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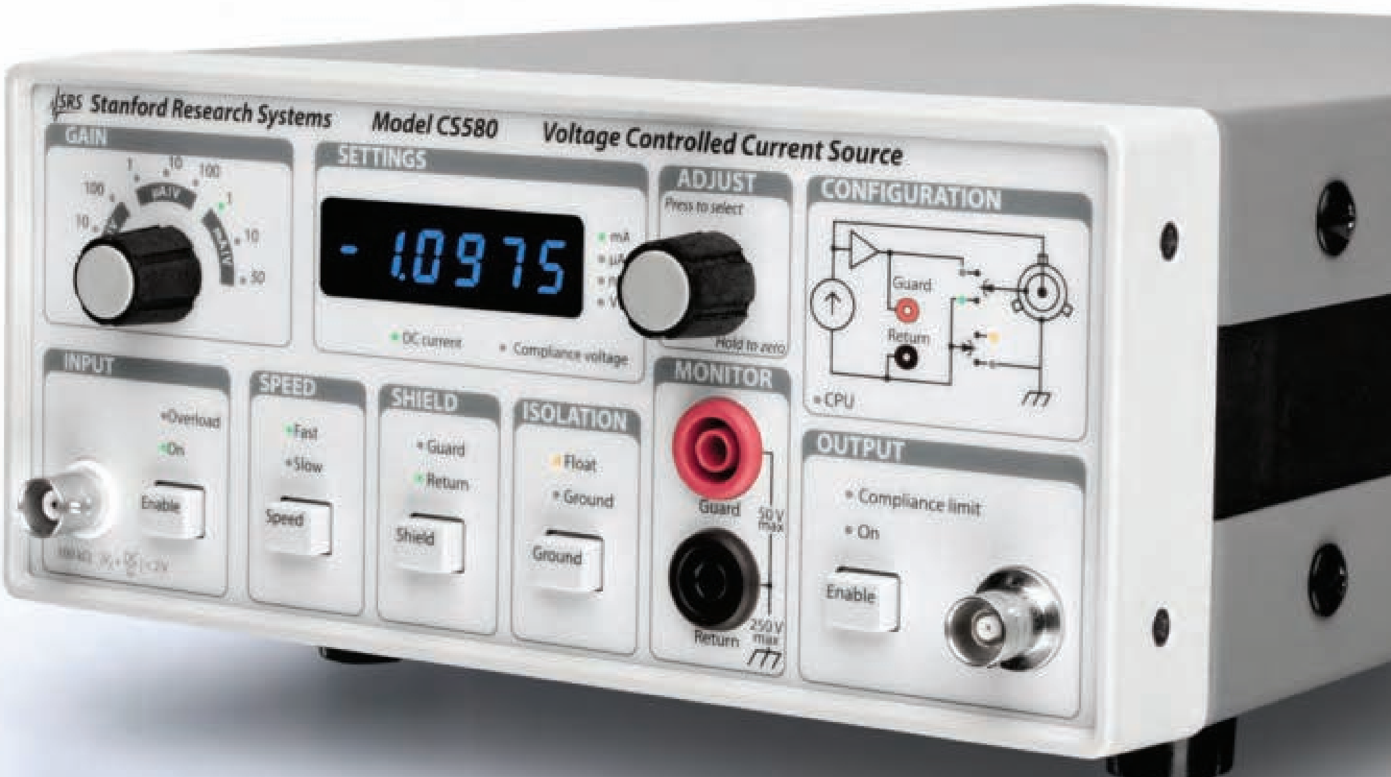

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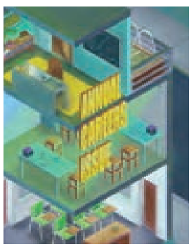
CAREERS ISSUE



ON THE COVER: In our sixth annual careers issue, our editors focus on career transitions. On **page 30**, Richard Fitzgerald presents statistics on the career choices made by recent recipients of US physics degrees. On **page 40**, Alex Lopatka presents firsthand accounts of the challenges involved with starting a first faculty position. And on **page 50**, Toni Feder explores the stimulating effect that a mid-career change in research focus can have. (Image by Freddie Pagani.)

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OU ET AL., *SCIENCE* (2024)

Transparent mice

The main reason that biological tissue is generally opaque is scattering, not absorption. Researchers have now shown that applying a solution containing the yellow food dye tartrazine can temporarily reduce the scattering and render raw chicken breast and the skin of live mice transparent.

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CAROL HIGHSMITH

Judges and science

Because of a recent US Supreme Court decision, federal judges in scientific cases will be responsible for understanding concepts that previously would have been explained in court by subject-matter experts. Now judicial education groups are considering offering more scientific resources to judges and their staffs.

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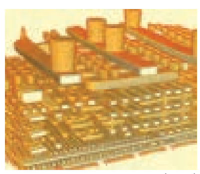

AIDUKAS ET AL., *NATURE* (2024)

Imaging transistors

Microchip production has advanced to the point that the chips' smallest features are hard to see with today's imaging techniques. An improvement to x-ray tomography algorithms now allows researchers to analyze nanometer-scale chip features and to improve resolution in other applications.

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READERS' FORUM

A proposed solution to arbitrary evaluations

It was a great pleasure to read Toni Feder's feature "When tenure fails" (Physics Today, October 2023, page 44). In particular, I enjoyed her insightful discussion of unwritten rules, including that of being a "good fit," in the tenure process. As Meg Urry, director of the Yale Center for Astronomy and Astrophysics, is quoted as saying of tenure candidates, "The vast majority could go either way, depending on how people spin it. It's kind of arbitrary." That tells me that the tenure evaluation system has failed.

Unfortunately, such flaws exist not only in job securement—including when a candidate is selected for a tenure-track position from among the few interviewed—but also in many other activities of scientific research, including peer review of scientific publications and grant applications. The need for evaluation reform is imperative for continued scientific innovation.

The ideal environment for innovation is open, diverse, democratic, tolerant, and motivating. How can we create and maintain such an environment?

As one possible solution, I have proposed a new open-science initiative: the Open ePrint and Rigorous Evaluation System for STEM.[1,2] Three types of research activities—original research, indirect contributions (for example, participation in the evaluation system), and funding requests—would be evaluated using quantitative, continually refined metrics. The rigorous, community-based evaluation system would reward the quality, not the quantity, of accomplishments. Community members would earn credits for their research and other activities, and as they accumulate experience and credits, they could advance in their role in the community. High-risk, high-reward research projects would have a better chance of being funded.

By implementing a sophisticated credit- and role-based incentive mechanism, we could establish a new self-sustaining ecosystem for the entire scientific community. Rigorous science requires rigorous evaluation, and scien-

ABIGAIL MALATE

tific innovation won't develop efficiently until such a system is built.

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2. W. Tan, "OePRESS: An Open ePrint and Rigorous Evaluation System for STEM," 13 September 2024, https://osf.io/preprints/osf/jvkmz.

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Defending *Oppenheimer*

In their letter in the July 2024 issue of Physics Today (page 11), Bárbara Cruvinel Santiago and Lindsay Rand criticize Christopher Nolan's *Oppenheimer* for glorifying the Trinity test while mostly ignoring the dangers of its widespread fallout. To be fair to the film's creators, the movie is more of an account of J. Robert Oppenheimer's life and the challenges he endured; it is not a documentary.

ISTOCK.COM/OGULCAN AKSOY

An alternate view: The Manhattan Project was now eight decades ago. If watching the movie prompts younger viewers to go learn about it, the context surrounding it, and its legacy of worldwide nuclear deployments and environmental issues—consequences with which Santiago and Rand are concerned—the movie will have done a tremendous public service. Personally, I enjoyed it immensely.

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I do not concur with the substance of a recently published letter by Bárbara Cruvinel Santiago and Lindsay Rand titled "Beyond the cinematic feat: Consequences *Oppenheimer* ignored" (Physics Today, July 2024, page 11). The film was half the extraordinary "Barbenheimer" phenomenon, which encouraged audiences to return to physical theaters, and it won the Academy Award for Best Picture. I think most physicists would agree that the film was remarkably successful in engaging broad audiences with the origins of nuclear weapons and with the consequences of their use.

As have many other critics of *Oppenheimer*, the letter writers point out the film's limited treatment of the devastation and death that occurred as a result of the Manhattan Project. In the *Los Angeles Times*, Justin Chang provides a more nuanced discussion, writing "I get those complaints. I also think they betray an inherent disrespect for the audience's intelligence and curiosity, as well as a fundamental misunderstanding of how movies operate."[1] That commentary is the first listed in the body of work for which Chang won the 2024 Pulitzer Prize for criticism.

Reference

1. J. Chang, "'Oppenheimer' doesn't show us Hiroshima and Nagasaki. That's an act of rigor, not erasure," *Los Angeles Times*, 11 August 2023.

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Nonlinear optical computing doesn't need nonlinear optics

A major stumbling block on the road to light-based neural networks can be overcome by flipping the script on how data are encoded.

Artificial neural networks are making their mark on both the world and its energy budget. The brain-inspired computing models behind so many popular and scientific machine-learning applications are proving to be tremendously powerful (see, for example, PHYSICS TODAY, October 2021, page 14). But they're also power hungry (see PHYSICS TODAY, April 2024, page 28).

One way, potentially, to lessen the energy burden is to design a computer that uses light, not electrons, to process data. Most of the computations that a neural network needs to do are linear operations: adding, subtracting, and multiplying by constants. An optical computer could perform those operations quickly and energy efficiently.

As adept as optical computing is with linear computations, though, it struggles mightily with nonlinear ones—a small but necessary ingredient in neural-network computing—for the simple reason that photons don't generally interact with one another. Some nonlinear optical materials can mediate

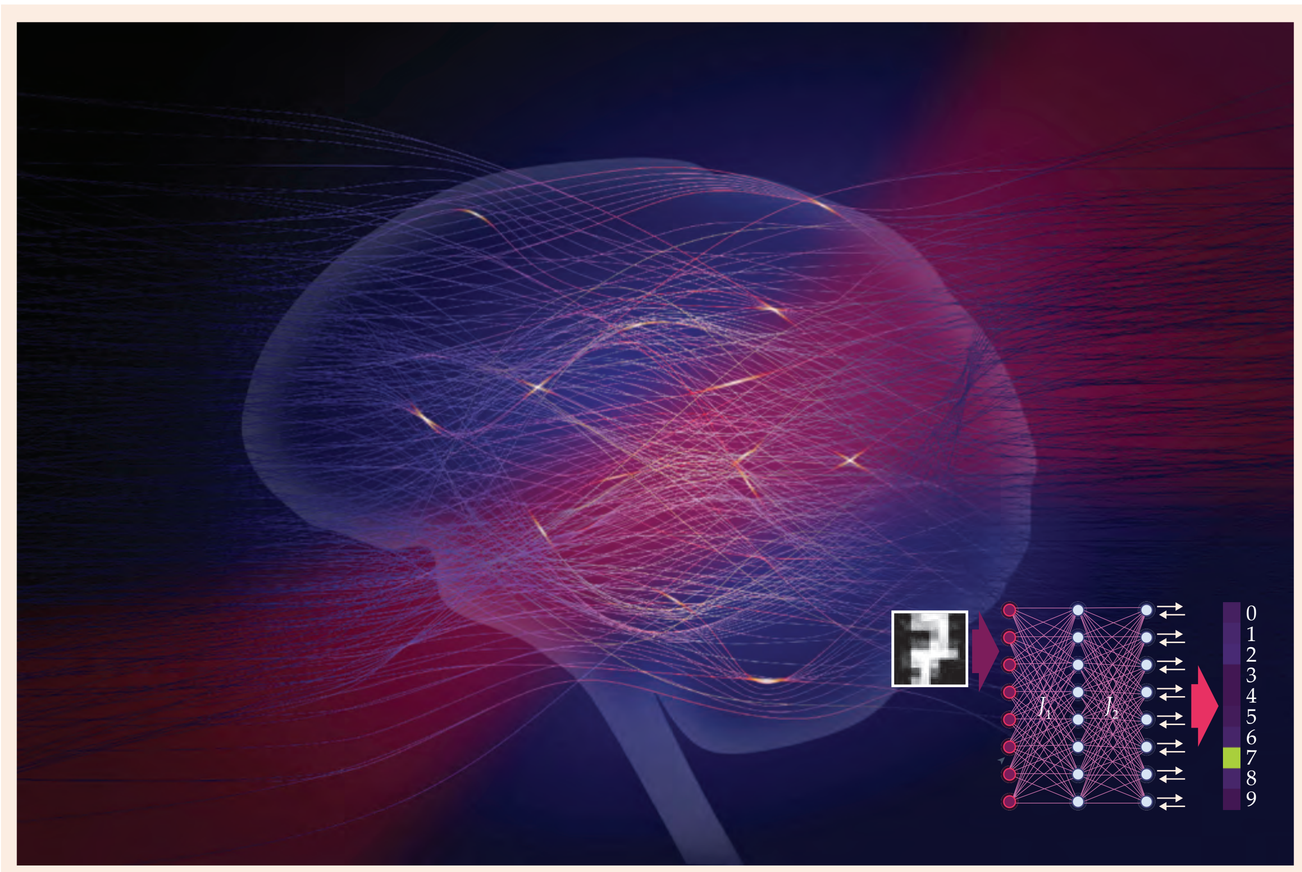

FIGURE 1. INSPIRED BY THE BRAIN, artificial neural networks process information by passing it among layers of nodes, known as neurons. Along the way are matrices of trainable parameters (represented in the inset as J_1 and J_2) which are iteratively adjusted to optimize the network to perform a specific task. Here, that task is recognizing images of numerals. (Image courtesy of Clara Wanjura; inset adapted from ref. 1.)

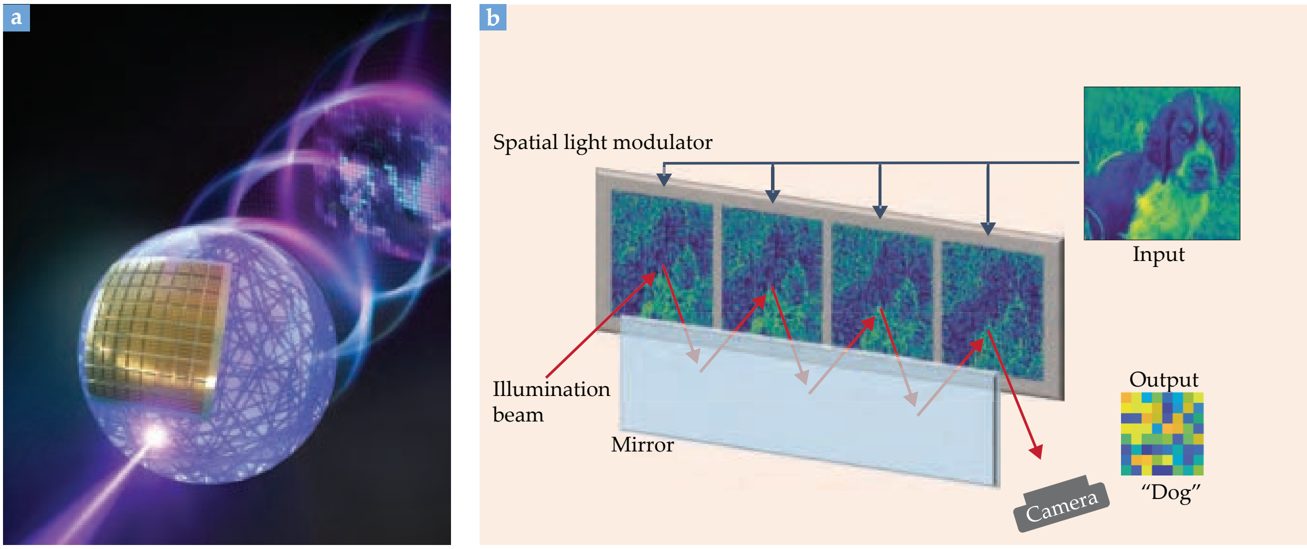

FIGURE 2. TO USE LIGHT as the basis for a neural network, researchers must rethink how they encode and process data. **(a)** A spherical cavity, partially lined with a reconfigurable array of mirrors, produces a random-looking speckle pattern when light bounces around inside it. But the speckles carry some surprisingly detailed information about an image encoded in the mirror array. (Courtesy of Fei Xia.) **(b)** In a more programmable implementation, four copies of an input image are encoded in a spatial light modulator, and an illumination beam is scattered off all of them. The system can be trained to classify the image, even one that it's never seen before. (Adapted from ref. 3.)

light–light interactions and thereby produce nonlinear responses, but they typically require impractically high optical power.

That chain of reasoning assumes that data are encoded in a light field, which is then processed and manipulated by the optical neural network. But as three groups have now shown, that's not the only way to do it. The groups' approaches differ, but their common insight is to encode the input data not in the light itself but in some part of the system with which the light interacts. Nonlinear functions can then be computed with ease, and neural-network implementations follow.

At the Max Planck Institute for the Science of Light in Erlangen, Germany, Clara Wanjura and Florian Marquardt showed theoretically that input data can be represented as frequency offsets in a system of coupled resonators.[1] The other two groups—one led by Hui Cao of Yale University and Sylvain Gigan of the École Normale Supérieure in Paris,[2] and the other led by Demetri Psaltis and Christophe Moser at the Swiss Federal Institute of Technology in Lausanne (EPFL)[3]—experimentally encoded data in arrays of pixels that light scatters off multiple times. In each case, the light-based systems can tackle rudimentary image-classification tasks with accuracies on par with digital neural networks.

Enlightened data processing

A neural network is really just a fancy mathematical function. It takes an input, such as the grainy image of a handwritten numeral shown in the inset in figure 1, and it produces an output: "7". To get from one to the other, it processes the data through layers of nodes, or neurons.

In a conventional neural network, each neuron computes a weighted average of all the signals feeding into it. Then, depending on whether the result exceeds a certain threshold, the neuron either fires or doesn't fire—that is, it produces either a 1 or a 0 to feed into the next layer. The weights used in the weighted average are so-called trainable parameters: The model is iteratively adjusted based on a series of inputs whose correct outputs are known, until eventually the network can correctly process inputs that it's never seen before.

The weighted averages, which consume the bulk of the computing power, even during the training phase, are the kind of linear operations at which optical computing excels. Summing two optical signals is as simple as superposing two light fields. And even a more complicated series of weighted sums can be done easily with a network of beamsplitters and phase shifters.[4]

For linear operations, optical computing can outshine electronic computing for all the same reasons as fiber-optic cables excel at transmitting data over long distances: Information encoded in an optical beam can be tightly compressed in both space and time, and it can travel long distances with little dissipation. So data can be processed with high throughput and low power.

But the big hurdle for optical neural networks is the simplest-sounding part of the computation: the decision of each neuron to fire or not, which is a nonlinear function of the input data. It can be computed with nonlinear optics, albeit with high optical power, or by converting signals from optical to electronic and back. But those approaches negate some of optical computing's biggest advantages.

Happily, neural networks aren't too picky about the nature of the nonlinear function. It doesn't have to be an all-or-nothing step function. In fact, most implementations use a smoothed step function for ease of computation, and many other nonlinear functions can be made to work if the network is suitably trained. So the question becomes, can a platform of all linear optics re-create any nonlinear function at all?

House of mirrors

The answer to that question—a resounding yes—depends on asking the right follow-up question: A nonlinear function of what? Linear optics, by definition, can compute only linear functions of an input light field, but they can produce a nonlinear response to other physical parameters, such as the positions of mirrors. To use those nonlinearities as the basis for a neural network, though, requires making some big changes to how the network is structured.

Cao and her group at Yale came to the study of optical nonlinearities while pursuing a different application: Rather than a neural network, they wanted to create a physical unclonable function (PUF), a sort of digital fingerprint that can serve as a security feature in the internet of things.[5] They took a golf ball–sized spherical cavity, as shown in figure 2a, and lined part of the interior with a reconfigurable array of tiny mirrors and the rest with a diffuse reflective coating. When they shot a laser beam into a hole in the cavity, the light bounced around inside before emerging as a speckle pattern out another hole.

The output speckles depend deterministically and reproducibly on the mirror configuration, but in a way that's almost impossible to replicate by anyone not in possession of that specific cavity. Those properties are what make the system a PUF—but is it also a neural network? It wouldn't initially seem to be: It has no discernible neurons, weighted averages, or trainable parameters. But in collaboration with Gigan and his postdoc Fei Xia, Cao and colleagues realized that the cavity could act as a so-called reservoir computer, a type of neural network in which all the computing is done first and all the interpretation is done later.

The speckle pattern is a highly nonlinear function of the mirror configuration. On average, the researchers estimate, light bounces thousands of times off the cavity surface before exiting, and at least a few hundred of those bounces are off the mirror array. The resulting speckles are full of information about correlations among pixels in the input data. And correlations are just what all neural networks use to work their magic.

To make sense of the speckle pattern, the researchers need only pass it through a decoder with one or a few layers of trainable weights, which is easy enough to do electronically. The mirror array, with more than 4 million pixels, can encode extremely detailed input images, and the system is capable of some complex computing tasks, including recognizing subtle features of human faces and spotting pedestrians in traffic scenes. Those tasks require up to 1 million trainable parameters in the output decoder. But that's less than a conventional neural network uses for the same tasks.

The EPFL researchers were also inspired by Cao and colleagues' PUF paper, but they took their implementation in a different direction. "We wanted to maintain a degree of programmability," says Mustafa Yildirim, one of the paper's co-first authors along with Niyazi Ulas Dinç. Like Cao, Gigan, and colleagues, they generate their nonlinearity by bouncing a light beam off an input image multiple times. But instead of leaving the scattering dynamics up to random chance, they send the light on a controlled zigzag path that scatters off a spatial light modulator with four distinct copies of the input, as shown in figure 2b.

The four copies of the input aren't all identical. In each one, every pixel is linearly scaled by a pair of trainable parameters, so the researchers can train their network much like a conventional one. Although the light bounces only four times off the input, the degree of nonlinearity was sufficient for the EPFL researchers to successfully train their system to perform simple image classifications, like distinguishing pictures of dogs, fish, and T-shirts. And because the input data are encoded four separate times, the network is highly robust against noise.

New architectures

Wanjura and Marquardt's work is the most abstract of the three groups. As theorists, they're focused on the mathematical concepts behind neuromorphic computing schemes. "I'd previously employed scattering theory in my topology studies," says Wanjura. "When I read Florian Marquardt's lecture notes on machine learning, I noticed that the scattering matrices I had worked with had some similarity to the math behind neural networks. So when I joined his group as a postdoc, we developed the idea further together."

Like a conventional neural network, the one that Wanjura and Marquardt envisioned is made up of discrete neurons. But unlike a conventional neural network, the information in it doesn't flow only one way. Rather, the light waves—or any waves, really—scatter back and forth across the network in both directions. With the input data and trainable parameters encoded in some of the neurons, the optical signal picks up a nonlinear dependence on both.

Wanjura and Marquardt proposed that the network could be realized by a system of coupled resonators, in which information is encoded in a resonator by detuning it from resonance. They're collaborating with Amir Safavi-Naeini and his experimental group at Stanford University to bring their ideas to fruition. But as a first step, they ran simulations of their network on an ordinary computer to show that it works for classifying images of handwritten numerals. "It's ironic," says Wanjura, "that the training simulations on a computer required a few hours, whereas a photonics experiment could ideally perform the entire training in a few milliseconds."

