# PHYSICS TODAY

December 2024 • volume 77, number 12

n of the American Institute of Physics

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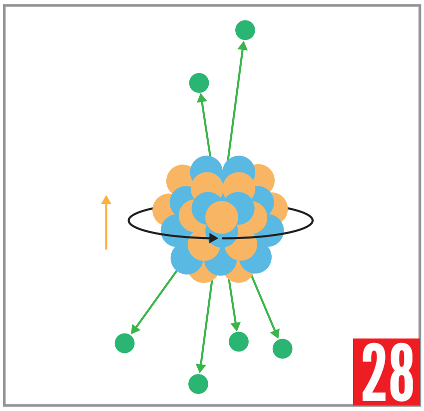

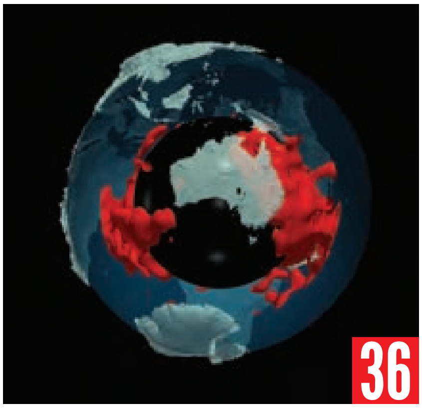

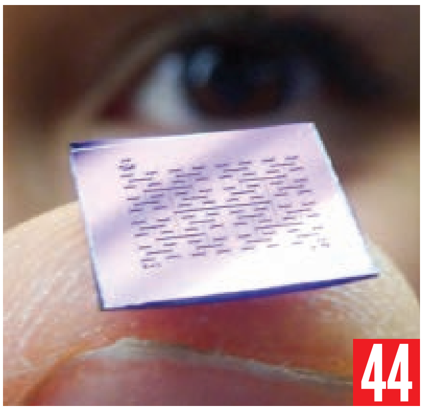

# PHYSICS TODAY

December 2024 | volume 77 number 12

## FEATURES



**ON THE COVER:** Chien-Shiung Wu (1912–97) was a particle physicist renowned for her meticulous experimental designs. She led the first tests that demonstrated photon entanglement and the violation of parity symmetry in weak interactions. To read about some of Wu's most notable experiments, turn to the feature by Chon-Fai Kam, Cheng-Ning Zhang, and Da Hsuan Feng on **page 28.** (Photo courtesy of the AIP Emilio Segrè Visual Archives, Physics Today Collection.)

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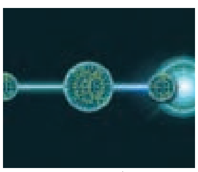

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### Frank Kameny

Along with being a leader of the gay rights movement, Frank Kameny was an astronomer. Documents from the Library of Congress illuminate Kameny's scientific work and the advocacy and activism he pursued after being fired from the federal government because of his sexual orientation.

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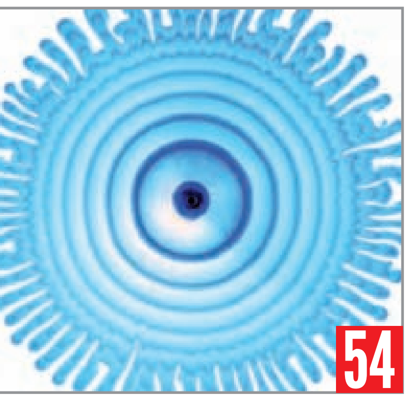


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**SUBSCRIPTION QUESTIONS?** +1 800 344 6902 | +1 516 576 2270 | **ptsubs@aip.org**

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

**Managing editors**
Andrew Grant *agrant@aip.org*
Johanna L. Miller *jlm@aip.org*

**Art and production**
Freddie A. Pagani, art director
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**Editors**
Ryan Dahn *rdahn@aip.org*
Laura Fattaruso *lfattaruso@aip.org*
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Gayle G. Parraway *ggp@aip.org*
Jennifer Sieben *jsieben@aip.org*

**Assistant editor**
Nashiah Ahmad *nahmad@aip.org*

**Digital operations**
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**Contributing editors**
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**Address**
American Institute of Physics
1 Physics Ellipse
College Park, MD 20740-3842
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Ideal candidates will have the experience and knowledge necessary to teach undergraduate and graduate courses in the primary areas of astronautical engineering. Candidates with appropriate qualifications may also be considered for an administrative appointment to serve as Director of the Master of Science in Astronautical Engineering program, in addition to teaching. Responsibilities and duties of this administrative role include, but are not limited, to the following: Overseeing of day-to-day operations of the program, including on-campus and online student recruitment and academic advisement; short-term and long-term class scheduling; overseeing recruitment, instruction, and advising of part-time instructors; and, in collaboration with the department's full-time faculty and School leadership, defining the program's strategic goals and guiding the program's development. The Director also is expected to advance the program's reach to students and the R&D customer base in academia, industry, government centers, and other stakeholders in the space enterprise.

Applicants must have an earned doctoral degree in astronautical engineering, or a related field, and are expected to have a strong commitment, experience, and track record in teaching. Applications must include a cover letter, a curriculum vitae, a teaching statement (up to 2 pages), and names of at least three professional/teaching references. Applicants are encouraged to include a succinct statement on fostering an environment of diversity and inclusion. Applicants may optionally include a research statement. These materials should be submitted electronically at **https://astro.usc.edu/pp-position** by January 15, 2025. Review of applications will begin immediately. Applications submitted after January 15, 2025, may not be considered.

# Commentary

# Room to breathe: A sense of belonging is vital for fostering diversity in STEM

"I can't breathe!" were Eric Garner's last words, which he repeated while a police officer had him in a choke hold that would render him unconscious and ultimately dead. They were the words repeated by George Floyd when a police officer kneeled on his neck. And they have been used by at least 70 other people who have died while in the custody of law enforcement in the past decade.[1]

The phrase has become an expression of solidarity against racial oppression. It represents barriers that not only prevent living life itself but abate economic mobility and living to one's potential. It is a symbol of the need for broad, systemic change.

I have experienced this oppression firsthand in the academic community. "Do not think that you are getting a position here; you better go to the HBCU [historically Black college or university] downtown," I heard in one interview at a research university. "Do not think that we are going to hire any Black people after you," I was told at another. At a time when I had locs, one faculty member said to me, "You better cut your hair because people will think that you smoke weed."

Presently, as a professor, life coach, and engineering consultant, I can now breathe more easily. But I had to fight to get to this point, and nothing was ever given to me easily. Many Black students and faculty are still partaking in that fight, and STEM academics and professionals have an obligation to improve the situation, to whatever extent they can.

## The need for change in STEM

In 2021, Black and African American people made up 12% of the US population ages 18–74 but only 9% of the STEM workforce.[2] That same year, only 8.9% of the US citizens and permanent residents receiving STEM degrees and certificates were Black.[3]

How do we increase the percentage of Black people in STEM degree programs and occupations? Strategies showing some success include culturally responsive pedagogical practices, hands-on learning, summer bridge programs, research experiences, counterspaces (supportive environments that provide safe and inclusive experiences that promote belonging), and mentoring opportunities. Regardless of the strategies, it is important for Black people to feel a sense of not only being welcome but also belonging.

## A sense of belonging

One feels welcomed when the interactions they partake in are warm, sincere, caring, and appreciative. One feels a sense of belonging when they can bring their authentic self to the workplace or classroom. Carol Goodenow has defined belonging "as students' sense of being accepted, valued, included, and encouraged by others (teachers and peers) in the academic classroom setting and of feeling oneself to be an important part of the life and activity of the class."[4]

Research has shown that non-white students tend to report a lower sense of belonging than white students[5] and that students are less likely to succeed in an academic environment in which they feel they do not belong.[6] When Black students learn during the college transition that it is normal to experience struggles and feelings of not belonging, they experience higher self-perceived potential for college success than those who do not receive that type of message.[7]

Many strategies can nurture feelings of belonging. At heart, however, as I have learned through the cumulation of my academic experiences, there are three key components of the educational journey that must be fostered—at the adviser–student, classroom, program, department, and college levels—for students to experience a sense of belonging.

▶ **Positive interpersonal relationships.** In an academic environment, a student has relationships with peers, faculty, advisers, and staff members. The frequency of interactions and the intensity of the relationships matter. With strong interpersonal relationships, students and faculty feel socially connected to those in their major, department, or unit. The fostering of positive connections and structures that encourage healthy interpersonal relationships is thus key to sustaining a culture of belonging.

▶ **Connection to discipline.** Just as important as the connections to other people is the connection to one's field. A student's major or the faculty in their area serve as an integral part of their life and their sense of self. We need to give resources to platforms that foster discipline-specific identities as well as "science capital," which includes, among other things, one's scientific literacy, access to science museums, and ability to talk to others about science.[8] If you are an academic, you may need to ask yourself: Could any student, through hard work, learn my discipline?

▶ **Growth mindset.** The belief that intelligence is a fixed trait—for example, thinking "I'm not a math person"—can be undermining. In contrast, students who believe that ability is a malleable quality are more likely to improve their grades.[9] They are more likely to seek challenges and more open to learning how to improve in the face of setbacks.[10] Academics must, in their evaluations and assessments, encourage students to have a growth mindset.

In order to create lasting change, academic institutions must commit to actively dismantling the barriers that have historically excluded Black voices in STEM. By fostering belonging through intentional support and inclusive practices, we can ensure that all students have the opportunity to thrive and reach their full potential.

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**Christopher Boxe**
*(christopher.boxe@howard.edu, @BoxemanTV)*
*Howard University*
*Washington, DC*

# LETTERS

## More on William Fowler

"Manhattan Project astrophysics" (Physics Today, March 2024, page 34) by Michael Wiescher and Karlheinz Langanke correctly credits William Fowler for his Nobel Prize work on nuclear fusion in stars and for chairing the Project Vista activity at Caltech, but it also states that he "developed ignition systems for nuclear weapons." I believe they may be thinking of a different Fowler, perhaps Clarence "Max" Fowler, who led high-explosives research at Los Alamos for many years, but not during the Manhattan Project. George Kistiakowsky led the wartime explosives division.

Willie Fowler was a prodigious lecturer. We students of his at Caltech proposed that the unit of lecture material be named the "Willie" in his honor, but that in practice, other lecturers' output could be measured in milliWillies.

**Victor A. J. van Lint**
*(vicvanlint@yahoo.com)*
*San Diego, California*

► **Wiescher and Langanke reply:** We welcome the opportunity for clarification. The phrase "developed ignition systems for nuclear weapons" may be a bit vague. We meant it first to refer to the development of the neutron trigger based on the use of a polonium-210 alpha-particle source, which in combination with the beryllium-9 material, causes the production of neutrons, a method that was developed at Caltech during William Fowler's early days there, where he was advised by Charles Lauritsen.[1] The second reference is, as we state in our article, to "the system that abruptly and symmetrically compressed the plutonium core of the Trinity bomb, causing it to detonate." In an article in *Nuclear Technology*, Thomas Chadwick and M. B. Chadwick mention Fowler being responsible for magnetic and x-ray studies of the approach.[2] Looking at the reference again, though, we admit it could have been a different Fowler.

In *History of the Naval Weapons Center*, J. D. Gerrard-Gough and Albert Christman describe how the detonators needed to work in nanoseconds, initiating each explosive block nearly simultaneously:

> Through the efforts of C. C. Lauritsen and his Caltech scientific staff, appropriate detonators were designed. Lauritsen's close association with [the Naval Ordinance Test Station] paid off as equipment, facilities and security were available at Inyokern for the development testing of these detonators, which were known as "sockets." Development and testing of the sockets were under the direction of William Fowler and Thomas Lauritsen, and while the program was not strictly within Bruce Sage's principal area of responsibility, China Lake Pilot Plant facilities were used to load and test-fire the detonators, which were made in Pasadena.
>
> The other problem was infinitely more complicated and concerned the intricate high explosive blocks themselves, their process, manufacture, and test.
>
> The scientists and technicians of Los Alamos pioneered the initial process. The explosive was cast to a uniform density in specially designed molds, and then the cast blocks were carefully machined into the required shapes. Machining explosives was virtually a new technique, and the military and civilian machinists, for the most part, had to teach themselves. The fact that they mastered the art in such an incredibly short time is almost beyond comprehension.[3]

We took that as sufficient evidence that Willie Fowler was involved in both aspects. We apologize that we could not provide all of our references, but Physics Today articles limit the number that can be included.

We hope this clarifies the situation. And both of us, as former postdocs of Willie Fowler at Caltech, fully subscribe to introducing the "Willie" unit in teaching.

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**Michael Wiescher**
*(Michael.c.wiescher.1@nd.edu)*
*University of Notre Dame*
*Notre Dame, Indiana*
**Karlheinz Langanke**
*(k.langanke@gsi.de)*
*GSI Helmholtz Center for Heavy Ion Research*
*Darmstadt, Germany*

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## Correction

**August 2024, page 22**—The Huntsman Telescope lenses have a focal length, not diameter, of 400 mm. PT

# Nobel Prize highlights neural networks' physics roots

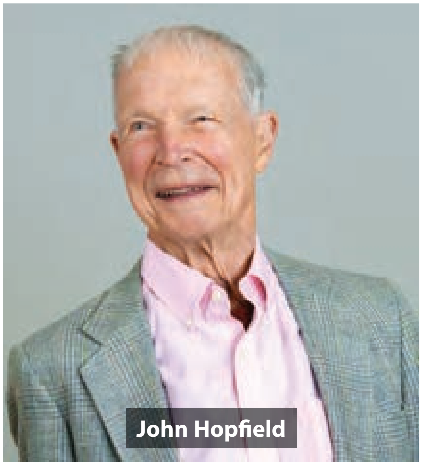
The road to the modern machine-learning marvels was paved with ideas from statistical mechanics and collective phenomena.

"Garbage in, garbage out." According to the old adage from computer science, what you get from a computer is no better than what you give it. And it would seem to imply that because computers can't think for themselves, they can never do anything more sophisticated than what they've been explicitly instructed to.

But that last part appears to be no longer true. Neural networks—computing architectures, inspired by the human brain, in which signals are passed among nodes called artificial neurons—have, in recent years, been producing wave after wave of stunning results. (See, for example, page 17 of this issue.) Individual artificial neurons perform only the most elementary of computations. But when brought together in large enough numbers, and when fed on enough training data, they acquire capabilities uncannily reminiscent of human intelligence, seemingly out of nowhere.

Physicists are no strangers to the idea of unexpected phenomena emerging from simpler building blocks. A few elementary particles and the rules of their interactions combine to yield almost the whole of the visible world: superconductors, plasmas, and everything in between. Why shouldn't a physics approach to emergent complexity be applied to neural networks too?

Indeed, it was—and still is—as showcased by this year's Nobel Prize in Physics, which goes to Princeton University's John Hopfield and the University of Toronto's Geoffrey Hinton. Beginning in the early 1980s, Hopfield laid the conceptual foundations for physics-based thinking about brain-inspired information processing; Hinton was at the forefront of the decades-long effort to build on those ideas to develop the algorithms used by neural-network models today.



MATT RASPANTI/PRINCETON UNIVERSITY

JOHNNY GUATTO/UNIVERSITY OF TORONTO

## Glassy memory

It was far from obvious, at first, that neural networks would ever grow to be so powerful. As recently as 2011, the flashiest milestones in AI were being achieved by another approach entirely. IBM Watson, the computer that beat Ken Jennings and Brad Rutter at *Jeopardy!*, was not a neural network: It was explicitly programmed with rules for language processing, information retrieval, and logical reasoning. And many researchers thought that was the way to go to create practical AI machines.

In contrast, the early work on neural networks was curiosity-driven research, inspired more by real brains than by computers and their applications. But the nature of the interdisciplinary connection was subtle. "The questions Hopfield addressed are not unrelated to things neuroscientists were worried about," says Princeton's William Bialek. "But this isn't about 'application of physics to X'; rather, it's about introducing a whole point of view that just didn't exist before."

By the 1980s, neuroscientists had known for decades that the brain is composed of neurons, which are connected to one another via synapses and alternate between periods of high and low electrical activity (colloquially, "firing" and "not firing"), and they were studying systems of a few neurons to understand how one neuron's firing affected those it was connected to. "Some thought of neurons in terms of logic gates, like in electronics," says Stanford University's Jay McClelland.

In a landmark 1982 paper, Hopfield took a different approach.[1] In physics, he argued, many important properties of large-scale systems are independent of small-scale details. All materials conduct sound waves, for example, irrespective of exactly how their atoms or molecules interact. Microscopic forces might affect the speed of sound or other acoustic properties, but studying the forces among three or four atoms reveals little about how the concept of sound waves emerges in the first place.

So he wrote down a model of a network of neurons, with an eye more toward computational and mathematical simplicity than neurobiological realism. The model, now known as a Hopfield network, is sketched in figure 1. (The figure shows a five-neuron network for ease of illustration; Hopfield was simulating networks of 30 to 100 neurons.) Each neuron can be in state 1, for firing, or state 0, for not firing. And each neuron was connected to all the others via coupling constants that could have any positive or negative value, depending on whether each synapse favors or disfavors the neurons to both be firing at the same time.

