the ill-advised attempt to make the shuttle into the sole US government launch vehicle. Commercial satellite launches would be left to US rocket makers, who would be encouraged to market their vehicles. NASA would also, as soon as it could, get out of the business of launching military and intelligence payloads on the shuttle. On the horizon was launching the modules of what would become the ISS, which Reagan had approved in 1983. The European Space Agency (ESA), Canada, and Japan soon joined that program, and their modules and contributions would need shuttle launches too.[5]

But many inside and outside the space advocacy community felt that the agency was aimless, bureaucratic, and unimaginative, leaving the US human space program stuck in low Earth orbit. Reagan appointed a national commission headed by former NASA administrator Thomas Paine. It produced a grandiose plan for a massive expansion of the agency's program and budget to fund human infrastructure across the inner solar system, including bases on the Moon and Mars. It not only had zero chance for success but also had the bad luck of coming out days after the *Challenger* accident. The first US woman in space, Sally Ride, then



PRESIDENT GEORGE H. W. BUSH speaking at the Smithsonian's National Air and Space Museum on 20 July 1989, the 20th anniversary of the *Apollo 11* landing. In the speech, Bush announced his Space Exploration Initiative, which aimed to return astronauts to the Moon and take them to Mars for the first time. On stage with Bush are NASA administrator Richard Truly (third from left) and *Apollo 11* astronauts Neil Armstrong (fifth from left), Michael Collins (fourth from right), and Buzz Aldrin (second from right). (Courtesy of NASA.)



PERCENTAGE OF THE FEDERAL BUDGET allocated to NASA since its establishment in 1958. It peaked around 4% at the height of the Apollo program in the mid 1960s but is now at half of 1%. (Adapted from 0x0077BE/Wikimedia Commons/CC0 1.0; data for years 2018–20 courtesy of Roger Launius.)

headed another committee that in 1987 produced a more modest report. She highlighted Mission to Planet Earth, a program designed to investigate the biosphere and environment, as one of the options, although she was not allowed to make that the preferred option in the report.[6]

When George H. W. Bush became president in 1989, he thought the moment was right to articulate a grand new vision for NASA. A space enthusiast, he gravitated immediately to the human spaceflight community's fixation on missions to the Moon and Mars, but he paid surprisingly little attention to the political demands that huge NASA budget increases would require. He announced the SEI on the steps of the Smithsonian's National Air and Space Museum on the 20th anniversary of the *Apollo 11* landing: 20 July 1989. Astronauts were to set foot on the Moon by the beginning of the 21st century and on Mars by 2020.

Initial reaction in the media and in the Democrat-controlled Congress was skeptical. The space agency quickly initiated a study that by fall 1989 produced the politically toxic estimate that it would take half a trillion dollars to establish bases on the Moon and Mars. Although additional studies dragged on for a couple more years, the SEI was effectively dead on arrival.[7]

Lack of direction

The shuttle and the proposed space station were important factors in NASA's huge estimates and failure of imagination. With the funding for those programs providing the foundation for many of NASA's centers and their relationships with contractors and politicians, agency engineers and executives could not imagine curtailing or canceling those programs or skipping the Moon and going directly to Mars, as some new voices in the space community were advocating. Any Moon or Mars architecture would have to be built in addition to the shuttle and station.

Bush had appointed a former shuttle astronaut, Richard Truly, as NASA administrator. Truly's first reaction to the SEI was that he couldn't see how ambitious new programs could be piled on to the agency's existing structure. It was an accurate perception. But seeing that it was something the president wanted to do, Truly went along and did nothing to change the process that produced a gigantically expensive and unimaginatively narrow set of options.

Another important context for the failure of Bush's SEI was the lack of public support for a greatly expanded civil space program, especially for trips to Mars, which reinforced the lack of interest in Congress.[8] Since the huge peak in spending for Apollo, which reached 4% of the federal budget in the mid 1960s, NASA's share has fallen to less than 1%. Brief bumps for shuttle development in the mid 1970s and to replace the lost *Challenger* in the later 1980s raised it to around 1%, but the agency's share then fell thereafter because the overall federal budget grew faster than NASA's did. (See the bar graph above.)

Appropriated budgets do not tend to change quickly because OMB and congressional appropriators assume that a certain level of spending is the agency's or department's fair share. It usually takes a sense of national crisis to drastically alter a budget allocation—which happened to NASA only once, for Apollo. When Bush proposed the SEI, the public and the politicians more or less accepted the status quo; doubling or tripling NASA's budget was a nonstarter.

Bush and his vice president, Dan Quayle, share blame for that political failure, but both felt betrayed by the space agency's tone-deaf response to the challenge. Disillusionment with NASA's leadership grew in the early 1990s, notably after the embarrassing flaw in the *Hubble Space Telescope*'s mirror came to light in mid 1990. In early 1992 Bush forced Truly to resign and made an outsider, Daniel Goldin, administrator. It was no coincidence that Goldin, a vice president at the defense contractor TRW, had primarily worked on classified space programs. Although Reagan's controversial Strategic Defense Initiative was fading, ballistic missile defense contractors had developed a reputation for being fast and innovative and for slashing the long time scales and huge budgets typical of the military–industrial complex that effectively includes NASA.

Goldin implemented what became known as the "faster, better, cheaper" approach to robotic spacecraft programs, with mixed but important results. He survived Bush's loss in the 1992 election and continued as Bill Clinton's agency chief because of his reputation as a reformer, notwithstanding his sometimes-abusive management style. But Goldin was stuck with the entrenched shuttle and station programs and with a stagnant or slightly declining budget: The sudden end of the Cold War and the disappearance of Soviet competition undercut the argument for NASA. To serve foreign-policy goals and save the space station, which was already years late and billions over budget, the Clinton administration negotiated a merger with the Russian program, creating the ISS. Ideas for human space programs beyond low Earth orbit were completely off the table.

OMB officials and Goldin started a new planning effort in 1999 to figure out what the agency should look like beyond 2000. That planning was the root of what would eventually become the Orion spacecraft for Artemis. But it took another fatal shuttle accident, that of *Columbia* in February 2003, to spark a more substantive public discussion of NASA's future. Beyond reviving criticisms of how the agency handled the vehicle's safety, the tragedy underlined how the shuttle was inherently less safe than earlier spacecraft. The accident report recommended that it be retired once the ISS was completed. Both the report and the public discussion surrounding the incident highlighted NASA's failure to develop a shuttle replacement and the human spaceflight program's lack of direction.[9]

Constellation

President George W. Bush spoke at NASA headquarters on 14 January 2004 to unveil the Vision for Space Exploration (VSE). The shuttle would be retired in 2010 following completion of the ISS. NASA would develop a crew exploration vehicle to fly to the ISS, the Moon, and eventually Mars. Its first flight would be in 2014, which implied that the agency would depend on the Russians to get to the station for at least four years. (It turned out to be nine.) The younger Bush was aware, as was his father, that the Moon was not popular as a primary goal because the US had been there before. But

SPACEX SPACECRAFT have supplied the International Space Station since 2012. This image from 2019 depicts a SpaceX Dragon cargo craft attached to the ISS while the station flies over the Indian Ocean. (Courtesy of NASA.)