All three of the groups' endeavors are still at the proof-of-principle stage. Because all their networks process data so differently from conventional neural networks, it remains to be seen whether any of them can be scaled up to rival the powerful, power-hungry hardware that operates applications such as ChatGPT. But the implementations show that there's potential value in thinking outside the box. "It's motivating us to take more risks in optical computing," says Dinç, "not just directly adapting everything from electronics."

Johanna Miller

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A molecular-scale waterwheel removes carbon dioxide from the air

A chemical trick that harnesses energy from a humidity gradient could become another tool to mitigate climate change.

After centuries of releasing carbon dioxide into the atmosphere, humans are now looking for ways to remove it (see PHYSICS TODAY, June 2022, page 26). One obstacle is that despite the climate changes being driven by the rising concentration of CO_2 in the atmosphere, that concentration is still relatively dilute, at about 420 ppm. Diffusion naturally moves molecules from high-concentration areas to low-concentration ones, but extracting CO_2 from air requires a reversal of that process. Separating an already dilute substance from air thus poses thermodynamic and kinetic challenges that can predispose the task to being energy-intensive and slow.

To reverse the typical diffusion process, cells and other biological systems use an efficient trick to move molecules against a concentration gradient. Cells, for example, pump out hydrogen ions to maintain a specific pH. The trick, known as active transport, works in a manner akin to a waterwheel: As one substance moves down its gradient (from high concentrations to low ones), the energy that is released is harnessed to move another substance against its gradient (from low concentrations to high ones).

Ian Metcalfe, of Newcastle University in the UK, and colleagues have now found a way to harness an artificial version of the active transport mechanism to pull CO_2 out of air.[1] Just like with a

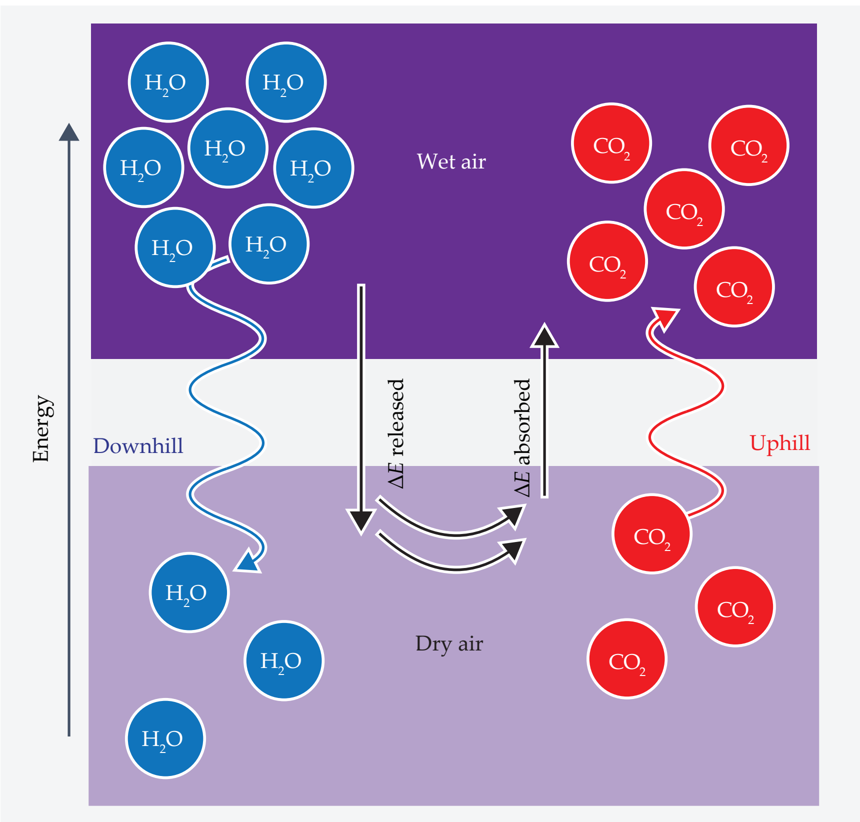


FIGURE 1. WATER MOVES ACROSS A MEMBRANE from wet air to dry air, and the energy ΔE released by the process is harnessed to move carbon dioxide in the opposite direction. (Adapted from ref. 1.)

waterwheel, the movement of water—in this case, at a molecular level—provides the driving force.

The method uses a difference in humidity between two air masses. The separation is made possible by a membrane containing a common carrier that bonds with either CO_2 or water molecules and shuttles them through the membrane to produce an equal and opposite exchange of the two substances. As shown in figure 1, moisture in an air mass on one side of the membrane causes water to move from the humid side to the dry side, which provides the energy for a corresponding transfer of CO_2 in the opposite direction.

Common carrier

Metcalfe and colleagues had not set out to replicate active transport; rather, they discovered the mechanism through a fortuitous experiment. They were investigating the use of molten-salt membranes for CO_2 separation, a small subset of the immense research field of direct air capture (see Physics Today, January 2020, page 44). Most experiments performed with such membranes involve some degree of leakage across them. When calculating the effectiveness of a membrane for a given task, researchers typically use a tracer gas to measure the extent of leaks and correct for them. Not satisfied with those typical conditions, Metcalfe and colleagues sought to design a leak-free membrane.

Leaks occur because it is hard to create a perfect seal between a hot membrane and the end of an open-ended tube. The researchers made the leak-free membrane by drilling many small holes into the end of an alumina cylinder that were then filled with a molten salt—in this case, a roughly equal mixture of lithium, sodium, and potassium carbonates. In early experiments led by Sotiria Tsochataridou, a member of the research team and a PhD student at the time, the team noticed that anytime moisture was introduced on one side, that water would transfer across to the dry side, and an equal number of CO_2 molecules would transfer in the opposite direction.

"It was something that I recognized when I saw it, and I thought, this might well be that we've got a common carrier," says Metcalfe about the early experiments. "We've got one species in there that's shuttling backward and forward, and if that's the case, we should be able to do some interesting things with it."

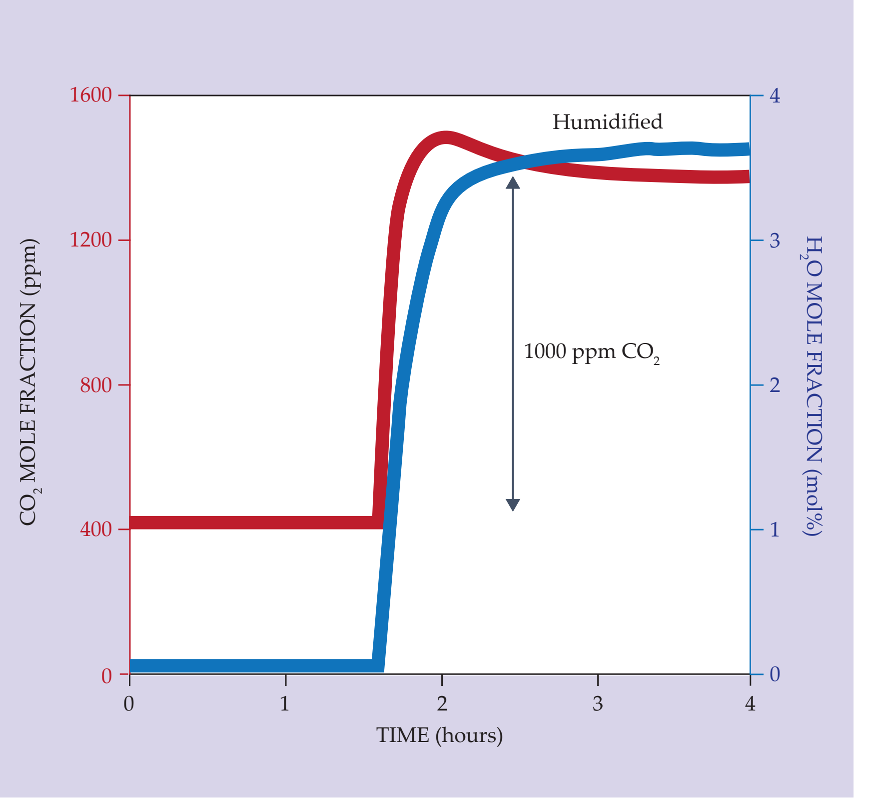


FIGURE 2. CARBON DIOXIDE CONCENTRATION (red line) rises in an air mass when the humidity (blue line) is increased after a period of equilibrium. Researchers took advantage of that relationship and designed a new method to extract CO_2 from the air. (Adapted from ref. 1.)

The experiments were exceptional not just because they were leak-free. Alumina is not the typical support material used for molten-salt membranes. Most often, the supports are conductive materials that help the membrane function by transporting charge. It was generally assumed in the community of membrane researchers that without a conductive support material, such membranes would not work. But alumina is not conductive, and it did work.

"We did a really daft experiment that gave us a really interesting result," says Metcalfe. "Everybody else was saying it wouldn't work, but nobody checked."

Equal exchange

Subsequent experiments confirmed the initial suspicion that the membrane contains a common carrier. Unlike a filter, in which one air mass is pushed through a medium to produce one input stream and one output stream, membrane separation involves two moving air masses and, subsequently, two inputs and two outputs. In membrane research, measurements of all four streams aren't always collected, but in this case, they were a necessary condition for noticing the common-carrier effect.

The experiments begin with streams of dry air on each side of the membrane that contain about 400 ppm of CO_2, close to the average concentration in today's atmosphere. When the streams have equal flow rates and water vapor is introduced into one of them, water quickly permeates from the humid side to the dry side and rises to 200 ppm. An equal quantity of CO_2 moves from the dry side to the humid side, leaving the dry side at a concentration of 200 ppm of CO_2 and raising the humid side to 600 ppm.

As shown in figure 2, when Metcalfe and colleagues dropped the flow rate on the humid side by a factor of five, the CO_2 concentration on that side increased by 1000 ppm, five times as much as the increase observed at equal flow rates, to a total of 1400 ppm. Before CO_2 concentrations reach 1400 ppm, though, there's a slight bump to an even higher concentration right after the water is introduced to the stream. That bump is from CO_2 that had been stored in the salt membrane suddenly being kicked out by the flux of water.

Metcalfe then enlisted the help of Patricia Hunt (Victoria University of Wellington in New Zealand) to explore the potential carrier reactions operating in the molten carbonate salts. Using density functional theory, she found that multiple reaction pathways could be at play in the membrane because of the similar chemical stability of several carriers. The carriers are generally composed of clusters of carbonates and lithium or sodium ions in varied proportions. And the carriers are highly selective—they bind with only water or CO_2, with a slight energetic preference for binding with CO_2.

The absorption of CO_2 and water into the melt is energetically favored, and the release of those species from the carriers is driven by concentration differences. The rate-limiting step is the release of CO_2 from solution on the humid side. The effective partial-pressure difference of water drives the water-binding process on the humid side and accelerates the release of CO_2. Because of the prevailing water partial-pressure difference across the interface, absorption of CO_2 on the dry side remains energetically favorable despite the CO_2 partial-pressure difference that develops.

Molten membranes

Although the discovery is a new way to pull CO_2 from the air, the method is far from having the conditions necessary for implementation in a direct air capture system. A CO_2 concentration of 1400 ppm is still much lower than the near-pure concentration of CO_2 necessary for movement into permanent storage, but Metcalfe and colleagues note that the new process could be a valuable preconcentration step that reduces the expense of other downstream extraction methods. Further adjustments to the flow rates and relative humidity levels could also push that concentration higher.

The extremely dry air used in the experiments is nowhere near the humidity of atmospheric air, even in the driest deserts. For that reason, the researchers also investigated using humidified air on both sides of the membrane while retaining a gradient in the humidity. They found that the membrane works even at humidity levels that reflect natural conditions, although the permeation rates do decrease somewhat. The natural swing of atmospheric humidity from day to night in many regions could provide enough of a gradient for the mechanism to be used for direct air capture.

For the carbonate salts used in the experiment to stay molten, they have to be at least 400 °C, which means the air must also be that hot. That could pose another barrier to economically scaling up the process. But there could be ways to lower the melting point, such as doping the salts with other materials.

Metcalfe is excited about the prospects of refining the method or finding other common carrier materials. "We wanted to try to change the way people think—there are ways to address the thermodynamic and kinetic barriers—and with that inspiration, and perhaps with clever engineering, they can take it further," he says.

Clear benefits of the new approach are that it is fast and highly selective—only water and CO_2 move through the membrane, with no leaks. Though polymer-based membranes make up the bulk of direct air capture membrane research, they are generally plagued by a low selectivity that allows gases besides CO_2 through. The carbonate salts and alumina used for the experiments are also relatively cheap base materials. It's unlikely that any single technology will provide a solution to looming climate change. Metcalfe and colleagues' molten-salt membrane adds a new, efficient tool to the effort.

Laura Fattaruso

Reference

1. I. S. Metcalfe et al., *Nat. Energy* (2024), doi:10.1038/s41560-024-01588-6.

AI can solve the crystallographic phase problem

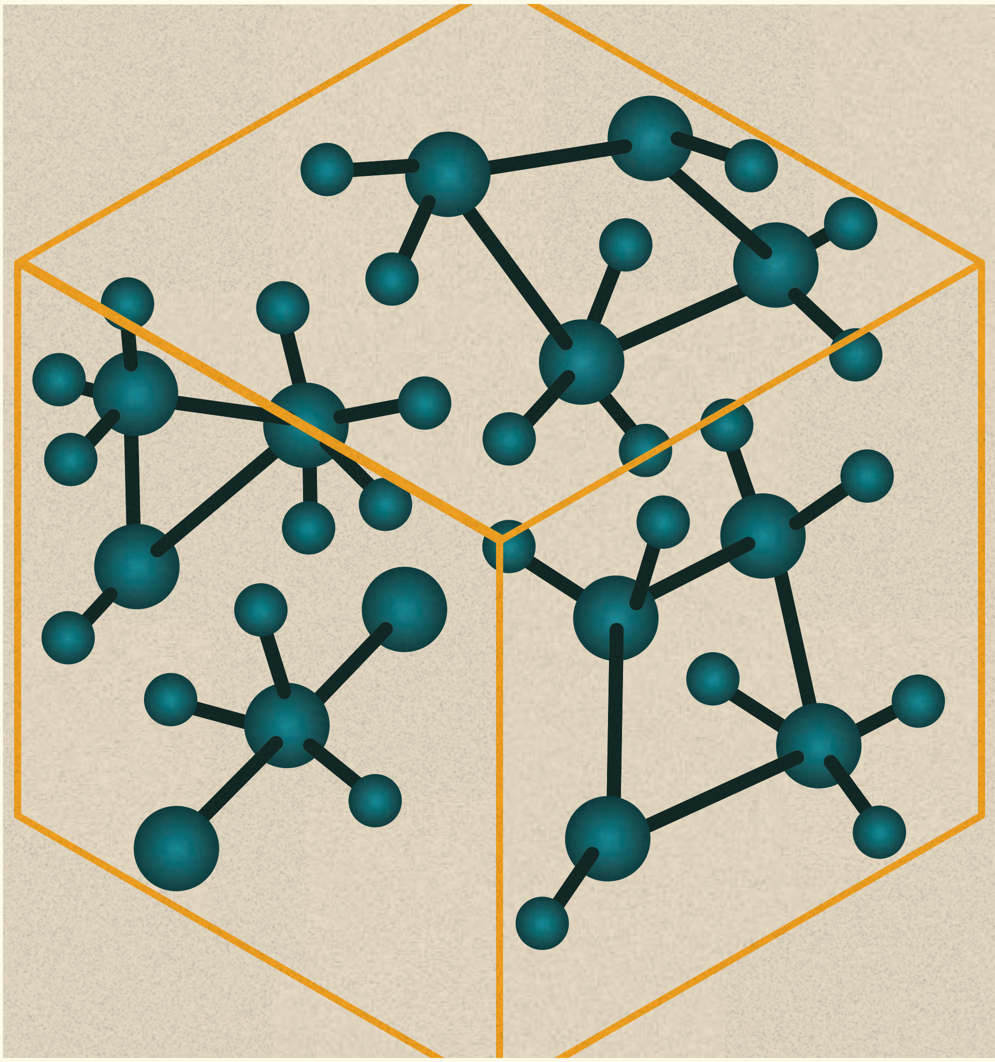
A neural network identifies molecular crystal structures with just a fraction of the data that other methods need.

As x rays scatter off a crystalline sample, detectors measure their intensity but are unable to measure their phase information. But both intensity and phase are necessary for x-ray diffractometry to reconstruct the position of each atom in such samples. The phase problem in x-ray crystallography does have some partial solutions, which have made the experimental technique spectacularly successful in condensed-matter physics and biophysics.

Each of the solutions, however, has certain limitations. For direct methods, a complete set of diffraction-peak measurements is plugged into a system of equations that estimates phases based on the probable location of electrons in the crystal lattice. The phase information can also be collected by other means, such as computational microscopy (see the article by Manuel Guizar-Sicairos and Pierre Thibault, Physics Today, September 2021, page 42). But they all need lots of high-resolution data and often require crystallographers to painstakingly grow high-quality samples. That's true even for molecules that are smaller than proteins, the typical targets of x-ray crystallography.

Now Anders Madsen and Anders Larsen of the University of Copenhagen and Toms Rekis of Goethe University Frankfort in Germany report that a deep-learning algorithm can determine the crystal structure of various molecules with up to about 50 atoms. Despite working with just 10–20% of the data that are typically required for direct methods, the AI approach generated crisp electron-density maps of a sample's structure.

Madsen and colleagues trained the AI algorithm with 49 million chemical crystal structures that they artificially generated. Then they tested the algorithm against 2300 real chemical structures that they obtained from the Cambridge Structural Database, an archive of more than 1.25 million 3D crystal structures determined by x-ray diffraction and neutron diffraction. For their proof of principle, the researchers chose molecular crystal structures that have a length scale of about 10 Å and fall into one of the relatively simple space groups, which describe the packing symmetry of a crystal's molecules. The first results were successful: The algorithm produced phase values and correctly identified the 3D structure for each of the 2300 test cases.



THE 3D STRUCTURE of molecules in a crystal can be determined by deep-learning AI. (Adapted from A. S. Larsen, T. Rekis, A. Ø. Madsen, *Science* **385**, 522, 2024.)

The phase problem isn't entirely solved. Many other molecular crystal structures in different space groups have yet to be evaluated, and Madsen and his team are testing the algorithm's effectiveness for more complex space groups and larger crystal sizes. Existing AI tools, such as AlphaFold, are already making exquisite predictions of proteins' 3D structures (see Physics Today, October 2021, page 14); Madsen and colleagues' algorithm fills a complementary niche for smaller molecules that are difficult to crystallize or for weakly scattering crystals that are unable to yield better than low-resolution diffraction data sets. (A. S. Larsen, T. Rekis, A. Ø. Madsen, *Science* **385**, 522, 2024.)

Alex Lopatka

Origami-inspired robot folds into more than 1000 shapes

Composed of small cubes, the robot needs only a few motors to be active at any one time to transform between configurations.

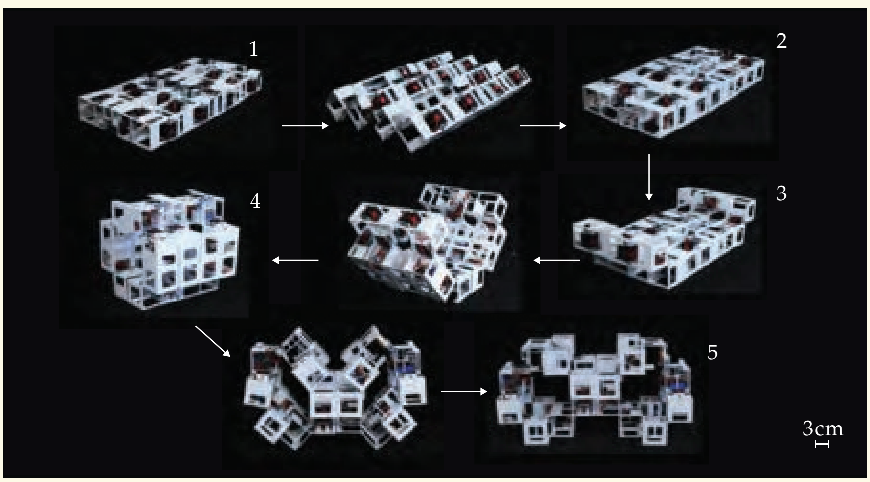
Robots that imitate life may capture the imagination, yet even simplistic-seeming robots can perform complex tasks. Jie Yin and his colleagues at North Carolina State University have developed a robot that is made up of 3D-printed cubes and employs simple movements to transform into hundreds of arrangements. The robot executes origami-like folds on multiple scales because of joints that connect different levels of the tessellated framework. The multilevel structure minimizes the power the robot needs to perform those actions.

The robot comprises 32 plastic cubes, each measuring about 8 cm across, that start in a flat 4 × 8 arrangement. Adjacent cubes can be linked by one of two types of joints: a flexible connection or a small, motorized hinge. The hinges can actively power the robot's movement, passively respond to the movement caused by another motor, or lock its current position to prevent movement. The joint positioning enables the cubes to be controlled individually or as a collection of modules. That multilevel, or hierarchical, design overcomes the typical dependence of a robot's shape-changing ability on the complexity of the actuation and control system.

Engineers in Yin's lab demonstrated that the 32-cube structure could arrange itself into more than 1000 configurations. For example, the figure below shows how the robot transforms from the initial flat structure to a 3D structure with hollows. It has 36 total hinges. Although a maximum of 16 rotate during a single step (from step 4 to 5), at no point are more than 3 motors active at the same time to power the movement. The array of configurations isn't just for show. Different sequences enable the robot to achieve forward locomotion at 1 m/min, faster than similarly structured robots. The robot can also roll along a flat surface and crawl up a 10° ramp.

Yin says that future robots designed with the hierarchical, origami-based concept could prove useful for navigating unpredictable terrain. In distant environments, such as the Moon, similar configurable robots could also function as modular structures or even divide into smaller robots to perform discrete tasks, with minimal power required, before reassembling again. (Y. Li et al., *Nat. Commun*. **15**, 6247, 2024.)

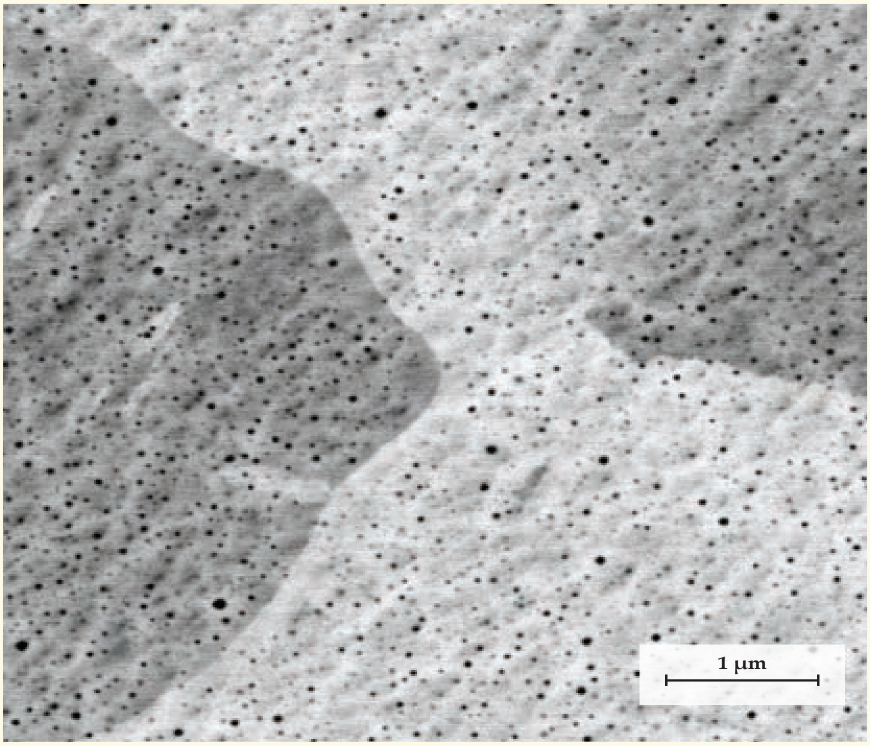
Jennifer Sieben



A ROBOT MADE UP OF 32 CUBES transforms from a flat arrangement into a structure of two loops. No more than three motors are active for any one step. (Adapted from Y. Li et al., *Nat. Commun*. **15**, 6247, 2024.)