That's exactly the same form as a spin glass, a famously thorny system from condensed-matter physics. (See Physics Today, December 2021, page 17.) Unlike a ferromagnet, in which the couplings are all

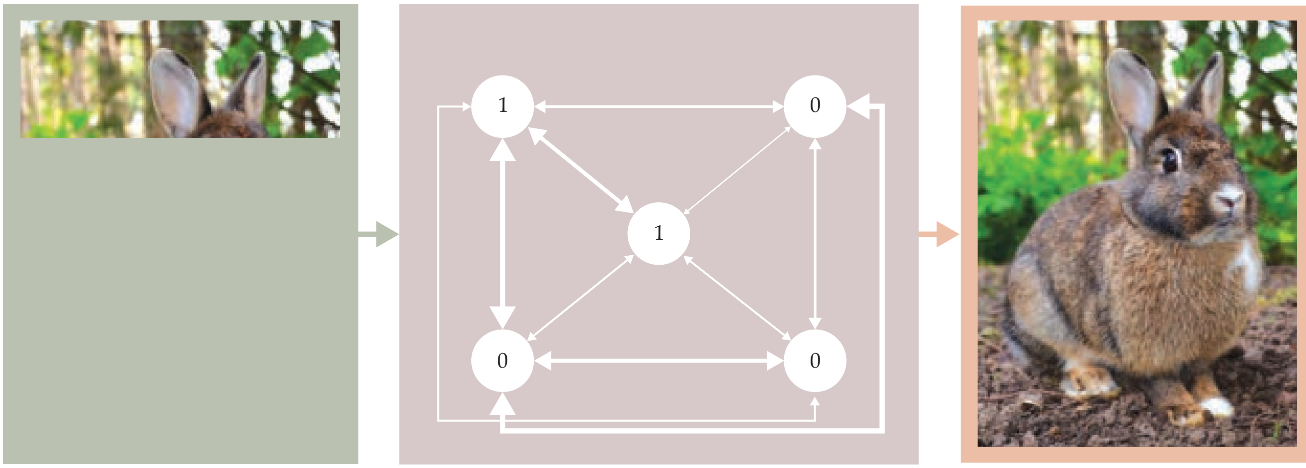



**FIGURE 1. A HOPFIELD NETWORK**, formally equivalent to a spin glass, functions as an associative memory: When presented with a partially recalled state, it uses an energy-lowering algorithm to fill in the gaps. The memories are stored in the strengths of the connections among the nodes. When John Hopfield showed that with the right combination of connection weights, the network could store many memories simultaneously, he set the stage for physics-based thinking about neural networks. (Figure by Freddie Pagani; rabbit photo by JM Ligero Loarte/Wikimedia Commons/CC BY 3.0.)

positive and the system has a clear ground state with all its spins aligned, a spin glass almost always lacks a state that satisfies all its spins' energetic preferences simultaneously. Its energy landscape is complex, with many local energy minima.

Hopfield argued that the landscape could serve as a memory, with each of the energy-minimizing configurations serving as a state to be remembered. And he presented an elegant way of setting the connection strengths—inspired by what happens at real synapses—so that the memory would store any desired collection of states.

But the Hopfield network is fundamentally different from an ordinary computer memory. In a computer, each item of data to be stored is encoded as a string of ones and zeros in a specific place, and it's recalled by going back to that place and reading out the string. In a Hopfield network, all the items are stored simultaneously in the coupling strengths of the whole network. And they can be recalled associatively, by giving the network a starting point that shares just a few features with one of the remembered states and allowing it to relax to the nearest energy minimum. More often than not, it will recall the desired memory. (See also the articles by Haim Sompolinsky, Physics Today, December 1988, page 70, and John Hopfield, Physics Today, February 1994, page 40.)

Those are both things that happen in real brains. "It was known experimentally in higher animals that brain activity was well spread out, and it involved many neurons," says Hopfield. And associative memory is something you've directly experienced if you've ever recalled a song you've heard before after hearing one random line.

Hopfield's model was a vast simplification of a real brain. Real neurons are intrinsically dynamic, not characterized by static states, and real neuron connections are not symmetric. But in a way, those differences were features, not bugs: They showed that collective, associative memory was an emergent large-scale phenomenon, robust against small-scale details.

## Learning how to learn

"Not only is Hopfield a very good physicist, but the Hopfield model is excellent physics by itself," says Leo van Hemmen, of the Technical University of Munich. Still, its 1982 formulation left many intriguing open questions. Hopfield had focused on simulations to show how the system relaxes to an energy minimum; would the model admit a more robust analytical treatment? How many states could the model remember, and what would happen if it was overloaded? Were there better ways of setting the connection strengths than the one Hopfield proposed?

Those questions, and others, were taken on by a flurry of physics-trained researchers who were inspired by Hopfield's work and entered the neural-network field over the 1980s. "Physicists are versatile, curious, and arrogant—in a positive way," says Eytan Domany, of the Weizmann Institute of Science in Israel. "They're willing to study thoroughly and then tackle a problem they've never seen before, if it's interesting. And everyone is excited about understanding the brain."

Another part of the appeal was in how Hopfield had taken a traditional physics problem and turned it on its head. "In most energy-landscape problems, you're given the microscopic interactions, and you ask, What is the ground state? What are the local minima? What is the entire landscape?" says Haim Sompolinsky, of the Hebrew University of Jerusalem. "The 1982 paper did the opposite. We start with the ground states that we want: the memories. And we ask, What are the microscopic interactions that will support those as ground states?"

From there, it was a short conceptual leap to ask, What if the coupling strengths themselves can evolve on their own energy landscape? That is, instead of being preprogrammed with parameters to encode specific memories, can the system improve itself by learning?

Machine learning in neural networks had been tried before. The perceptron—a neural-network-like device that sorted images into simple categories, such as circles and squares—dates back to the 1950s. When provided with a series of training images and a simple algorithm for updating its connections between neurons, it could eventually learn to correctly classify even images it hadn't seen before.

But the perceptron didn't always work: With the way the network was structured, sometimes there wasn't any way of setting the connection strengths

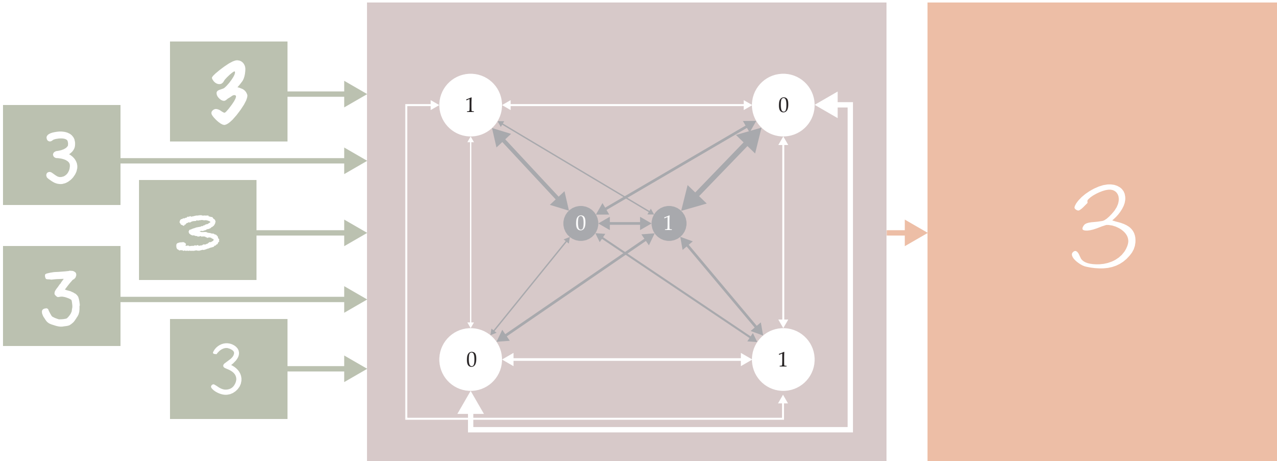



**FIGURE 2. A BOLTZMANN MACHINE** extends the Hopfield network in two ways: It augments the network to include hidden nodes (shown in the center of the network in gray) that aren't involved in encoding the data, and it operates at a nonzero effective temperature, so that the entire space of configurations can be characterized by a Boltzmann probability distribution. Geoffrey Hinton and colleagues developed a way to train the Boltzmann machine as a generative model: When presented with several inputs that all shared a common feature, it produced more items of the same type. (Figure by Freddie Pagani.)

to perform the desired classification. "When that happened, you could iterate forever, and the algorithm would never converge," says van Hemmen. "That was a big shock." Without a guiding principle to chart a path forward, the field had stalled.

## Finding common ground

Hinton didn't come to neural networks from a background in physics. But his collaborator Terrence Sejnowski—who'd earned his PhD under Hopfield in 1978—did. Together, they extended the Hopfield network into something they called the Boltzmann machine, which vastly extended the model's capabilities by explicitly drawing on concepts from statistical physics.[2]

In Hopfield's 1982 simulations, he'd effectively considered the spin-glass network at zero temperature: He allowed the system to evolve its state only in ways that would lower its overall energy. So whatever the starting state, it rolled into a nearby local energy minimum and stayed there.

"Terry and I immediately started thinking about the stochastic version, with nonzero temperature," says Hinton. Instead of a deterministic energy-lowering rule, they used a Monte Carlo algorithm that allowed the system to occasionally jump into a state of higher energy. Given enough time, a stochastic simulation of the network would explore the entire energy landscape, and it would settle into a Boltzmann probability distribution, with all the low-energy states—regardless of whether they're local energy minima—represented with high probability.

"And in 1983, we discovered a really beautiful way to do learning," Hinton says. When the network was supplied with training data, they iteratively updated the connection strengths so that the data states had high probability in the Boltzmann distribution.[3] Moreover, when the input data had something in common—like the images of the numeral 3 in figure 2—then other high-probability states would share the same common features.

The key ingredient for that kind of commonality finding was augmenting the network to include more nodes than just the ones that encode the data. Those hidden nodes, represented in gray in figure 2, allow the system to capture higher-level correlations among the data.

In principle, the Boltzmann machine could be used for machine recognition of handwriting or for distinguishing normal from emergency conditions in a facility such as a power plant. Unfortunately, the Boltzmann machine's learning algorithm is prohibitively slow for most practical applications. It remained a topic of academic research, but it didn't find much real-world use—until it made a surprising reappearance years later.

## How the networks work

Around the same time, Hinton was working with cognitive scientist David Rumelhart on another learning algorithm, which would become the secret sauce of almost all of today's neural networks: backpropagation.[4] The algorithm was developed for a different kind of network architecture, called a feedforward network, shown in figure 3. In contrast to the Hopfield network and Boltzmann machine, with their bidirectional connections among nodes, signals in a feedforward network flow in one direction only: from a layer of input neurons, through some number of hidden layers, to the output. A similar architecture had been used in the multilayer perceptron.

Suppose you want to train a feedforward network to classify images. You give it a picture of a rabbit, and you want it to produce the output message "This is a rabbit." But something is wrong, and instead you get the output "This is a turtle." How do you get things back on track? The network might have dozens or hundreds—or today, trillions—of internode connections that contribute to the output, each with its own numerical weight. There's a dizzying number of ways to adjust them all to try to get the output you want.

Backpropagation solves that problem through gradient descent: First, you define an error function that quantifies how far the output you got is from the output you want. Then, calculate the partial derivatives of the error function with respect to each of the internodal weights—a simple matter of repeatedly applying calculus's chain rule. Finally, use those derivatives to adjust the weights in a way that decreases the error.

It might take many repetitions to get

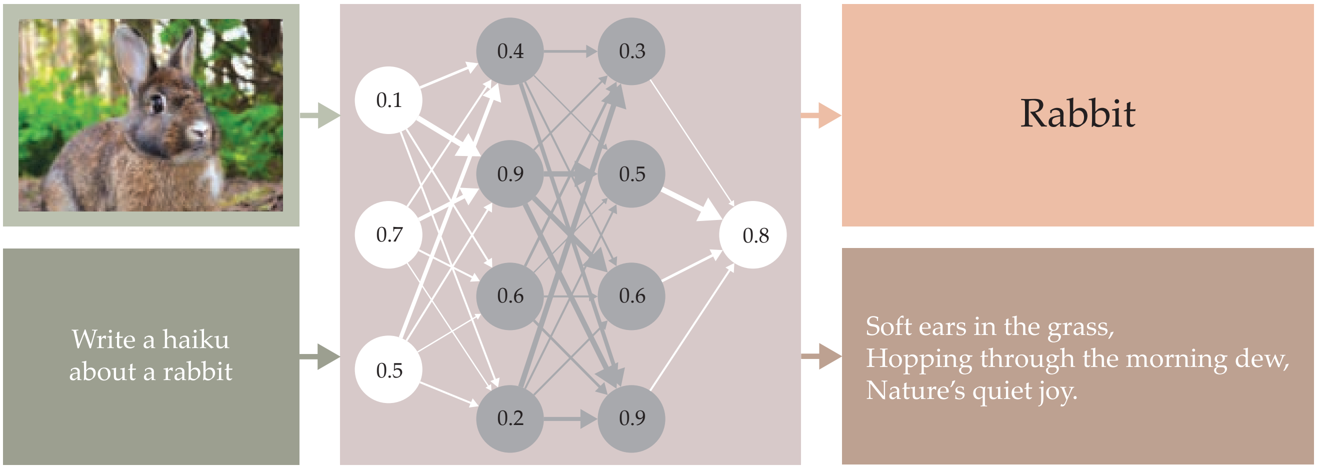



**FIGURE 3. A FEEDFORWARD NETWORK**, trained by backpropagation, is the basic structure of the neural networks used today. By passing numerical signals from an input layer through hidden layers to an output layer, feedforward networks perform functions that include image classification and text generation. (Figure by Freddie Pagani; rabbit photo by JM Ligero Loarte/Wikimedia Commons/CC BY 3.0; haiku generated by GPT-4, OpenAI, 22 October 2024.)

the error close enough to zero—and you'll want to make sure that the network gives the right output for many inputs, not just one. But those basic steps are used to train all kinds of networks, including proof-of-concept image classifiers and large language models, such as ChatGPT.

Gradient descent is intuitively elegant, and it wasn't conceptually new. "But several elements had to come together to get the backpropagation idea to work," says McClelland. "For one thing, you can't take the derivative of something if it's not differentiable." Real neurons operate more or less in discrete on and off states, and the original Hopfield network, Boltzmann machine, and perceptron were all discrete models. For backpropagation to work, it was necessary to shift to a model in which the node states can take a continuum of values. But those continuous-valued networks had already been introduced, including in a 1984 paper by Hopfield.[5]

A second innovation had to wait for longer. Backpropagation worked well for networks with just a couple of layers. But when the layer count approached five or more—a trifling number by today's standards—some of the partial derivatives were so small that the training took an impractically long time.

In the early 2000s, Hinton found a solution, and it involved his old Boltzmann machine—or rather, a so-called restricted version of it, in which the only connections are those between one hidden neuron and one visible (non-hidden) neuron.[6] Restricted Boltzmann machines (RBMs) are easy to computationally model, because each group of neurons—visible and hidden—could be updated all at once, and the connection weights could all be adjusted together in a single step. Hinton's idea was to isolate pairs of successive layers in a feedforward network, train them as if they were RBMs to get the weights approximately right, and then fine-tune the whole network using backpropagation.

"It was kind of a hacky thing, but it worked, and people got very excited," says Graham Taylor, of the University of Guelph in Canada, who earned his PhD under Hinton in 2009. "It was now possible to train networks with five, six, seven layers. People called them 'deep' networks, and they started using the term 'deep learning.'"

The RBM hack wasn't used for long. Computing power was advancing so quickly—particularly with the realization that graphics processing units (GPUs) were ideally suited to the computations needed for neural networks—that within a few years, it was possible to do backpropagation on even larger networks from a cold start, with no RBMs required.

"If RBM learning hadn't happened, would GPUs have come along anyway?" asks Taylor. "That's arguable. But the excitement around RBMs changed the landscape: It led to the recruitment and training of new students and to new ways of thinking. I think at the very least, it wouldn't have happened the same way."

## What's new is old

Today's networks use hundreds or thousands of layers, but their form is little changed from what Hinton described. "I learned about neural networks from books from the 1980s," says Bernhard Mehlig, of the University of Gothenburg in Sweden. "When I started teaching it, I realized that not much is new. It's essentially the old stuff." Mehlig notes that in a textbook he wrote, published in 2021, part 1 of 3 is about Hopfield, and part 2 is about Hinton.

Neural networks now influence a vast number of human endeavors: They're involved in data analysis, web searches, and creating graphics. Are they intelligent? It's easy to dismiss the question out of hand. "There have always been lots of things that machines can do better than humans," says the University of Maryland's Sankar Das Sarma. "That has nothing to do with becoming human. ChatGPT is fabulously good at some things, but at many others, it's not even as good as a two-year-old baby."

An illustrative comparison is the vast data gap between today's neural networks and humans.[7] A literate 20-year-old may have read and heard a few hundred million words in life so far. Large language models, in contrast, are trained on hundreds of billions of words, a number that grows with each new release. When you account for the fact that ChatGPT has the advantage of a thousand times as much life experience as you do, its abilities may seem less like intelligence. But perhaps it doesn't matter if AI fumbles with some tasks if it's good at the right combination of others.

Hinton and Hopfield have both spoken about the dangers of unchecked AI.

Among their arguments is the idea that once machines become capable of breaking up goals into subgoals, they'll quickly deduce that they can make almost any task easier for themselves by consolidating their own power. And because neural networks are often tasked with writing code for other computers, stopping the damage is not as simple as pulling the plug on a single machine.

"There are also imminent risks that we're facing right now," says Mehlig. "There are computer-written texts and fake images that are being used to trick people and influence elections. I think that by talking about computers taking over the world, people take the imminent dangers less seriously."

## What can physicists do?

Much of the unease stems from the fact that so little is known about what neural networks are really doing: How do billions of matrix multiplications add up to the ability to find protein structures or write poetry? "People at the big companies are more interested in producing revenue, not understanding," says Das Sarma. "Understanding takes longer. The job of theorists is to understand phenomena, and this is a huge physical phenomenon, waiting to be understood by us. Physicists should be interested in this."

"It's hard not to be excited by what's going on, and it's hard not to notice that we don't understand," says Bialek. "If you want to say that things are emergent, what's the order parameter, and what is it that's emerged? Physics has a way of making that question more precise. Will that approach yield insight? We'll see."

For now, the biggest questions are still overwhelming. "If there were something obvious that came to mind, there would be a horde of people trying to solve it," says Hopfield. "But there isn't a horde of people working on this, because nobody knows where to start."

But a few smaller-scale questions are more tractable. For example, why does backpropagation so reliably reduce the network error to near zero, rather than getting stuck in high-lying local minima like the Hopfield network does? "There was a beautiful piece of work on this a few years ago by Surya Ganguli at Stanford," says Sara Solla, of Northwestern University. "He found that most high-lying minima are really saddle points: It's a minimum in many dimensions, but there's always one in which it's not. So if you keep kicking, you eventually find your way out."