THE *ARTEMIS 2* CREW is introduced on 4 April 2023. From left are Jeremy Hansen, Victor Glover, Reid Wiseman, and Christina Koch. (Courtesy of James B. Blair, NASA.)

he emphasized a return—by 2020 and perhaps as early as 2015—as a necessary step to developing the technologies for traveling to Mars.

To make the speech sound visionary, it was again important to make a human Mars landing the ultimate objective, reflecting a long history of public fascination with the red planet. But the commitment to Mars was vague. Learning from the failure of the SEI, Bush proposed only a modest increase in NASA's budget, of $1 billion over five years. But another $10 billion was to come from retiring the shuttle, terminating the ISS not many years after its assembly, and taking money from space-science programs not focused on lunar and Martian exploration.[10]

That budget plan was not without its critics, notably among the space station's foreign partners and the US science community, but it at least prevented the VSE from immediate political failure. Nevertheless, it too proved unrealistic. After Sean O'Keefe, the first NASA chief appointed by Bush, left in early 2005, aerospace engineer Michael Griffin took over. Seeing a lack of clear goals for what was now called the Constellation program, he refocused the human exploration program more firmly on getting to the Moon. But Griffin faced shuttle and ISS costs higher than had been projected and declining interest in the VSE from the White House. Quagmires in Iraq and Afghanistan did not help. NASA got no significant budget increases, and the dividend for retiring the shuttle was years in the future. As soon as Constellation began, launch dates started to recede farther into the 2010s.

The architecture that Griffin settled on was a lengthened shuttle solid-rocket booster with an upper stage, called the Ares I, as the launch vehicle to put the crew exploration vehicle (now called Orion) in low Earth orbit. A heavy lift booster called Ares V, which used a core stage derived from the shuttle external tank and two stretched solid-rocket boosters, would carry the lunar lander, called Altair, and the propulsion stage that would send the combined Orion–Altair craft to the Moon.

The reuse and extension of shuttle technology reflected the entrenched character of what one might call the shuttle–industrial complex. The three large NASA human spaceflight facilities—Kennedy Space Center on Merritt Island, Florida; Marshall Space Flight Center in Huntsville, Alabama; and Johnson Space Center in Houston, Texas—were closely tied to Boeing, Lockheed Martin, and solid-rocket maker Morton Thiokol. Those companies lived off cost-plus contracts that did not penalize them much, or at all, for being late and over budget. As always, that cozy, self-interested system was fortified by US senators and representatives determined to keep jobs in their districts.

In the first decade of the 2000s, the commercial rocket industry was still in its infancy, which made it easy for NASA and the giant aerospace corporations to dismiss new companies as pretenders who couldn't produce anything viable. Several notable startups had folded. Elon Musk's SpaceX was struggling to fly its first rocket, the small-satellite launcher Falcon 1, while Jeff Bezos's Blue Origin had launched nothing and was swathed in secrecy.[11] So there were few viable alternatives. But Constellation's flat budgets, which allowed no Apollo-like investment peak, guaranteed schedule slips while the corporations racked up billions in overruns. Bush's VSE was in deep trouble.

The emergence of Artemis

When Barack Obama won the presidency in 2008, space policy was not high on his priority list because of the Iraq War and a financial crisis that threatened the whole economy. But Constellation was at the top of the agenda for his campaign's space expert, the former NASA official Lori Garver, who soon became the agency's deputy administrator. During the transition team's investigation, Garver found that four years into the Ares I program, the rocket's launch date had slipped five years. With the shuttle's retirement date also slipping, no extra money was available for the Ares V or Altair. A new blue-ribbon commission recommended various options, one of which involved canceling Constellation and choosing a flexible path to go somewhere other than the Moon—perhaps an asteroid. That is exactly what Obama did in early 2010. The VSE was dead.[12]

That decision produced a firestorm of protest in the old-line space establishment, which faced massive layoffs when the shuttle program ended. Famous Apollo astronauts, including Neil Armstrong, testified before Congress that the country had lost its way without an ambitious human spaceflight program led by the NASA centers and companies who had always done it. Congressional pressure on Obama and NASA led Obama to make his first concession and save the Orion spacecraft, which was essentially a modern version of the Apollo command and service modules.

Senators, notably Richard Shelby (R-AL) and Bill Nelson (D-FL), then collaborated with the giant corporations and, more discreetly, with NASA centers to force the Obama administration to accept a heavy-lift booster that was essentially a redesign of the Ares V. It came to be called the Space Launch System (SLS), but critics dubbed it the Senate Launch System. The result was a spacecraft and booster with no clear objective except to keep the shuttle–industrial complex in business just as that program was about to end. (The final flight was in July 2011.)

Garver was caught in the middle as the primary advocate for the new commercial space industry. She championed what came to be called the Commercial Crew Program, an extension of the one nontraditional project Griffin had approved, commercial cargo launches to sustain the ISS. SpaceX was one of the winners of the cargo competition and proposed a crewed version of its Dragon spacecraft.

The Commercial Crew Program barely survived the attack from the human spaceflight establishment and suffered budget cuts in Congress that stretched out its schedules. Garver left in 2013, feeling that she was undercut by her own boss, Charles Bolden, a pioneering Black shuttle astronaut who was Obama's NASA administrator. In 2014 the agency gave Commercial Crew contracts to upstart SpaceX and, for considerably more money, to old-line Boeing. SpaceX's Dragon crew flights began in 2020; Boeing's Starliner has been a string of embarrassments. As of this writing, it has yet to launch an astronaut.

During the Obama administration, NASA's official objective for the SLS and Orion was to send astronauts to an asteroid to prepare for later trips to Mars. That plan inspired little enthusiasm, and it evolved into something that many found even less inspiring: using a robotic vehicle to retrieve a tiny asteroid and bring it into lunar orbit, where astronauts would sample it. Orion was too small for a months-long trip to a solar-orbiting asteroid and would need an extra habitat module to do that. Instead, the agency examined building a small space station called Gateway in distant lunar orbit, and, like with the ISS, NASA soon partnered with ESA, Canada, and Japan. A lunar landing remained in the long-range plans if money became available. In effect, the remnants of Constellation evolved back into a lunar program through the rear door.