Perforating gold can make it stronger

Often considered a nuisance, voids in a metal may improve certain mechanical properties if they are small and uniformly distributed.



HOLES MEASURING ABOUT 18 NM ACROSS permeate a sample of gold in this scanning electron micrograph. (Courtesy of Jia-Ji Chen.)

Poking holes in a metal may not seem like a great way to strengthen it. Small voids can rapidly expand, and a metal peppered with large fissures isn't useful for many applications. Metal suppliers and industrial users often put considerable effort into preventing the formation of internal voids. Yet a new study of gold suggests that permeating the 3D structure of a metal with minute holes can augment the metal's strength. The findings lend support to predictions that sufficiently small voids would enhance metals' desirable mechanical properties.

Hai-Jun Jin (Chinese Academy of Sciences) and colleagues fashioned holey gold by removing the silver from a gold–silver alloy via a corrosion process. The reaction yielded gold that was weakened by a network of nanosized channels. To bolster the fragile metal, the researchers compressed and heated the samples. Beyond a threshold material density, the channels closed up to form an array of isolated, evenly spaced voids of roughly equal size. The researchers tuned both the size of the voids, which ranged from 18 to 180 nm, and the void distribution by adjusting the corrosion reaction, the degree of compression, and the annealing temperature.

Jin and colleagues then took their millimeters-wide samples and stretched them to measure stress and strain. The smaller the embedded holes, the stronger the metal: The gold with 18 nm voids withstood twice the stress before deforming than the samples of bulk gold. The researchers also found that the hole-ridden samples were just as able to be stretched without fracturing as conventional gold.

Electron micrographs of the samples pre- and post-stretching indicate that the size of the holes is central to their beneficial influence. Unlike the voids that are the scourge of metal suppliers, the ones in the Jin team's samples are two or three orders of magnitude smaller than the metal's grain size, so they are unlikely to be the source of fractures. They also seem to impede the progress of linear defects that propagate through the metal.

Jin and his team plan to try perforating other pure and alloyed metals, including some, such as copper, that are used more frequently than gold for structural applications. (J.-J. Chen et al., *Science* **385**, 629, 2024.)

Andrew Grant

Sizes of tropical glaciers reach historic lows

New measurements of radioactive isotopes provide evidence for the retreat of Andean glaciers since the end of the last ice age.

Most glaciers worldwide are retreating because of climate change. To put the current retreat into perspective, researchers have conducted surveys that estimate historical glacial extent. They have found that many glaciers, including many high-altitude mountain glaciers, are not as small as they were in the past. By the early Holocene, roughly 12 000 years ago, Earth had come out of its last ice age, and variations in the planet's orbit caused warmer summers and, consequently, smaller glaciers.

Tropical glaciers today, located in mountainous regions, appear to be decreasing in size more than glaciers in other regions. New results by Andrew Gorin of the University of California, Berkeley, and colleagues show that several glaciers in South America—where nearly all tropical glaciers are found—have retreated to a minimum extent not seen during any other time since the early Holocene, when humans were just starting to domesticate plants and animals for agriculture.

QUESHQUE GLACIER, located in the Peruvian region of the Andes mountains, is one of four tropical glaciers where researchers collected samples of bedrock to better understand how glacial extent has changed during the past 12 000 years. (Courtesy of Emilio Mateo, Aspen Global Change Institute.)

During that time in Earth's history, the average temperature in most tropical regions was low, compared with today, before it started to sharply rise over the next several thousand years. One of the few previous measurements of Holocene glacial extent in South America goes back only 7000 years. The evidence indicates that the world's largest tropical glacier, the Quelccaya ice cap in Peru, is smaller today than it was in the mid-Holocene. To better reconstruct how glacial extent may have changed further back in the early Holocene, Gorin's colleagues took expeditions to several Andean glaciers starting in 2012 to collect bedrock samples that were once buried but have since been exposed at Earth's surface.

Gorin and colleagues analyzed the samples using an established method among isotope geochemists: measuring the carbon-14 and the beryllium-10 composition of rocks. The radioactive isotopes are products of cosmic-ray reactions with silicon and oxygen in quartz, so they become concentrated in quartz bedrock only if it is exposed at the surface.

The radioactive isotope concentrations in nearly all the samples were low—so low, in fact, that the only way the samples could have that level is if they were never exposed to cosmic rays during the Holocene. That would imply that either ice covered the bedrock or the bedrock was exposed earlier in Earth's history before it eroded away. The researchers' modeling failed to support the erosion possibility. The most likely explanation, Gorin and his colleagues conclude, is that the melted glaciers exposed the bedrock and are smaller now than at any other time during the Holocene. Tropical glaciers provide a warning: As global temperatures continue to climb, more glaciers may soon reach similar minimums. (A. L. Gorin et al., *Science* **385**, 517, 2024.)

Alex Lopatka PT

NASA balloons study atmosphere and cosmos

Goals include determining the origins of cosmic rays and electron microbursts.

A BALLOON carrying the XL-Calibur experiment was prepped and launched on 9 July from the Esrange Space Center near Kiruna, Sweden. The experiment measured the polarization of Cygnus X-1, an x-ray source consisting of a black hole and a supergiant star.

From late May through mid-July, instruments aboard four NASA scientific balloons collected data on cosmic rays, clouds, the Sun's magnetic field, and more. Launched from Kiruna, Sweden, the balloons and their payloads were retrieved from locations across northern Canada after flights lasting three to seven days.

NASA's balloon program has sent scientific experiments into the stratosphere for more than 30 years and currently flies 10–15 balloons per year. Since the program's establishment, balloons continue to reach ever-higher altitudes.

One attraction of balloons is the price tag: Whereas the cost of space missions rises into the tens of millions to billions of dollars, balloons average a few million dollars apiece, says the acting chief of NASA's Balloon Program Office, Andrew Hamilton. They also provide a stable platform to test new technologies for later use on space missions. The *Compton Gamma Ray Observatory*, a photon-detecting satellite launched in 1991, for example, contained instruments that were first developed on scientific balloons. Made with a thin membrane of polyethylene, NASA balloons can carry payloads of up to about 3600 kilograms.

Studying from the sky

The first balloon of the recent campaign carried a superconducting magnet that measured the flux of high-energy cosmic-ray isotopes. Scientists are especially interested in two beryllium isotopes: One is stable, and the other is radioactive. The ratio of the isotopes impinging on the magnet provides insights on how long they took to reach Earth and thus the distance they traveled. Although cosmic rays were discovered more than 100 years ago, scientists have not pinpointed the source of the most powerful ones, says Nahee Park, a project scientist and an astrophysicist at Queen's University in Kingston, Ontario.

The next balloon carried a telescope that measured the polarization of x rays emitted from Cygnus X-1, a supergiant–black hole binary system that is one of the brightest x-ray sources seen from Earth. The goal is to understand how such objects accelerate electrons, which then emit x rays. Another onboard instrument used spectropolarimetry—measurements of the polarization of light at different wavelengths—to better define the size and shape of ice particles in clouds. And a third instrument measured Earth's total UV levels and ozone concentration.

Another balloon flew a 1 meter telescope, the largest solar telescope yet to leave the ground. Equipped with three spectro-polarimeters, it imaged the Sun's photosphere and chromosphere and probed the star's magnetic field. The

Sun's magnetic field is more complex than Earth's, says Sami Solanki, the experiment's principal investigator and the director of the Max Planck Institute for Solar System Research in Göttingen, Germany. And, he notes, the magnetic field drives all solar activity. The instruments examined sunspots, of which there were many because the Sun was near its solar maximum.

The final balloon carried an x-ray imager that took photos of short, intense bursts of electrons that entered Earth's atmosphere. Called electron microbursts, they collide with atmospheric gases and produce x rays that are reabsorbed too quickly to be observed from the ground. High-resolution images could provide insights into the origins of microbursts, says the principal investigator, Montana State University physics professor John Sample. The imager flew on NASA's largest scientific balloon, which clocks in at 1.7 million cubic meters—60 million cubic feet—the size of a football stadium. Nicknamed the "Big 60," the balloon reached an altitude of nearly 49 kilometers, a record for the agency's launches from Sweden. The altitude is limited by the buoyancy force of the helium inside the balloon and the total weight of the payload and balloon.

Weather limitations

NASA launches balloons from several sites around the world: the Columbia Scientific Balloon Facility in Texas; Fort Sumner, New Mexico; McMurdo Station in Antarctica; the Esrange Space Center in Sweden; Alice Springs, Australia; and Wanaka, New Zealand. Sites need to be isolated from the public for safety reasons, including potential balloon crashes. They are also situated where the wind speeds are low at ground level.

"Sweden is a fantastic place for us to launch because it is in the far northern latitude," says Hamilton. The flight path above the Arctic Circle experiences constant sunlight during the summer months, so it minimizes pressure changes and gas loss in the balloons. And solar experiments can collect data around the clock.

At takeoff, minimal clouds and no precipitation are a must, and a bit of wind helps push the balloon up. "Even a light drizzle is a no go," says Robert Mullenax, a meteorologist at the Columbia Scientific Balloon Facility. Rainy weather spread out the launch dates this year. The second balloon did not fly until six weeks after the first, and the third and fourth followed in the next four days. Because NASA shared the range with the French national space agency, there were fewer available launch dates, says Mullenax.

Once the balloon is in flight, "there is a direct line of sight between the balloon and the ground, so operators can talk to it directly," says Hamilton. Data are stored on the payload and can be transmitted from the payload up to a satellite, then down to a control center. The method is useful when the balloon moves over a launch site's horizon and direct communication no longer works.

Controllers generate a risk map in the planned landing area to pinpoint where to drop a payload. Once a place is picked, a signal is sent to detach the balloon from the payload. The payload falls away with a parachute. In the process, it rips a hole in the balloon, and the helium escapes. NASA recovers the balloon and the payload in the following weeks.

The research teams on the four campaign experiments will spend the next few years analyzing their data, says Hamilton. In the coming months, they plan to present first results at gatherings that include the 2024 American Geophysical Union meeting in Washington, DC, and the 2025 International Cosmic Ray Conference in Geneva.

Hannah H. Means


NASA

NASA'S LARGEST BALLOON, measuring 1.7 million cubic meters, ascends toward the stratosphere carrying BOOMS, the Balloon Observation of Microburst Scales experiment. It took flight on 13 July from the Esrange Space Center near Kiruna, Sweden.

Particle physicist Carolina Deluca retools when she needs to

Deluca has leveraged her physics background and artistic skills to pursue careers outside of academia.


CAROLINA DELUCA in her studio. (Courtesy of Carolina Deluca.)

"If I am fed up, I find ways to move on." That attitude has taken Carolina Deluca from working in experimental particle physics to starting a business to teaching middle and high school physics. "I am not scared of change," she says.

Deluca earned her physics PhD in 2009 in Barcelona, Spain, where she grew up. She spent time at Fermilab and then was based at CERN for two postdocs. She still lives nearby, in a small town in France about 8 km from the Swiss border. There was an unwritten rule in particle physics, she says, "that at the end of your second postdoc, you should get something more permanent." Missing that window can make a candidate look less appealing and landing a job even harder. When she was in that position in 2015, she says, "people were retiring and posts were not being replaced." As a result, the ambience among postdoctoral researchers became "competitive and sometimes aggressive."

THIS TAU NEUTRINO CARTOON is one of many cards Carolina Deluca designed for the game Particools in collaboration with Anna Sfyrla, a physics professor at the University of Geneva. (Courtesy of Carolina Deluca.)

"The environment didn't bring out the best in me," says Deluca. Plus, she had a family, so she didn't have the flexibility to go wherever a job might take her. Deluca began to feel that the "life-and-death deadlines" of the experiments were arbitrary. "The rest of humanity didn't care if the paper for the Higgs boson came out this week or next."

With the stress of work, Deluca returned to her childhood hobby of drawing. "A colleague at CERN saw my drawings and asked if I would do a poster for a conference," she recalls. The poster was a success, and it led to more side jobs. She turned her artistic skills into a career move.

Her illustration business got off to a good start. Deluca took on both science and nonscience art projects. She illustrated projects for CERN, for universities, and for conferences. She made a coloring book about the ATLAS experiment and designed cards for Particools, a Guess Who?–style game based on standard-model particles. Producers from the TV show *The Big Bang Theory* asked to use her scientific posters for their set, she says. But they sent a contract that would have granted them "universal and permanent rights without any payment," says Deluca. "I refused."

For science-based art projects, she says, "you need to have knowledge to propose ideas and to make the illustrations relatable. You want to convey to the general public concepts that are super abstract. So my physics background helps a lot."

Work had come mainly through word of mouth, she says. "I learned that being an entrepreneur requires qualities that maybe I don't have. I don't like to sell myself."

Then the COVID-19 pandemic hit. "Things slowed down, and people developed other ways of doing things."

She also realized that she missed physics. "I didn't miss the research world, but I like making physics relatable to people and doing that in a creative way," she says. With art projects slowing down, she decided to become a teacher.

In 2022, Deluca started teaching physics at a middle school in France. So far, she says, she enjoys the contact with physics, the satisfaction of conveying ideas, and helping teenagers learn. "Teaching has a creative aspect," she says.

Now Deluca is working on getting certification to teach middle and high school in Switzerland where, she says, conditions for teachers are better. "If I manage to get into a stable position, then I would like to teach for at least a few years." And once things settle a bit, she says, she hopes to get back to illustrating as a side hustle.

Toni Feder

Research space increases at US universities

Laboratory and research space at US colleges and universities crept up nearly 17% from 2011 to 2021, to a total of 236.1 million square feet (21.9 million square meters). That's according to a report on infrastructure use by the National Center for Science and Engineering Statistics. In total, 584 research-performing institutions provided data about their science, engineering, and medicine departments.

Five fields accounted for nearly 84% of total science and engineering research space in fiscal year 2021. Biological and biomedical science labs took up the largest chunk, with roughly 25% of the total. The next three largest fields were engineering and health sciences, each with about 17%, and agricultural sciences, with about 14%. Physical sciences had 23.9 million square feet, roughly 10% of the total. No other field accounted for more than 4% of research space.

Universities reported breaking ground on 4 million square feet in new projects in FY 2020 and FY 2021 combined. Planning ahead, institutions anticipated spending $6.1 billion for repairs and renovations of research space through 2023; the actual data from last year are not yet available.

The report is available at https://ncses.nsf.gov/pubs/nsf23308. It also includes data on the condition of research infrastructure and a list of the 30 institutions that boast the most research space.

Tonya Gary

SCIENCE AND ENGINEERING RESEARCH SPACE IN ACADEMIC INSTITUTIONS

	Fiscal year					
	2011	2013	2015	2017	2019	2021
Total research space* (square feet in millions)	202.2	211.8	214.5	221.2	226.9	236.1
Biological and biomedical sciences	53.7	57.2	55.9	57.7	58.3	60.0
Computer and information sciences	5.0	4.3	4.3	4.2	4.6	4.6
Engineering	31.7	33.4	34.2	35.2	38.3	40.5
Geosciences, atmospheric sciences, and ocean sciences	7.8	7.8	8.1	8.5	8.6	9.0
Mathematics and statistics	1.5	1.7	1.8	1.8	1.8	1.8
Physical sciences	21.8	22.9	22.7	23.2	23.5	23.9
Other S&E (includes health and agricultural sciences)	80.7	84.5	87.4	90.6	91.8	96.4

* Totals may not add up due to rounding.

Adapted from M. T. Gibbons, *University Science and Engineering Research Space Increased More Than 30 Million Square Feet in the Past Decade*, NSF 23-308, National Center for Science and Engineering Statistics (2022), table 1.

Q&A: Tareq Abu Hamed champions environmental cooperation in the Middle East

The Palestinian director of a research institute in Israel uses dialog and science diplomacy to tackle regional challenges related to water, energy, climate adaptation, and more.

TAREQ ABU HAMED

Tareq Abu Hamed is a Palestinian Israeli from East Jerusalem. He was in high school in the late 1980s, during the first Intifada. Palestinian universities were closed, and tensions between Arabs and Jews in the region were high. He decided to study abroad, in Turkey. Today, he is the executive director of the nongovernmental Arava Institute for Environmental Studies in southern Israel.

Abu Hamed earned his undergraduate and graduate degrees in chemical engineering—his bachelor's and master's degrees from Gazi University and his PhD from Ankara University. He also holds a master's degree in public policy from the Hebrew University of Jerusalem. For his PhD, he focused on using bacteria to clean oil spills. Later, as a postdoc at Israel's Weizmann Institute of Science, he worked on hydrogen fuel for transportation and then, at the University of Minnesota, on solar energy. "I became attracted to renewable energy," says Abu Hamed. "I said to myself, 'Why clean oil spills? Why not get rid of oil?'"

Since then, Abu Hamed has devoted himself to renewable energy, clean water, and other environmental issues in the Middle East. In 2008, he joined the Arava Institute, drawn by its mission to advance cross-border environmental agreements in the face of political conflict. Founded in 1996, the institute resides on Kibbutz Ketura, with employees and students living on-site. "The kibbutz is a Jewish community," he says. "At the time, I wanted to give my wife and daughters the opportunity to experience firsthand living in a community that is not an Arab community, not a Muslim community." He has been there ever since, except for 2013–16, when he worked in Israel's Ministry of Innovation, Science, and Technology.

During his stint at the science ministry, Abu Hamed served as deputy chief scientist and then acting chief scientist. While there, he says, he established a unit of engineering research, which formed new partnerships with other countries and increased the number of scholarships for women and minorities in Israel. "Being at an organization that funds research was a great experience for me," he says. "But in the public sector you are a public servant. You implement the agenda of the elected government. You do not have a lot of space to dream and to build your own work. I am a researcher. I am not built for the public sector. Three years was enough for me."

PT: Describe the activities of the Arava Institute.

ABU HAMED: The Arava is an academic and research institution with roughly 50 employees. Those of us in the Middle East live in a region where we share most of the natural resources. The region does not suffer from a lack of science, technology, or natural resources. No, the region suffers from a lack of trust.

Trust is the scarcest resource in the Middle East. The lack of understanding, the lack of trust, prevents us from working together to deal with the environmental challenges and the climate change challenges that the region is facing.

ARAVA INSTITUTE FOR ENVIRONMENTAL STUDIES

A WASTEWATER TREATMENT SYSTEM is installed for a pilot test at a school in a Bedouin community in southern Israel's Negev desert. Designed by Arava Institute researchers in partnership with Laguna Innovation, the system includes solar panels and treats wastewater through anaerobic digestion and biofiltration. The resulting water is suitable for irrigation.

The Arava Institute has three main activities. The first is the academic program. Students spend a semester here, and then they go back to their universities. They get credit through Ben-Gurion University of the Negev. One-third of students are international students, mainly from North America. One-third are Jewish Israelis, and one-third are Arab students—Israeli Palestinians, Palestinians from the West Bank and Gaza, Jordanians, Moroccans, Sudanese, and more. Before the war, we had 60 students. Now we have 35.

We also have research centers focused on renewable energy, transportation, sustainable water management, climate change, and political ecology. And we have the Jordan–Israel Center for Community, Environment, and Research. We do a lot of work with communities in the region. We apply the technologies and the cooperative relationships that we develop to benefit local farmers and communities.

Our third pillar is environmental diplomacy. Through projects on the ground, we try to solve environmental challenges that are stuck for many years because of the political conflict. We work with academic institutions, civil society organizations, and governments in the region.

PT: What are some examples of scientific and diplomatic projects?

ABU HAMED: We have projects on the dual use of land—using the same land for agriculture and solar energy production. We test the impact of solar panels on the performance of agriculture and on water conservation—the shade from the solar panels leads to less evaporation. We also study the impact of the plants on the performance of the photovoltaic panels because you create a kind of microclimate in which the temperature is lower.

We do a lot of work with communities on desalination and wastewater treatment. Our wastewater treatment system is modular, scalable, and runs on solar energy, without any noise or smell. And the recycled water is high quality.

We work with farmers in Gaza, the West Bank, and Bedouin communities in Israel to help them use solar energy to pump water. This helps people cope with and adapt to climate change. The lack of rain increases the salinity of the aquifer, and that increased salinity prevents farmers from diversifying their crops. Once farmers have high-quality water, they can diversify.

We also have a project for managing water, energy, and food between Israel, Jordan, and Palestine.

PT: How is the Arava Institute funded?

ABU HAMED: Most of the funding comes from the US. We also have funding from the USAID's Middle East Regional Cooperation program and the European Union. The total annual budget is \$3 million–\$4 million. We are a small organization with a huge impact on the ground.

PT: I understand that the institute was nominated for a Nobel Peace Prize?

ABU HAMED: Yes. That was early this year. We heard from some of the nominators. It's in recognition of the environmental diplomacy work we do in the region.

PT: How is the war in Gaza affecting what you do?

ABU HAMED: The war impacts everyone in this region, physically and mentally. As a nongovernmental organization, we have a lot of challenges. But we have not lost any Arab partners since October 7. Our partners trust the Arava Institute.

Currently, we have a major project we call Jumpstarting Hope in Gaza. A coalition of civil society organizations in Palestine and Israel is working to provide people in Gaza with decentralized technologies to produce drinking water, treat wastewater, and produce electricity. We are planning to send them into Gaza in full coordination with the Israeli army.

Our partners in Gaza managed to build refugee camps, and we are trying to help convert them into sustainable camps, with prefabricated houses instead of tents. We are in the final stages of getting permits to send these systems into Gaza.

PT: Is the Arava Institute unique? Are there other scientific institutions that take the diplomacy-for-peace approach in the Middle East?

ABU HAMED: I think we are the only organization in the region that uses

ARAVA INSTITUTE FOR ENVIRONMENTAL STUDIES

THE ARAVA INSTITUTE FOR ENVIRONMENTAL STUDIES hosts Arab, Jewish Israeli, and international students from outside the Middle East in roughly equal parts.

science diplomacy with students and researchers. SESAME [the synchrotron light source in Allan, Jordan] has members from around the region. But you don't have a lot of Israeli scientists that go and stay there to build long-lasting relationships with scientists from other countries. The Malta Conferences Foundation brings scientists from the whole region together and builds long-lasting relationships.