When physics-trained researchers work on problems like that, are they still doing physics? Or have they left physics behind for something else? If "physics" is defined as the study of the natural, physical world, that would arguably exclude artificial neural networks, which by now are wholly human-made abstractions with little resemblance to biological neurons. "We don't build airplanes that flap their wings," says Solla. "And backpropagation is a totally unrealistic mechanism in a real brain. The engineering goal is to make a machine that works. Nature gives us some intuition, but the best solution is not necessarily to copy it."

But must physics be defined solely by its subject matter? "In multidisciplinary fields, what makes the difference between disciplines—mathematics versus computer science versus physics—is their methods and mindsets," says Princeton's Francesca Mignacco. "They're complementary but different. Neural-network models are so complicated that it's hard to achieve rigorous mathematical descriptions. But statistical physics has precisely the tools to tackle the complexity of high-dimensional systems. Personally, I've never stopped asking questions just because they might or might not be physics."

"Physics is limited only by the ingenuity of people applying physical ways of thinking to systems in the real world," says Hopfield. "You can have a narrow view of that, or you can welcome more applied physics. I'm one of the welcomers."

**Johanna Miller**

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# Chemistry Nobel honors protein design and modeling

## The prizewinning research enhances understanding of nature's molecular toolkit and enables the construction of novel proteins.

David Baker, Demis Hassabis, and John Jumper are the recipients of the 2024 Nobel Prize in Chemistry for their work on protein design and structure. Baker, of the University of Washington in Seattle, receives half the prize for using computational methods to design proteins. Hassabis and Jumper, at Google DeepMind in London, share the other half for predicting protein structures with neural network–based AI, the method that earned its developers this year's Nobel Prize in Physics (see page 12 of this issue).

To design amino acid sequences that would fold into desired structures, the earliest computational approaches searched through a vast number of sequences for a few that, when combined together, could yield new 3D structures. To make the process more efficient, Baker and his research group developed the Rosetta computer program in the 1990s. It takes structural-fragment data from various existing proteins and uses an energy-optimization procedure to assemble them together into a new form.[1,2] With Rosetta, Baker and colleagues created an entirely new and large protein known as Top7: Its sequencing and structure were significantly different from the proteins found in the research community's databases.

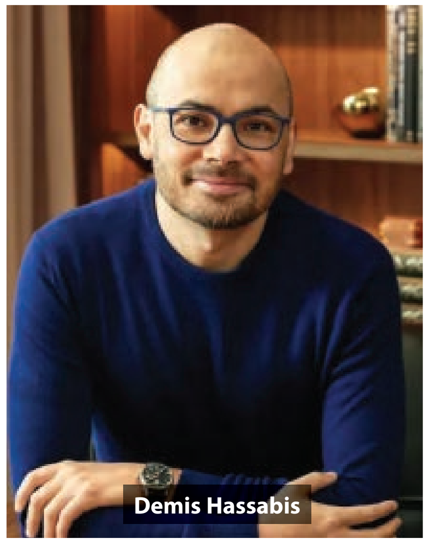
When Rosetta was developed, computational resources were meager enough that Baker founded a citizen science project called Rosetta@home. It's still in use today, and people can donate computational power from their personal computers to help complete Rosetta's calculations. Before the work by Baker's team, protein engineers had relied mostly on the modification of naturally occurring proteins—the achievement behind the 2018 chemistry Nobel (see Physics Today, December 2018, page 22). The *de novo* design capabilities ushered in by Rosetta have allowed biochemists to build proteins from scratch.[3] Such engineered proteins can be used for various functions, such as performing logic operations inside human cells (see Physics Today, June 2020, page 17).

So much of a protein's function depends on its 3D structure. Starting in the 1950s, researchers have used methods such as x-ray crystallography to empirically identify protein structure. But even today, x-ray crystallography is time-consuming, and not all proteins can be crystallized for the measurements. Since 1994, protein researchers have held a biennial challenge—the Critical Assessment of Structure Prediction (CASP) experiment—to improve theoretical structure predictions by testing them against experimental observations. The prediction accuracy, graded on a scale of 0 to 100, has been steadily improving for years, in part because AI models are adept at pattern recognition.

From 2016 to 2020 at DeepMind, an interdisciplinary team led by Hassabis and Jumper reworked its neural network algorithm to dramatically improve the prediction of protein structures.[4,5] The transformative work was published in 2021—unusually recent for a Nobel Prize.[6] For the 2018 CASP experiment, DeepMind's original AlphaFold model predicted protein targets better than any other model, receiving a grade of almost 70 for the most difficult targets. (In the previous CASP experiment, the best model in that category scored around 40.) DeepMind overhauled the AI algorithm for the 2020 CASP assessment, and AlphaFold2 leaped ahead of the competition and for the most difficult targets scored near 90—that's a grade equivalent to that of an experimentally determined structure. The prizewinning research was covered in detail in Physics Today in October 2021 (page 14).

The accurate design of proteins and the prediction of their structure have far-reaching implications in medicine and many other fields—the vitellogenin protein on page 18, for example, is important for the immunity of honeybees. Earlier this year, Hassabis, Jumper, and colleagues reported the development of AlphaFold3, an upgraded model that also predicts the structures of biochemical complexes that contain nucleic acids, small molecules, and other components.[7]


IAN C. HAYDON/UW MEDICINE

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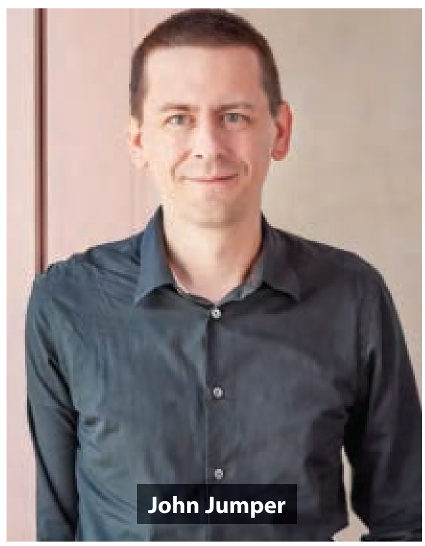


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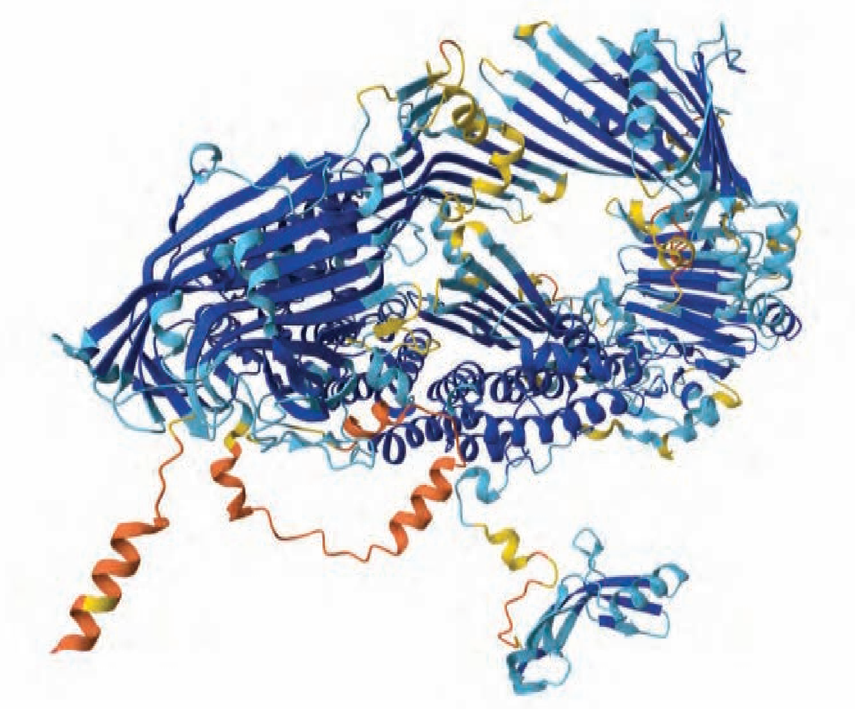

**ALPHAFOLD2'S PREDICTED STRUCTURE** of the vitellogenin protein, which contributes to immunity in honeybees. The colors represent regions of the protein predicted with high (blue) through low (yellow and orange) confidence. (AlphaFold Protein Structure Database/CC BY 4.0.)

Hassabis has a background in computer science and video game design. Before studying proteins and AI, Jumper majored in physics and mathematics. Only after dropping out of a physics PhD program did he become interested in biology. "I think of myself as a physicist who likes to work on these really complex, really interesting systems of biology," says Jumper. When asked what led him to join DeepMind, he recalls thinking that "machine learning and AI were exciting, and they were possibly going to solve some really important problems, and DeepMind was the most exciting place to do it."

**Alex Lopatka**

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# UPDATES

## Carbonate rocks may release more carbon dioxide as climate warms

An analysis of 60 years of water chemistry data from Arctic and subarctic Canadian rivers finds that some regions exhibit a major increase of dissolved sulfates, a product of weathering reactions that also release $CO_2$.

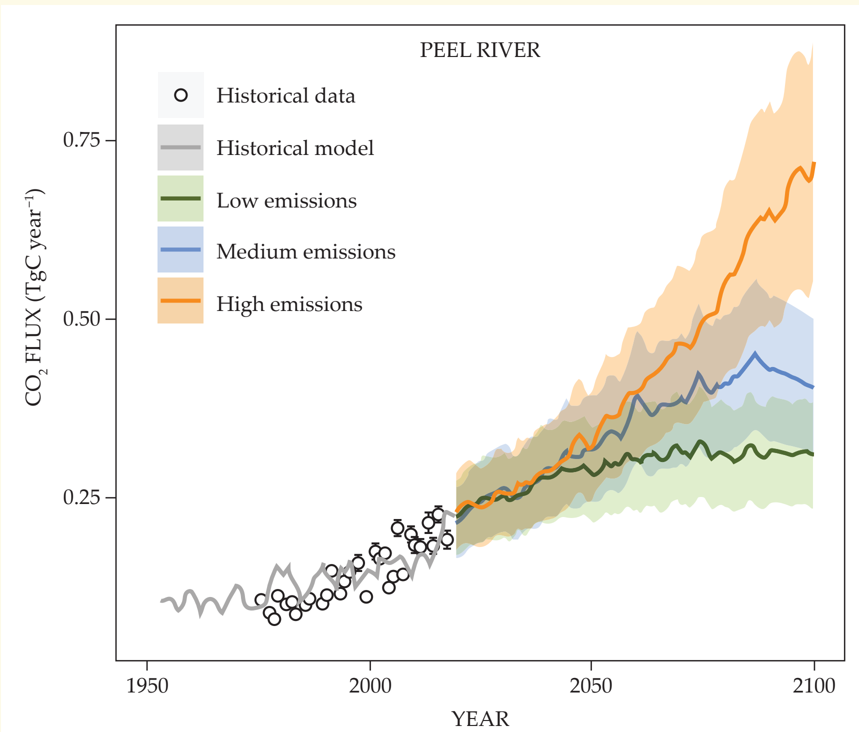
Rocks at Earth's surface experience natural weathering reactions that can both release carbon dioxide into the atmosphere and pull it out. Quantifying those exchanges is a challenge, and climate change throws another confounding factor into the mix: Temperature changes can alter the rates of weathering reactions. That may be especially important in the Arctic, where air temperatures are rising nearly four times as fast as the global average. In a new study, Ella Walsh (at the time at the University of Oxford) and colleagues show that warming temperatures in western Canada over the past six decades have driven increased rates of weathering reactions that release $CO_2$.

For their analysis, Walsh and colleagues used water chemistry data collected from rivers in the Mackenzie River basin in Canada between 1960 and 2020. The basin, which includes several smaller river watersheds, covers an area of about 1.8 million km$^2$, roughly 20% of Canada. A modeling study published over a decade ago had estimated that increased temperatures, rainfall, and vegetation, all associated with climate change, would produce weathering reactions in the basin that would draw more $CO_2$ from the atmosphere over time. The rocks' silicate and carbonate minerals react with $CO_2$ to form bicarbonate, which dissolves in river water and is ultimately delivered to the ocean.

But Walsh says that the contribution of sulfide weathering wasn't factored into those estimates. Oxidation of sulfide minerals, like pyrite, produces sulfuric acid. That acid reacts with carbonate minerals to release $CO_2$ and dissolved sulfate to river waters. The research team analyzed the sulfate flux for individual river basins, known as catchments, within the larger system. "By looking at this catchment scale, we were able to look at what some of the possible drivers are, why some catchments have greater increases than others," says Walsh.

The Mackenzie River, which is central to the basin, saw a 45% increase in sulfate flux with 2.3 °C of warming over the study period. One catchment had sulfate concentrations that rose by as much as 36% per decade. Others showed no significant changes in sulfate concentrations. Steeper


**THE MELTING OF PERMAFROST** changes the Arctic landscape, as illustrated by a thaw slump into the Peel River in Canada. Such landscape changes can increase the rate of carbon dioxide release from rock weathering.




**HISTORICAL ESTIMATES AND FUTURE PROJECTIONS** for the flux of carbon dioxide from the Peel River watershed highlight the way that temperature increases over time could increase the release of carbon dioxide from the Arctic landscape. Projections are shown for three emissions scenarios adopted by the Intergovernmental Panel on Climate Change. Black circles represent data collected by Environment and Climate Change Canada. (Adapted from E. V. Walsh et al., *Sci. Adv*. **10**, eadq4893, 2024.)

slopes, more exposed bedrock, and more permafrost were all associated with faster increases of sulfate concentration. Melting permafrost produced major landscape changes—such as a thaw slump observed in the Peel River, shown in the photo—that increased exposure of sulfides to weathering. Peatland cover had the opposite effect. And the types of rocks present control the reactions—places with both sulfide- and carbonate-rich rocks contribute the most to increased $CO_2$ emissions.

Walsh and colleagues extrapolated their findings to consider how much $CO_2$ flux in the Mackenzie River basin would result from different climate change emissions scenarios, as shown in the graph. The increases—possibly several teragrams of carbon per year by the end of the century—are large enough to warrant consideration for future carbon budgets and climate models. But the high spatial variability means that accurately representing such fluxes would require conducting similar studies across other regions. Walsh says that understanding how weathering processes are affected by climate change may also be important for assessing concerns about future water quality. (E. V. Walsh et al., *Sci. Adv*. **10**, eadq4893, 2024.)

**Laura Fattaruso** PT

# With no end in sight for the war in Ukraine, CERN ceases cooperation with Russia

A nuclear-physics laboratory is the exception and the focus of both hope and controversy.

CERN has ended collaborations with Russian institutes as of 30 November, when a five-year cooperation agreement expired. The CERN Council—a body made up of government representatives from the particle-physics laboratory's member states—decided in December 2023 not to renew the agreement "in light of the ongoing military invasion of Ukraine by the Russian Federation."

The decision follows earlier measures by CERN: On 8 March 2022, two weeks after the 24 February invasion, CERN suspended Russia's status as an observer. In spring 2023, the CERN experimental teams decided not to include the names of Russian institutes in author lists on publications. And collaborations with Belarus were discontinued at the end of June 2024.

CERN's actions are on a par with those of many scientific institutions across Europe and beyond. Some facilities and individual scientists took a harder line earlier, while others continue to work with colleagues affiliated with Russian institutes. Even aside from restrictive measures, collaborations have withered because of complications in moving money, goods, and people since the invasion and ensuing sanctions. (See Physics Today, June 2022, page 22.)

The council's decision affects people, funding, and research. Opinions about the decision among CERN researchers are mixed, highlighting a tension between a desire to criticize Russia for its actions and a hope that science can serve as a bridge to maintain peaceful communication.

Before Russia invaded Ukraine, about 1000 scientists from a few dozen institutes in Russia worked at CERN. Several hundred of those scientists were affiliated with the Joint Institute for Nuclear Research (JINR) in Dubna, about 130 km north of Moscow. An international organization whose 16 member countries are mostly in eastern Europe and Asia, JINR has a separate cooperation agreement with CERN that remains active.

## On the ground

The council's decision hits some Russian scientists and technicians hard. Many have been based at CERN for years, and without a CERN connection, they will lose their visas and have to leave. For the past two and a half years, ever since Russia invaded Ukraine, colleagues at the laboratory and on the experiments have been helping them find new affiliations.

Over that time, says Joachim Mnich, CERN's director for research and computing, "we identified a few dozen scientists who could not return to Russia or didn't want to for personal reasons. In a few cases it would have been a personal tragedy." Some scientists had signed statements against the Russian government, making returning dangerous for them. The laboratory also prioritized scientists who were essential to operating the accelerator or experiments. About 90 have found affiliations in Europe or


SAMUEL JOSEPH HERTZOG, © 2021 CERN

**THE LARGE HADRON COLLIDER** and its experiments at CERN involve the work of scientists from 24 member countries and beyond. As of this month, individuals at Russian-affiliated institutes can no longer participate.

the US and can stay at CERN, according to a lab press officer, and a much smaller number are still looking for jobs outside Russia.

Scientists who return to Russian-affiliated institutes will be treated like anyone else who leaves a CERN collaboration "for whatever reason," says Mnich. They will be included on publications for a year. The roughly 100 PhD students who had to leave will retain access to CERN data for a year to finish their theses. If they need longer, Mnich says, "we will see whether we can extend. We are trying, in particular, to mitigate the damage for young people."

With ties formally cut, CERN and partners will have to cover for Russia's planned contributions. That includes 2.3 million Swiss francs ($2.7 million) a year for maintaining and operating experiments plus 50 million Swiss francs—spread over time—for in-kind contributions to upgrade the accelerator and experiments, according to Mnich.

Scientists from Russian institutes have contributed to data analysis and to the design, construction, and operation of the ATLAS detector at CERN, says spokesperson-elect Stéphane Willocq of the University of Massachusetts Amherst. ATLAS scientists have been working on transferring tasks and know-how to other institutions within the collaboration, he adds.