During his administration, Donald Trump placed Mike Pence in charge of space policy. Along with the new NASA administrator, Jim Bridenstine, Pence steered the agency back to human lunar landing as the prime objective. They were easily able to sell Trump on the nationalistic and blatantly political goal of landing on the Moon by the end of 2024. It was never a realistic date (nor is the current target of December 2025). In 2019 NASA officially named the program Artemis after the mythological twin sister of Apollo.

What emerged is a marriage of the old and new ways of doing human spaceflight. On the one side is the congressionally mandated SLS and Orion, which currently cost $4.1 billion per launch—an expense even the agency admits is much too high.[13] As it has done for decades, NASA purchases those vehicles from Boeing, Lockheed, and other aerospace firms under arcane and expensive federal acquisition regulations. (The Orion's service module is supplied by ESA through its contractor Airbus.)

On the other side is the ascendant commercial space industry, especially SpaceX, which gained enormous credibility when its Dragon cargo vehicle worked and its Falcon 9 booster dramatically lowered launch costs by including a recoverable first stage. To get astronauts to the surface, NASA invited corporate proposals for what it called the Human Landing System. The first contract went to SpaceX in 2021 and the second to a Blue Origin–led team in 2023. Based on the model of ISS commercial cargo and crew, NASA contracted for competing services through fixed-price agreements under the Space Act of 1958 rather than purchasing the vehicles. Those agreements are public–private partnerships in which companies are expected to invest some of their own money. Other companies have been contracted to deliver robotic spacecraft and cargo to the lunar surface.

The sustainability of Artemis

Rather than being a product of a grand presidential announcement, Artemis evolved into a lunar—and, at least nominally, Mars—program over the course of a decade, driven primarily by congressional politics and the need to sustain jobs in NASA's human spaceflight infrastructure. Public enthusiasm for sending astronauts to the Moon has remained weak—only 12% of respondents in a recent poll chose it as one of the "top priorities" for NASA (monitoring asteroid threats got 60% and Earth's climate 50%).[14] Artemis seems like a program unlikely to survive politically.

But the opposite is true. As the fates of the two Bush initiatives reveal, there is no public or political appetite for a greatly expanded NASA budget. But there is also no appetite for downsizing or eliminating the human space program either, especially in Congress and the White House. When the shuttle program came to an end and the ISS was completed, it freed up budget room for a deep-space human exploration program, even one that, for a while, lacked a convincing purpose or sense of urgency.

Another factor in Artemis's sustainability is human spaceflight as a contemporary symbol of great-power status. Weinberger expressed that clearly in 1971, and it has been implied in multiple presidential announcements since. Traditionally, analysts and space advocates have talked about the space program's soft power in terms of prestige, but that is a vague, hard-to-quantify term. NASA chief economist Alexander MacDonald has offered economic-signaling theory as a more potent tool. A strong civil space program is a signal to other countries of the economic, technological, and scientific power of a nation, and, by implication, potential or actual military power.[15]

Israeli space-policy expert Deganit Paikowsky has elaborated a related concept: the "space club." What started as a US–Soviet contest just to orbit a satellite has become a series of ways and levels in which nations—and, more recently, corporations—can signal their geopolitical power. The highest level of the space club consists of nations that can launch their own space travelers: Only the Soviet Union/Russia, the US, and China have achieved that.[16]

Having no US astronauts flying while other countries, notably China and Russia, are continuing to launch theirs is a prospect few US political leaders want to contemplate. A significant fraction of the public would probably feel the same if the Chinese were to land astronauts on the Moon and the US did not. Many space advocates have been fantasizing for years that a new Cold War space race with China would make all their wishes come true. Although a new race of 1960s intensity seems unlikely, leaving the Moon to Chinese astronauts would likely be politically intolerable.

Artemis, finally, has a couple of secondary factors on its side. It is an international program, with hardware contributions from ESA, Canada, and Japan. US space diplomacy has engaged many more nations through the Artemis Accords, a set of ground rules for operating on and around the Moon, Mars, and other objects in the solar system. Politically that makes it more difficult for the US Congress and presidential administrations to cancel Artemis.

There also seems to be a growing global consensus among national policymakers that the Moon's time has come again. As low Earth orbit becomes accessible to privately launched astronauts and tourists, the zone where nations can push the boundaries of technology is in cislunar space. It is where India, the United Arab Emirates, and others are developing their robotic spaceflight capabilities. It is also the easiest place to test the human spaceflight technologies needed for deeper human voyages to destinations such as Mars, although it must be said that the red planet remains 20 to 25 years away—as proponents of crewed travel to Mars have perennially claimed since the 1960s.

That brings us to the final question: Does sending humans into deep space, and spending huge sums of money to do so, make any sense? In the 1960s and 1970s, the space physicist James Van Allen argued that human spaceflight is dangerous and wasteful and that robotic spacecraft can produce much more science for much less money. Scientists have made that argument repeatedly: It was reiterated last year by the astronomers Donald Goldsmith and Martin Rees in *The End of Astronauts*. But they end up admitting that human spaceflight is not going away and just update an old argument that has had little impact on space policy.[17] The achievements of robotic space science—like the Mars rovers and the *James Webb Space Telescope*—have been spectacular, and spacecraft are getting more capable, autonomous, and cost-effective. But human spaceflight will not end any time soon for precisely the reasons I have outlined.

Significant questions remain as to whether humans can adapt successfully to cislunar space and beyond, where radiation exposure is greatly increased and the medical problems of microgravity are no less problematic than in low Earth orbit. It may be that humans are poorly adapted to deep-space travel and may be displaced by cyborgs and intelligent machines in a "post-human" future.[18] In any case, that is too far off for meaningful predictions. If we are going to see whether humans will adapt to deep-space travel, it has seemed to many, including me, that we should do that at the Moon first, where Earth is easily reachable in an emergency. If we find that we do not have the technology to protect human bodies adequately on journeys of years, then we may have to reconsider whether we want to do it.

In the short run, domestic and international political reasons alone will sustain the Artemis program and its Chinese equivalent well into the 2030s. We are going back to the Moon to stay, at least for a while—and maybe for the long term.

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The astrophysicist and science communicator Carl Sagan on the set of his famous 1980 television series *Cosmos: A Personal Voyage*.