What makes the Arava Institute unique is that we bring people together for at least a semester, and we have dialog as part of our academic program. The students and faculty talk about conflict, Israeli Independence Day, Nakba, culture, religion, family stories. We discuss everything. When something happens in the region, the students don't go to their rooms. No, they come together to discuss what's happening.

Toni Feder PT

UNIVERSITY OF NOTRE DAME

DEPARTMENT OF PHYSICS AND ASTRONOMY

The Department of Physics and Astronomy at the University of Notre Dame invites applications for three tenure-track faculty positions at the assistant professor level. Applications from exceptional researchers at a higher rank will also be considered.

Experimental Condensed Matter Physics

This position is within the newly established Stavropoulos Center for Complex Quantum Matter (https://quantummatter.nd.edu/). The successful candidates are expected to complement current efforts and areas of expertise towards the Center's mission to synthesize materials of interest for novel technologies and to study them with cutting-edge experimental and theoretical methods. The Stavropoulos Center is led by László Forró, the Aurora and Thomas Marquez Chair Professor of Physics. The condensed matter group at Notre Dame consists of 10 experimental and 7 theoretical faculty members, specializing in hard condensed matter, quantum materials, complex networks, and biological physics.

Further information and application details at: https://apply.interfolio.com/153476. Review of applications begins on November 1 and will continue until the position has been filled.

Experimental High Energy Physics

Two positions are in HEP, focusing on the CMS experiment and neutrino physics respectively. The HEP group at Notre Dame consists of 7 experimental and 4 theoretical faculty, doing experimental research with CMS, DUNE, MINERvA, EMPHATIC, and NA61, along with instrumentation and computing R&D. Our theory group does research on collider, astrophysical, and cosmological tests of the Standard Model and its possible extensions. The successful candidates will be expected to complement our efforts on the CMS experiment and in neutrino physics, and establish leadership within the relevant experimental collaboration(s).

Further information and application details at: https://apply.interfolio.com/153483 (CMS) and https://apply.interfolio.com/153489 (neutrino physics). Applications must be received by October 18 to receive full consideration.

For all positions, applicants should submit a curriculum vitae, list of publications, detailed research plans, and a statement of teaching and mentoring. Applications must be submitted through Interfolio, where descriptions of the requested items can also be found. Candidates must also arrange for at least three letters of recommendation.

We seek faculty members committed to developing and sustaining an environment of inclusive excellence in research, teaching, and service. The successful candidates must demonstrate the ability to develop a highly successful research program, attract independent research funding, teach effectively at both the graduate and undergraduate levels, and engage with students from diverse backgrounds. Applicants must have a Ph.D. or equivalent advanced degree. Salary and rank will be commensurate with the successful applicant's experience and research accomplishments. The expected start date is August 2025.

The department is committed to diversifying its faculty and encourages applications from women and members of traditionally underrepresented groups.

The Department of Physics and Astronomy at Notre Dame has 46 tenured and tenure-track faculty; another 26 research, teaching and concurrent faculty, as well as professors of the practice; more than 110 graduate students; and about 100 undergraduate physics majors. Additional information about the department and the College of Science can be found at http://physics.nd.edu and http://science. nd.edu respectively.

FREDDIE PAGANI

Richard Fitzgerald is the editor-in-chief of PHYSICS TODAY.

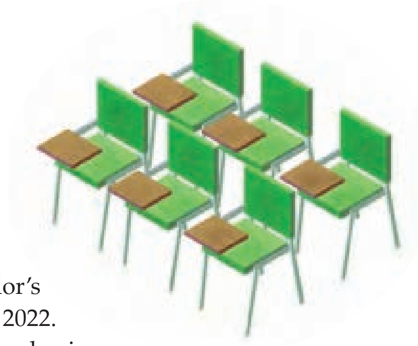
Careers by the numbers

Richard J. Fitzgerald

What's the next career step for new recipients of physics bachelor's degrees? Of physics PhDs? Data give some insights.

Everyone's career follows a different path. Nevertheless, aggregated data can highlight features and trends in the overall career landscape. Here we present a collection of snapshots and trends that paint a picture, albeit an incomplete one, of the career options available to—and taken by—students who have received physics degrees in the US. The data come from surveys by the American Institute of Physics' Research team (AIP also publishes PHYSICS TODAY); more information and additional reports, on both astronomy and physics careers, can be found at the team's website, https://aip.org/statistics.

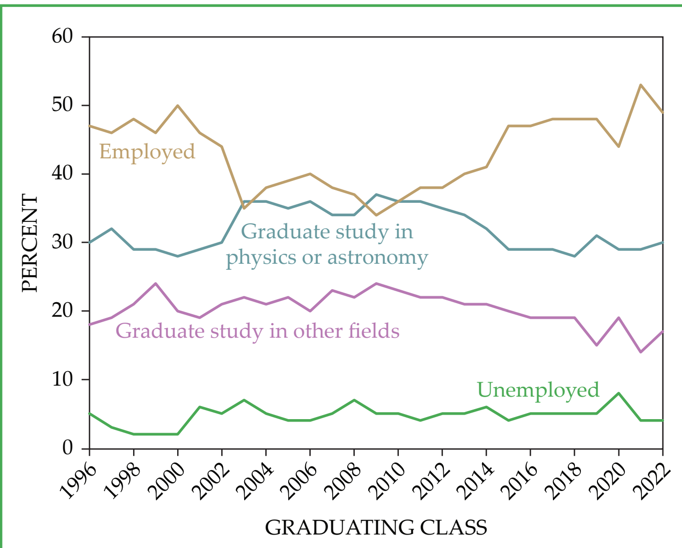
Physics bachelor's degree recipients



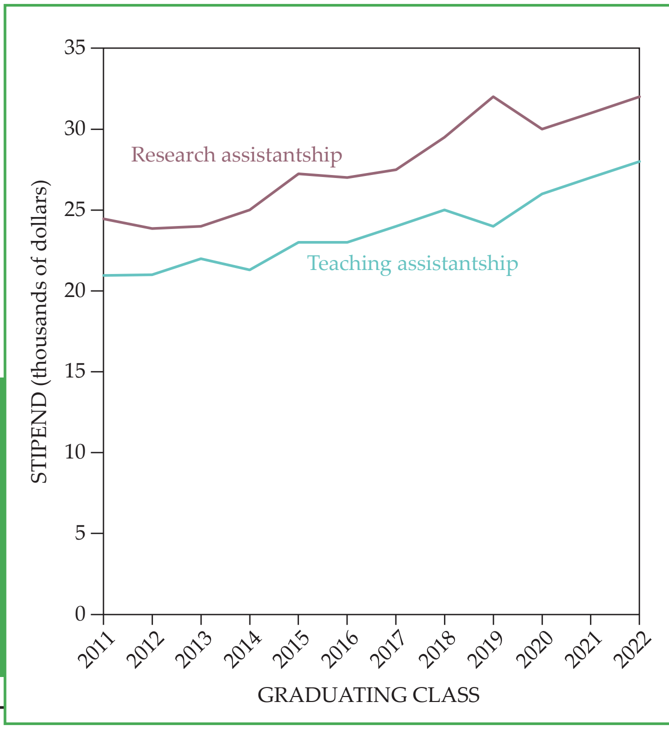
Each year, the AIP Research team surveys all US physics departments and bachelor's and PhD recipients in physics. The most recent employment data are from the class of 2022.

In the US, 8618 undergraduates in the class of 2022 received a bachelor's degree in physics. That marks a 4.5% decline from 2021 and the second straight annual decrease after two decades of increases.[1] Physics enrollments have been falling, so the number of bachelor's degrees awarded will likely continue to fall.

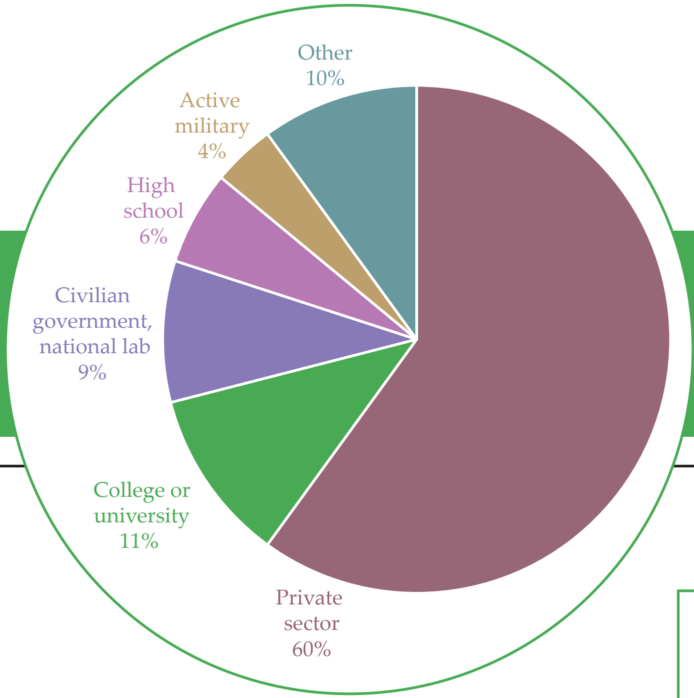
Nearly half of all new physics bachelor's recipients in the classes of 2021 and 2022 reported that they entered the workforce. A majority of the positions in the private and public sectors were in STEM. Of those who continued on to graduate school, roughly two-thirds were in physics or astronomy. Engineering is the next most popular field of study for physics bachelor's recipients; other common areas include math, computer science, education, business, law, and medicine.



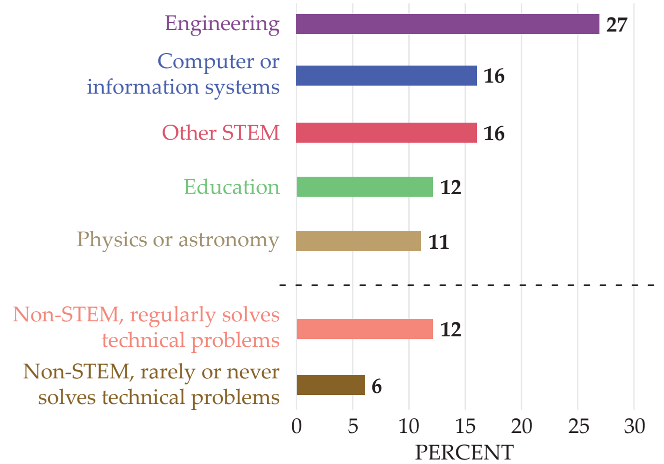
WHERE NEW PHYSICS BACHELOR'S RECIPIENTS ARE, one year after getting their degree, for those who received their degree in the US and stayed in the US. The proportion of survey respondents who reported being in graduate school in physics or astronomy has held steady for several years. The results for 2020 were the first to be affected by the COVID-19 pandemic. (Courtesy of Jack Pold and Patrick Mulvey; data from degree-recipient follow-up surveys by AIP Research.)



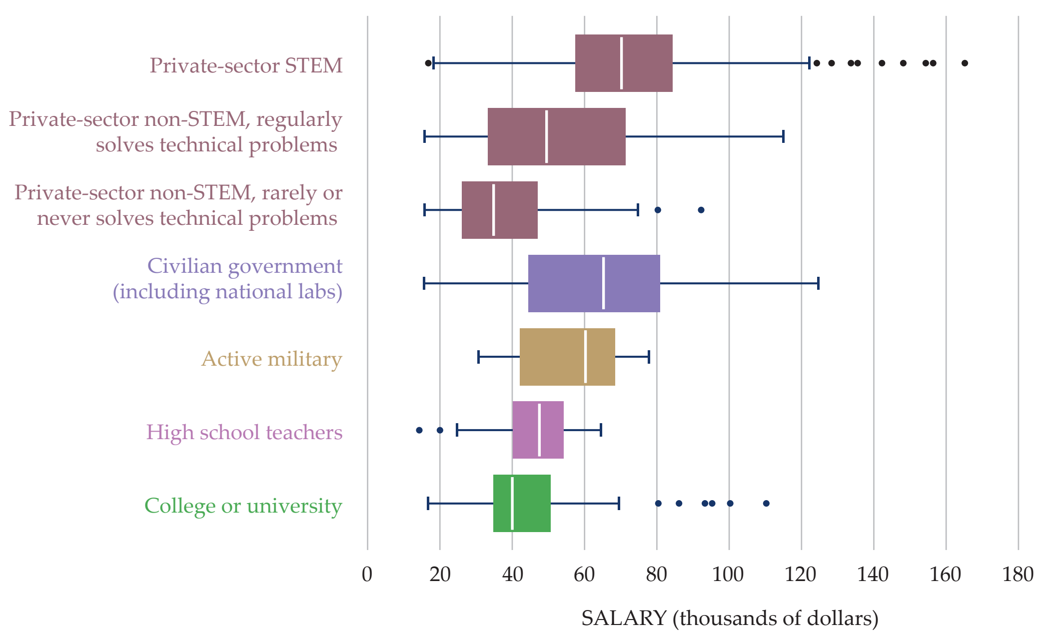
MEDIAN GRADUATE STUDENT STIPENDS. The overall stipend increases from 2011 to 2022 are slightly below the US median earnings increase during that period for all individuals with a bachelor's degree or higher,[2] and the median stipends are lower than the median starting salaries for physics bachelor's degree recipients who entered the workforce, as seen on page 33. (Courtesy of Jack Pold and Patrick Mulvey; data from degree-recipient follow-up surveys conducted by AIP Research.)



WHERE NEW PHYSICS BACHELOR'S RECIPIENTS WORK, one year after getting their degree, classes of 2021 and 2022 combined. (Data from AIP Research, *Physics Trends: Where New Bachelors Work*, 1 February 2024.)

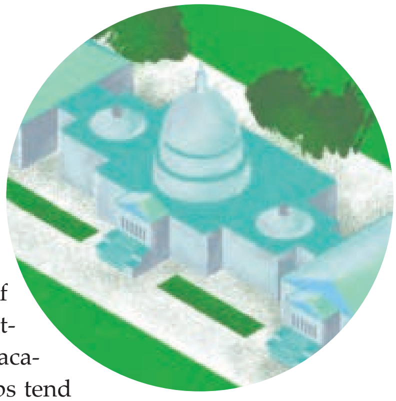


WHAT WORKING PHYSICS BACHELOR'S RECIPIENTS DO, in the winter after getting their degree from a US college or university, classes of 2021 and 2022 combined. The data reflect all employment sectors. "Regularly solves technical problems" includes respondents who selected "Daily," "Weekly," or "Monthly" on a four-point scale that also listed "Rarely or Never." (Data from AIP Research, *Physics Trends: Field of Employment for New Physics Bachelors*, 12 September 2023.)



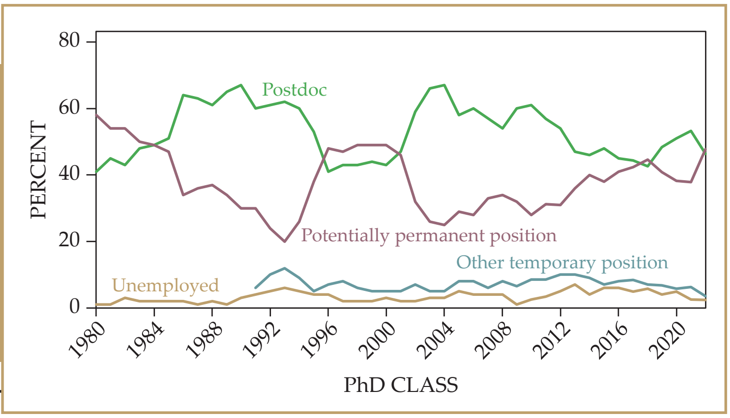
WHAT WORKING BACHELOR'S RECIPIENTS MAKE. Starting salaries are for full-time employed, US-educated physics bachelor's degree recipients from the classes of 2021 and 2022 combined. In this box-and-whisker plot, the boxes represent the middle 50% (25th to 75th percentiles) of salaries, and the vertical line in each box is the median salary. The lines extending to either side of the boxes denote the starting salary ranges excluding outliers, which are indicated by the dots. (Data from AIP Research, *Physics Trends: Starting Salaries for Physics Bachelors*, 12 September 2023.)

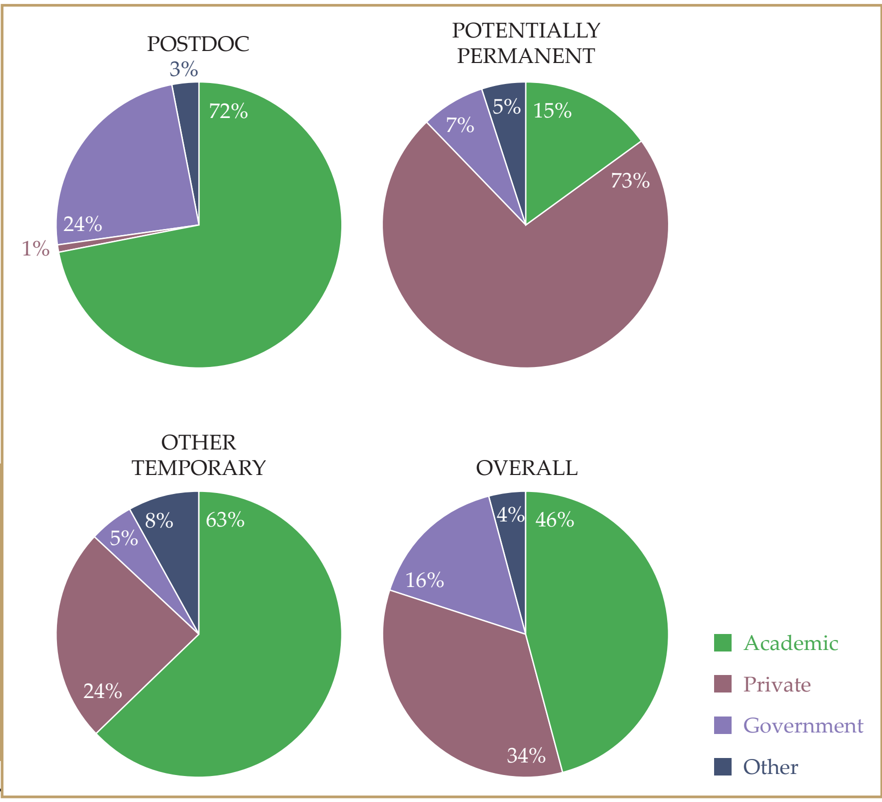
New physics PhDs



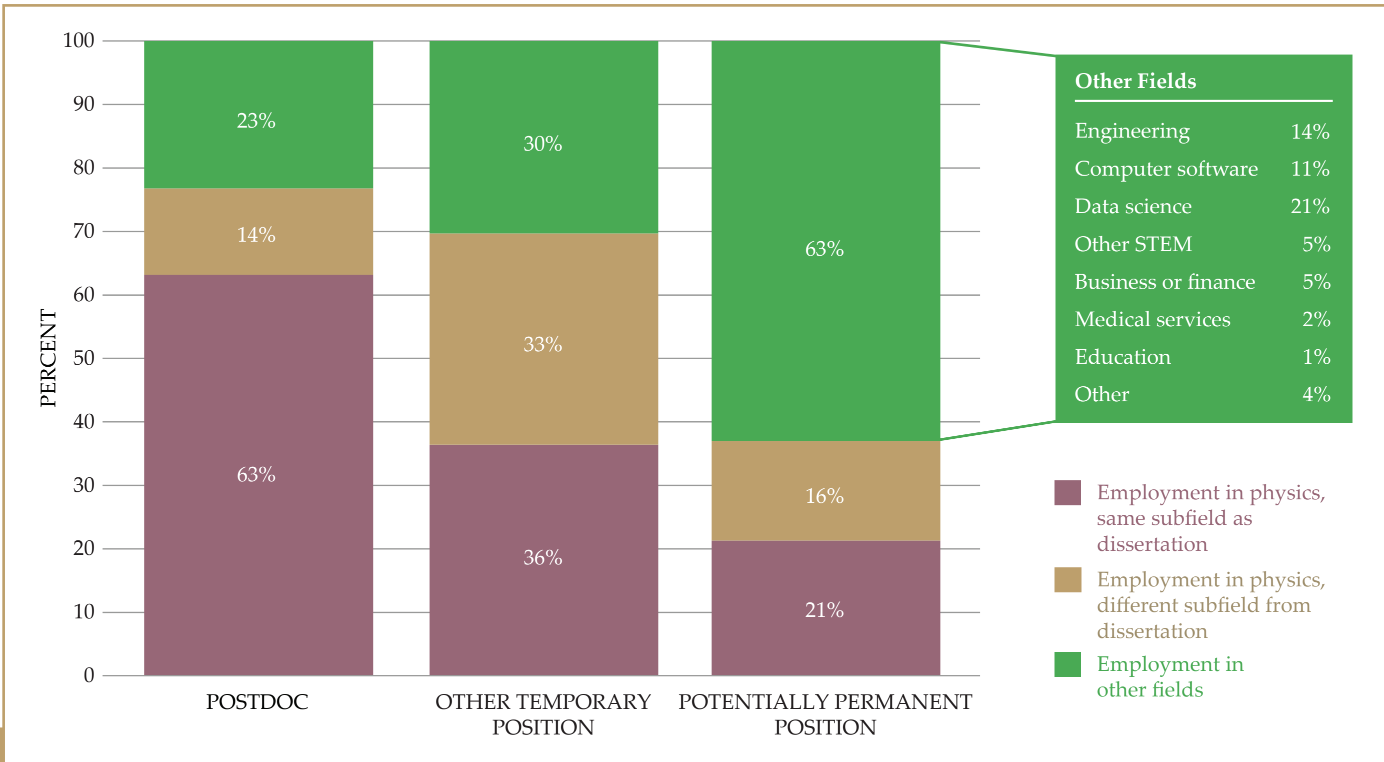
The classes of 2021 and 2022 produced an average of 1900 physics PhDs in the US. Of those, 14% left the country. The others are roughly evenly split between accepting postdocs and potentially permanent positions.[3] Postdoctoral researchers primarily go into academia or government, and they generally stay in the same subfield. Private-sector jobs tend to pay the most and temporary positions the least.

EMPLOYMENT STATUS OF NEW PHYSICS PhDs, in the winter after receiving their degree. The data are for those who received their PhD degree from a US institution and remained in the US. The 1991 survey was the first to include "other temporary" employment as a separate category. (Courtesy of Jack Pold and Patrick Mulvey; data from degree-recipient follow-up surveys conducted by AIP Research.)