Researchers at other CERN experiments and at the Large Hadron Collider accelerator are similarly working to spread knowledge and mitigate the impact of imminent departures, says Mnich. "My personal feeling is that in most cases, we have achieved this," he says. "There may be exceptions where science will suffer."

## Hot and cold

Scientists at CERN and beyond who support the break in relations tend to see it as a no-brainer, given that Russian science institutes have expressed support for the war. Many of them say that CERN should also cease collaborations with JINR because of its close ties to Russia.

Tetiana Hryn'ova is a member of the ATLAS experiment who hails from Ukraine and is employed by the CNRS. The discussion at CERN, she says, "was focused on whether to continue to cooperate with Russian institutes and JINR while they support the war and work on military and dual-use projects." She notes that JINR collaborates with at least 78 Russian institutes that, based on the OpenSanctions database, are sanctioned by the US, the European Union, Japan, and other countries "for acquiring and attempting to acquire items in support of the Russian military." And nearly 80% of JINR's budget and 93% of its employees are from Russia, according to public records. Vladimir Putin visited JINR on 13 June for a meeting on defense and security in Russia, Hryn'ova says, further underscoring the institute's connections to the Russian government.

"If Putin is talking with JINR and its scientists about how they can contribute to the war effort, I believe JINR should be boycotted," says Gerson Sher, a retired NSF programs officer for Eastern Europe who devoted a half century to promoting US–Soviet and, later, US–Former Soviet Union scientific cooperations in basic research.

Although ongoing, CERN's collaboration with JINR is constrained: Existing efforts can continue; but no new joint projects can be launched, and only scientists already involved with CERN can participate. That is particularly problematic for young scientists and PhD students, says Sasha Glazov, a particle physicist at DESY, the German Electron Synchrotron, in Hamburg.

Originally from Dubna, Glazov says that attending a joint CERN–JINR summer school as a student was inspiring for him. Absent such opportunities, young physicists will turn their sights elsewhere. Local experiments are possible in Russia, says Glazov, "but they are less interesting than at the Large Hadron Collider at CERN." Young physicists may look to China or other countries in Asia that take a softer stance toward the war in Ukraine. Or, he says, they may put their skills to work in ways that support Russian military aims.

Scientists who are discouraged by the cessation of relations with Russia see continued collaboration with JINR as keeping the door open for the future. "It's positive to maintain this channel of communication and collaboration," says Hannes Jung, an emeritus particle physicist at DESY and a member of the CMS experiment at the Large Hadron Collider.

In spring 2022, after the invasion of Ukraine, Jung and other scientists created the Science4Peace Forum to promote science as a driver for peace. He and other critics see the decision to cut ties as flying in the face of CERN's historic role of fostering collaborations across borders.

But Sher says that relationships will resume when the war ends. "I believe passionately in cooperation as a tool of diplomacy and a benefit for science," he says. But the war in Ukraine is not the Cold War. "It's a hot war."

**Toni Feder**

**MORE THAN A MILLION BRASS SHELL CASINGS** from the World War II stash of the Soviet Navy were melted and machined into parts for a calorimeter for the CMS experiment at CERN. They were delivered in 2002 and 2003. As of this month, collaborations between CERN and Russian institutes, which were first formalized in 1967, are over. (Courtesy of peterginter.com.)

# UK coalition gears up to demonstrate commercial viability of fusion energy

The government is aiming to build a prototype plant in the next two decades.

The UK plans to build a prototype fusion plant by the early 2040s that can put electricity on the grid and demonstrates that fusion energy is commercially viable. Researchers with the Spherical Tokamak for Energy Production (STEP) hope to produce about 100 MW of net electricity with the new plant, sustain the amount of tritium needed to spur fusion reactions, and show that the plant can be maintained over time, says Paul Methven, CEO of UK Industrial Fusion Solutions, a private entity established by the UK government that is responsible for the delivery of STEP. The goals are "massively ambitious," he says, "but just about doable."

The idea that fusion energy is "getting closer to commercialization started with the UK going out for a site and creating the STEP program," says Stephen Dean, the president of Fusion Power Associates, a research and advocacy organization that disseminates fusion-development information. In doing so, he says, the UK took the lead on the spherical tokamak.

Achieving the STEP milestones will position the UK to be at the forefront of fusion energy, says Methven. It will also create thousands of jobs, he says. UK Industrial Fusion Solutions will work with the UK Atomic Energy Authority, private companies, and other partners to deliver the plant.

The STEP team released the initial concept design in August. Magnetic fields within the spherical tokamak will confine a plasma of deuterium and tritium and heat it to more than 100 million degrees Celsius to spur nuclear reactions and produce energy. The tokamak will measure about 10 meters in diameter. In comparison, ITER, the international fusion-reaction prototype under construction in France, has a diameter of 19.4 meters (see PHYSICS TODAY, August 2023, page 18). STEP's small size should help keep down construction costs, but it also leads to increased stress on the materials, including the confinement wall, says Christopher Holland, a research scientist at the Center for Energy Research at the University of California, San Diego.

So far, the UK government has invested £300 million (about $390 million) into STEP, but it's too early to know how large the tab will grow. The facility will be located at the West Burton site of a former coal station in Nottinghamshire. (The last UK coal plant, at Ratcliffe-on-Soar, closed in late September.) Ash cleanup and other preparations are underway, says Methven. Construction is to begin around 2030.

## Navigating the roadblocks

"The first challenge is to get to the burning plasma," says Steven Cowley, director of the Princeton Plasma Physics Laboratory. That's when energy released in fusion reactions heats the plasma faster than it cools, and the reactions become self-sustaining. Fusion from magnetic confinement has never produced more energy than is inputted.

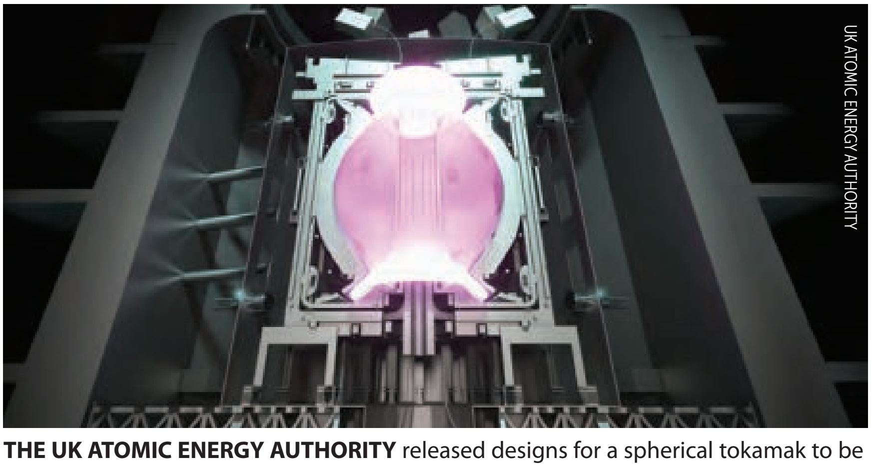
Neutrons released during fusion reactions damage the tokamak walls. Methods are still needed to fix damage to the confinement walls without being exposed to the extremely radioactive environment, says Cowley. Robots may be used to conduct remote maintenance.

Tritium production presents another hurdle for researchers. Nuclear fusion fuel typically consists of a 50-50 blend of deuterium and tritium. The latter exists naturally only in trace amounts and has a half-life of about 12 years, so breeding and stockpiling is difficult, says Holland.

STEP builds on advances in fusion around the world: Lawrence Livermore National Laboratory achieved ignition at the National Ignition Facility through a different approach to fusion (see "National Ignition Facility surpasses long-awaited fusion milestone," PHYSICS TODAY online, 13 December 2022). MIT developed low-cost high-temperature superconducting magnets in 2021 that reached a magnetic field of 20 tesla, high enough to be used in a fusion reactor. A few months later, researchers at the Experimental Advanced Superconducting Tokamak in China obtained a steady-state plasma at 70 million °C that lasted more than 17 minutes; the previous record of 6.5 minutes at the same

UK ATOMIC ENERGY AUTHORITY

**PAUL METHVEN**, the CEO of UK Industrial Fusion Solutions, leads the development of the UK's first prototype fusion power plant.



UK ATOMIC ENERGY AUTHORITY

**THE UK ATOMIC ENERGY AUTHORITY** released designs for a spherical tokamak to be completed by the early 2040s.

temperature was achieved in 2003 by France's Tore Supra tokamak.

Entities around the world are working on putting fusion energy on the grid. In the private sector, for example, Commonwealth Fusion Systems in Massachusetts plans to focus on energy production in the 2030s with a high-field tokamak. Helical Fusion in Japan is constructing a stellarator—another magnetic confinement approach—to produce energy in about a decade. Others are also making progress (see "Investments in privately funded fusion ventures grow," Physics Today online, 13 October 2020). In the public sector, EUROfusion, a consortium of European fusion research institutes, plans to demonstrate net-energy production in the coming decades.

"There are several horses in the race, but no one is sure who is in the lead or even when they will finish," says Dennis Whyte, a fusion researcher at MIT. He says that STEP's purpose "is not just to have a successful device on the grid but to build a fusion industry and the platform for the supply chain. STEP researchers are making a commitment to take on all the challenges."

**Hannah H. Means**

# UCSD institute will tackle fusion engineering problems

## Researchers collaborate with colleagues at national labs, companies, and universities in efforts to make nuclear fusion a viable source of clean energy.

At a fusion technology workshop at the University of California, San Diego (UCSD), in September 2023, participants asked themselves, "Is fusion a big enough program here that it should have its own institute?" recalls Javier Garay, the associate dean for research at the university's engineering school. "We decided yes."

Barely a year later, on 8 October, UCSD launched the Fusion Engineering Institute to focus on gaps in technology for fusion reactors, strengthen relationships with other universities and labs, and increase the number of fusion researchers. The institute, for which Garay is the founding director, is funded by the Department of Energy, UCSD's engineering school, and private industry; institute officials declined to provide numbers.

The institute's researchers hope to spur progress toward the long-elusive goal of harnessing nuclear fusion to produce clean energy. The two main approaches are magnetic confinement, achieved with tokamaks and stellarators, and inertial confinement, which uses lasers. Both methods heat a plasma to kick-start the fusion of hydrogen nuclei.

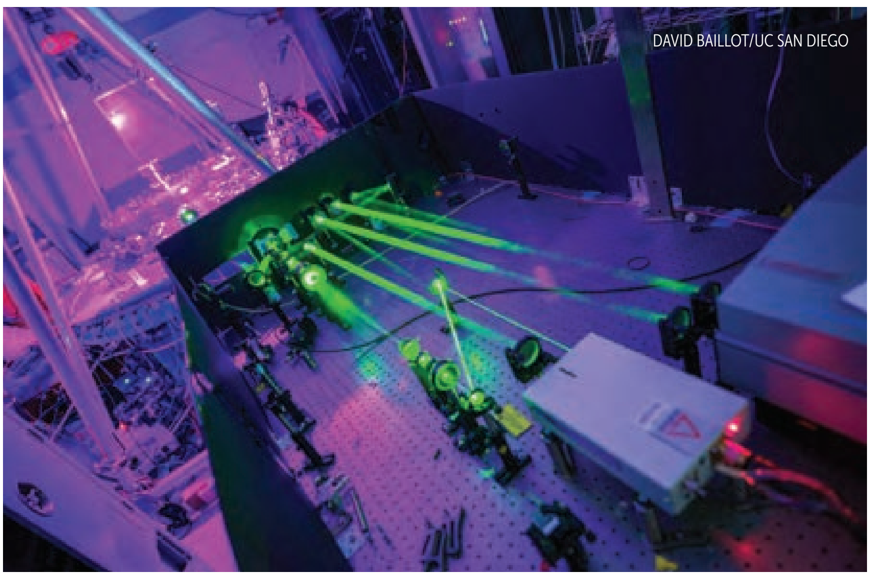
To be commercially viable, the process has to produce more energy than is used to create it and then steadily produce electricity. A short burst of net energy was first achieved in 2022 by the National Ignition Facility at Lawrence Livermore National Laboratory (see "National Ignition Facility surpasses long-awaited fusion milestone," Physics Today online, 13 December 2022).

Developing materials that can withstand heat and damage from nuclear reactions and designing methods to remotely maintain fusion reactors are high priorities at the new institute. Researchers will focus on engineering issues in materials science, laser technologies, robotics, and diagnostics to help facilitate the conversion of fusion energy into usable electricity. Already, says Garay, UCSD students work with scientists at the nearby DIII-D National Fusion Facility, which is operated by General Atomics for DOE and houses a tokamak.

Researchers will collaborate with the San Diego Supercomputer Center to integrate AI into research efforts. For example, AI will improve laser target tracking and placement for inertial confinement schemes, says Farhat Beg, codirector of the new institute.

As the institute matures, Garay says, he hopes to double the number of PhD students working on fusion topics from the current 30–40. UCSD undergraduates and researchers from other universities will also have opportunities to work with the institute. Researchers from those universities, national labs, and private industries will help inform the UCSD fusion curriculum, present guest lectures, and direct joint research projects. In addition, UCSD is looking to hire two fusion engineering faculty members.

**Hannah H. Means**




**LASER INTERFEROMETRY** is used to probe the density and other properties of deuterium plasmas in Farhat Beg's lab at the University of California, San Diego. The lab now works with the university's Fusion Engineering Institute.

# Q&A: Hyejin Youn applies statistical physics to human behavior

The physicist examines crime, transportation, innovation, and more in the burgeoning field of computational social science.


MINSEO JEON

Hyejin Youn

How does a physicist end up on the faculty at a business school? Hyejin Youn says that for her, "one thing led to another." While a graduate student working on complex systems in 2008, Youn and two colleagues published a paper in *Physical Review Letters* that looked at traffic. Using data and simulations, they found that the aggregate of individual choices about routes does not optimize traffic for all drivers in the area and that drivers end up wasting a "considerable amount" of time on the road. "Counterintuitively," they wrote, "simply blocking certain streets can partially improve the traffic conditions."

Their results were picked up by *The Economist*, and soon Youn was being invited to speak at workshops, conferences, and other events for business schools and economics departments. It turns out that the mathematical and computational models she used for energy optimization in physics map directly to those in economics. "These audiences asked questions I was never asked by physicists, things I had never thought about," she says. "They wanted to know about humans. I became very curious about social systems."

Youn earned her undergraduate, master's, and doctoral degrees at the Korea Advanced Institute of Science and Technology in Daejeon. She spent a few years as a postdoc at the Santa Fe Institute and as a senior research fellow at Oxford University before joining the faculty of the Kellogg School of Management at Northwestern University in 2017. In September, she accepted a position in South Korea, at Seoul National University, where she is a professor of strategy and international management in the business school.

In the past, Youn says, social science was based on observation in the field or small lab experiments, introspection, and judgment about how people behave. But with the developments of massive data collection, computational power, and AI, physicists and other STEM scientists are entering the emerging field of computational social science.

**PT:** Why did you go into physics?

**YOUN:** I felt that physics explains the world. And if a theory doesn't work with empirical data, we are ready to leave the theory behind. I was fascinated by this intellectual framework that tries to be as logical as possible but at the same time doesn't lose touch with the real world.

My parents didn't like the idea of my studying physics—they thought I wouldn't be able to get a good-paying job. I told them that physicists can go anywhere. I pointed to the quants on Wall Street. I didn't care about the quants. That was a device to persuade my parents.

**PT:** How did you segue from statistical physics to computational social science?

**YOUN:** I didn't intend to go into social sciences. I was just following my curiosity. As a graduate fellow and later a postdoc at the Santa Fe Institute, I learned about work that other physicists were doing. They included my PhD adviser, Hawoong Jeong, who worked on complex systems; my postdoctoral adviser, Geoffrey West, who worked on scaling frameworks for physics, biology, and urban systems; Albert Barabási, who worked on network science; and Doyne Farmer, who tried to understand economics with an agent-based model. I was inspired.

As a statistical physicist, I studied Ising models. I looked at spins, at how a liquid becomes ice or a gas, how these phase transitions happen. I thought everything could be explained by the Ising model—even politics, because the voting system can be explained by a spin-glass model. So, when I entered social science, my mindset was that I could explain every social system with physics. Then I realized that is absolutely not true. Humans are more complicated than spin systems. They can't be understood in terms of pure physics. I went down a rabbit hole about human systems.

**PT:** Describe some of your research.

**YOUN:** I've studied how cities scale their socioeconomic properties with population size. When a city doubles in population, what is the expected change in the number of crimes per capita? What about creativity, as measured by the number of patents? And productivity in terms of GDP? Remarkably, these factors scale superlinearly with population size, all sharing a similar power-law exponent of 1.15—meaning creativity and crime increase at a higher rate than the population expands.

Some inessential properties disappear when we aggregate the system, and some essential properties survive. The method, known as coarse graining or renormalization, highlights that while humans are individually diverse and adaptable, cities collectively follow underlying principles that govern their behavior.

**PT:** Where do the data come from?

**YOUN:** For productivity, we look at GDP, income, and patents. For creativity, we look at patents. We search for hundreds of thousands of key words—things like autonomous vehicle and Google glass and technical codes for wireless communications. We analyze millions of patents using statistics. It's all automated.

**PT:** What are you working on now?

**YOUN:** I started to work with economists, sociologists, and biologists who were interested in technology and to look at technology in terms of network science. I was interested in how technology, or the creation of new ideas, can be understood in terms of combinations of existing ideas. We apply techniques that were developed in physics to identify clusters and examine how they evolve. We find that there have been periods of technologies merging and splitting over time. I want to understand why technological innovation happens, whether there is any phase transition in the innovation process, and what the fundamental unit of innovation is.

**PT:** What's a research topic that you are particularly excited about?

**YOUN:** Economists often think that innovation slowed down in the US after 1870. Before that, we had the technologies of the steam engine, the train, the toilet, the telephone. The common understanding was that there was little new technological invention after the late 19th century.

As a physicist, I was curious: Is it really true that there was a phase transition in innovation around 1870? I looked at how often new words appear in patent filings and found that it's true: The introduction of new key words slowed down around 1870. But, if invention is understood in terms of combining technologies, innovation appears to be invariant. The apparent phase transition disappears.