SCIENCE HISTORY IMAGES/ALAMY STOCK PHOTO

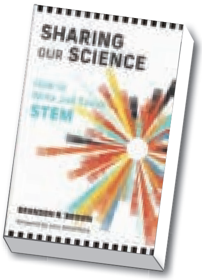
The elements of scientific style

Sharing Our Science

How to Write and Speak STEM

Brandon R. Brown

MIT Press, 2023. $26.95
(paper)



Looking back on my undergraduate classes in chemistry and physics, my fondest memories are of each course's laboratory components. Those weekly events were always fun and novel: working at the bench with my classmates; learning about different reactions, experiments, and analyses; and seeing—or sometimes smelling—the material presented in lectures. Writing the lab reports, however, was a different matter. Without fail, I found them tedious, repetitive, and uninspired. They nearly snuffed out my love of science.

Author Brandon R. Brown has a similar take on the day-to-day drudgery of lab reports and, more broadly, all aspects of communicating science, from writing emails and cover letters to giving technical and nontechnical presentations. In his new and valuable book, *Sharing Our Science: How to Write and Speak STEM*, Brown urges scientists to "question some defaults of the traditional structure" and provides the skills, tools, and inspiration to breathe life into communication. Most importantly, he urges researchers to expand the public's understanding and appreciation of science.

Brown is a gifted and creative writer. He is direct and critical of standard practices in writing and speaking about science but saves the harshest critiques for mistakes he made during his 30-year career in science and related fields. The book's 13 chapters are divided into three sections that focus respectively on how to master the nuts and bolts of sound writing, overcome specific challenges in explaining science, and engage and move your audience.

Readers won't need to get too far into the book to pick up on Brown's unconventional perspective: Chapter 2 starts off with a bang by arguing that scientists would do well to embrace the same storytelling techniques that fiction writers use. Brown highlights the value of dramatic tension to grab and keep an audience. A second highlight is chapter 5, in which Brown heroically targets common writing mistakes and provides engaging solutions. Although he notes that his mother thought it would be too dry, by the end of it I was revising unfinished emails and other documents open on my desktop.

Another favorite is chapter 7, "Numbers

on the Brain." There Brown explains how to avoid complexity and improve clarity when presenting and discussing numbers. Other chapters are dedicated to structure, audience, anecdotes, metaphor, speaking science, scientific subcultures, and social scales. But the best chapter is the last one, which comprises a moving account of his wife's cancer diagnosis and her subsequent treatment and recovery. At one point, they dissected an ambiguous phone message left by one of her doctors that left them so anxious that they resorted to transcribing it on paper and examining the doctor's word placement. It makes the most robust case for scientists to communicate their work effectively.

Sharing Our Science succeeds because Brown reflects on his experiences framing and communicating science to different audiences while working in academia as a professor, an administrator, and a fundraiser and working outside the ivory tower as a reporter, a spokesperson, and a deputy director of a nongovernmental organization. In one example, he describes how he failed to persuade a wealthy alumnus to finance an integrated-science center at his university. Here, he highlights how different audiences have different values, interests, and definitions of success. When Brown pitched the inherent benefits of interdisciplinary research, the potential donor replied that he was not interested in having college majors "playing together." Because Brown did not consider "what might intrigue" the guest, or, more bluntly, how integrated science would benefit the donor, he could not close the deal.

Scientists may be more willing to listen to advice from one of their own. Brown teaches physics at the University of San Francisco and has published peer-reviewed research. When reminding his readers that communicating science is not easy for scientists and that the material is often difficult for audiences to absorb, Brown draws on the advice he gives second-year physics majors: "If you want to stick with physics as we move from Newton to Heisenberg, you have to get comfortable with discomfort." In other words, scientists need to be willing to work hard on their communication skills to be able to effectively reach the broader public.

If I have one quibble with the book, it's that Brown frequently refers to scientists—and himself—as "nerds." No malice is intended; it is an attempt to promote solidarity. But the idea that all scientists are socially inept is a negative stereotype that nonscientists frequently hold. It remains a barrier to effective science communication. The irony is that Brown's book is an excellent guide for scientists hoping to shed common misconceptions.

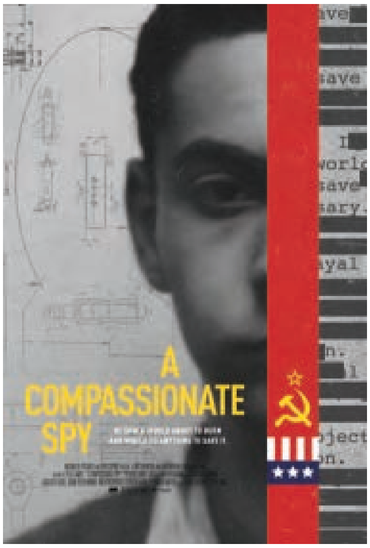
Although *Sharing Our Science* occasionally recalls William Strunk Jr and E. B. White's *Elements of Style* (1959), it is much more than just another reference book whose fate is to languish beneath the piles of papers on your desk. It is an engaging read that will help scientists achieve a richer and more rewarding career. Brown has produced a multifaceted, timely, and relevant book deserving of discussion among colleagues and students. You may not always agree with him, but I imagine Brown would be pleased if he sparked a dialog on the essentials of effective science communication.

Christopher Reddy
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

NEW BOOKS & MEDIA

A Compassionate Spy

Steve James
Magnolia Pictures/
Participant, 2023

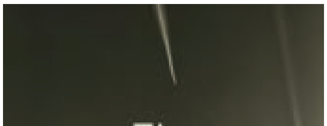


On the heels of the release of the 2023 biopic *Oppenheimer* comes yet another story from the Manhattan Project. *A Compassionate Spy* delves into the life of Theodore Alvin Holtzberg, the youngest scientist recruited to work on the project. As a teenage Harvard University graduate, Ted Hall, as he came to be known, was very concerned about a postwar US monopoly on the atomic bomb. In his efforts to create a balance of power, Hall spied for the Soviet Union and provided vital secrets that led to the Soviets creating a bomb of their own. The documentary provides a glimpse into Hall's life of spying, his impact on history, and the love shared between him and his wife during their 50-year marriage.

—TG

The MANIAC

Benjamín Labatut
Penguin Press, 2023. $28.00



Two years after the US release of the Chilean novelist Benjamín Labatut's breakthrough book, *When We Cease to Understand the World*, the author has returned with an unofficial sequel. Like its predecessor, *The MANIAC* is a work of fiction based on reality: It is so experimental that labeling it historical fiction seems to sell it short. It comprises a triptych of stories about Paul Ehrenfest, John von Neumann, and the Go master Lee Sedol's match with the artificial intelligence AlphaGo. Labatut plays with typography, literary form, and sentence structure throughout the book, the heart of which is a fictionalized oral history about von Neumann. Told from the perspective of colleagues such as Eugene Wigner and family members such as his daughter Marina, it examines the Hungarian's polymathic brilliance, his famously eccentric personality, and the mental anguish he experienced during his terminal bout with cancer. As always, Labatut's prose dazzles.