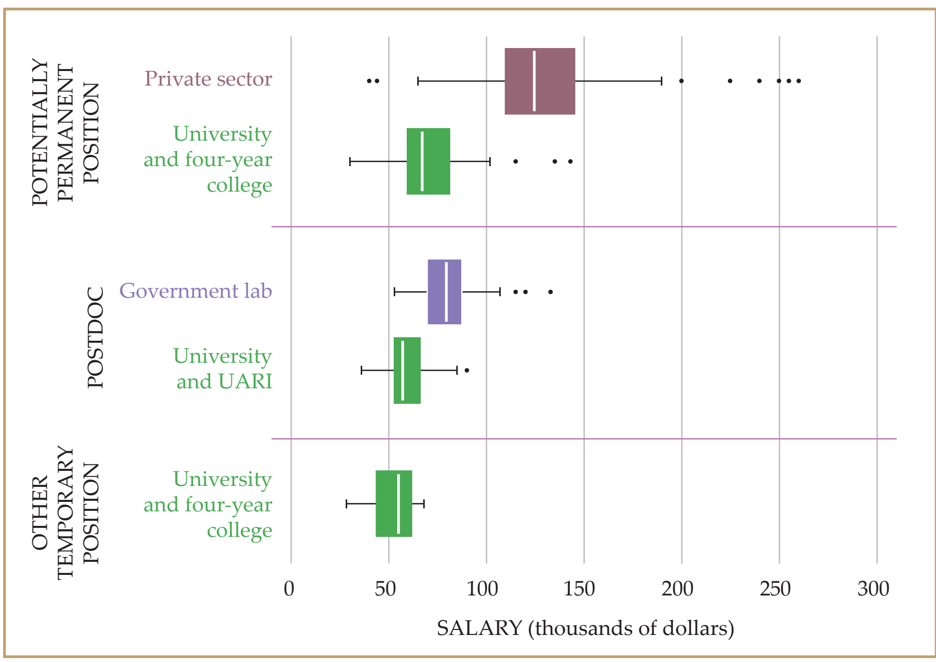




EMPLOYMENT SECTOR FOR NEW PHYSICS PhDs, classes of 2021 and 2022, broken down by job status. Data are for those who received their PhD degrees in the US and remained in the country. (Courtesy of Jack Pold and Patrick Mulvey; data from degree-recipient follow-up surveys conducted by AIP Research.)

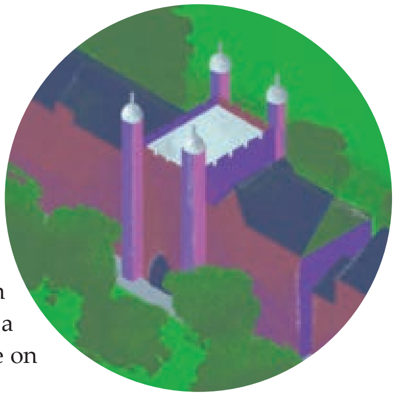


EMPLOYMENT FIELD FOR NEW PHYSICS PhDs, classes of 2021 and 2022 combined. "Physics" includes respondents who said that either their primary or secondary employment field was in physics or astronomy. Data are for PhDs who received their degrees in the US and remained in the country. The inset lists the other fields for the potentially permanent positions; the components of the other temporary positions do not add up to 100% because of rounding. (Courtesy of Jack Pold and Patrick Mulvey; data from degree-recipient follow-up surveys conducted by AIP Research.)

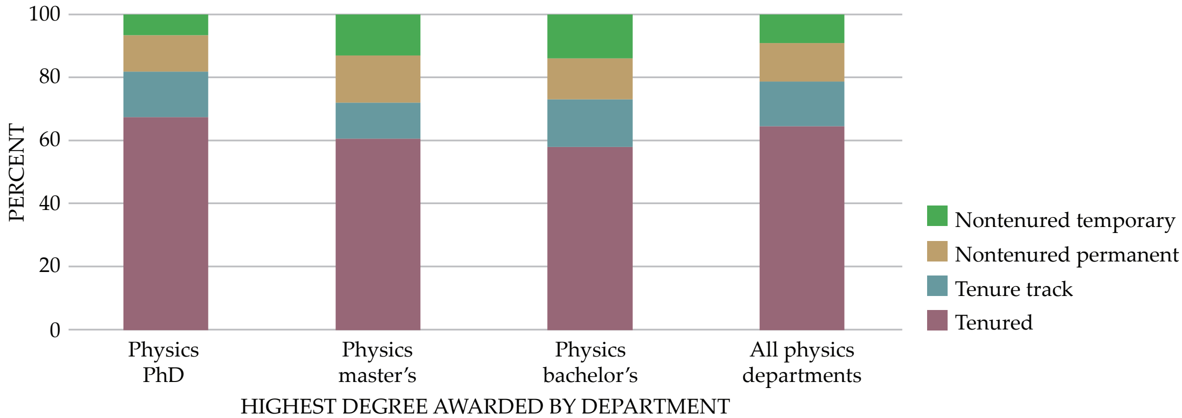


STARTING SALARIES FOR NEW PHYSICS PhDs, classes of 2021 and 2022 combined. Government labs include federally funded R&D centers, such as Los Alamos National Laboratory. UARIs are university-affiliated research institutes. For how to read the box-and-whisker plot, see the bachelor's salary graph on page 33. (Courtesy of Jack Pold and Patrick Mulvey; data from degree-recipient follow-up surveys conducted by AIP Research.)

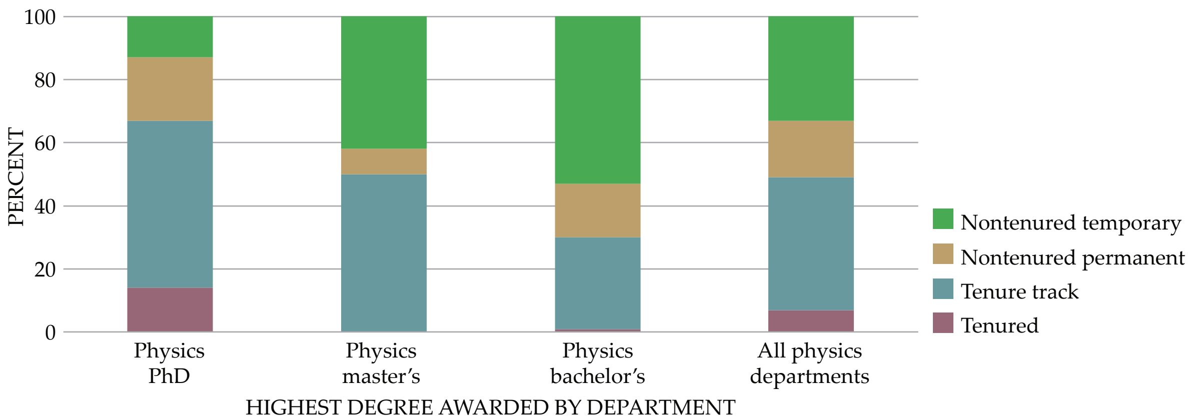
The academic workforce



In addition to collecting information about and from degree recipients, the AIP Research team also gathers data every two years about the US academic physics workforce as a whole. The tenure status of faculty members in a department has a strong dependence on the highest degree (bachelor's, master's, or PhD) that it awards.[4]



TENURE STATUS OF CURRENT PHYSICS FACULTY MEMBERS, according to the highest degree that the department awards. Here the data include anyone engaged in teaching or research in the 2021–22 academic year. (Courtesy of Anne Marie Porter; data from the 2022 AIP Academic Workforce Survey.)



TENURE STATUS FOR NEW PHYSICS FACULTY HIRES, according to the highest degree that the department awards, for the 2021–22 academic year. (Courtesy of Anne Marie Porter; data from the 2022 AIP Academic Workforce Survey.)

Additional resources

- "You have options: Career paths for physicists," *SPS Observer*, Fall 2024, p. 22.
- AIP Research, https://aip.org/statistics.
- National Center for Science and Engineering Statistics, https://ncses.nsf.gov.
- National Center for Education Statistics, https://nces.ed.gov.
- National Science Board, National Science Foundation, *Science and Engineering Indicators 2024: The State of U.S. Science & Engineering*, NSB-2024-3 (March 2024), https://ncses.nsf.gov/pubs/nsb20243.

I thank Patrick Mulvey, Jack Pold, Anne Marie Porter, Susan White, and Freddie Pagani for their assistance with the data and graphs.

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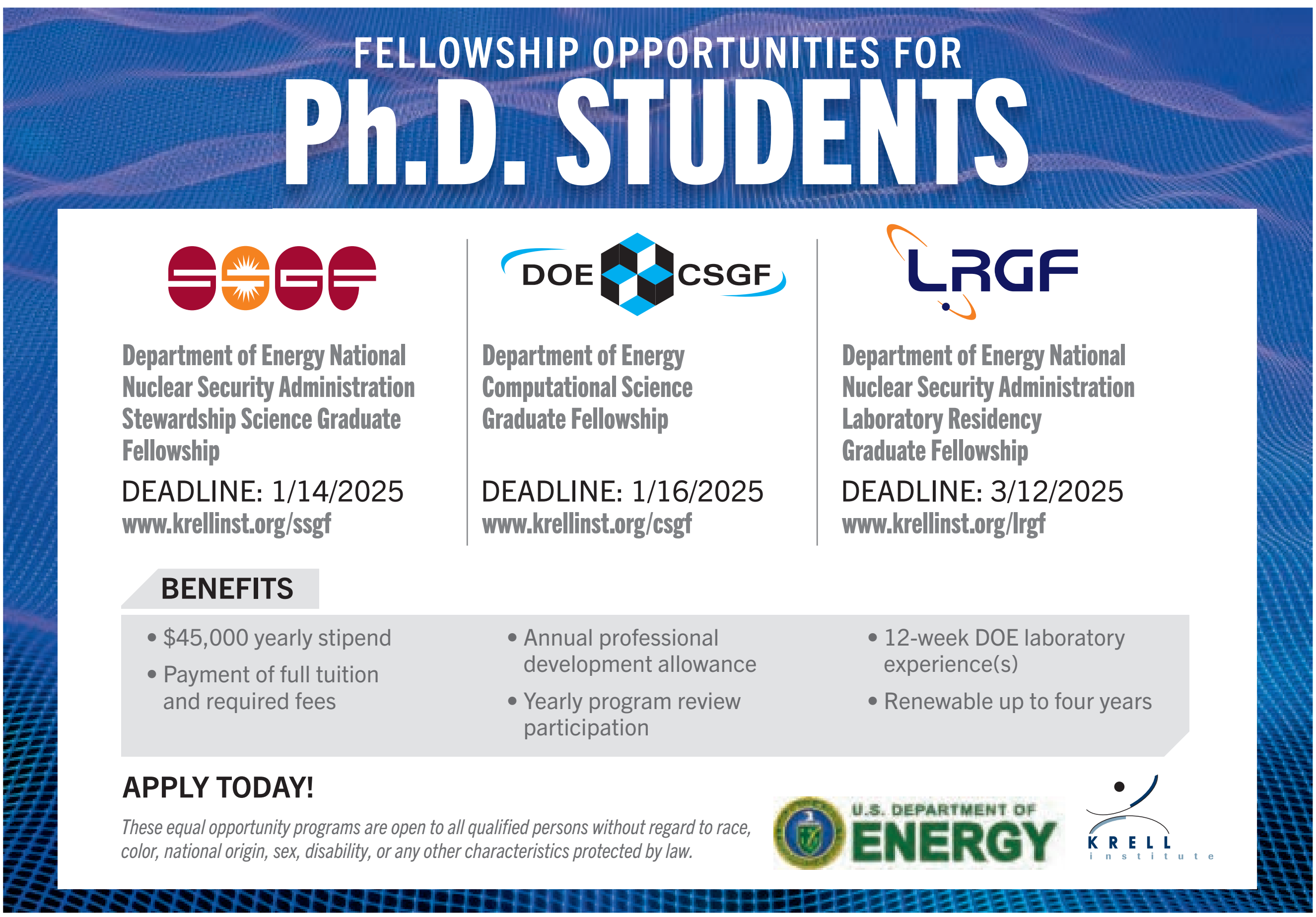
1. S. Nicholson, P. J. Mulvey, *Roster of Physics Departments with Enrollment and Degree Data, 2022*, AIP Research (September 2023).
2. US Bureau of Labor Statistics, "Median usual weekly earnings of full-time wage and salary workers by educational attainment" (July 2024), https://www.bls.gov/charts/usual-weekly-earnings/usual-weekly-earnings-over-time-by-education.htm.
3. *AIP Physics Trends: Physics PhDs 1 Year Later*, AIP Research (12 September 2023), https://ww2.aip.org/statistics/physics-phds-1-year-later.
4. A. M. Porter, J. Taylor, *The State of the Academic Workforce in Physics and Astronomy Departments, 2000–2022*, AIP Research (3 May 2024).



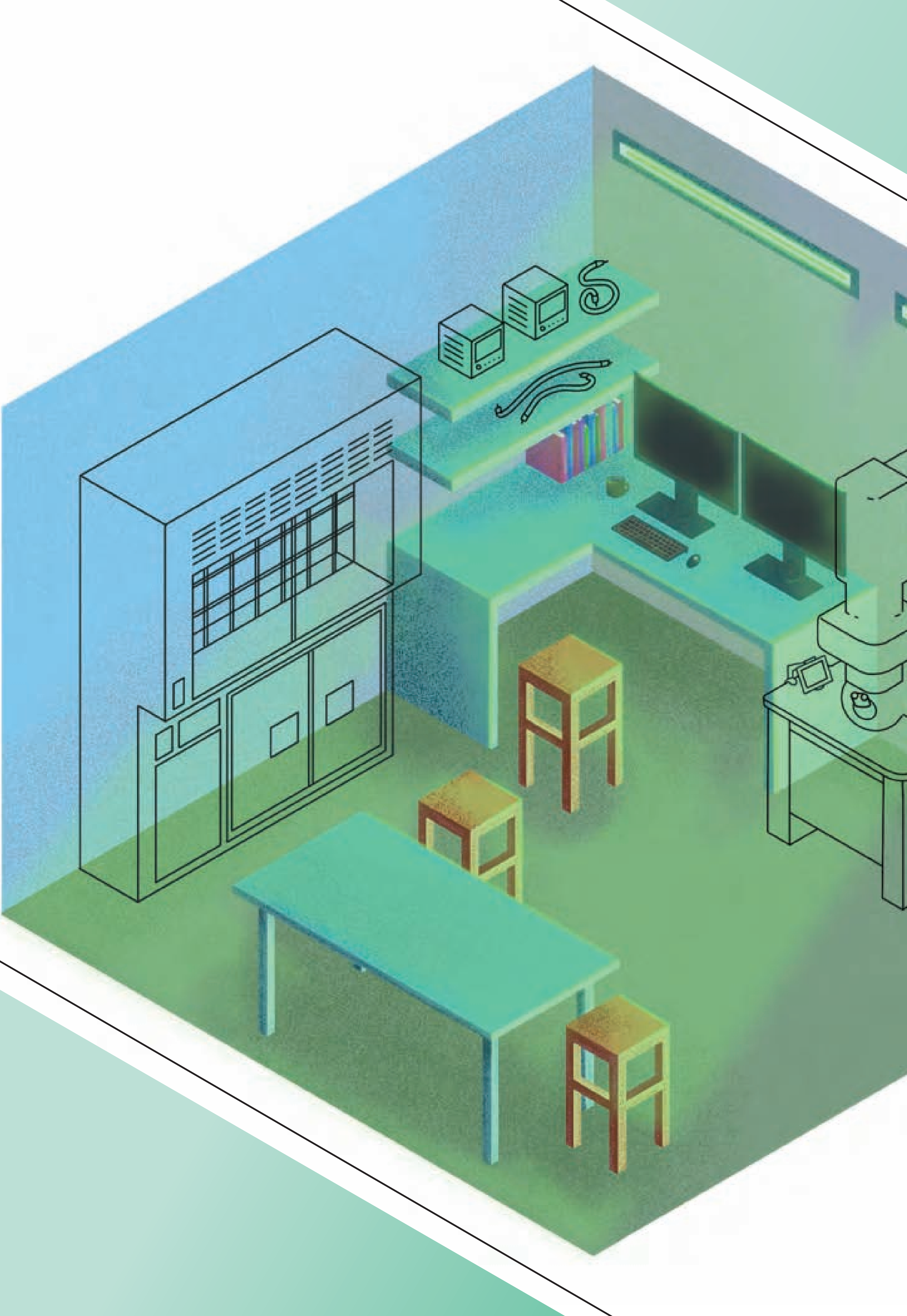
UNIVERSITY of
SOUTH FLORIDA

ASSISTANT PROFESSOR IN QUANTUM SCIENCE

The Department of Physics at the University of South Florida (AAU institution), Tampa, is seeking to fill a 9-month, full-time, tenure-earning position at the Assistant Professor level in experiment or theory in quantum materials, quantum sensors, photonics, quantum computing, and related fields. All areas that encompass new applications in healthcare, environmental sensing, secure communications, and information science are included.

Applicants must have a doctorate in Physics or a closely related field, relevant postdoctoral experience, strong record of publications, and demonstrate potential for attracting extramural funding. Salary will be commensurate with qualifications and experience. The starting date is August 7, 2025.

To apply, please visit **http://employment.usf.edu** (Job ID 37844) and attach a cover letter, curriculum vita, a statement of teaching philosophy (1 page), and a research plan (2-3 pages). In addition, applicants should have three letters of recommendation sent to Prof. Lilia Woods, Chair, Search Committee at **physearch@usf.edu**. Learn more about the university at **www.usf.edu**.



FREDDIE PAGANI

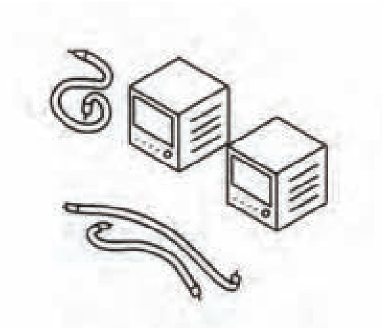
Alex Lopatka is an editor at PHYSICS TODAY.

Early-career faculty face many challenges

Alex Lopatka

Navigating a host of clear—and sometimes not-so-clear—responsibilities is critical to succeeding in academia.

Jamie Tayar describes her assistant professorship in the University of Florida's department of astronomy as akin to running a small business. "You have to bid on contracts or grants, hire and manage personnel or students, deal with the finances, and communicate results to stakeholders in the form of grant reports, papers, and colloquia," she says. "Then on the side, you have a gig teaching classes and doing committee work."



Even getting a faculty position in the first place is competitive.[1] (For more on academia as a career path, see "Stepping off the tenure track," by Lisa Balbes, PHYSICS TODAY online, 10 August 2022; for advice on applying for faculty positions, see the article by Omar Magaña-Loaiza, PHYSICS TODAY, October 2020, page 30.) And once employed, an academic faces a ballooning number of duties. At a large research university, faculty are expected to secure grant funding, build a research group, and teach courses. At a small liberal arts school, the pressures of research may be less, but the teaching load is likely larger. Regardless of the type of institution, new faculty face other responsibilities, too, including serving on department or university committees and counseling students on personal matters.

To learn more about the experiences of early-career physicists and physical scientists in the US, PHYSICS TODAY emailed a short list of questions, listed in the box on page 46, to physics department chairs at colleges and universities and to other select individuals. Nine faculty members who obtained their PhDs within the past decade responded to the questionnaire, along with a postdoc who will soon be applying for a faculty position. In their responses and in follow-up conversations, they discussed the time-consuming challenges of securing funding, building laboratories, teaching classes, and finding students to join their groups. Many of those duties are often learned on the job, sometimes without much formal training.

By no means is the questionnaire meant to be an exhaustive survey. For a more quantitative snapshot of the state of the physical sciences, see the article on page 30. And to read about how some faculty have made mid-career changes in their research focus, see page 50.

Competing for cash

Throughout their careers, faculty members must win grants to support their work. Without the money and prestige of prior grants, it can be especially difficult for early-career professors to hire their first graduate students and postdocs, pay for lab instrumentation, and secure subsequent grants. Over the past decade, less than 30% of proposals submitted each year to NSF have been funded.[2]

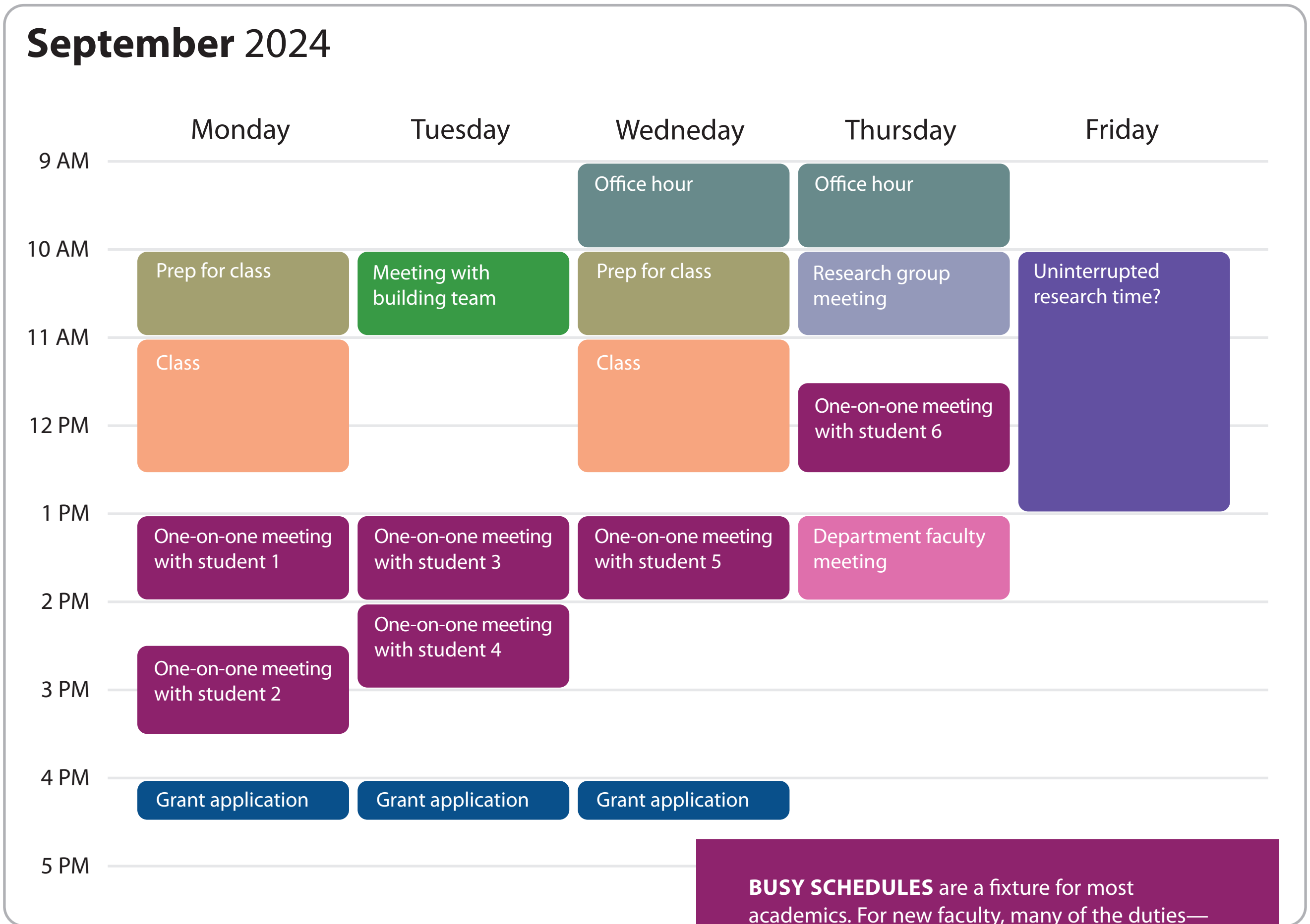
Wonhee Ko, an assistant professor of condensed-matter physics at the University of Tennessee, Knoxville, has applied for 10 research grants since he started there in August 2022—so far without success. He did negotiate more than $1 million in startup funding from the school, and since then, he has received internal university support. Ko says that those grants have each provided $50 000–$100 000 for a year or two of work. Additional funding comes in part from grants awarded to his research collaborators. "Everything matters for new professors," he says.