My model also explains why multiple inventors often arrive at the same discovery at the same time. In the model, ideas are like particles in a network. It doesn't matter if it was Isaac Newton or Gottfried Leibniz who came up with calculus. Or Charles Darwin or Alfred Russel Wallace who developed the theory of evolution by natural selection. Connections are made stochastically and probabilistically, with human inventors acting as vehicles for these processes.

If the invention and the creation of new ideas is explained by this simple model, it seems like everything becomes physics. Then the question arises, Where is the human agency?

How do I reconcile the nonhuman model with the human model? I am still struggling with this.

**PT:** How is it different being in a business department than in a physics department?

**YOUN:** Physicists tend to think in a context-free way; businesspeople look at context. If you are trained as an innovation scholar, you understand the history of telecommunications and semiconductors, and you want to know the nitty-gritty details—about individuals, firms, strategies, and markets. As a physicist, I was trained to seek universal and invariant theories, and such details are often irrelevant to me. I just want to understand if a structure emerges and whether the structure can be modeled with a simple rule. My strengths are complementary to the strengths of my colleagues.

One of my roles is to integrate interdisciplinarity into the business school. We want to bring more STEM people into business and train business school students to be more capable of dealing with data and mathematics.

**PT:** Is there anything else you'd like to mention?

**YOUN:** My lifetime goal is to explore whether certain human behaviors fall outside the laws of physics. Are questions such as why wars happen or why some people have more opportunities than others too complex for physics to answer? I don't know, but it's worth exploring. I think physicists can contribute to answering those questions.

**Toni Feder**

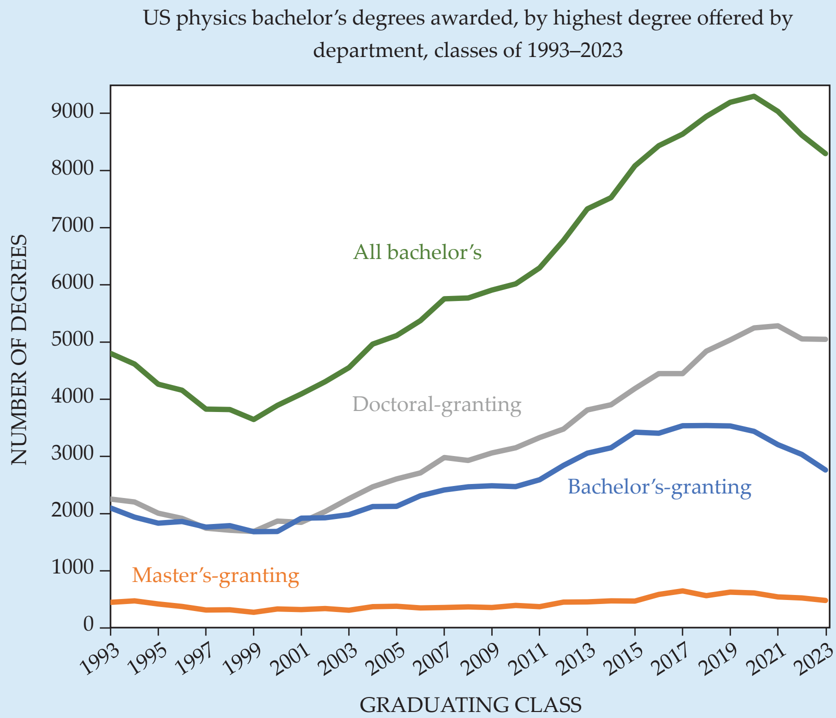




# Physics bachelor's degrees in the US trend downward

For the third year in a row, the number of physics bachelor's degrees awarded by US institutions has declined. In the 2022–23 academic year, 8295 students received their degree, a drop of 11% from the all-time high of 9296 in 2020, according to a report released in September by the statistics team at the American Institute of Physics (AIP; publisher of Physics Today).

Physics departments whose highest degree offered was a bachelor's or master's experienced the steepest declines, of more than 20%. Departments that offered a PhD awarded about 4% fewer bachelor's degrees in 2023 than in 2020.




The number of US bachelor's degrees awarded in the broader physical sciences declined about 10% from 2018 to 2022, according to data from the National Center for Education Statistics. About 30% of those degrees were in physics. The reason for the decrease is not clear, says Patrick Mulvey, research manager for AIP's statistics group. Additional data on the recent decline in physics bachelor's degrees awarded by department type and on the number of physics degrees awarded in the 2022–23 academic year by institution can be found in the report at https://ww2.aip.org/statistics/roster-of-physics-department-with-enrollment-and-degree-data-2023.

**Tonya Gary**

## *FYI* SCIENCE POLICY BRIEFS

### AGU offers ethics framework for geoengineering research

The American Geophysical Union released a framework on 22 October proposing ethical principles for geoengineering research. Also known as climate intervention, geoengineering involves large-scale attempts to alter the climate system with the purpose of countering climate change. The unintended consequences of large-scale deployment are largely unknown, and any research into it must be grounded in sound ethical principles, the report states. "The fundamental issue with this field is public trust, and so we offered some ways in which we think public trust would be enhanced," said Daniele Visioni, one of the framework's coauthors.

The key principles emphasize responsible assessment of physical, environmental, and social consequences of the research and propose that potentially impacted groups be included in the discussion of research purposes and design. Visioni noted that several proposed small-scale outdoor experiments, such as the Harvard SCoPEx program and the University of Washington CAARE project, have been blocked by local opposition despite meeting the current legal requirements for environmental reviews and the like. He argued that the framework provides a path for projects to avoid such obstacles by proactively engaging stakeholders earlier in the process.

Other principles include making funding and research processes transparent, requiring reviews and approvals from an independent body before research begins, and establishing mechanisms for accountability to public institutions and representatives. Eventually, Visioni hopes the principles are used not just to block unethical research methods but also to foster more projects by providing researchers with a better understanding of responsible practices, he said. —cz

### White House releases national plan for spectrum R&D

The White House Office of Science and Technology Policy published its National Spectrum Research and Development Plan on 9 October. The strategy outlines priorities for fundamental and applied spectrum research. It also lays out strategies for the public and private sector to work together to maximize the usefulness of the US's finite RF spectrum, which is used in a wide range of wireless communications.

Most of the priorities support the goal of dynamic spectrum sharing—an emerging technology that would allow users in the same geographic area to use the same electromagnetic frequency without interfering with each other. Dynamic spectrum sharing was identified as a critical area of development in the National Spectrum Strategy published in November 2023.

The strategy also identifies several interagency "spectrum R&D accelerators," including data collection, spectrum-sharing simulation environments, and test beds. The report does not, however, share details on where these accelerators should be based nor how they would be funded.

While the Biden administration has expressed a desire to more effectively manage finite spectrum bands, Congress has yet to reinstate the Federal Communications Commission's spectrum auction authority, which lapsed in March 2023. Earlier this year, Senator Maria Cantwell (D-WA), chair of the Senate Commerce, Science, and Transportation Committee, introduced a bill that would use spectrum auction funds to finance CHIPS and Science Act programs. The bill has not made any progress since April. —LM

## DOE and big tech throw support behind nuclear technology

The Department of Energy opened applications in October for up to $900 million in funding for small modular reactors (SMRs). Most of the funds, up to $800 million, are for two Generation III+ SMR projects that are close to a final design, with deployment scheduled for the early 2030s. The other $100 million will provide support for site selection and preparation, supply chain development, design, and licensing. SMR deployment in the US faced a major setback last year when the company NuScale Power terminated plans to build an SMR because of concerns over the reactor's commercial viability. Amid those headwinds, some lawmakers are seeking to further support advanced reactor development, with the House Appropriations Committee pushing to provide DOE with additional funds to support deployment of at least one SMR.

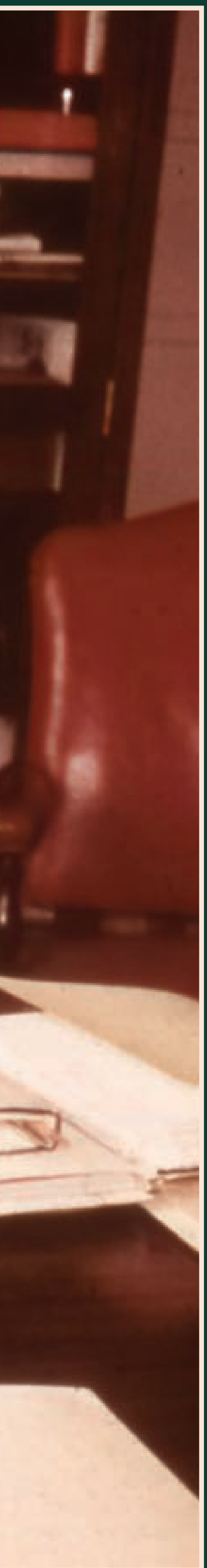
DOE's funding notice came as tech giants Amazon and Google both announced agreements to support new SMR projects. Amazon will back the development of four advanced SMRs in Washington and an SMR in Virginia. The company has also invested $500 million in X-energy that the nuclear startup said will fund the completion of the reactor design that will be used for the Washington projects. X-energy's Xe-100 design has received significant funding through DOE's Advanced Reactor Demonstration Program. Google has agreed to purchase electricity from multiple SMRs to power its data centers and offices. The company intends to bring the first of those SMRs online by 2030. —CZ PT

*FYI* (https://aip.org/fyi), the science policy news service of the American Institute of Physics, focuses on the intersection of policy and the physical sciences.

AIP | FYI



AMERICAN ASSOCIATION OF PHYSICS TEACHERS/COURTESY OF THE AIP EMILIO SEGRÈ VISUAL ARCHIVES



**Chon-Fai Kam**, a postdoctoral researcher of physics at the University at Buffalo in New York, focuses on quantum information and quantum computing. **Cheng-Ning Zhang** is president of the Nanjing University North American Alumni Association. **Da Hsuan Feng** is an honorary professor of physics at the School of Physics and Optoelectronic Engineering at Hainan University, China.



# Chien-Shiung Wu's trailblazing experiments in particle physics

**Chon-Fai Kam, Cheng-Ning Zhang, and Da Hsuan Feng**

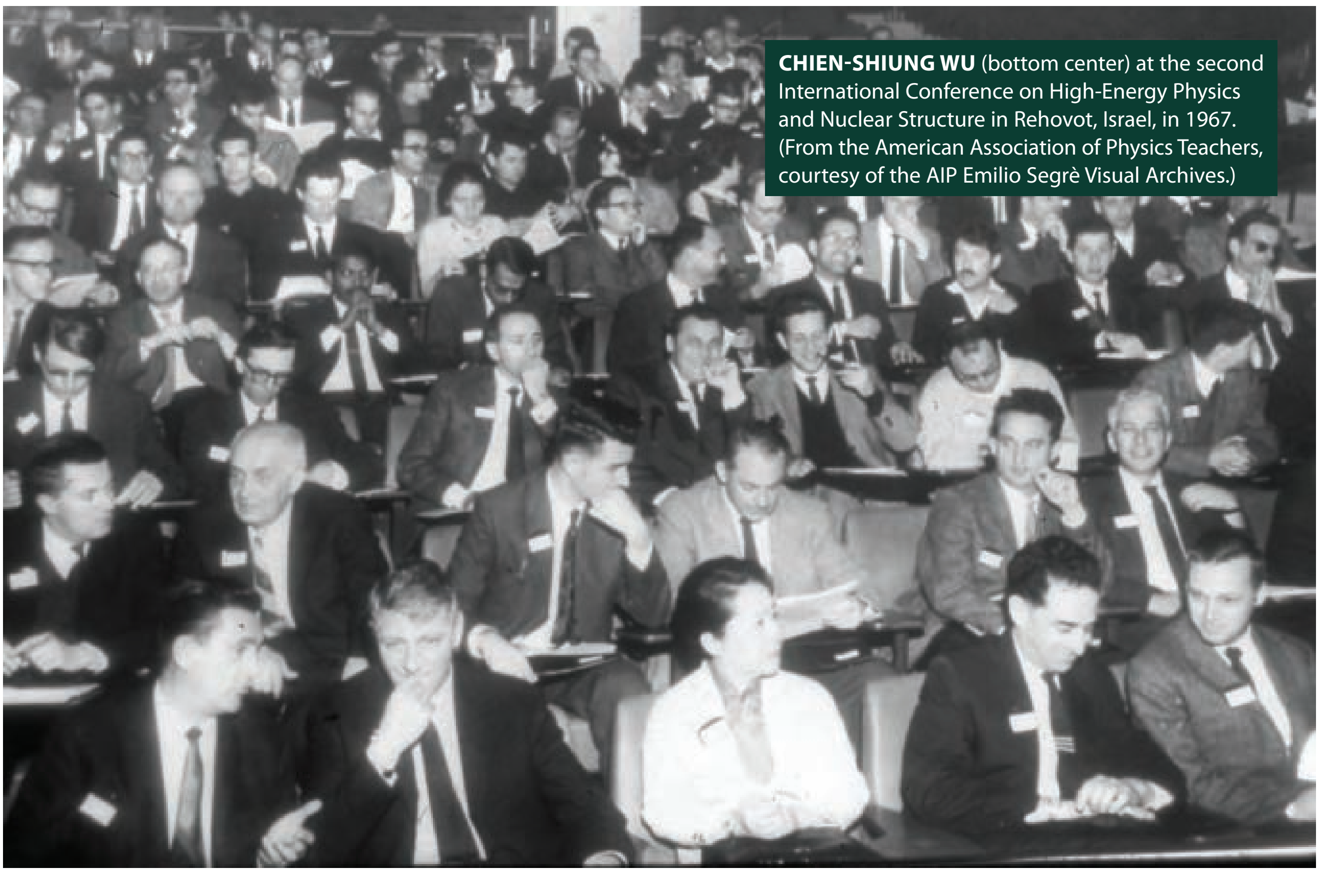
**The Chinese American physicist led groundbreaking experiments that demonstrated parity violation and photon entanglement. Many in the physics community say Wu deserved more accolades in her lifetime.**

The US Postal Service in 2021 released a commemorative stamp honoring a woman from China named Chien-Shiung Wu, a nuclear physicist who played a crucial role in the Manhattan Project. That brought her into the exclusive ranks of physicists, including Albert Einstein, Enrico Fermi, and Richard Feynman, who have been celebrated by the USPS. It also brought renewed attention to the ways that Wu's career and work have not always received the recognition and acclaim they deserve.

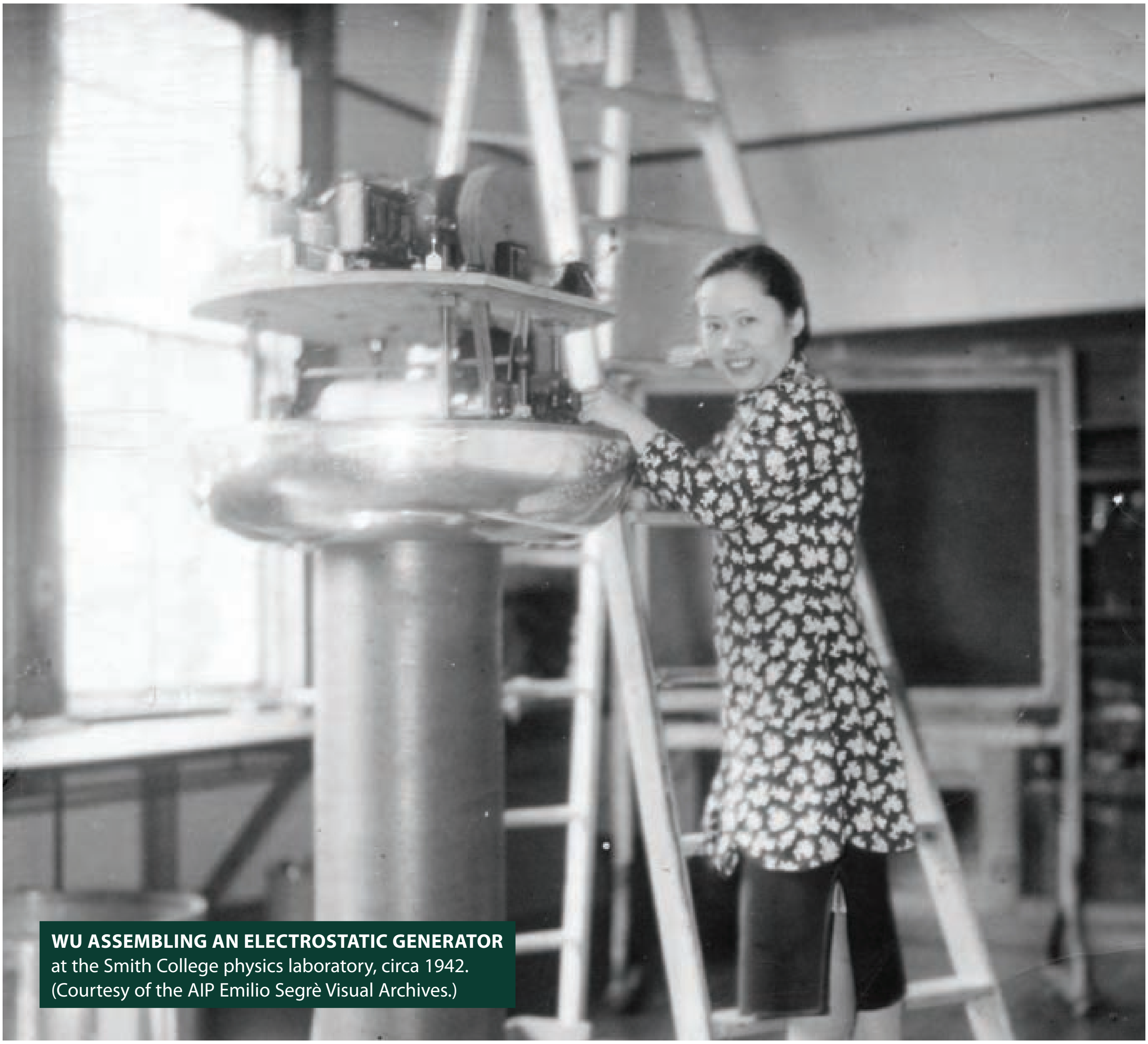
For the Manhattan Project, Wu worked on the process of separating isotopes of uranium-235 and uranium-238 by gaseous diffusion; the process was later scaled up at the K-25 plant in Oak Ridge, Tennessee. She also refined Geiger counters to better measure nuclear radiation levels. She is thought to be the sole Chinese individual involved in the Manhattan Project.[1,2]

Wu's expertise in neutron absorption cross sections made a lasting impression on J. Robert Oppenheimer, the head of the Manhattan Project; he had been a member of her doctoral committee in 1940 at the University of California, Berkeley. Oppenheimer affectionately referred to her as *Jiejie*, meaning elder sister in Chinese.[3]

In celebration of Wu's legacy, the USPS released her commemorative stamp on 11 February 2021, the International Day of Women and Girls in Science. Wu worked more than 40 years in the male-dominated physics field and became adept at testing fundamental physics theories through pre-



**CHIEN-SHIUNG WU** (bottom center) at the second International Conference on High-Energy Physics and Nuclear Structure in Rehovot, Israel, in 1967. (From the American Association of Physics Teachers, courtesy of the AIP Emilio Segrè Visual Archives.)