—RD PT

NEW PRODUCTS

Focus on cryogenics, vacuum equipment, materials, and semiconductors

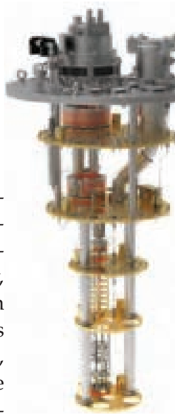
The descriptions of the new products listed in this section are based on information supplied to us by the manufacturers. Physics Today can assume no responsibility for their accuracy. For more information about a particular product, visit the website at the end of its description. Please send all new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

Andreas Mandelis

Customizable diaphragm gas pump

The N 938 diaphragm gas pump from KNF delivers precise vacuum control for fuel-cell, laboratory and medical, measurement technology, and other applications. A key feature of the new pump is its process-compliant vacuum performance: Because of the in-house-developed brushless motors, parameters such as motor speed, acceleration, starting curve, and current limit can be defined according to user needs. With flow rates of 7–35 L/min with the single-head version and 11–53 L/min with the dual-head standard version, the N 938 series can achieve a final vacuum of up to 140 mbar absolute. Its maximum operating pressure is 1 barg. The standard version features an aluminum pump head, an ethylene propylene diene monomer diaphragm, and fluorinated propylene monomer valves for reliable, efficient operation. Available pump-head materials include anodized aluminum, polyphenylene sulfide, and stainless steel. Depending on specific requirements, the pump's maximum media temperature can be increased up to 60 °C. If required, the pump can be configured for even lower vacuum levels. ***KNF Neuberger Inc****, 2 Black Forest Rd, Trenton, NJ 08691-1810, https://knf.com*

Compact dilution refrigerator



The ProteoxS, the latest addition to Oxford Instruments NanoScience's dilution refrigerator family, cools quickly and can reach a base temperature of less than 10 mK. The smallest, lowest-cost system in the range, the ProteoxS facilitates low-temperature physics for university laboratories that have limited infrastructure or budgets. The system has extensive wiring capabilities and can integrate cold electronics and optical fibers. It is compatible with vector 6/1/1 T three-axis magnets, solenoid magnets of up to 12 T, and the company's bottom-loading mechanism, which reduces the sample cooldown time to eight hours. While the magnet is operating, the system can reach 30 K, which enables users to measure electron transport. The ProteoxS is suitable for general research, photonics, and sensing applications. It can also be used by those starting out in superconducting quantum computing who require only a small number of qubits or in spin-based quantum computing where a large plate size is not needed. ***Oxford Instruments plc****, Tubney Woods, Abingdon OX13 5QX, UK, https://nanoscience.oxinst.com*

Epoxy for dam-and-fill encapsulation

Master Bond Supreme 3DM-85 is a no-mix, non-solvent-based, one-component epoxy formulated to serve as the damming compound in dam-and-fill encapsulation applications. The thixotropic paste can also be used for bonding and sealing, especially where no flow is needed, since it cures in place and will not run or slump. Designed for heat-sensitive components that cannot withstand high curing temperatures, the compound requires a relatively low heat cure of 85 °C for two to three hours. It is usable over a temperature range of −73 °C to 177 °C. Supreme 3DM-85 is a toughened system that resists rigorous thermal cycling. A reliable electrical insulator with a thermal conductivity of 0.72–1.44 W/(m·K), it facilitates effective heat dissipation and prevents overheating, especially in densely packed electronic assemblies. Supreme 3DM-85 forms strong bonds with a wide range of substrates found in semiconductors and electronics, including metals, composites, ceramics, silicon, and plastics. ***Master Bond Inc****, 154 Hobart St, Hackensack, NJ 07601-3922, www.masterbond.com*

W. Jason Morgan

Renowned geophysicist W. Jason Morgan died peacefully in his sleep on 31 July 2023 at the home he shared with his daughter, Michèle, and her husband in Natick, Massachusetts.

With Morgan we lose one of the leading figures of modern-day Earth and planetary science. His theoretical work and careful observations supported the hypotheses of continental drift, seafloor spreading, and deep mantle plumes, and he established plate tectonics as the reigning paradigm in the geophysical sciences.

By 1596 Flemish cartographer Abraham Ortelius had mapped the African and South American coastlines and suggested that the two continents had once been joined but were pulled apart by “earthquakes and floods.” By 1912 German meteorologist Alfred Wegener had gathered paleoclimatic and paleontological evidence for an ancient supercontinental landmass, Pangaea, and coined the term “continental drift.” By 1967 Morgan had unified and codified the theory of plate tectonics largely as we know it today. The mechanism for moving rigid lithospheric plates about Earth’s surface involves convection of the plastically deforming mantle. Convection was crucially missed by Lord Kelvin in his erroneous calculations of Earth’s age and dismissed by Harold Jeffreys and other physicists but is today as widely accepted as the notion that Earth revolves around the Sun.

Born 10 October 1935 in Savannah, Georgia, Morgan graduated from Georgia Tech in 1955 with a degree in physics and then did a two-year stint in the US Navy. He joined Princeton University’s department of physics as a graduate student under Robert Dicke and worked in the company of Jim Peebles and Rainer Weiss, among others. Morgan’s 1964 thesis, “An astronomical and geophysical search for scalar gravitational waves,” found no perceptible support for changes in the fundamental gravitational constant.

It was at Princeton, where Morgan would spend his career, that geologist and oceanographer Harry Hess enticed him to move into geophysics. As a postdoc, Morgan worked on convection currents in Earth’s mantle with the peripatetic Walter Elsasser. With the publication of two papers on gravity anomalies and convection currents, Morgan established himself as an original thinker unafraid of upsetting the scientific status quo. He worked out essential elements of the theory of density anomalies in a dynamic, viscous mantle and proposed a radically new interpretation for the structure of the deep Puerto Rico Trench, ideas that were widely controversial at the time.

Sharing an office with Frederick Vine, who linked marine geomagnetic anomalies to the process of seafloor spreading, proved to be pivotal for Morgan. He and Vine joined the faculty of the department of geology (now geosciences) in 1967. The next year Morgan published “Rises, trenches, great faults and crustal blocks,” which celebrated author John McPhee rightfully called “one of the last of the primal papers that, taken together, constituted the plate-tectonics revolution.” Incontrovertible evidence for seafloor spreading had been gathered by Hess and Vine, through the discovery of symmetric lineations of Earth’s remnant magnetic field recorded in alternating bands moving away from mid-ocean ridges.