Rogerio Jorge, a theoretical plasma physicist who has been at the University of Wisconsin–Madison since January 2024, was awarded his first multiyear research grant of $500 000 from NSF in the spring. "Each grant proposal requires me to think about which tasks are needed to accomplish a research goal, how long each task will take, which one must come first, and how many people are needed," he says. "Project management skills are a key part of many research breakthroughs."

To help write research proposals, Tiffany Lewis turned to her experience volunteering as a grant reviewer. "Something that comes up a lot in review panels is risk. Is it likely that the project will succeed?" says the assistant professor of theoretical astrophysics at Michigan Tech. "That can be addressed directly in the text of the proposal." In recent proposals, Lewis has included what she anticipates learning both if the project succeeds and if it doesn't.

"A lot of the proposal is trying to anticipate outcomes," Lewis says. A well-planned proposal with a few possible outcomes, she says, gives reviewers confidence in an applicant's research skills and how they will use the funding. Lewis has written about half a dozen proposals, most of which were submitted in the spring and are under review. "I'm looking forward to the feedback," she says, "and to refining my projects."

Richard Anantua, an assistant professor of astrophysics at the University of Texas at San Antonio, says the proposal pro-



BUSY SCHEDULES are a fixture for most academics. For new faculty, many of the duties—and the challenges of managing all of them—are learned on the job. (Illustration by Freddie Pagani.)

cess can be time consuming and inefficient. Some online submission portals, for example, require proposers to manually enter the names of coauthors. For some of his published papers, Anantua was part of a team that numbered in the hundreds.

The timing of grant funding has sometimes made it difficult for Anantua to pay some members of his research group. One year, he says, "I found myself having to pay a student in October by using a grant from a previous summer. For early faculty, this makes a big difference because we sometimes don't have a stream of grants to fall back on." The timing can require faculty to reevaluate their research budgets: In Anantua's case, the money that was supposed to support the student ended up arriving after the work was already done.

Building laboratories

When faculty members have to prepare lab space, it can take time away from conducting research. For several months before James W. Dottin III stepped foot on Brown University's campus, he had weekly meetings with the building team to design every aspect of his stable-isotope lab. After setbacks and redesigns and after deciding on so many particulars—for example, how many outlets were needed, power requirements, and the number and color of cabinets—Dottin had some decision fatigue. "I don't have time to care about how many drawers and their sizes," he says.

Dottin has been an assistant professor of geochemistry at Brown for about a year, and his lab has reached the point of what the building team calls "substantial completion." A mass spectrometer he ordered has been delivered, but it can't be installed until the power requirements are met, the room is checked for air leaks, and the air pressure is balanced. "I'm hoping that we'll be able to get in there soon

to start testing sample preparatory methods," he says. "And then by the end of fall, we'll hopefully be making measurements."

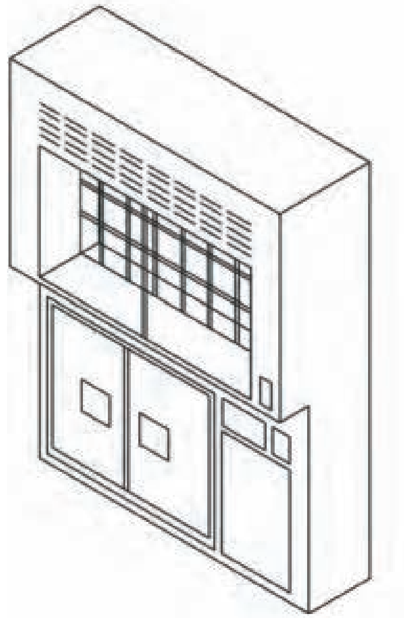
Ko's experience was similar. During his job interview, he negotiated for the physical space and the money to prepare a lab for his research. Once on campus, he says, "I had to talk a lot with the building manager. I had to get the right utilities. I had to change the position of pipes in the ceilings. That took almost a year."

As university staff readied the lab space, Ko ordered equipment, including a $1.2 million scanning tunneling microscope, with his startup funding. He took pictures and notes as the building manager and company technician installed the microscope. If things go wrong, he says, "students and I will need to know how to fix it."

Finding students

Once an applicant has landed an academic job, they need to build a research group. Although most faculty routinely need to recruit students, postdocs, and visiting researchers to join their group, the value of collaborators is especially high for early-career faculty, who are expanding their research programs.

WONHEE KO helps prepare his scanning tunneling microscope. Building a research space can mean many meetings with the facility staff and understanding how everything fits into place. That work limits the available time to conduct research. (Courtesy of Wonhee Ko.)



THE LABORATORY OF JAMES W. DOTTIN III, an assistant professor at Brown University, took more than a year to build. The lab will be used for Earth and planetary sciences research. (Courtesy of James W. Dottin III.)

As a postdoc at Harvard University and during his first two years as an assistant professor, Anantua served as the Event Horizon Telescope collaboration's outreach coordinator, an opportunity that involved speaking to many students. "Several students have reached out to me over the years due to my science communication," he says. And he makes sure his website has a modern-looking design and is continuously updated because he says it attracts students to his group.

At Harvard, Anantua met a PhD student who later came to work with him at the University of Texas as a postdoc. The postdoc was already prepared to do their own research, which gave Anantua more time to write grants and work on other projects. "As a faculty member, having research-ready members in your group is invaluable," he says.

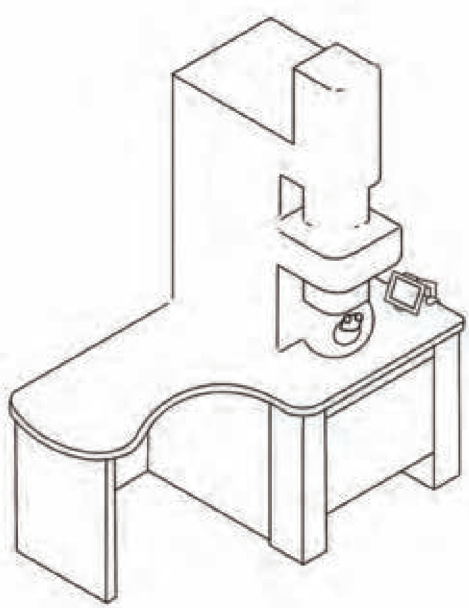
Dottin uses his own graduate school experience to help build his team. "I remember that the project is not the only reason a prospective student should consider when deciding on a grad program," he says. "I make sure to be truthful and candid, showing the students who I really am so that they can make the most informed decisions. I'm up front about my scientific knowledge gaps and strengths, my work habits, my expectations for them." (For more on student–adviser pairings, see Physics Today, October 2020, page 22.) Dottin's group—consisting of him, a lab manager, and an undergraduate research intern—is expanding in the next few months with the addition of two postdocs, two graduate students, and one postbaccalaureate scholar.

A similar strategy worked for Nicholas MacDonald, who joined the University of Mississippi as an assistant professor of astrophysics last year. He was approached by several prospective graduate students and met with them one-on-one to discuss research projects, and he invited them to his group's weekly seminar series. "That gave these students a chance to read papers in my discipline and to meet international researchers in my field." MacDonald hired one of the students, who had worked for him the previous summer as a research assistant.

Managing a team

"Group building and group management were the skills I was worried about when I started my position," says Lewis of Michigan Tech. After reaching out to several academic role models for advice, she decided to structure group meetings so that students can casually present their research projects. And in the summer, Lewis started a journal club to familiarize students with the field's literature. She currently advises two graduate students, one postbaccalaureate scholar, and four undergraduates. Lewis says that she typically assigns prospective group members a small project and then assesses whether they are a good fit for her research group. "If they do reasonably well with the project and they're good at communicating when they get stuck, we continue on."

Lewis says she introduces her group members to collaborators and others in the field and provides them with



The questions that Physics Today asked early-career faculty members

1. What have you done to bring graduate students to your research group?
2. What has been your experience in applying for research grants?
3. Talk us through the process, if applicable, of building a research lab. What equipment did you need, and how did you find it?
4. What skills, if any, have you had to use as a new faculty member that you didn't expect or that no one taught you?
5. Is there any advice you would give to a senior graduate student or postdoc looking for a faculty position?
6. Is there anything else you want to share about starting out as a new faculty member?

opportunities to travel to conferences and other professional events. In addition, she says, "I try to be very mindful of the things that academics often just assume. I communicate social expectations at conferences, how to appropriately introduce yourself in a professional setting. I also try to not assume that my students have money when I ask them to do things. I don't assume that they can just go and buy a new computer."

Jorge of the University of Wisconsin has focused on fostering an encouraging, collaborative environment for members of his research group. "I know it's really hard as a graduate student or undergraduate student to just say something because they're really afraid that it may be completely wrong," he says. At his weekly group meetings, Jorge reminds everyone to ask whatever questions they have, no matter how basic they may seem. "I've gone through a few groups in a few different countries," he says, "and I always liked when supervisors allowed me to voice my opinions."

> "Having that tight first-year faculty community has been invaluable."
> —Yashashree Jadhav

Jorge's group consists of two postdocs, three graduate students, and three undergraduates. He didn't do much advertising for the positions. "One postdoc is somebody that was referred by a previous supervisor. And I ended up taking him because he had the right skills," says Jorge. All the graduate students contacted him after a welcome event hosted by the department. "The group is the right size," he says. "I don't want to get any more people for at least a few years."

Finding support

Teaching pressures are common and add to faculty members' already busy schedules. When Ko started teaching introductory physics in 2022 at the University of Tennessee, he hadn't taught since graduate school 10 years earlier. "I forgot how difficult it was to learn physics," he says. "It was hard to know what incoming freshmen knew and what they didn't." He changed his approach and adjusted how he graded homework to become a more effective teacher.

Lewis spent more time preparing for lectures in her first semester at Michigan Tech than she anticipated. "I don't know if you remember any classes that you took about a decade ago," she says, "but for me the details are kind of fuzzy." She retaught herself some electricity and magnetism concepts to get through the semester.

Zachary Maas, a visiting assistant professor of astronomy at Indiana University Bloomington, teaches several introductory courses in addition to conducting research. To improve his instructional skills, he attended the Faculty Teaching Institute—a professional development workshop sponsored by the American Association of Physics Teachers, the Amer-

NICHOLAS MACDONALD discusses research with his students. Group meetings are an important time for students to ask questions and develop as researchers. Learning to effectively manage a team is not often a skill early-career faculty already have. (Courtesy of Dan Bradley.)

ican Physical Society, and the American Astronomical Society (see the article by Stephanie Chasteen, Edward Prather, and Rachel Scherr, Physics Today, April 2024, page 30). Maas says he learned many interactive teaching methods and is implementing them in the classroom, although time management is a balancing act. "I have tons and tons of checklists," he says. "I write down my weekly goals, and I put every single thing in my calendar and make sure there are reminders set all over the place."

Many of the faculty members who were interviewed spoke about the importance of maintaining a support network to help cope with the competing responsibilities they faced in their new jobs. "The first year as a faculty member is very overwhelming," says Maas. "In grad school, I could focus on one thing at a time." During his first year teaching at Bloomington, he was preparing grant proposals, lectures for teaching, assignments for students, and working on his own research. "I had to say no to new opportunities," he says. "Being in a supportive community and reaching out to friends and mentors really got me through that first year."

During her first faculty position, as a temporary lecturer at Elon University in North Carolina, Yashashree Jadhav says that "one of the things that helped me a lot was making friends! Having that tight first-year faculty community has been invaluable in learning about university-wide requirements, keeping each other updated about university deadlines, faculty events, and more." Jadhav, who also attended the Faculty Teaching Institute, now works as a permanent physics lecturer at the Stevens Institute of Technology in New Jersey.

The University of Florida's Tayar says, "Having a supportive network has been a huge help for me, and I highly encourage that for other people." Colleagues and other professors in Tayar's department have shared teaching suggestions, showed her successful grant applications, and served as sounding boards for ideas and new research opportunities. "Maybe some people can do this job alone," says Tayar, "but that certainly hasn't been something I could or would want to do."

REFERENCES

1. K. H. Wapman et al., *Nature* **610**, 120 (2022).
2. National Science Board, "New Report Details Recent Trends in NSF Awards," news release, 11 July 2023.

PT

THE UNIVERSITY OF CHICAGO

Quantum Science & Engineering (Experimental and Theoretical)

Department Summary

The Pritzker School of Molecular Engineering (PME) is a unique interdisciplinary school launched by the University of Chicago in 2011 with the aim of translating molecular and quantum science into technological solutions with potential societal impact in quantum information technology, environmental sustainability, energy/water/materials and health and immunology. The PME currently has 17 faculty engaged in both fundamental and applied aspects of quantum science and engineering. PME is also affiliated with Argonne National Laboratory and the Center for Molecular engineering at Argonne, and joint appointment is encouraged when appropriate.

This position is part of a cluster hire in quantum science at the University of Chicago, with other openings in both theoretical and experimental quantum science and engineering.

Position Description and Qualifications

We invite applications at the ranks of Assistant Professor, Associate Professor, and Professor. Before the start of employment, qualified applicants must hold a doctoral degree or equivalent in a field related to experimental quantum science and engineering, or related disciplines. They must also have a strong record of independent research in these fields. Areas of interest include (but are not limited to) quantum computing (all platforms), quantum sensing, quantum communication, quantum simulation, quantum materials, and quantum optics.

Candidates for Associate or Full Professor must have evidence of leadership in their field and an outstanding track record of independent research, allowing them to qualify for appointment as a tenured professor in the Pritzker School of Molecular Engineering (or jointly with another department in the University). All successful candidates will be expected to establish and maintain a robust research program and teach at the graduate and undergraduate levels.

Review of applications will continue until the position is filled.

Application Instructions

Candidates should apply online through the University of Chicago's Interfolio website: http://apply.interfolio.com/153653

The following materials are required:

- Cover letter
- Curriculum Vitae including Bibliography
- Research statement (a statement describing past and current research accomplishments and outlining future research plans)
- Teaching statement (a description of teaching philosophy and experience)
- Contact information for three references who can provide confidential letters of evaluation

The following materials are optional:

- Up to three published or unpublished research papers

Please contact Karen Jackson at kjackson10@uchicago.edu with any questions.

Position Description and Qualifications

We invite applications at the ranks of Assistant Professor, Associate Professor, and Professor. Before the start of employment, qualified applicants must hold a doctoral degree or equivalent in a field related to theoretical and/or computational quantum science and engineering, or related disciplines. They must also have a strong record of independent research in theoretical quantum science and engineering. Areas of interest include (but are not limited to) quantum information, quantum computing, quantum communication, quantum sensing, quantum error correction, quantum mechanical materials modeling, quantum optics and quantum simulation.

Candidates for Associate or Full Professor must have evidence of leadership in their field and an outstanding track record of independent research, allowing them to qualify for appointment as a tenured professor in the Pritzker School of Molecular Engineering (or jointly with another department in the University). All successful candidates will be expected to establish and maintain a robust research program and teach at the graduate and undergraduate levels.

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FREDDIE PAGANI

Toni Feder is a senior editor at Physics Today.

The promises and perils of a mid-career pivot

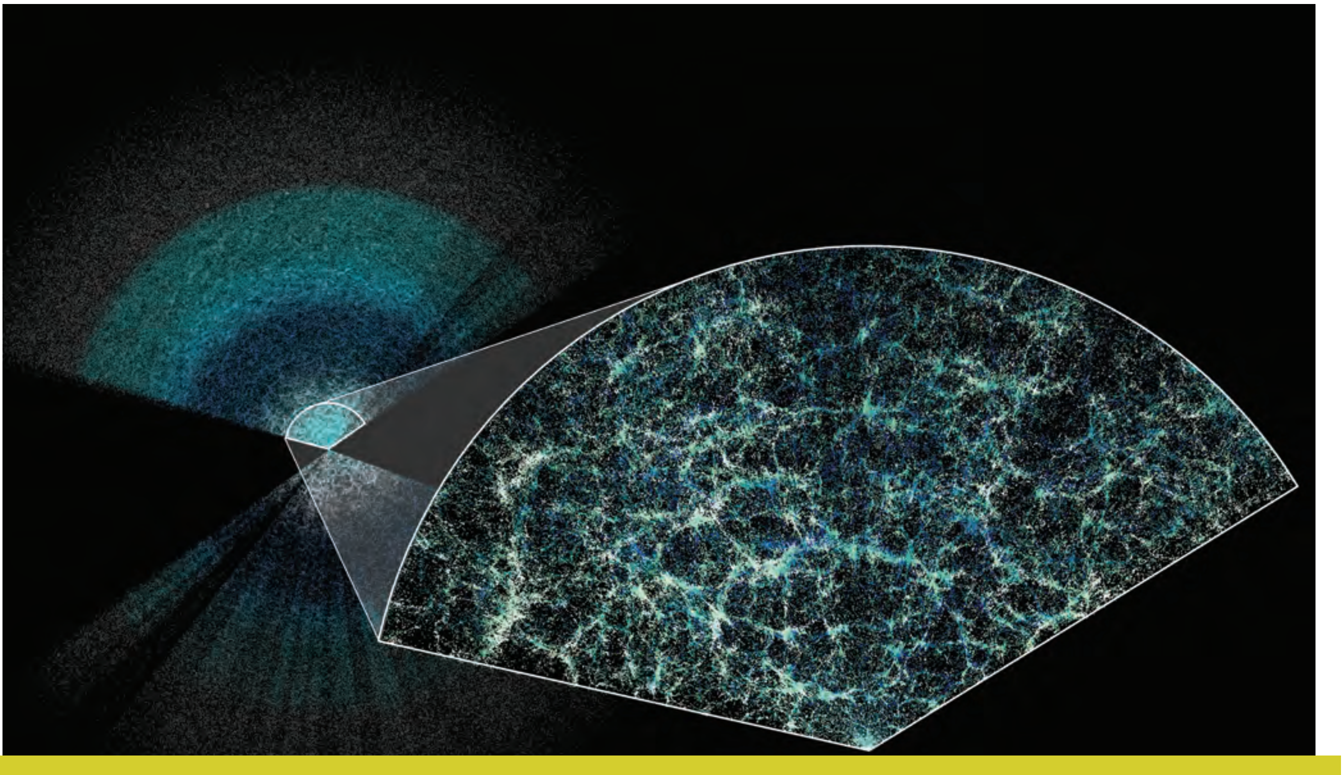
Toni Feder

Astrophysics to physical oceanography. String theory to machine learning. High energy theory to biophysics. Such leaps in research focus can be challenging—and rewarding.

Scouting for a new research area, Larry Abbott, who had made his name as a theoretical particle physicist, says it was "love at first sight" when he heard neurons pulsating on an audio monitor. Alexie Leauthaud was forced to evacuate her home in the Santa Cruz Mountains during a 2020 wildfire. That experience, plus a comprehension of the scale of climate change–induced migration, prompted her to expand beyond her research on dark energy and dark matter into ways to adapt to the warming planet. Nabil Iqbal became interested in applying his skills to real-world problems after volunteering on a COVID-19 task force for the Bangladeshi government. The string theorist is now testing the waters in machine learning.

For established academic researchers, changing focus is often tricky. They have built up a knowledge base and reputation, won grants, assembled equipment, hired students, and formed networks of colleagues. Structurally, universities and funding agencies often pose barriers to working in a new area. And a switch has elements of starting over—described by those who have done it as simultaneously scary and exhilarating.

More people should switch fields, says Abbott, who is now a theoretical neuroscientist at Columbia University. "Tenure gives you the security to stick your neck out. Moving into a new field is exciting. It rejuvenates your research."



WHAT DO COSMOLOGY AND GARDENING HAVE IN COMMON? Alexie Leauthaud, an associate professor at the University of California, Santa Cruz, does research in both. She is a spokesperson for the Dark Energy Spectroscopic Instrument, which made the largest-yet 3D map of the universe, a slice of which is shown here. (Courtesy of Claire Lamman/DESI collaboration; custom color-map package by cmastro.)

Finding a mentor in the new field and accessing funding to branch out are two keys to successfully switching—or expanding—one's research area. Some scientists find both on their own. And in 2022, the Simons Foundation launched the Pivot Fellowship to encourage such research switches across STEM fields. "We want to facilitate conversations that wouldn't happen otherwise," says Alyssa Picchini Schaffer, who designed and coordinates the fellowship program.

Old school

In the mid 1980s, Abbott was at Brandeis University and, like other particle physicists, "waiting for the Higgs particle." Realizing that it would be a "long time before new data came in," he went searching for topics to pursue in condensed-matter physics, when he happened to visit Eve Marder in her neuroscience laboratory. They began talking regularly, and eventually Abbott made a suggestion related to her research. "She came back the next week and said, 'You were wrong,'" recalls Abbott. The quick turnaround time of the experiment for testing his hypothesis convinced him that he "was doing the right thing in switching to neuroscience."

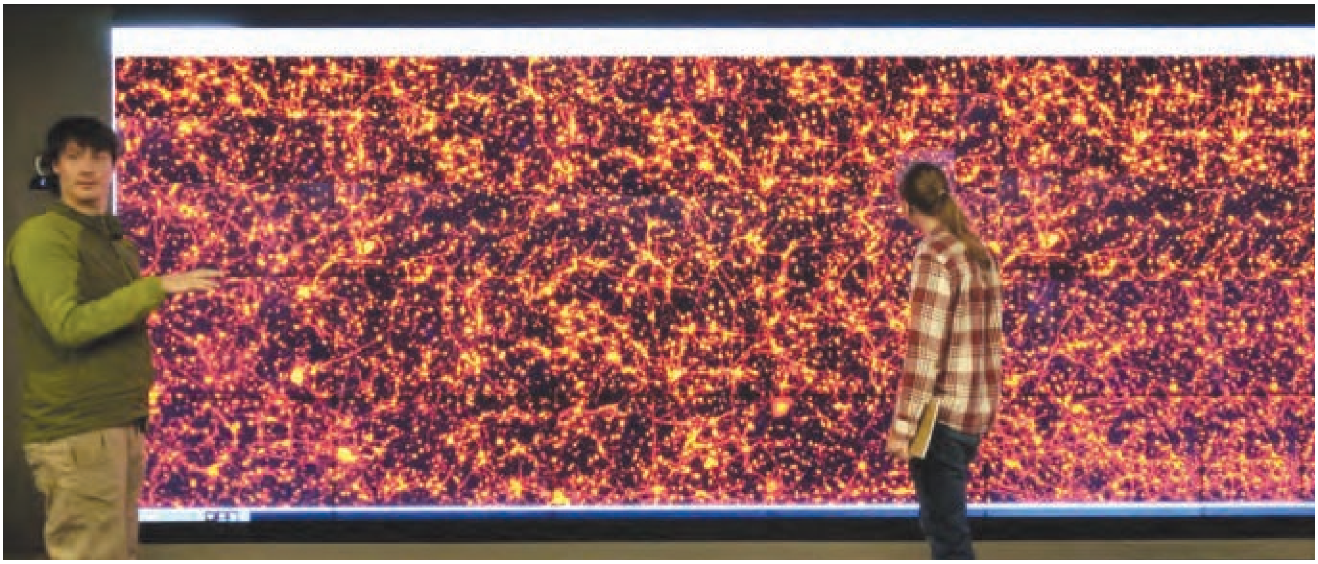
Still, says Abbott, "I was terrified. I was ignorant of the field. Nobody knew me. I had no grants, no students." But he had help from Marder: She mentored him, and publishing with her lent Abbott legitimacy in his new field. "Neuroscientists welcomed me," he says. As a particle physicist, Abbott had been funded by the US Department of Energy. "I told them what I was doing," he says. "I would say they looked the other way until I got my own grant in neuroscience.