**WU ASSEMBLING AN ELECTROSTATIC GENERATOR** at the Smith College physics laboratory, circa 1942. (Courtesy of the AIP Emilio Segrè Visual Archives.)

cise experiments.[4] Her highly classified work significantly advanced the process of splitting and harnessing the power of uranium atoms and ultimately contributed to the creation of the world's first atomic bomb.[5]

But that is not the end of the story; it's not even the beginning.

## Broken mirror

Wu gained international recognition for her experiment confirming the theory that earned the 1957 Nobel Prize in Physics for its authors, Tsung-Dao Lee of Columbia University and Chen Ning Yang of the Institute for Advanced Study in Princeton, New Jersey.[6] The year before, the two young Chinese theoretical physicists proposed the idea that parity symmetry in weak interactions might not be obeyed in the natural world. Wu, with her outstanding influence and extraordinary talent in the fields of experimental physics and beta decay, led a team of scientists from Columbia and the National Bureau of Standards in Washington, DC, to test the groundbreaking prediction by Lee and Yang.

The experiment, which Wu conducted in late 1956 and early 1957, measured whether an equal number of beta particles are emitted by radioactive cobalt-60 nuclei in the direction of their spin and in the opposite direction. She found that far more beta particles flew off in the direction opposite the spin of the nuclei, thus shaking the conventional understanding of symmetry in the physical world (see the illustration on page 34). The experiment revealed that a fundamental particle and its mirror image are not always identical.[7] The universe, at times, can distinguish between left and right.

The experimental verification by Wu and her collaborators of the theoretical proposal of parity violation by Lee and Yang resulted in the Nobel Prize being awarded to the two theorists. But the accolade eluded Wu. This was a case in which the typical pattern of favoring experimentalists for the prize was flipped.

Less well known until recently are Wu's groundbreaking contributions to the foundations of quantum mechanics.

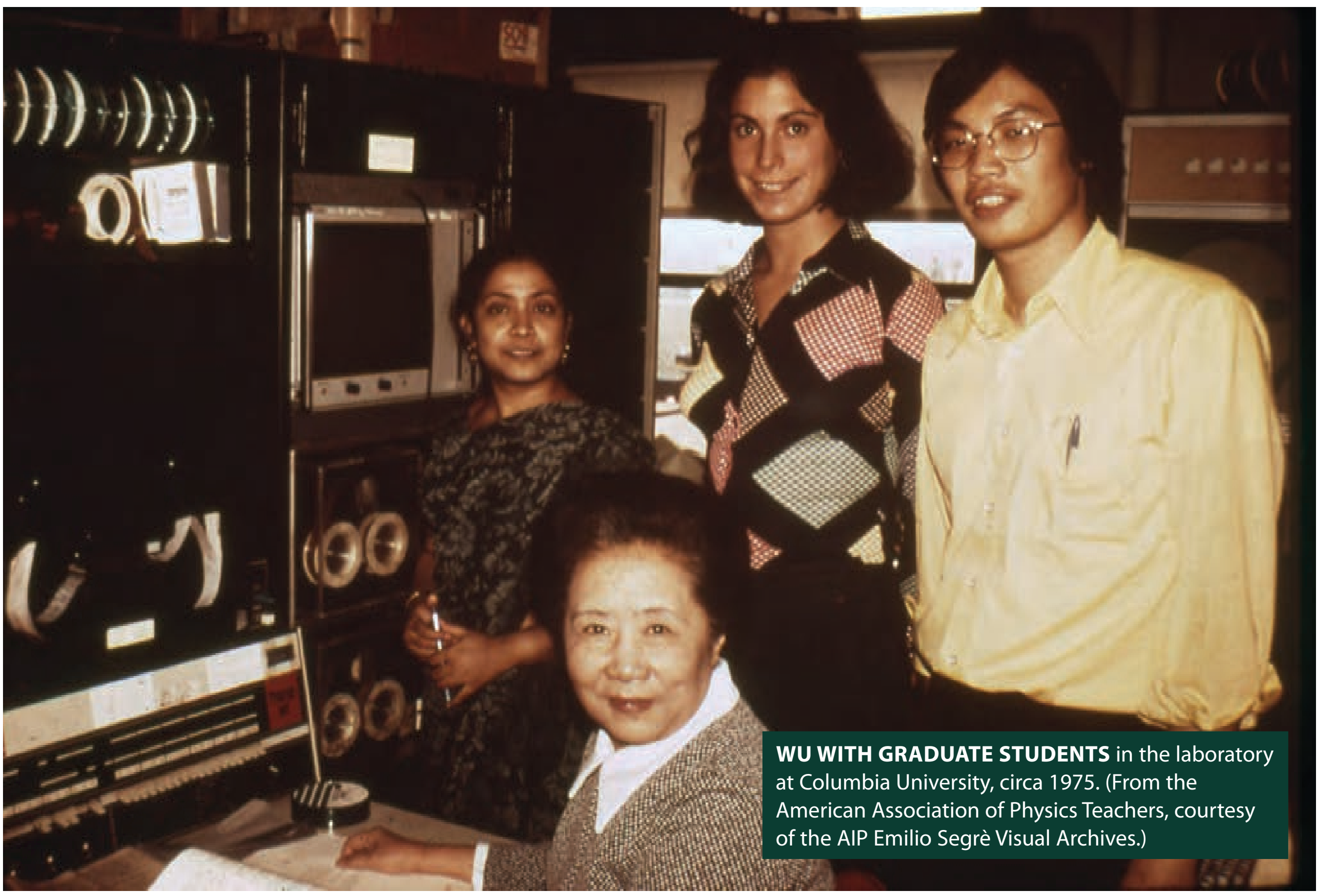
At a September 2022 gathering outside Washington, DC, to commemorate Wu and the 110th anniversary of her birth,[8] Lars Brink, who was a member of the Nobel Committee for Physics for several years between 2001 and 2013 and served as its chair in 2013, said he believed that Wu's parity violation experiment was "Nobel class." He reported that Yang had once told him at a dinner that Wu should have been a co-recipient of the 1957 prize.

Going further, Brink said that the parity violation experiment was just one of what he called Wu's "two gems in a box of pearls." The second gem, though lesser known in the scientific community, revolves around an inaugural experimental validation of photon entanglement that Wu conducted in 1949.[9] Despite the introduction of the idea of quantum entanglement in the 1930s, the research community's focus on particle physics meant that only intermittent attention was paid to the topic until later in the 20th century. In recent decades, quantum entanglement has emerged as the cornerstone of the burgeoning fields of quantum information, quantum computation, and quantum technology.

## Early entanglement

The concept of quantum entanglement was brought to light in May 1935 by Einstein, Boris Podolsky, and Nathan Rosen, who were all at the Institute for Advanced Study at the time. Their groundbreaking paper, "Can quantum-mechanical description of physical reality be considered complete?," delved into the novel idea.[10] In that influential work, later dubbed the EPR paper, the trio investigated a pair of particles deliberately prepared with a separation far exceeding the range of their mutual interaction and with a total momentum of zero. Their exploration revealed a dilemma: There is an inherent inconsistency among locality, separability, and completeness when describing physical systems with wavefunctions.

The EPR paper asserts that by measuring the position of the first particle without disturbing the second, it should be possible to predict with certainty the value of the second particle's position because of the perfectly correlated positions of the particle pair. On the other hand, by performing a measurement of the first particle's momentum rather than position, it should be possible to predict with certainty the value of the second particle's momentum because of the perfectly anticorrelated momenta of the particle pair. The uncer-



**WU WITH GRADUATE STUDENTS** in the laboratory at Columbia University, circa 1975. (From the American Association of Physics Teachers, courtesy of the AIP Emilio Segrè Visual Archives.)

**IRVING SHAKNOV** (**left**, wearing cap), a graduate student of Chien-Shiung Wu, earned a Bronze Star for valor in World War II. After completing his PhD, he joined the Operations Evaluation Group, a military service agency to the US Navy. He was killed in the Korean War on the night of 14 May 1952, at the age of 30. (Center for Naval Analyses, "Irving Shaknov: A Singular Life," https://www.cna.org/about-us/research/history/irving-shaknov-a-singular-life.) **LARS BRINK (right)**, a theoretical physicist at Chalmers University of Technology in Sweden, served as a member of the Nobel Prize Committee for Physics and was its chair in 2013. He gave a lecture about Chien-Shiung Wu's Nobel-worthy experiments just one month before he died in October 2022. (Alex Ljungdahl © Nobel Outreach AB 2013.)

tainty principle in quantum mechanics, however, prevents the precise attribution of values to both the position and momentum of a single particle.

The EPR dilemma thus forces the conclusion that the quantum mechanical description of physical reality given by wavefunctions is not complete if one insists that the real states of spatially separated objects are independent of each other. The key in the EPR thought experiment is a nonfactorizable wavefunction describing two particles moving away from each other into spatially separated regions and yet always having perfectly correlated positions and anticorrelated momenta. Here, nonfactorizable means that a wavefunction cannot be expressed as a simple product of the wavefunctions of its local constituents. The peculiar property of composite quantum systems, characterized by a nonfactorizable wavefunction, is now recognized as quantum entanglement.

But these are merely philosophical deliberations based on thought experiments. During World War II, physicists' interests were predominantly drawn to the mechanism of nuclear fission. It wasn't until October 1946, 11 years after the EPR paper, that John Wheeler, back at Princeton University after working on the Manhattan Project, outlined an experiment to test proposals about quantum electrodynamics that were made by Paul Dirac in the 1930s.

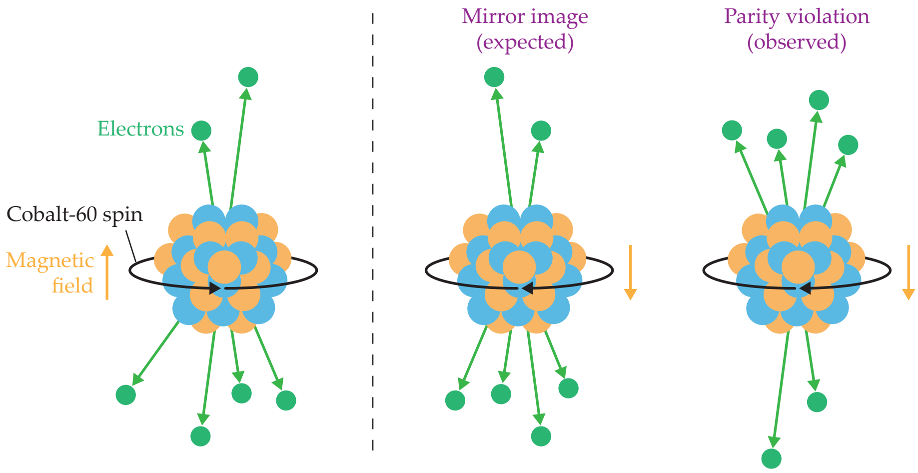
In a paper titled "Polyelectrons," Wheeler considered positronium, an unstable hydrogen-like system composed of an electron and a positron.[11] His proposal involved the detection of an entangled pair of gamma-ray photons produced by the annihilation of the electron and positron. Wheeler highlighted that the gamma-ray photons mainly come from the spin-singlet state—a quantum state characterized by antiparallel spins and a total angular momentum of zero. The conservation of total angular momentum requires that the gamma-ray photons head in opposite directions with orthogonal linear polarizations.

Intriguingly, spatially extended unbound singlet states are exactly what Einstein, Podolsky, and Rosen proposed in their thought experiment to illustrate the incompleteness of quantum theory. To measure the entangled gamma-ray photons experimentally, Wheeler proposed that the photons each undergo Compton scattering by collision with electrons and then be individually detected. Coincident detections would indicate that the two gamma-ray photons were generated from the same annihilation event.

Each scattering event can be described by a scattering angle relative to the photon's initial trajectory and by an azimuthal scattering direction. Although the scattering angles of a gamma-ray pair may be identical, the scattering directions can be parallel or perpendicular. Wheeler proposed studying the asymmetry between the probabilities of the two relative directions for a given scattering angle by calculating the ratio between the difference and the sum of the probabilities. That proposal quickly inspired two independent groups to conduct more detailed computations.

## QED

British physicist Maurice Pryce, with Oxford University, and his PhD student John Clive Ward authored a June 1947 paper




**PARITY VIOLATION** was demonstrated in an experiment led by Chien-Shiung Wu.[7] She and her colleagues measured the emission of beta-decay electrons from cobalt-60 nuclei polarized in an applied magnetic field. If the weak interaction conserved parity, then the direction of electron emission should be independent of the direction of the nuclear spin. The observation of a dependence on the polarization direction of the nuclei confirmed the theory that weak interactions do not obey mirror symmetry.

exploring the angular correlation effects of annihilation radiation.[12] Five months later, three physicists from Brookhaven National Laboratory—Hartland Snyder, renowned for collaborating with Oppenheimer on the initial theoretical analysis of stellar collapse into black holes, Simon Pasternack, and John Hornbostel—published a paper that explored the same topic.[13] Both research groups found that the maximum asymmetry ratio is 2.85 and occurs when the scattering angle is 82°.

Wu seized the historical opportunity. In November 1949, Wu and her graduate student Irving Shaknov conducted photon measurement experiments in the basement of Columbia's Pupin Hall to verify the theoretically predicted angular correlations of entangled gamma-ray photons.

In the underground laboratory, Wu and Shaknov used accelerated deuterium nuclei to bombard copper foil and produced unstable copper-64 nuclei. The isotope undergoes beta decay, generating positrons that annihilate with nearby electrons and produce pairs of gamma photons moving in opposite directions. In the experiment, Wu and Shaknov loaded $^{64}$Cu nuclei into an 8-millimeter-long microcavity and used two sets of gamma-ray detector systems composed of photomultiplier tubes and anthracene crystal scintillators (see the illustration on page 35).

Intriguingly, Wu was not the first to try to verify Wheeler's prediction on angular correlation. Ernst Bleuler and Helmut Bradt at Purdue University had already observed the angular correlation between a pair of gamma-ray photons.[14] As they reported in an April 1948 letter to *Physical Review*, they found an asymmetry ratio of 2.1 ± 0.64 at a scattering angle of 90°, but the large margin of error meant that the experiment provided insufficient evidence to validate or refute the theory. In August 1948, R. C. Hanna, at the Cavendish Laboratory in the UK, concluded from similar experiments that the asymmetry ratios observed are systematically smaller than what theory predicts.[15]

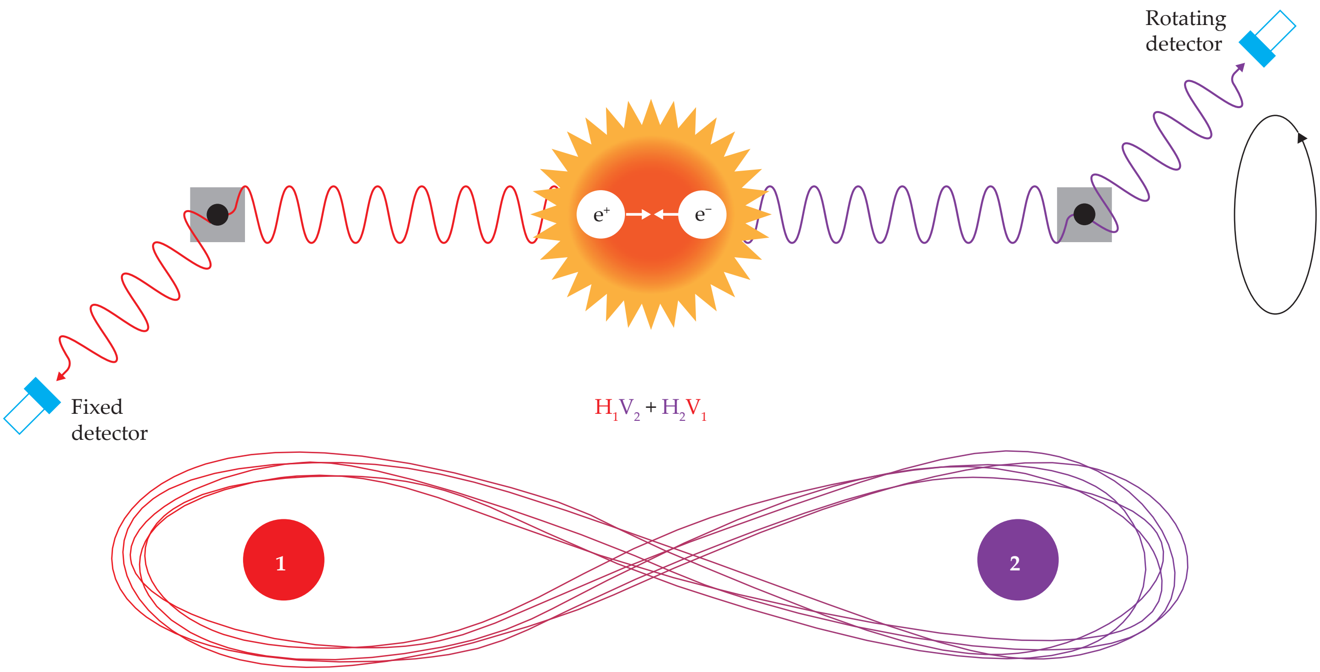
But Wu stood among the foremost experimentalists of her time, known for her ingenious and precise designs. Aiming to eliminate potential experimental errors in her angular correlation measurements, she maintained one detector in a fixed position and oriented the second at four different positions, with relative azimuthal angles of 0°, 90°, 180°, and 270°. Subsequently, the second detector was fixed, and the first one was rotated. The entire measurement process spanned a continuous period of 30 hours.