In that 1968 landmark paper, Morgan formulated crucial insights on the mechanisms that linked together those and other geophysical observations and developed detailed computer calculations supporting the existence of tectonic plates and their motion across the globe’s surface. In a 1971 article, Morgan further postulated the existence of convectively upwelling “mantle plumes” to explain the presence of “hot spots” and the morphology of seamount chains in the oceans, which had not initially fit into the overarching theory.

The plate-tectonics theory ranks among the major scientific revolutions of the 20th century. Within a few years after Morgan’s paper was published, any debate was, essentially, over, and opponents of the theory were relegated to the distant corners of the scientific enterprise. The study of mantle plumes, which consumed many of Morgan’s later years, continues vigorously to this day.

Morgan’s research would earn him several major scientific accolades, culminating in a 2002 National Medal of Science. “I am definitely a theorist,” he recounted in an interview for the National Science and Technology Medals Foundation. “I’m not an experimentalist at all—I’m an observer of nature, and I participate on experimental projects. And as I say, it’s mainly for the chance of seeing the data firsthand.”

JAKE NAUGHTON

W. Jason Morgan

“And when you’re intimately involved with the data,” he continued, “you begin to see the patterns as they emerge. And being actively involved is a much better education than passively reading about somebody else’s experiment.” Even well past retirement and into his old age, Morgan participated in geological field trips and oceanographic expeditions and kept his passionate interest in teaching and education.

Patient, kind, soft-spoken, and perennially practically dressed, Morgan had none of the ego traditionally associated with men of his scientific stature. In conversation, he would take long pauses to formulate deep thoughts, fed from encyclopedic knowledge and profound insight. After retiring from Princeton, Morgan became a visiting researcher at Harvard University, where, for the next 20 years, true to his calling, he continued to mentor a new generation of solid-Earth researchers.

Loved by all who knew him, he will be missed.

Frederik J. Simons
Princeton University
Princeton, New Jersey

Roman Jackiw

Roman Jackiw, a giant of theoretical physics and an emeritus professor at MIT, passed away on 14 June 2023 in Boston. He was born Roman Volodymyr Yatskiv on 8 November 1939 in the small lakeside resort of Lubliniec, Poland, where his Ukrainian father took the family to avoid World War II military action and the Communists. The family moved through Austria and Germany before emigrating to the US a decade later.

Jackiw's academic journey began with his education in New York City. In his junior high and high schools, he was taught by Xaverian and Christian Brothers monks, respectively. From independent reading, he developed an early passion for physics. He completed his undergraduate studies in physics, with minors in mathematics and history of science, at Swarthmore College in 1961 before earning a PhD from Cornell University in 1966. Jointly supervised by the notable physicists Hans Bethe and Kenneth Wilson, he wrote a thesis titled "Nonperturbative solutions of the Bethe–Salpeter equation for the vertex function."

After Cornell, Jackiw followed in Wilson's footsteps and became a junior fellow at Harvard University's Society of Fellows. In 1969 he joined the faculty at MIT, where he eventually became the Jerrold Zacharias Professor of Physics.

Jackiw's scientific contributions were profound and spanned numerous fields, including particle physics, condensed-matter physics, and gravity. His greatest contributions, though, were to quantum field theory, which he began working on as a graduate student at a time when the subject was in a lull. Over his career he added whole new avenues to the understanding of that theoretical framework.

Famously, as a young postdoc working with John Bell at Harvard, Jackiw discovered the so-called Adler-Bell-Jackiw axial anomaly and used it to explain the decay of pions into photons. He turned lemons into lemonade by both interpreting and making physical predictions from what seemed to be an inconsistency in the Feynman diagrams. His subtle and entirely new kind of computation has many generalizations that have played a central role over the past half century.

JIANNIS K. PACHOS

Roman Jackiw

Jackiw also spearheaded the fruitful dialog between quantum field theory and pure mathematics. He introduced the mathematical Chern–Simons theory into physics, where it has thrived ever since, and derived the coupling-constant quantization. He used deep mathematical properties of Yang–Mills theory to derive nonperturbative phenomena, including the existence of theta vacua, which led to the fundamental and still unsolved strong *CP* problem. He pioneered the subject of lower-dimensional gravity and its connection to Liouville theory. Two-dimensional Jackiw–Teitelboim gravity is now, 40 years after his initial work, a currently active subject in theoretical physics.

Jackiw was often out of sync with the rest of theoretical physics, which at times caught up to him years or decades later. His research was unceasing and prolific throughout his life. Jackiw's contributions earned him numerous accolades, including the Dannie Heineman Prize for Mathematical Physics from the American Physical Society in 1995 and the Dirac Medal from the Abdus Salam International Centre for Theoretical Physics in 1998. His mark on theoretical physics is indelible.

Among Jackiw's collaborators was So-Young Pi, his wife of 42 years. They wrote 46 papers together, including on conformal symmetries, solitons, and Chern–Simons theory. During a sabbatical at the University of Leeds, Jackiw worked with Pi and Giandomenico Palumbo, who appears between them in the photo.

On a personal note, being Jackiw's thesis student was both a great privilege and a great pleasure. His many students knew him for his formidable intellectual acumen and insights, along with his uncompromising, ungilded, and accurate assessments of our successes and failures, a testament to his unwavering commitment to the truth. His frank assessments were softened by his genuine personal warmth and unwavering loyal support for each of his students over their career. He was and continues to be a great inspiration to many of us in both life and physics.

Andrew Strominger
Harvard University
Cambridge, Massachusetts

Editor's note

This issue marks the last month that the obituaries department will appear in print in Physics Today. Going forward we will be publishing obituaries only online.

Progress in science is inseparable from the unique stories and experiences of the people involved. Since the very first issue of Physics Today, back in May 1948, obituaries have provided opportunities to honor members of the community and their contributions. And since 2005, readers have been able to submit obituaries online to be posted on the Physics Today website.

Our shared history is a central part of what unites us as a community, and Physics Today remains committed to preserving and sharing individuals' legacies. Our collection of online obituaries can be easily found on our website or reached directly at https://physicstoday.org/obits. You'll also find a link there for submitting obituaries and reminiscences. PT

QUICK STUDY

Marc Neveu is a planetary scientist and astrobiologist at NASA's Goddard Space Flight Center and the University of Maryland in College Park.

Ceres, a window into how planets could harbor life

Marc Neveu

Exploration of the large asteroid by NASA's *Dawn* mission reveals a puzzling, active, water-rich world.

When discovered in 1801 through the telescope, Ceres was thought to be a new planet, like Uranus, discovered just 20 years earlier. Within a few years, however, more such objects were found, and it became clear that many orbited the Sun between Mars and Jupiter in what became understood as the solar system's main asteroid belt. Ceres happens to be its largest member.