FOOD SUSTAINABILITY, rainwater capture, and composting are among the directions that Alexie Leauthaud is pursuing as she expands her research to focus on adaptation to climate change. The images show the campus site of her experiments, which include studying how to optimally irrigate lettuce with rainwater. (Courtesy of Alexie Leauthaud.)

Seeing physics in everything

Retinal implants, a sports sensor, and AI methods to distinguish between authentic and fake Jackson Pollock paintings are among the projects that Richard Taylor, head of the physics department at the University of Oregon, is currently working on. Shown below are then-graduate students Julian Smith (left) and Conor Rowland (right), quantifying the fractal character of retinal neurons to replicate the fractality in a bionic eye.

Taylor branched out from low-temperature nanoelectronics after earning tenure. "I don't know what the tolerance of my physics colleagues and my institution to my research transitions would have been if they hadn't worked," he says. Switching, he adds, requires building a new team and finding new collaborators. When students see someone pivot, he says, it sends a message that they can use physics in many broad ways in their future careers. His advice is to "follow your interests." (Photos courtesy of Richard Taylor.)



I never went a day without funding, even though I was switching fields."

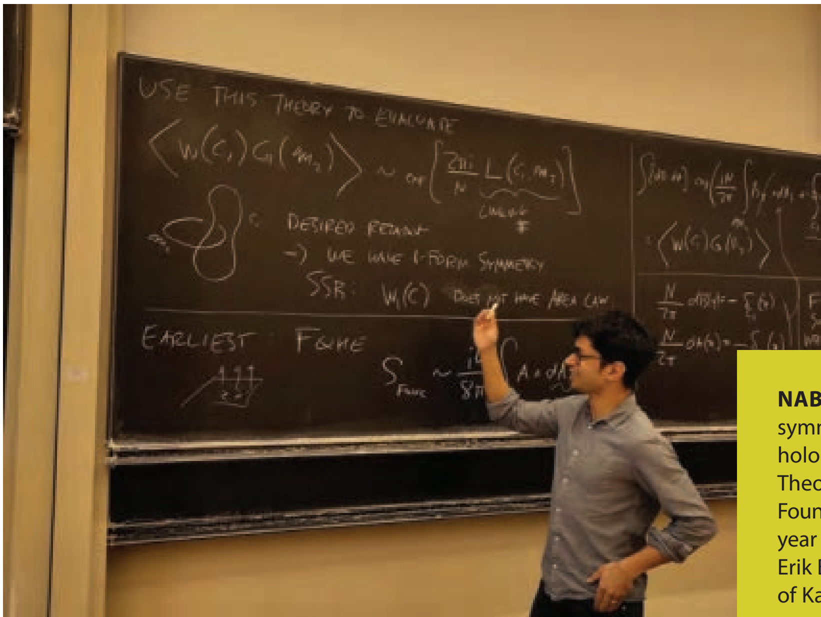
Geoffrey West is a high-energy theorist who, after a long career at Los Alamos National Laboratory, began exploring other fields and then was lured to the Santa Fe Institute. It was the early 1990s, and West was taking stock of his life and career. "I come from a family of short-lived males," he says. "I was in my mid 50s and was preparing that I had 10 years to live, maximally. That, coupled with the cancellation of the Superconducting Super Collider, made me focus on biology: What leads to aging and mortality?"

West connected with biologist James Brown. Together, they made advances in the studies of life expectancy, sleep, cancer, city sustainability, and more. West describes his contributions as being "very much from a physics viewpoint." His early work in biology was done "with funding not intended for it." But his results turned out to be high profile, and soon an art collector approached him at a public lecture and offered to fund his research.

"One of the curious things that I didn't realize was the difference in cultures between biology and physics," says West. "Biology can be very qualitative. It's not very precise. It was a language problem. I spent a huge amount of time trying to boil down complicated math into something simple."

Expanding horizons

"When a field gets too crowded, it's time to get out. I get claustrophobic," says Mark Raizen, an experimental physi-



NABIL IQBAL lectures on generalized global symmetries at a school on quantum field theory and holography held last February at the Institute for Theoretical Physics in Jena, Germany. A Simons Foundation Pivot fellow, Iqbal is spending this academic year exploring machine learning with his Pivot mentor Erik Bekkers at the University of Amsterdam. (Courtesy of Katharina Wölfl.)

cist at the University of Texas at Austin. "If I start to feel like I am hearing the same talks over and over again, it gets boring." Around 2001, after more than a decade working on cold optical lattices, he made a "conscious decision" to stop. The decision was difficult, he says, because he had "inertia, funding, reputation, and knew the people in the field."

Raizen pivoted to soft condensed matter and short-time Brownian motion, and more recently, he has focused on the production and application of isotopes to medicine (see Physics Today, May 2024, page 24). Unrestricted money tied to his endowed chair gave him the means to try new things. In addition, he says, his university was supportive and provided internal funds. "We didn't require any expensive new equipment. That would be a barrier."

The safe way to switch research areas, says Raizen, is to phase things out slowly while adding a new area. That can be hard, he adds, because by the time someone dives into a new field, they are often less engaged in the established one. "When I recruit students, if I'm not excited, then it's not motivating for them."

Leauthaud, an associate professor at the University of California, Santa Cruz, has added climate change adaptation to her research portfolio. She is not bored with cosmology—she recently took on the role of spokesperson for the Dark Energy Spectroscopic Instrument (see Physics Today, October 2016, page 28). But she realized that "climate change is a serious threat to the academic endeavor itself" and decided she wanted to "work on solutions, education, and preparation."

Her first move, in 2021, was to teach a class for nonphysics majors on the reports of the Intergovernmental Panel on Climate Change (IPCC). Next, she applied for small research grants, mostly for work on growing food more sustainably.

To some extent, says Leauthaud, the direction of her climate-related work is "hodgepodge. It depends on what grant opportunities I see." Recently, for example, she and colleagues on campus got money to work on harvesting rainwater and composting.

Leauthaud partnered with professors in her university's education and environmental studies departments to create projects that connect college students with the local community through experimenting with urban food production. She is splitting her time about 75-25 between astrophysics and climate change adaptation. In the long term, though, she plans to shift more into studying climate change. "I would do modeling for solutions. The food system is broken, and modeling could benefit policymaking. I'm reading the science and trying to foresee the problems that will face us in 10 years."

"I tell my students that the problem is so big, there is no single solution," says Leauthaud. "Pick something that interests you and work on that, even if it seems small and even if only part-time."

Money for change

The Simons Foundation created its Pivot Fellowship to make it easier for researchers to explore new fields. Awardees must demonstrate success in a quantitative field and use their fellowship to explore a different field. Part of the aim is to cross-pollinate and support interdisciplinary research, says Picchini Schaffer.

Pivot fellows spend a year working with a mentor. The fellowship pays each recipient their salary, plus $10 000 for

VIVIANA ACQUAVIVA presented her work at a meeting of Pivot fellows and their mentors last April. An astrophysicist by training, she spent her fellowship getting involved in climate change modeling. The Simons Foundation created the fellowship to stimulate cross talk among disciplines. (Courtesy of Pierre Gentine/LEAP.)

travel and other incidentals, and gives their mentor $50 000 for research costs. After the year in training, Pivot fellows are invited to apply to the Simons Foundation for research awards in their new field for up to $1.5 million over five years.

Iqbal, a professor of mathematical and theoretical physics at Durham University in the UK, is one of this year's seven Pivot fellows. He had been trying to get into machine learning, but, he says, his heavy teaching load made it "hard to find time to learn something new." The fellowship gives him a break from teaching and the opportunity to delve into "a problem in deep learning that involves geometry." He is spending this academic year at the University of Amsterdam with his Pivot mentor, Erik Bekkers.

Most of Iqbal's work has been in quantum field theory and string theory. Machine learning is much more applied, he says. "You can run feedback loops, and if you have an idea to make something work better, you can test it." At this point, he says, he's not sure what he'll do after his fellowship. "I love my current field, so it's hard to say if I'd leave it completely. I'll have to see where I can be productive."

Viviana Acquaviva describes herself as an astrophysicist, a data scientist, and "a climate scientist in training." Last year, as an inaugural Pivot fellow, she took a leave from her home base at the New York City College of Technology to dive into climate science at Columbia University's LEAP (Learning the Earth with Artificial Intelligence and Physics) lab.

Acquaviva says she has "always jumped around in astrophysics quite a bit." About a decade ago, she made a "radical shift into machine learning." And a couple of years ago, she was looking for a "new source of juice." That's when she happened on the LEAP lab and thought, "I am a physicist, I know some AI, and I'd like to learn about Earth sciences."

Acquaviva is applying her data and simulation skills from astrophysics to issues related to climate change. One project involves developing metrics to evaluate climate models, and another looks at the role of the ocean in the global carbon cycle. "Ideally, we'd like to see our work become part of the models that go to the IPCC and then to governments."

The Pivot fellowship has been great, says Acquaviva. "It's hard to do something new. Good mentors will help you succeed and introduce you to a new network of people." Picchini Schaffer notes that many outcomes from the Pivot fellowships are possible. "One is that a fellow learns something else and brings it back to their original field. That's not a pivot, but it's still positive." She anticipates that 7–10 new fellows will be chosen each year.

Academic silos

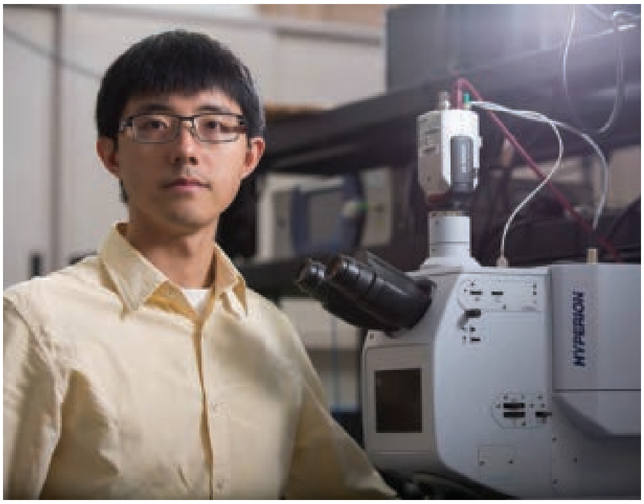
Shifting research focus often involves cross-disciplinary collaboration. Although the academic enterprise has praised such efforts for decades, university research remains fairly compartmentalized. "Look at how people are hired," says Leauthaud. "The incentive is to ultraspecialize. It's ultrasiloed. In academia, we are overwhelmed with the things we are asked to do. There is no incentive to get a bigger picture, and as a professor, you really don't have time."

And switching research areas can be risky for faculty members. "You may not fit into any department. You may not get promotions," says Leauthaud. People who pivot can take a hit to their careers, says Raizen. "You will not be cited as much,

Taking flight into biophotonics

A butterfly's wing color can be important for responding to light and heat, finding a mate, evading prey, and more. Nanfang Yu, an associate professor of applied physics at Columbia University, and his students image butterfly wings from UV to IR wavelengths. He is collaborating with biology professor Naomi Pierce, curator of the moth and butterfly collection at the Museum of Comparative Zoology at Harvard University, to learn about the multifunctional structural and optical features of their wings.

For Yu, the project combines his expertise in nanophotonics and his lifelong interest in nature. He credits encouragement from his department and funding from the Gordon and Betty Moore Foundation for the freedom to follow his broad interests; his research is roughly three-quarters nanophotonics and one-quarter biophotonics. (Image of Yu courtesy of Jane Nisselson; butterfly image courtesy of Nanfang Yu and Cheng-Chia Tsai.)



you lose momentum. The built-in incentive is to not pivot."

Establishing credentials in a new field is a challenge, says Mark Bowick, deputy director of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. Even before he got tenure, he worked in both string theory and soft-matter theory. "Often, people trained in one field don't know much about other fields and tend to undervalue them," he says. In recent years, Bowick's focus has been on active matter. Early in the pivot process, he adds, it's easy for people in your new field to think you are a dilettante. "You don't get invited to talks. You are like a beginning graduate student." In the meantime, he says, colleagues in your old field think you are "washed up."

Despite the challenges, researchers who have pivoted say it's worth it. "I have found it very energizing," says Brandeis University's Albion Lawrence, who as an inaugural Pivot fellow expanded his research from string theory to physical oceanography. "I come from a nonempirical field and wanted to think about data," he says. "I'm having more fun now." Lawrence describes his intellectual heritage as thinking about physics broadly. "It never seemed insane to me to go work on something else." PT

NEW PRODUCTS

Focus on test, measurement, quantum metrology, spectroscopy, and spectrometry

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.

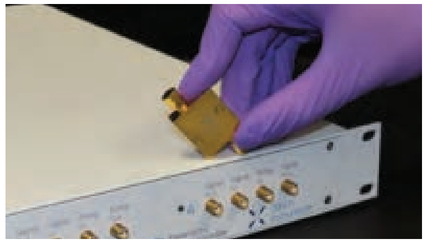
Andreas Mandelis

Diode-pumped 785 nm laser

Hübner Photonics has extended its Cobolt 05-01 series platform to offer the performance needed for high-resolution Raman spectroscopy measurements. The new Cobolt Disco 785 nm single-frequency laser delivers up to 500 mW of power in a perfect TEM_{00} beam. Its innovative design features excellent wavelength stability, a linewidth of less than 100 kHz, spectral purity better than 70 dB, and low noise less than 0.1% rms. The laser is housed in a robust, hermetically sealed package to ensure a high level of reliability. ***Hübner Photonics Inc***, *2635 N First St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com*

Optical transmission spheres

Knight Optical has unveiled a collection of Kreischer transmission spheres crafted for optimal performance in interferometry. Uncoated and housed in metal casings, the transmission spheres are available in 4- and 6-inch apertures with a bayonet mount compatible with most interferometers. The standard transmission spheres are polished to a precision of $\lambda/20$ for 633 nm Fizeau interferometers. The innovative design of the product allows for the measurement of an extended range. Compared with other transmission spheres on the market, they accommodate a larger radii of curvature on convex surfaces, according to the company. The 4-inch series is available in F-numbers from 0.75 to 3.3 and the 6-inch series from 1.1 to 2.4. Additional F-numbers can be provided on request. Knight Optical also offers custom transmission spheres, which can be tailored with precision levels from $\lambda/10$ to $\lambda/40$ and various focal lengths. ***Knight Optical USA LLC***, *1130 Ten Rod Rd, Ste D-103, North Kingstown, RI 02852, www.knightoptical.com*



High-fidelity qubit readout

Zurich Instruments and QuantWare are collaborating to address the challenges of high-fidelity qubit readout in order to make quantum computing technology more accessible. To provide an out-of-the-box solution for tuning the full qubit readout chain, the companies are integrating QuantWare's traveling-wave parametric amplifier Crescendo-S, made for readout at scale, with controller and readout electronics from Zurich Instruments. The Crescendo-S offers multiqubit readout capability, low noise, and a scaling-ready form factor. Its control signal requirements are optimally served by Zurich Instruments' SHFPPC Parametric Pump Controller, which covers all signal generation and processing for parametric amplification. The integrated instrument is controlled by LabOne Q software, which features a platform for amplifier and readout calibration procedures. The companies are also investigating ways to further improve the off-the-shelf compatibility of QuantWare's quantum processing units with Zurich Instruments' quantum computing control systems. ***Zurich Instruments AG***, *Technoparkstrasse 1, 8005 Zurich, Switzerland, www.zhinst.com*

Correlated microscopy platform

Quantum Design has added a new measurement technique to its innovative FusionScope correlated microscopy platform. It is now possible within the same instrument and user interface to obtain data from energy-dispersive x-ray spectroscopy (EDS) and from scanning electron microscopy (SEM) and atomic force microscopy (AFM). Based on silicon drift detector technology, FusionScope's x-ray spectrometer detects characteristic x rays and precisely measures their energy. With its advanced algorithms and an established spectral library, the platform's software uses those x rays to identify and determine the quality of the element type. The EDS in FusionScope is completely integrated with SEM and AFM and uses the same shared coordinate system for locating specific regions of interest. FusionScope enables comprehensive material characterization in fields such as life, Earth, and material sciences; semiconductor, battery, automotive, and aerospace industries; pharmaceuticals; forensics; mining; and geology. ***Quantum Design***, *10307 Pacific Center Ct, San Diego, CA 92121, www.qdusa.com*

Time-correlated single-photon counter

PicoQuant is now equipping its PicoHarp 330 time-correlated, single-photon-counting, and time-tagging unit with up to four detection channels and a dedicated sync channel with advanced channel configuration. According to the company, the enhancement broadens the scope of potential experiments and optimizes the efficiency of data collection in complex setups. Those improvements are especially beneficial in quantum optics experiments, such as quantum key distribution (QKD), quantum entanglement, and Bell test experiments. The unit offers down to 2 ps rms jitter, essential for accurate timing in QKD and photon correlation techniques. Each channel operates independently but can synchronize with the others through a common sync channel, providing flexibility in experimental setups. If synchronization is not required, the sync input can serve as an additional detection channel, suitable for coincidence correlation or counting experiments with up to five channels. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

Isolated probing system

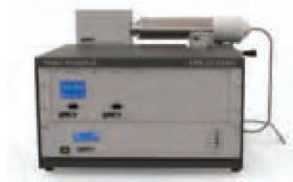
Rohde & Schwarz has released its R&S RT-ZISO isolated probing system for measurements of fast switching signals, especially in environments with high common-mode voltages and currents. The R&S RT-ZISO provides precise differential measurements of up to ±3 kV on reference voltages of ±60 kV, with a rise time of less than 450 ps. It suppresses fast common-mode signals that can distort and interfere with accurate measurements. Its power-over-fiber architecture galvanically isolates the device under test from the measurement setup, providing a much higher common-mode rejection ratio (CMRR) than conventional differential probes. Its key features include bandwidth options of 100 MHz to 1 GHz, a CMRR of greater than 90 dB (greater than 30 000:1) at 1 GHz, and an input and offset range of ±3 kV. According to the company, the isolated probe, when used with the instruments of its MXO oscilloscope series, enables measurements with the world's fastest acquisition in the time and spectrum domain. The R&S RT-ZISO is suitable for a wide range of applications, including switching analysis of power converters with wide-bandgap materials, double-pulse testing, and floating and shunt measurements. ***Rohde & Schwarz GmbH & Co KG***, *Muehldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*

Biomolecule characterization

RedShiftBio has introduced Aurora, the latest system using the company's novel microfluidic modulation spectroscopy (MMS) technology to provide, in a single automated analysis, ultrasensitive and ultraprecise measurements of the structure of biomolecules. The MMS modality combines a quantum cascade laser, a microfluidic flow cell, and the powerful delta analysis software package to produce high-resolution secondary-structure information. In a significant reduction from first-generation MMS instruments, the compact, benchtop-friendly Aurora requires only a 50 μl sample volume. It delivers accurate, reproducible measurements across a broad concentration range from 0.1 mg/mL to greater than 200 mg/mL in therapeutically relevant conditions; there is no need to buffer exchange or dilute samples before measuring. According to the company, Aurora is 20 times as fast and 30 times as sensitive to changes in structure than circular dichroism or Fourier-transform IR spectroscopy. Aurora can be used to study a wide range of biomolecules, including monoclonal antibodies–based biotherapeutics, proteins, enzymes, peptides, antibody–drug conjugates, and mRNA. ***RedShift BioAnalytics Inc***, *80 Central St, Boxborough, MA 01719, www.redshiftbio.com*

Compact Raman spectrometers

Wasatch Photonics has announced its WP Raman X series of compact Raman spectrometers and systems for research and original equipment manufacturer (OEM) instrument development. Replacing the company's previous line, the X series of products can be used at 532, 638, 785, 830, and 1064 nm excitation, covering the fingerprint and functional range of Raman peaks with 10 cm^{-1} resolution or better. The company's Raman products use a high numerical aperture optical design combined with high-efficiency volume-phase holographic transmission gratings. Those features ensure superior signal collection and high throughput, and they deliver sensitivity approaching that of high-end Raman systems at a fraction of the size and cost, according to the company. Configuration options include a choice of f/1.3 or f/1.8 input aperture, detector cooling level, slit size, and sample coupling. Available models include stand-alone spectrometers for modular Raman spectroscopy, spectrometers with an integrated excitation laser to reduce size and cost, fully integrated Raman systems for maximum signal in the smallest footprint, and OEM versions of each type. ***Wasatch Photonics***, *808 Aviation Pkwy, Ste 1400, Morrisville, NC 27560, https://wasatchphotonics.com*



Gas-analysis mass spectrometry system

Hiden Analytical has launched its HPR-20 OEMS (online electrochemical mass spectrometry) system for continuous analysis of evolved gases and vapors in electrochemistry. An ultralow-flow, real-time sampling capillary allows for seamless connection for headspace sampling and connection to electrochemical cells. The Hiden QIC-ULF quartz-lined, ultralow-flow sampling interface, operating at up to 200 °C, provides fast response times of less than 3 s for most common gases and vapors, including water vapor. The standard system with a 200 amu mass range can detect to less than 100 ppb. For even more precise measurements, the optional 3F series 300 amu system with a triple-stage mass filter extends detection levels to 5 ppb, with enhanced contamination resistance. Features include a 3D data plot for viewing mass versus electron energy and intensity and an automated spectral analysis that provides peak identification and composition analysis. It is equipped with the latest Microsoft Windows MASsoft Professional software for seamless data acquisition, display, and control of quadrupole parameters. ***Hiden Analytical****, 37699 Schoolcraft Rd, Livonia, MI 48150, www.hidenanalytical.com*

Thin-film characterization

Craic Technologies now offers its Film Thickness Mapping Solution to enable researchers to visualize morphology and defects in thin films. The solution incorporates state-of-the-art microscopy and imaging systems capable of capturing clear, detailed high-resolution images of thin-film samples. Advanced spectroscopic techniques, including UV-visible–near-IR microspectroscopy and Raman microspectroscopy, provide spectral data for characterizing thin-film composition and properties, such as refractive index and chemical composition. The intuitive software interface and automated mapping algorithms enable users to generate precise film-thickness maps across large sample areas rapidly, thus facilitating efficient data acquisition and analysis workflows. The Film Thickness Mapping Solution is compatible with a wide range of sample types, including semiconductors, optical coatings, polymers, and biological materials, and is suitable for diverse research and industrial applications in materials science, nanotechnology, and surface engineering. ***Craic Technologies Inc****, 948 N Amelia Ave, San Dimas, CA 91773, www.microspectra.com* PT

QUICK STUDY

Samantha McBride is an assistant professor in the department of mechanical engineering and applied mechanics at the University of Pennsylvania. She conducted the work described in the work described here while she was a PhD student at MIT.

Self-removing salt crystals

Samantha McBride

A newly discovered mechanism by which salt crystals leap off nanoengineered surfaces may lead to the development of industrial materials that resist the buildup of minerals from fresh and salt water.