Finally, on 1 January 1950, Wu and Shaknov published their experimental results as a letter of less than 1000 words.[16] The asymmetry ratio reported by Wu and Shaknov is 2.04 ± 0.08; the theoretical prediction is 2.00. With the satisfactory agreement of their result and the theoretical predictions, the experiment marked the first conclusive verification of photon entanglement, nearly 15 years after the publication of the EPR paper.

## Bell inequalities

Building on the EPR paradox, John Bell published a landmark 1964 paper in which he introduced the famous eponymous Bell's theorem. That work demonstrated that for certain measurements, no local hidden-variable theories could explain the predictions of quantum mechanics; it thus provides a foundation for experimental tests of quantum entanglement. Inspired by Bell's work, John Clausen, while working as a postdoc at the University of California, Berkeley, designed and carried out experimental tests of Bell's theorem. A visit by Clauser to Columbia in 1975 reignited Wu's interest in the angular correlation of high-energy gamma-ray photons, which could be used to test the inequality at the heart of Bell's theorem.

Together with her graduate students Leonard Kasday and John Ullman, Wu conducted a new experiment on the angular distribution of Compton-scattered photons. One detector in the experiment could be set to arbitrary azimuth angles with respect to a second, fixed detector. The researchers concluded that if the polarization of the high-energy photons could be perfectly detected, their results would violate Bell's inequality and thus provide direct evidence against the exis-




**IN THEIR 1949 EXPERIMENT,** Chien-Shiung Wu and Irving Shaknov used copper-64 as a source for positrons, which collide with electrons to generate two gamma-ray photons polarized at right angles to each other, one horizontal (H) and one vertical (V). Those photons undergo Compton scattering in aluminum and are then measured by the flash generated as they collide with an anthracene crystal. The scattered photons were measured by a fixed detector on one side and a rotating detector on the other side.[17] The coincidence rates of the scattered annihilation photons demonstrated their entangled state.

tence of local hidden variables.[17] That finding not only reinforced the predictions of quantum mechanics but also contributed to the ongoing debate about locality, determinism, and the fundamental nature of reality.

On 4 October 2022, just over a week after Brink's remarks about the significance of Wu's experiments, the Royal Swedish Academy of Sciences announced that it had selected Alain Aspect, Clauser, and Anton Zeilinger as the recipients of that year's Nobel Prize in Physics "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science." Because Wu died in 1997 and Nobel Prizes are not awarded posthumously, she could not have been considered for her early photon entanglement experiment. Despite at least 12 Nobel nominations and two leading-edge experimental contributions in topics that ultimately received the accolade, Wu never received the honor (see "Physics Nobel nominees, 1901–70," Physics Today online, 29 September 2022). That oversight, though, does not diminish her accomplishments.

Wu's scientific achievements transcend the development of the atomic bomb. She contributed to a profound and meticulous understanding of the physical universe. "As a woman in a field almost entirely dominated by men, when most doors were closed to women, she was a trailblazer with an indomitable spirit and determination and a focus on scientific inquiry," said Columbia's Elena Aprile at the 2022 anniversary celebration of Wu's life and work.[8] Aprile joined the physics department faculty at Columbia in 1986; she was the second woman to join the department, more than four decades after Wu.

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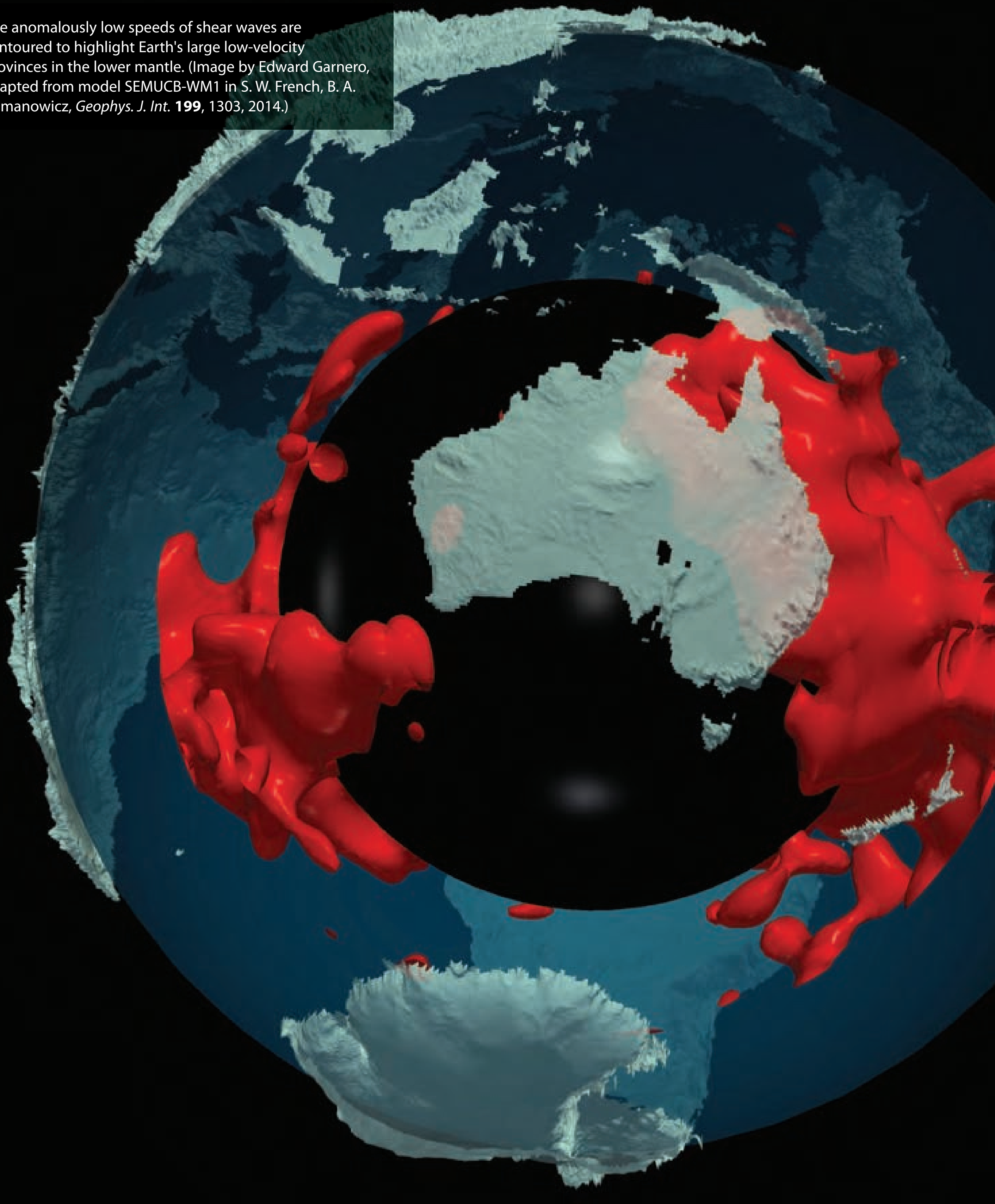


The anomalously low speeds of shear waves are contoured to highlight Earth's large low-velocity provinces in the lower mantle. (Image by Edward Garnero, adapted from model SEMUCB-WM1 in S. W. French, B. A. Romanowicz, *Geophys. J. Int.* **199**, 1303, 2014.)

**Ed Garnero** is a professor in the School of Earth and Space Exploration (SESE) at Arizona State University in Tempe. **Claire Richardson** is nearing completion of her PhD at SESE. They use seismology to study the nature of planetary interiors.

# The mysterious, massive structures in Earth's deep mantle

**Edward Garnero and Claire Richardson**

**Seismic waves traversing the interior of the planet reveal continent-sized regions with distinct physical properties. Researchers are investigating what they are, how they got there, and what their role is in Earth's dynamic convecting interior.**

Roughly 3000 km below us, almost halfway to the center of Earth, lies the boundary between the solid rock mantle and the predominantly liquid-iron outer core. Grade-school textbooks typically depict Earth's interior as basic, brightly colored concentric shells of the crust, mantle, outer core, and inner core. But recent research dramatically alters that simplistic view to include two enormous anomalous structures sitting at the base of the mantle, on top of the core–mantle boundary. Positioned on nearly opposite sides of the globe, one anomaly is underneath the Pacific Ocean, and the other sits beneath western Africa and parts of the Atlantic Ocean.

The two structures are the size of large continents and extend in some places more than 1000 km vertically into the mantle. Those massive features, called large low-velocity provinces (LLVPs), are characterized by significant reductions in seismic wave velocities for both shear and compressional waves (commonly known as *S* and *P* waves, respectively). The speed at which seismic waves travel depends on the composition and temperature of the media that they travel through. For example, heating a rock causes seismic waves to slow down, while cooling it causes them to speed up. Thus, maps of variations in seismic wave speeds, like the two shown in figure 1, can be used to infer properties of Earth's interior.

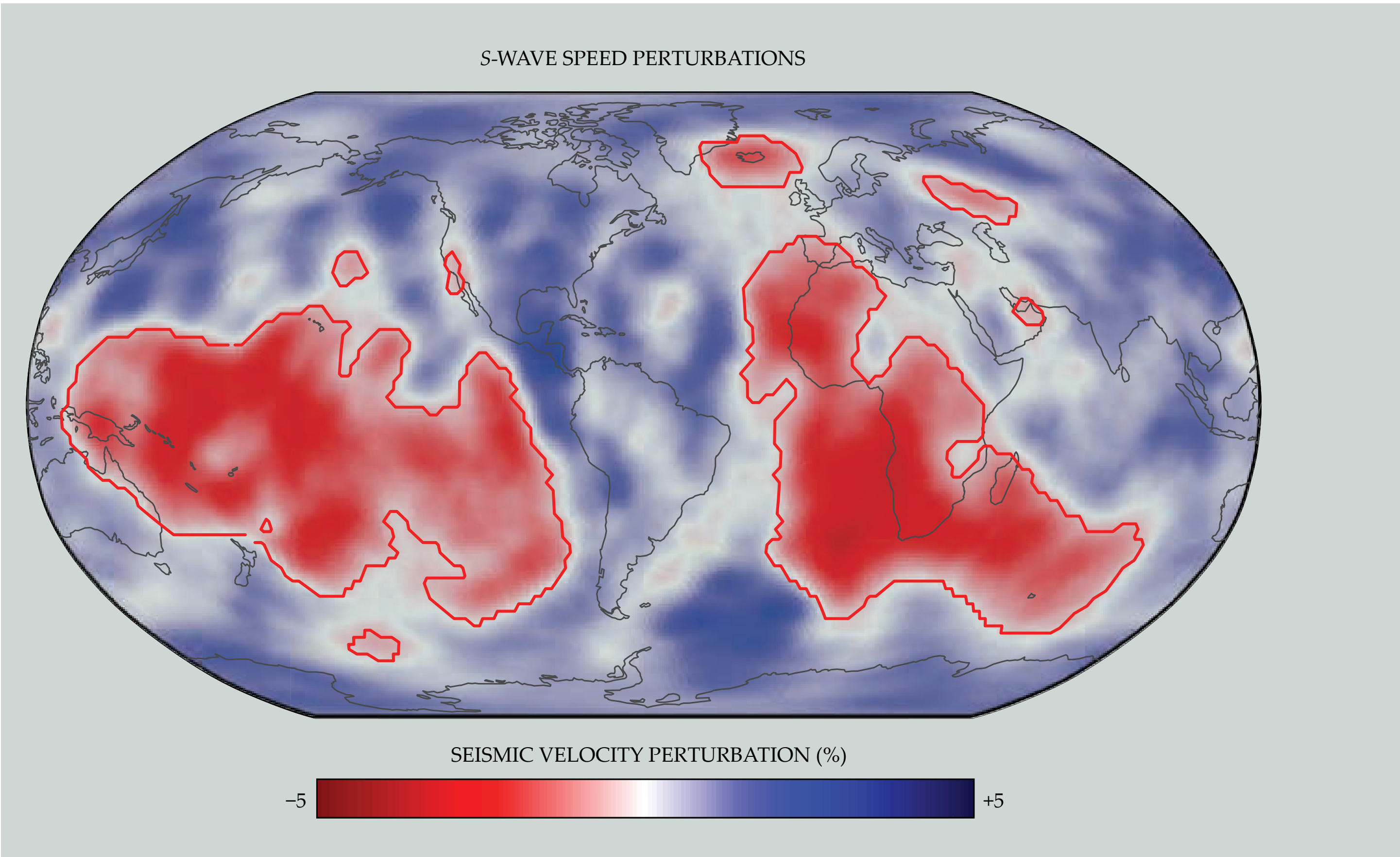
Seismic images of Earth's deep interior have been foundational in progressively revealing its character. The nature of the interior continues to be illuminated through the detailed study of vibrations traveling through the planet. Insights gleaned from seismic studies include better understanding of phenomena such as internal convection, mantle plumes, the fate of tectonic plates descending into the lower mantle, planetary geochemical cycles, heat flowing from the core to the mantle and giving rise to the magnetic field, Earth's evolution, and even supercontinent cycles.

Using earthquake waves that travel deep into Earth's mantle, researchers have observed the sides of LLVPs to be seismically sharp—that is, the velocity reduction from the surrounding mantle rock to an LLVP occurs over a relatively short lateral distance. That appears incompatible with a solely thermal explanation for LLVPs, which would predict a more gradual transition of wave speeds from the surrounding lower mantle to LLVP regions. Most current explanations for the origin of LLVPs, therefore, center on their material being compositionally different from the surrounding lower mantle rock's, with the LLVP material producing much lower wave speeds.

## Slow motion discovery

The discovery of LLVPs was not sudden but rather involved several decades of studies by researchers worldwide. The ear-

**FIGURE 1. SEISMIC WAVE SPEED PERTURBATIONS** can be used to discern changes in temperature and composition in Earth's interior. Seismic tomography uses the waves from earthquakes around the globe to produce 3D maps of how the speeds of shear (*S*) and compressional (*P*) waves differ from the predictions of 1D reference velocity models, in which values change only with depth. Shown here are *S*-wave and *P*-wave perturbation maps for the lowermost 100 km of the mantle. Two large low-velocity provinces, outlined in red, cover around 30% of Earth's core–mantle boundary surface area. (Adapted from ref. 16.)



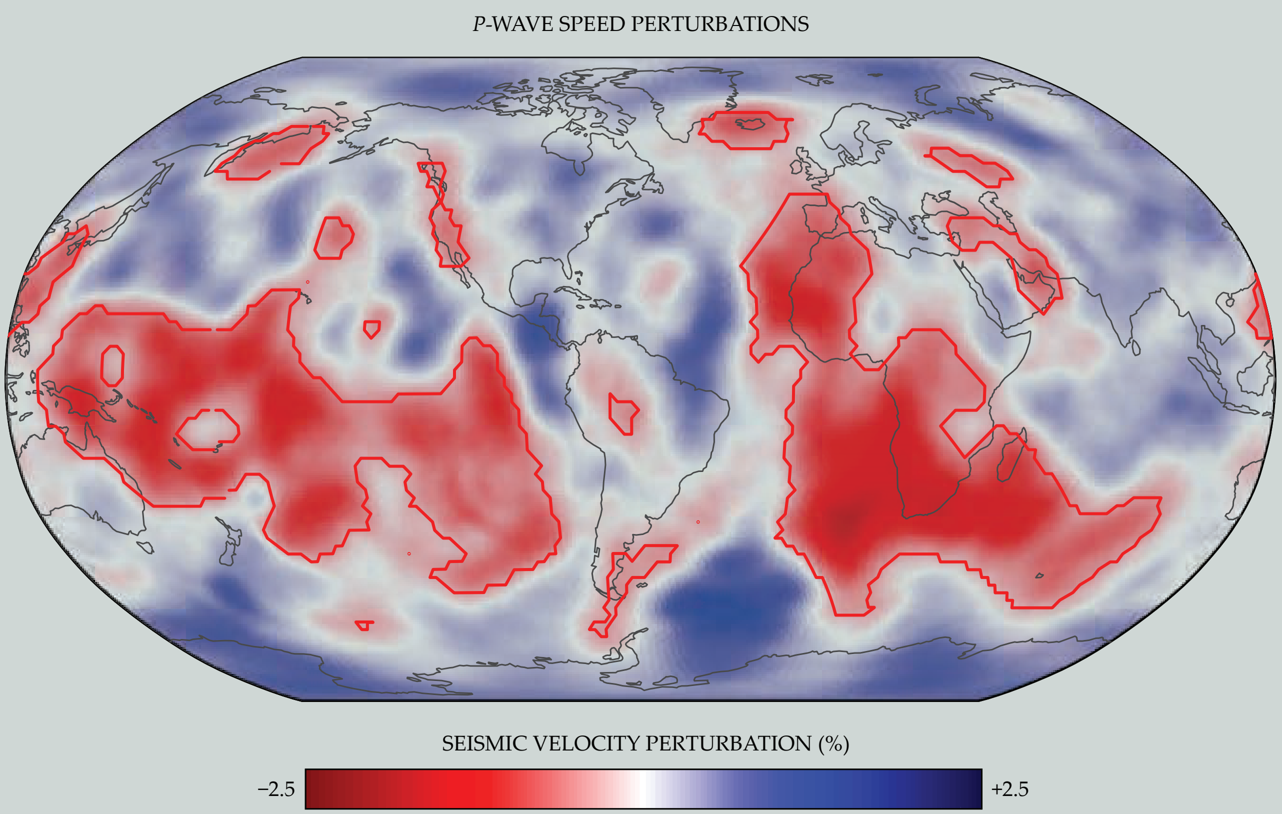
liest work entailed a method called seismic tomography, which, like medical tomography, utilizes up to millions of waves traversing the medium of interest—Earth's mantle—to image the interior. Tomography revealed evidence for velocity reductions over very large scales (for example, smoothly varying speeds over about 10 000 km), which led to the idea that rocks in those regions are warmer.[1] Researchers continue to use tomographic studies to refine details of deep-mantle heterogeneity.