Asteroids are too small to be shaped by their own gravity—hence their irregular forms. They are thought to be the remnants of planet formation. In the early 1990s, the first detailed images of asteroids were returned by the *Galileo* spacecraft on its way to Jupiter and revealed gray, potato-shaped bodies whose craters indicated ancient surfaces. Up to that point, telescopic observations of asteroids had only provided estimates of their size and shape from their brightness variations as they spun and their surface composition by spectroscopy. For Ceres, those observations pointed to a rather round body with a hydrated surface mineralogy.

But those observations, which would prove quite accurate, did not uncover how much a part liquid water has played, and continues to play, in shaping Ceres's surface. Nor did they hint that Ceres could teach us how life's ingredients may come together.

Getting out there

What initially motivated the exploration of Ceres was the prospect of seeing up close what a large planetary building block looked like at the dawn of the solar system. In 2001, what became the *Dawn* mission team took advantage of a happy convergence of two trends. First, ion engines were becoming a reliable means of energy-efficient space propulsion (see the article by Igor Levchenko, Dan Goebel, and Katia Bazaka, Physics Today, September 2022, page 38). A spacecraft could orbit one planet and then move on to orbit another, without breaking the propellant bank.

Second, Ceres and Vesta—another large asteroid with a dry mineralogy akin to some meteorites found on Earth—were converging along their orbits, a once-in-17-year occurrence enabling fast travel from one to the other. NASA seized the chance to investigate two very different protoplanets in one go, selecting, out of two dozen competitors, the *Dawn* proposal for an ion-engine-enabled mission.

The spacecraft launched in 2007 and studied Vesta in 2011–12. It arrived at Ceres in 2015, carrying cameras and spectrometers able to discern minerals, molecules, and chemical elements at its surface. Equipped with a radio antenna, it was able to probe the distribution of mass inside Ceres by precisely tracking its own orbit.

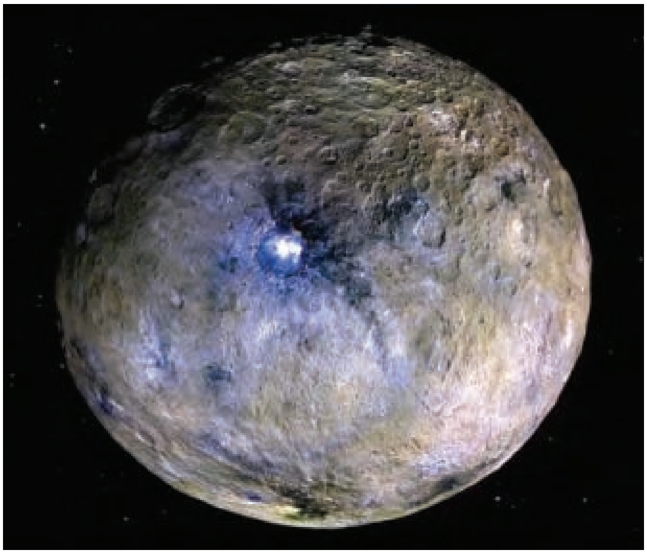


FIGURE 1. CERES shown in false-color renderings that highlight differences in surface materials, with blue material richer in carbonate minerals and brown material richer in clays. (Courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA.)

More than meets the eye

Dawn images immediately revealed two surprises. First, Ceres is heavily cratered, as shown in figure 1. Its shape (volume) and orbit (mass) had constrained its bulk density to be consistent with a half-rock, half-ice object, suggesting Ceres to be the closest ice-rich world to the Sun. The relatively warmer temperatures expected at Ceres's surface from the balance of solar illumination and blackbody reradiation, about 170 K, should have enabled surface topography such as crater rims to be smoothed out over geologically relatively short times. Persistent craters suggested instead a strong, rock-rich crust inconsistent with an ice-rich body.

Second, against that seemingly dull backdrop is a blindingly bright spot in the center of a low-latitude crater named Occator (figure 2). In planetary exploration, bright material can suggest recent activity, because over time surfaces get coated with dust, and fresh ices sublimate to space. Indeed, Occator's central and secondary bright spots appear to cover the underlying surface and are essentially crater-free. Their absence indicates an age of millions of years at most—the blink of an eye in geological time.

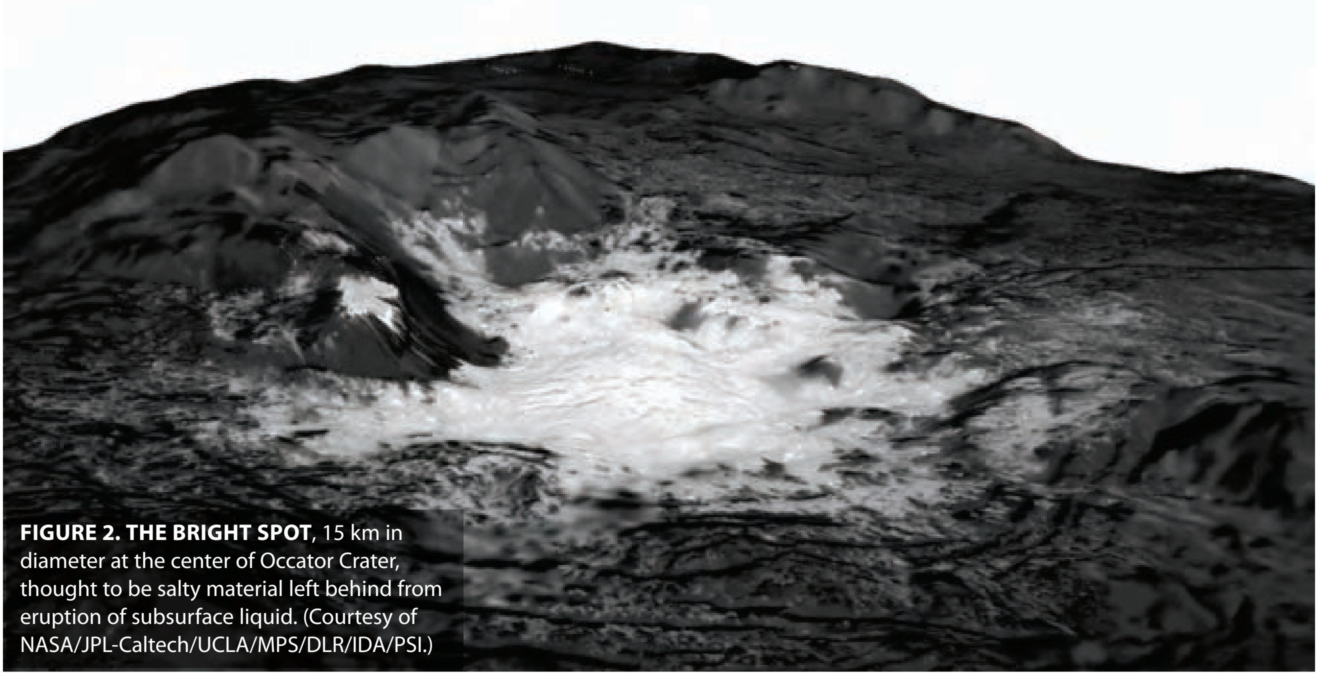


FIGURE 2. THE BRIGHT SPOT, 15 km in diameter at the center of Occator Crater, thought to be salty material left behind from eruption of subsurface liquid. (Courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/PSI.)