Water is indispensable not only in people's daily lives but also in industry. Fresh water is used frequently in power plants to transform thermal energy into mechanical energy by the spinning of a steam turbine. With the escalating threats to the freshwater supply posed by climate change, it is more crucial than ever to preserve the planet's limited water resources. Of the total water on Earth, a mere 1% is fresh water in liquid form, and 2% is fresh water locked in solid forms, such as glaciers and snowcaps. The remaining 97% is salt water, found in oceans and seas.

Harnessing salt water for industrial processes could significantly alleviate the strain on freshwater demands. Yet substituting salt water for fresh water in industrial processes is not a straightforward solution. Both fresh and saline waters contain dissolved minerals that tend to accumulate on surfaces. A familiar example is the soap scum that appears in sinks and showers. Mineral buildup is an even bigger problem in industrial processes, particularly those involving phase changes such as evaporation or boiling. The problem would only worsen if the more plentiful but more mineral-rich salt water is used.

Self-cleaning materials would go a long way toward reducing inefficiencies in the system, but existing coatings aren't doing the trick. The key might be nanoengineering surface textures.

My colleagues and I in the Kripa Varanasi research group at MIT studied drop evaporation and the effects of different surfaces. When salt water on a hydrophobic surface evaporates, spherical structures of salt crystals form. Those structures are part of the problematic buildup on surfaces. And under the right circumstances, the structures remove themselves from the surface.

A scaly problem

Mineral buildup, a process known as scaling, is typically caused by the accumulation of calcium or magnesium salts. It

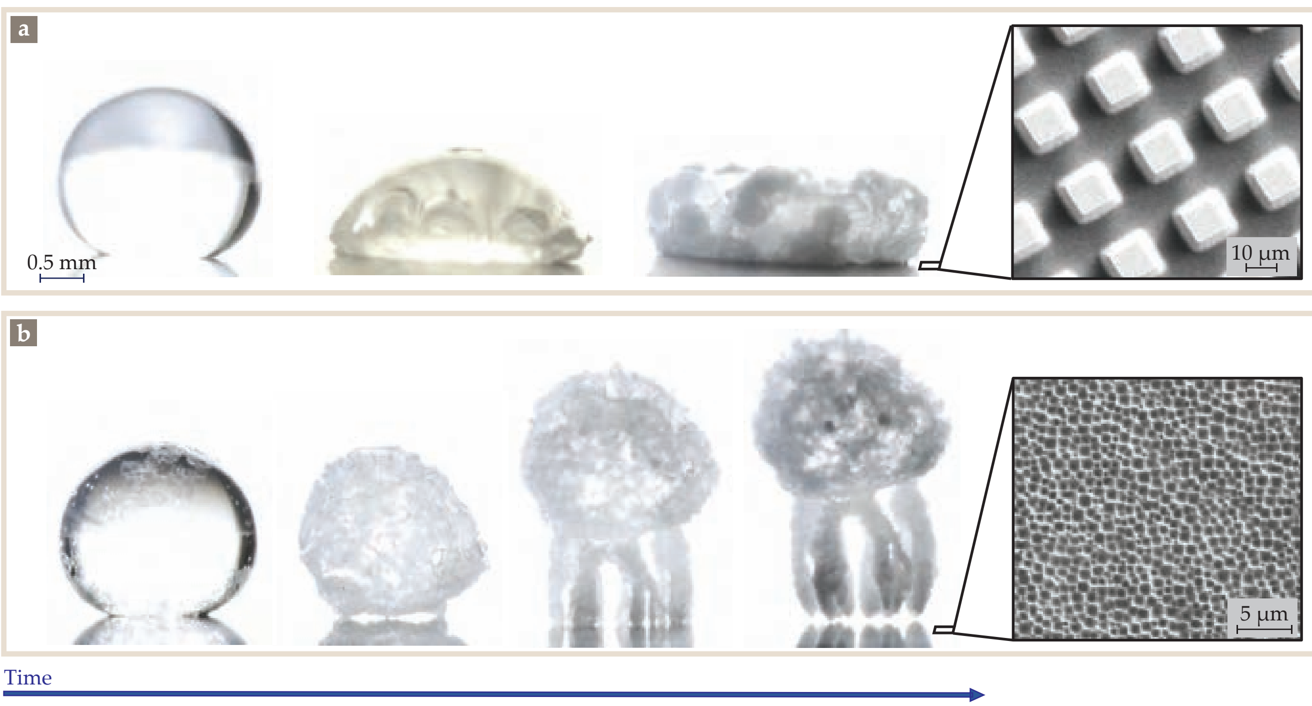


FIGURE 1. CRYSTAL-CRITTER GROWTH. A drop of salt water evaporates and leaves behind salt crystals. The structure of those crystals is dependent on the texture of the surface. **(a)** On a microtextured superhydrophobic surface, the gaps between the pillars are large enough for salt crystals to embed themselves in the surface. The overall salt-crystal structure spreads out and clings to the surface. **(b)** In contrast, a nanotextured surface does not have large enough gaps for the crystals to grow into. Instead, evaporative flux at the 90 °C surface causes crystalline legs to grow such that minerals are ejected from the material. (Adapted from S. A. McBride, H.-L. Girard, K. K. Varanasi, *Sci. Adv*. **7**, eabe6960, 2021.)

poses a range of detrimental and costly effects that can disrupt crucial industrial processes. Scaling impedes flow in pipes and other fluid transmission systems, hinders heat transfer in boilers and heat exchangers, and reduces the efficiency of chemical reactors.

Existing approaches to combat mineral scaling primarily rely on chemicals or manual cleaning methods. Antiscalants, although effective, are typically toxic and can pose major risks to local ecosystems when discharged into the environment. Manual cleaning is expensive and time-consuming, and it doesn't prevent subsequent mineral accumulation.

Those challenges underscore the necessity for alternative solutions that sustainably and efficiently address scaling. One approach is interfacial engineering, which is designed to modify the material properties of the surface that is exposed to water and dissolved minerals. With thicknesses ranging from 10 to 1000 nm, interfacial coatings are significantly thinner than the underlying bulk industrial materials they are employed to protect.

Crystal critters

The Varanasi group was investigating such interfacial coatings when we noticed an unusual behavior: scales falling away from the material. Crystals formed from evaporating drops, as expected, but when the material was heated to above 50 °C, the crystals self-ejected from the coating. Tall, thin structures grew and pushed the salt-crystal structure upward, away from the surface. Their resemblance to jellyfish (see figure 1) and other creatures, in addition to their eerie, lifelike growth, prompted us to name the structures "crystal critters."

We discovered the unusual behavior while investigating why superhydrophobic materials initially perform well for antifouling purposes but eventually fail after sustained exposure to natural water sources. Superhydrophobic materials are materials that repel water so strongly that a drop of water on the surface would appear almost perfectly round when viewed from the side; the contact angle is greater than 150°. Typically, superhydrophobicity arises from a micron-scale material texture, and our investigation determined that those were the cause of the antifouling failure. As shown in figure 1a, a water droplet on the surface first begins to evaporate and spread out, and the contact angle gets smaller. Salt crystals then accumulate in the open spaces between the micropillars of the surface texture. The spread of crystals along the surface leads to a loss of hydrophobicity.

But superhydrophobic materials can also be made with nanoscale, rather than micron-scale, textures, as shown in figure 1b. When salt crystals start to grow near the interface, the nanometric textures induce pressure on them. Since crystals cannot grow into the underlying material due to its small porosity, their growth instead pushes the entire crystal structure upward and off the surface. Thus, the critters rise from the surface before eventually rolling or falling off the material at the end of evaporation (figure 2), and the surface becomes clean and free of salt.

Although our initial investigation into crystal critters used pure salt water, real-world saline sources, such as ocean water, contain various other substances. We found that the addition of model contaminants—including calcium salts, colloidal particles, and surfactant—enhances the self-ejection effect. When other substances are present, the solubility limit of sodium chloride decreases. That decrease hastens the formation of crystals during evaporation and thus accelerates the self-ejection.

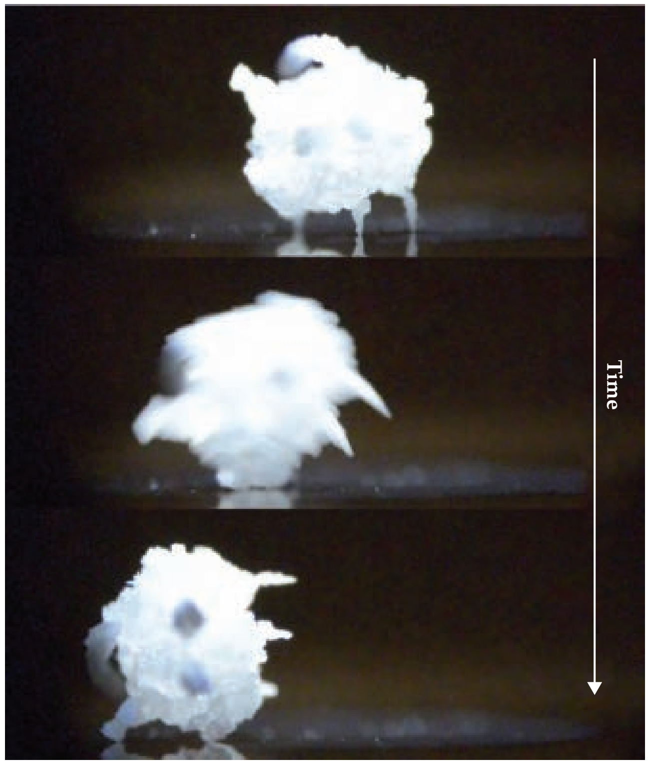


FIGURE 2. DESCALING SURFACES is often a toxic process. But when salt crystals grow on surfaces they cannot cling to, the balls of crystals rise from the surface on spindly crystal legs. Once evaporation is complete, there is little force keeping the mineral structures adhered to the surface, and the crystals often roll or fall off the surface. The detachment can happen in as quickly as four minutes.

The discovery of the crystal-critter phenomenon opens up the possibility of using salt water as an alternative to fresh water for some industrial processes. It may be applicable to heat-exchange processes involving phase change, such as spray cooling of hot surfaces, which already relies on the evaporation of water drops or films on hot surfaces for efficient heat exchange. By integrating crystal self-ejection into such systems, engineers may be able to design sustainable processes that utilize waste brine instead of limited freshwater resources.

Additional resources

- S. A. McBride, H.-L. Girard, K. K. Varanasi, "Crystal critters: Self-ejection of crystals from heated, superhydrophobic surfaces," *Sci. Adv.* **7,** eabe6960 (2021).
- S. A. McBride, J. R. Lake, K. K. Varanasi, "Self-ejection of salts and other foulants from superhydrophobic surfaces to enable sustainable anti-fouling," *J. Chem. Phys.* **158**, 134721 (2023).
- J. Goldberg, "These strange salt 'creatures' could help unclog power plant pipes," Scienceshots (28 April 2021).
- F. Geyer et al., "When and how self-cleaning of superhydrophobic surfaces works," *Sci. Adv.* **6**, eaaw9727 (2020).

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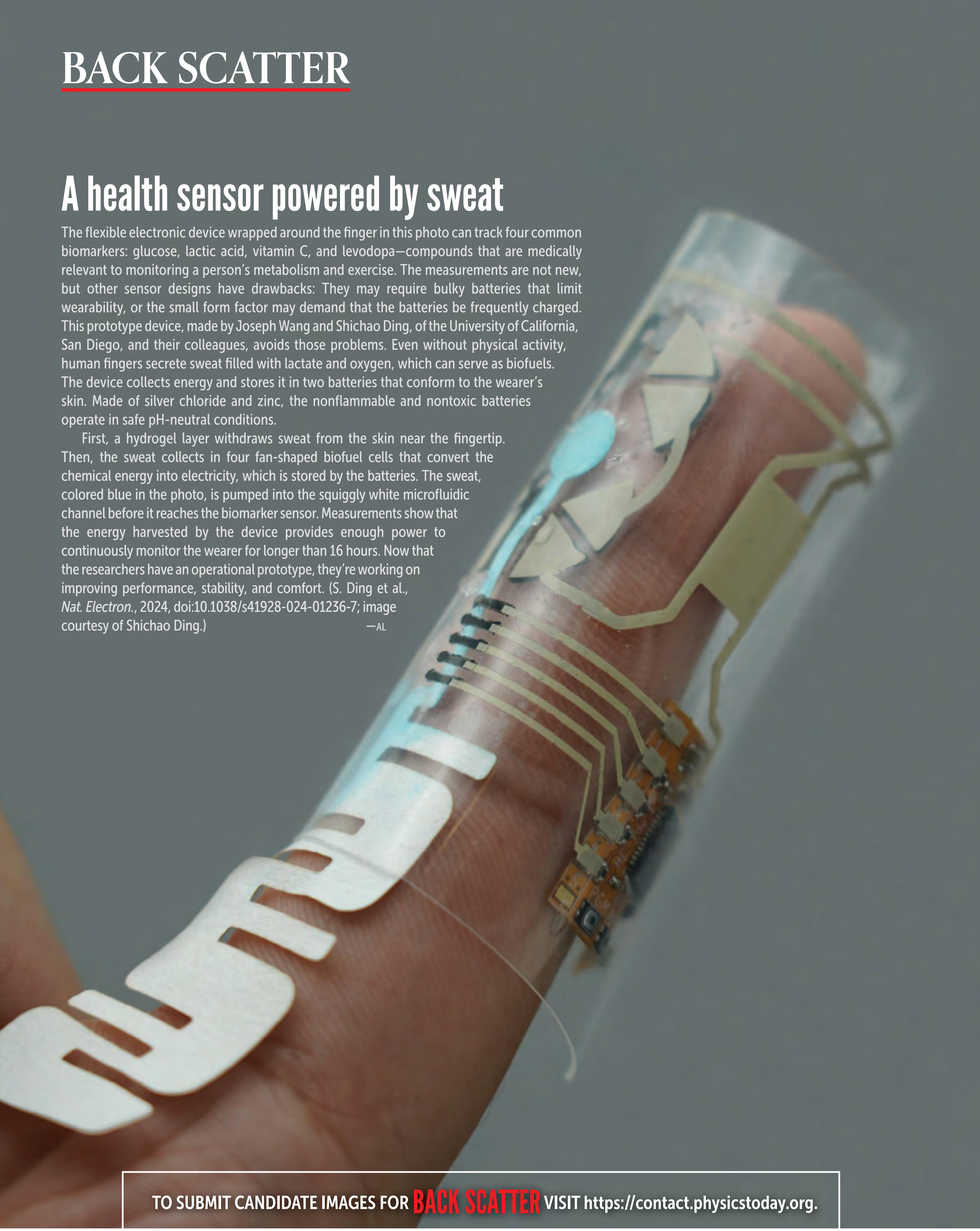
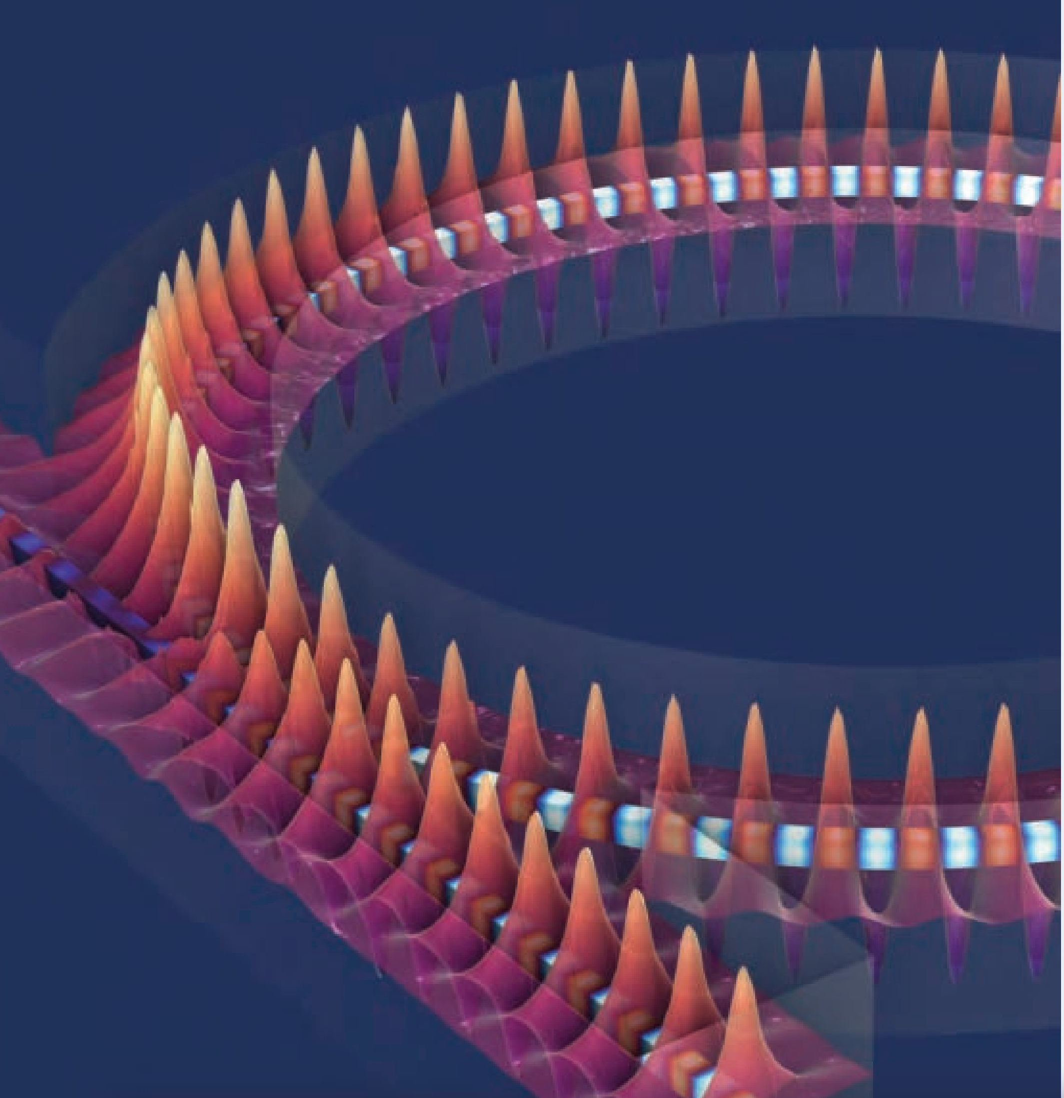
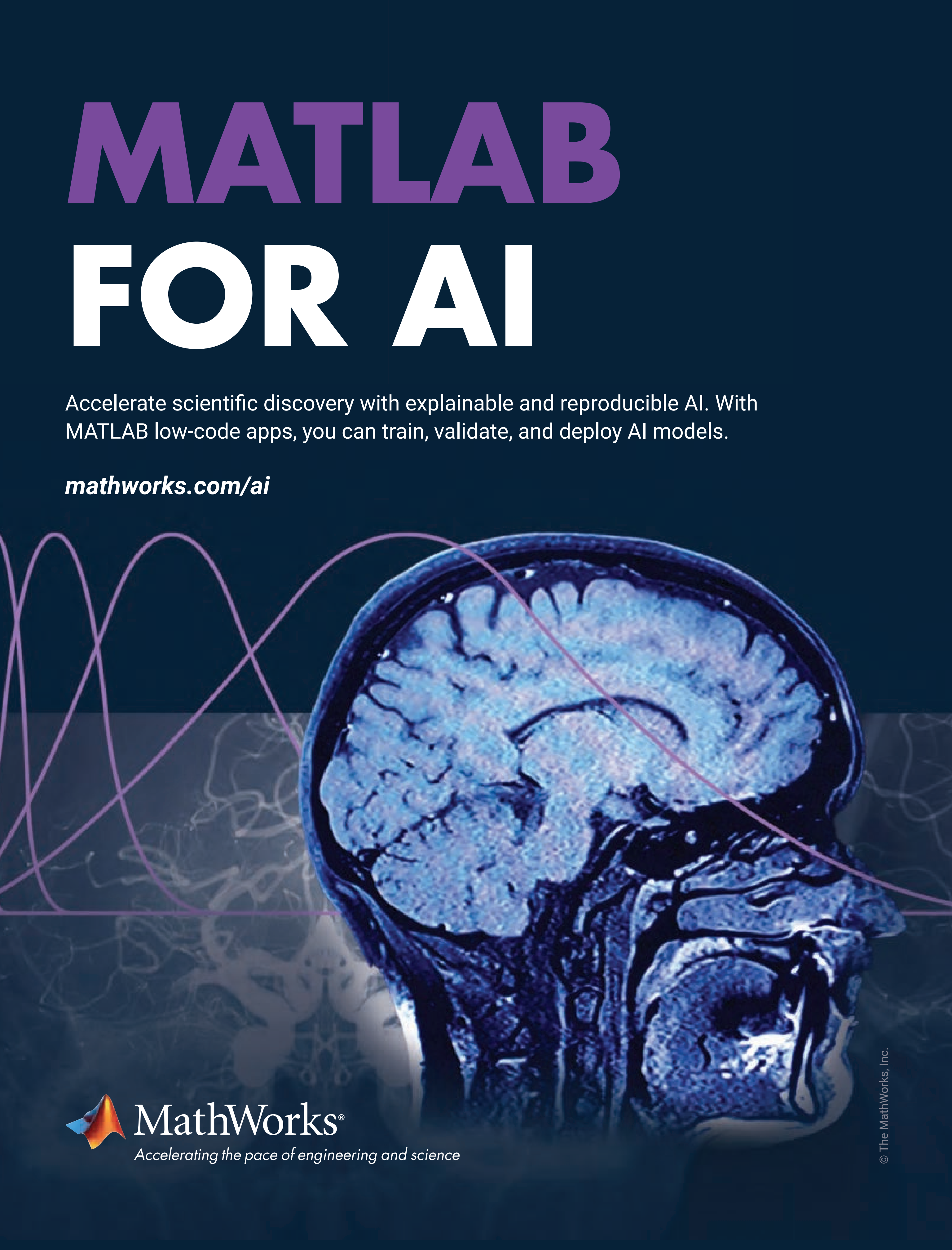


A health sensor powered by sweat

The flexible electronic device wrapped around the finger in this photo can track four common biomarkers: glucose, lactic acid, vitamin C, and levodopa—compounds that are medically relevant to monitoring a person's metabolism and exercise. The measurements are not new, but other sensor designs have drawbacks: They may require bulky batteries that limit wearability, or the small form factor may demand that the batteries be frequently charged. This prototype device, made by Joseph Wang and Shichao Ding, of the University of California, San Diego, and their colleagues, avoids those problems. Even without physical activity, human fingers secrete sweat filled with lactate and oxygen, which can serve as biofuels. The device collects energy and stores it in two batteries that conform to the wearer's skin. Made of silver chloride and zinc, the nonflammable and nontoxic batteries operate in safe pH-neutral conditions.

First, a hydrogel layer withdraws sweat from the skin near the fingertip. Then, the sweat collects in four fan-shaped biofuel cells that convert the chemical energy into electricity, which is stored by the batteries. The sweat, colored blue in the photo, is pumped into the squiggly white microfluidic channel before it reaches the biomarker sensor. Measurements show that the energy harvested by the device provides enough power to continuously monitor the wearer for longer than 16 hours. Now that the researchers have an operational prototype, they're working on improving performance, stability, and comfort. (S. Ding et al., *Nat. Electron.*, 2024, doi:10.1038/s41928-024-01236-7; image courtesy of Shichao Ding.) —AL

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