Dawn's instruments revealed at least 10% of the matter blanketing Ceres's surface is made of iron and carbon and the rest is ammonium clays and magnesium carbonates. On Earth, those clays and carbonates form when volcanic rock is altered by liquid water with dissolved carbon dioxide; the nitrogen in the ammonium is sourced from organic matter. Ceres therefore appears to have harbored liquid water with soluble carbon and nitrogen—two elements on which life as we know it is based.

The bright spots are much richer in carbonates and sodium chloride. If those recent deposits are left behind by erupted liquid water known as cryolava, their liquid source reservoirs are likely cold and briny, because water with sodium chloride fully freezes at 251 K.

Water ice generally sublimes to space, but it seems abundant in Ceres's crust. Indeed, surface images show morphologies evoking flows of ice, perhaps solidified cryolava, including an apparently volcanic edifice—Ahuna Mons—and several potentially older, smoothed-out relatives. Reconciling their presence with the crustal strength apparent from the persistence of craters is a challenge; researchers have invoked the mechanical strength of salts and hypothesized the presence of gas hydrates (see the article by Wendy Mao, Carolyn Koh, and Dendy Sloan, Physics Today, October 2007, page 42).

The spacecraft's radio tracking investigation of Ceres's gravity revealed the dwarf planet's deep interior to be differentiated into a denser rocky core and an outer layer. Detailed analysis of the topography showed that outer layer to be weak at several dozen kilometers depth, consistent with the presence of liquid-filled porous rock.

A window into habitability

Emerging from those findings is an overall picture of a world that, not unlike ocean moons such as Europa and Enceladus, harbors subsurface liquid water in contact with rock that can be erupted through the overlying icy crust onto the surface. (See the Quick Study by Michael Manga and Max Rudolph, Physics Today, January 2023, page 62.) On Ceres, any liquid is likely a brine that upon eruption leaves behind bright salt deposits. Unlike the ocean moons, Ceres does not experience heating by the dissipation of tides, since it is so distant from the body it orbits (the Sun). And its relatively small size implies that the heat from the decay of naturally occurring radioisotopes in its rock has largely dissipated. Thus, its inferred liquid water reservoir is not an extensive global ocean; it's more likely a set of local pockets of fluid-filled porous rock.

On Earth, clay-forming reactions between liquid water and rock produce chemical energy that microbial communities exploit to thrive in the absence of sunlight. More generally, in any environment on Earth where liquid water, energy, and a source of carbon, nitrogen, and other elements such as sulfur and phosphorus exist, so does life. Life is more abundant where fluxes of chemical energy and nutrients are higher, and less abundant if stressed by temperature extremes (hot or cold), salinity, pH (acidic or alkaline), or radiation. The possible presence of life motivates the exploration of such habitable environments found to be or have been present on Mars's surface and subsurface, and in the oceans surrounding the rocky cores of some icy moons.

The habitability of environments inside Ceres today is likely precluded by the expected high salinity and low temperature of any liquid, as well as the little chemical energy remaining now that water–rock reactions appear to have largely reached equilibrium. Researchers can only speculate about the presence of any significant biosphere in a warmer past. Ceres is the only ice-rich world, however, with abundant rock mineralogy expressed at the surface. Farther out in the solar system, that mineralogy is masked by ubiquitous ice. Ceres is thus the only place where investigations can tease out, even from orbit, the details of interactions between liquid water, rock, and organic compounds. On Earth those interactions eventually led to the emergence of life.

Additional resources

► J. Castillo-Rogez et al., "Concepts for the future exploration of dwarf planet Ceres' habitability," *Planet. Sci. J.* **3**, 41 (2022).

► J. Castillo-Rogez et al., "Science drivers for the future exploration of Ceres: From solar system evolution to ocean world science," *Planet. Sci. J.* **3,** 64 (2022).

► J. E. C. Scully et al., "The varied sources of faculae-forming brines in Ceres' Occator crater emplaced via hydrothermal brine effusion," *Nat. Commun.* **11**, 3680 (2020).

► M. C. De Sanctis et al., "Relict ocean worlds: Ceres," *Space Sci. Rev.* **216**, 60 (2020).

► S. Marchi, C. A. Raymond, and C. T. Russell, eds., *Vesta and Ceres: Insights from the Dawn Mission for the Origin of the Solar System*, Cambridge U. Press (2022).

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BACK SCATTER

Torricelli's barometer

Italian physicist Evangelista Torricelli challenged two prevailing Aristotelian ideas in 1644—that air could not exert weight on Earth and that nature abhors a vacuum—with a novel experiment. In contrast to those conceptions, held by Torricelli's mentor Galileo Galilei among others, the experiment proved that air has mass and that a stable vacuum can occur naturally. This 17th-century illustration by Gaspar Schott, a German Jesuit mathematician and science writer, combines aspects of Torricelli's original apparatus with later variations built by contemporary scientists. It accompanies Schott's commentary on advances in vacuum science in his 1664 Latin text *Technica Curiosa*, a copy of which is held at the Niels Bohr Library and Archives of the American Institute of Physics (publisher of Physics Today).

Glass tubes of various shapes and sizes, each sealed at one end, are filled with mercury and their open ends submerged in a mercury-filled vat. The mercury in the tubes begins to flow into the vat, creating a vacuum at the top of each tube. At approximately 760 mm above the vat's surface, however, the mercury stops flowing, no matter a tube's shape, length, or angle relative to the horizontal. That phenomenon, Torricelli realized, was caused by the weight of the air pressing on the mercury in the vat to balance the weight of the mercury in the tube, and it allowed him to measure atmospheric pressure. Torricelli is credited with inventing the barometer, whose traditional unit is defined as 1 atm = 760 mm Hg, the height of the suspended mercury that Torricelli observed in his experiment. The torr (1/760 atm) is named in his honor. —KC

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