Just over 20 years ago, seismologists studying the pulses of energy that pass through the deepest mantle found an additional "bump" in the waveforms, which was produced by the movement of waves on both sides of the sharp LLVP margins.[2] The bump provided the first hint that the LLVPs were compositionally different from the surrounding mantle.[3] The finding also indicates that LLVPs must be made of material that is intrinsically denser than the typical mantle rock they displace. Without that higher density, they'd be swept away and upward by mantle convection currents.

Density depends on both temperature and composition. Some denser rocks, such as those containing elevated iron content, can have reduced seismic wave speeds because wave speed is affected by both the density and strength of a material. From their long-lived, stable position above the hot core, LLVPs have elevated temperatures that should make them less dense. But the density increase caused by the LLVPs' composition may be greater than the density reduction caused by their elevated temperature. LLVP density remains an active area of research.[4]

Akin to the way that images of distant galaxies have come into focus because of the advancement from Earth-based telescopes to the *Hubble* and *James Webb* space telescopes, refinement of seismic imaging techniques has brought details of Earth's interior into clearer view. That improvement has been greatly assisted by the continually growing number of seismic sensors around the planet. And with seismic imaging, much like ultrasound and MRI techniques for imaging the human body, the greater the density of crisscrossing energy recorded by well-distributed sensors, the better the imaging abilities. Refinement of computational tools has also contributed to advances in seismic imaging.

Current seismic images reveal that just as large continents have specific shapes and varying details to their coastlines, LLVPs exhibit intricate and uneven 3D shapes that significantly depart from the smoothly varying structures presented in early renderings. For example, the African LLVP extends farther up into the mantle than the Pacific



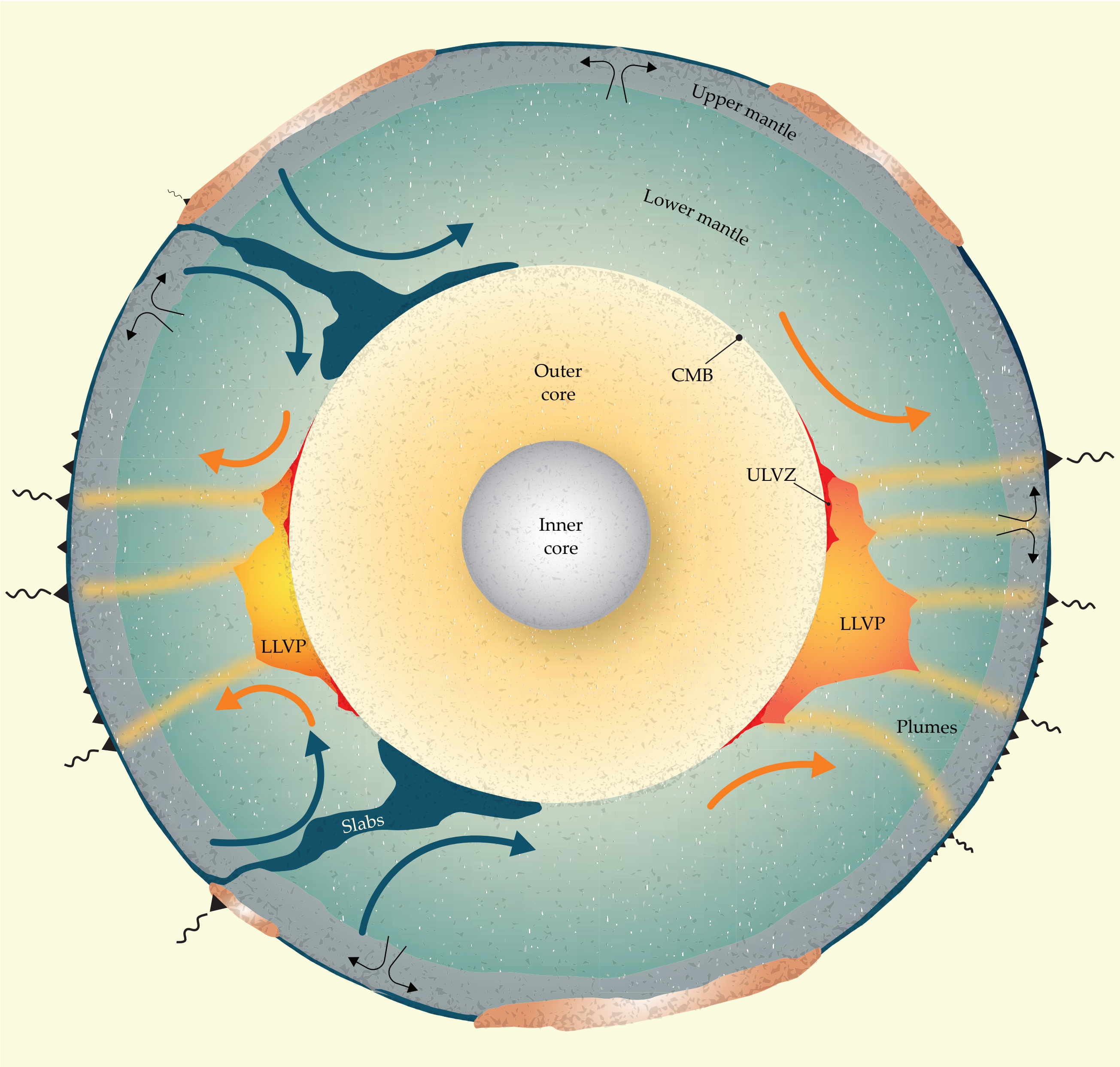



**FIGURE 2. TWO CONTINENT-SIZED LARGE LOW-VELOCITY PROVINCES (LLVPS)** sit in the lower mantle of Earth's dynamic interior. The LLVP structures extend roughly 1200 km above the core–mantle boundary (CMB) in places and are likely compositionally distinct from the surrounding mantle rock (green). The convection forces that shape the anomalies are nonuniform and related to mantle currents induced from subducting slabs (blue structures in the mantle), which were once tectonic plates in oceanic regions (blue outer shell). Mantle plumes (yellow) have been mapped to originate near LLVP margins. Plumes give rise to hot-spot volcanism (black triangles at the surface). Thin anomalous structures that may be partially molten, called ultralow-velocity zones (ULVZs, dark red), are also found near LLVPs.

LLVP.[5] That raises the possibility of differing density structures—and possibly different chemistries—between the two anomalies.

The strength of convective flow around the LLVPs could also differ. Deep-mantle convective flow strength is primarily controlled by subduction, the process of tectonic plates falling into the interior when they become cold and dense enough. Subduction-related downwelling flow varies according to tectonic plate speeds, locations, and densities as the plates fall into the mantle.

LLVP shape is closely linked to the surrounding dynamic mantle. Increasingly finer-scale features of LLVPs are visible in seismic images made with modern modeling capabilities. But imaging limitations remain because the uneven

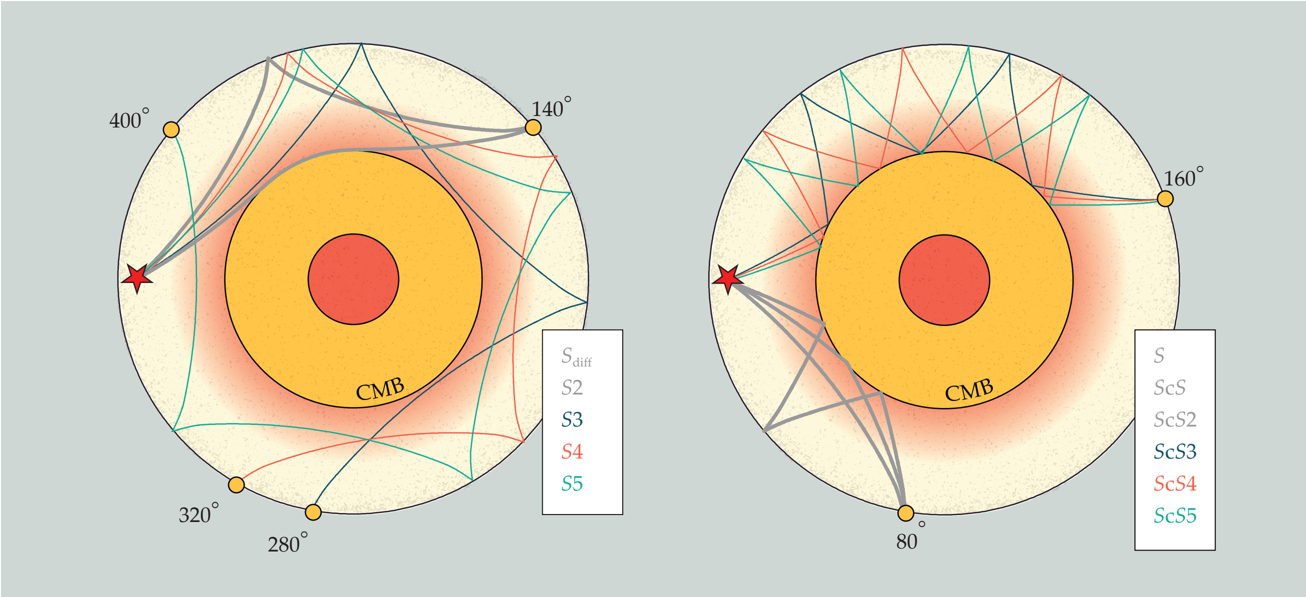



**FIGURE 3. ECHOES OF SEISMIC WAVES** produced by refraction and reflection from the underside of Earth's surface **(left)** and off the core–mantle boundary (CMB; **right**) add additional and redundant sampling of the lower half of the mantle (light red shading), where large low-velocity provinces reside. Seismic waves, depicted by their ray paths, are shown for *S* waves between an earthquake (red star) and receiver locations (yellow circles). Ray paths (gray) commonly analyzed by seismologists include direct *S* waves (*S*), diffracted *S* waves ($S_{diff}$), *S* waves that bounce once between earthquake and receiver (*S*2), and *S* waves that bounce off the CMB once and twice (*ScS*, *ScS*2). Waves having additional reflections are less commonly used but are present in the data. Those include *S* waves with multiple reflections off the surface (*S*3, *S*4, *S*5) and off the CMB (*ScS*3, *ScS*4, *ScS*5). Measuring all available *S* and *P* waves will improve tomographic images of the deep Earth.

global distributions of seismometers and of earthquakes create uneven sampling of the interior.

## Learning from LLVPs

As seismic imaging of LLVPs has improved, the importance of LLVPs for understanding the dynamic and mineralogical properties of Earth, throughout its 4.5-billion-year history, has become increasingly apparent. The low-resolution, smooth structures in the earliest images of LLVPs were thought to be solely the result of temperature variations caused by large-scale mantle convection currents. Convection in the mantle is like convection in a pot of boiling water: Cold material sinks, and hot material rises. The mantle, however, is predominantly solid rock, and thus convection is extremely slow, occurring on time scales of millions of years.

As tectonic plates, often referred to simply as slabs, sink from Earth's surface into the interior at subduction zones, the surrounding mantle is pulled viscously downward with them, as illustrated in figure 2. Once slabs reach the base of the mantle, they convect laterally along the core–mantle boundary toward warmer upwelling regions. Those warmer zones are thought to harbor the roots of hot mantle plumes that rise through the entire mantle and lead to hot-spot volcanism that occurs above LLVPs, such as in Hawaii. The reduced velocities found in tomographic images in the 1980s and 1990s supported that model of hot, plume-generating LLVPs.

When sharper sides of LLVPs were detected starting in the 2000s, however, the dominant hypothesis about their material changed from its being purely a result of thermal differences to being both thermally and compositionally distinct from the surrounding mantle. That hypothesis, which carries significant consequences for unraveling the dynamic behavior and composition of the mantle, remains the prevailing view.[3]

If any compositionally distinct material exists at the base of the mantle, it, too, is subject to the forces of mantle convection and is swept toward regions of convective upwelling currents. If the material is denser than that of the surrounding mantle, it will stagnate beneath upwellings, resulting in piles of material. Thermochemical simulations of mantle convection over the past 120 million years agree with findings from seismology about the locations of those chemically distinct piles.[6] Long-lived, chemically distinct LLVPs may therefore contain chemical signatures from earlier in Earth's history.

The piles can be slowly eroded as convection entrains small amounts of their material in mantle plumes. The plumes deliver some of the material to the surface, where it shows up in hot-spot volcano eruptions as trace-element isotopic anomalies.[7] In fact, the locations of hot-spot volcanoes, as well as the original location of Earth's largest volcanic eruptions responsible for massive accumulations of igneous rocks, predominantly overlay LLVP margins. Those locations are consistent with geodynamical convection predictions of mantle plumes that rise off the LLVP edges.[8] Compositionally distinct LLVPs will also modify patterns of heat flow from the core into the mantle, which affect the convective currents in the liquid outer core that generate Earth's magnetic field.[9]

Although many questions about LLVPs have been answered by modern seismic imaging, many more are arising with new images. For example, it's possible that broad, large upwellings extend from the top of LLVPs.[10] The upwellings have been referred to as superplumes in past literature; tomography, however, presents just a snapshot in time of anomalous seismic wave speed patterns, and convection experiments are required to assess the likelihood that material is ascending, descending, or neutrally buoyant.

Another interesting possibility relates to supercontinent cycles, in which supercontinents, such as Pangaea, repeatedly form and break up over hundreds of millions of years. Mantle convection models have shown that during such cycles, compositionally distinct LLVPs can merge on the opposite side of the globe from the supercontinent and then return to two antipodal LLVP piles when supercontinent breakup occurs.[11]

Do upward advecting pieces of LLVPs eventually become the large accumulations of igneous rocks seen at Earth's surface? Are the two LLVPs composed of the same material? Do LLVPs migrate along the core–mantle boundary over time? Questions like these are topics of ongoing research.

## Terrestrial or extraterrestrial?

If a convecting system has large enough density perturbations from composition or temperature effects, anomalous structures can reside at either the top or bottom—buoyant material at the surface, denser material at the base. Otherwise, they will mix into the background material over time. Hence, hypotheses for the origin of compositionally distinct LLVPs involve either their slow growth over time from the accumulation of dense material or their quick growth when Earth formed or shortly thereafter.

The slow crystallization of Earth's mantle from an early magma ocean may have facilitated the creation of LLVPs: Denser minerals would have crystalized first and then sunk to the mantle's base, where they may have experienced subsequent chemical alteration.[12]

Several possibilities for slow-growing, dense LLVPs have been raised over the years. One is the accumulation of relatively dense, iron-rich, subducted former oceanic crust over geologic time scales. The outermost core can also contribute to anomalous material in the deepest mantle through processes that involve chemical exchange across the core–mantle boundary. For example, a recent study suggests that hydrogen stored in former oceanic crust subducted to the core–mantle boundary can be exchanged for carbon in the core.[13] That process might occur over much smaller volumes than LLVPs, but it could explain the origin of some small-scale features known as ultralow velocity zones, also found above the core–mantle boundary, that have extreme seismic velocity reductions.

Early in Earth's history, shortly after the solar system formed, a Mars-sized planet named Theia is hypothesized to have collided with proto-Earth to form the Moon. The Moon thus likely began its existence with contributions from both Earth and Theia. Because the Moon's volume is a fraction of that hypothesized for the much larger Theia, the question, Where did the rest of Theia go? provides an interesting possibility for the origin of Earth's LLVPs. Qian Yuan and colleagues present a case for Earth's massive lower-mantle anomalies being dense Theia remnants[14]—in other words, extraterrestrial. If planetary collisions were common in the early solar system, it's interesting to consider whether remnants of impactor bodies reside in other planetary bodies as well.

## Improving our seismoscope

Although we now know the large-scale shapes of LLVPs, sharpening the focus on the finer-scale details has its challenges. We are imaging massive structures up to 3000 km below Earth's surface with earthquake waves that imperfectly sample the interior. Seismic tomography uses those waves to produce images of heterogeneities in wave speed throughout Earth's mantle. Medical tomography, such as CAT scans, uses the same method but differs in a couple of key aspects. First, the locations of the energy source and its recordings can be controlled. Second, the energy can be administered as redundantly as needed.

In deep-Earth imaging, the earthquakes that act as the energy source are far from being uniformly distributed. Furthermore, seismic sensors are predominantly on land, and they're irregularly spaced, with some continents only sparsely instrumented. Thus, the efficacy of seismic imaging is geographically variable. Still, LLVP models from different research groups agree quite well, especially for features at longer length scales (1000 km or more).[15] Smaller-scale features (less than 1000 km), including LLVP attributes and ultralow velocity zones, differ among models, which may result from the amounts and types of data used and the imaging methodology employed.

Continuing to increase seismic sensing across the planet, especially in the ocean and on poorly instrumented continents, will bring better agreement to finer-scale details in tomographic imaging. In the meantime, incorporating less commonly used seismic waves that bounce multiple times through the interior, as shown in figure 3, can further improve coverage, without the time, labor, and cost required for deploying more sensors.

Earthquakes are the primary source of energy used in seismic imaging of the mantle. Roughly 140–150 earthquakes of magnitude 6 or larger happen every year, each of which can be used in deep-mantle seismic imaging studies. Data from thousands of seismic sensors are freely available; every earthquake has up to tens of unique seismic waves that can be measured: Waves can reflect multiple times from the underside of

Earth's surface and off the core–mantle boundary (see figure 3). Many of those waves are not routinely used in tomography—but they can be.

The amount of information available for Earth imaging continues to grow, with several millions of measurements already made. The densification of interior sampling will result in continued improvement in LLVP resolution. But interpreting a larger amount of data is not without challenges. Not too long ago, seismologists personally viewed and hand-measured all their data. Now, far too many measurements are recorded from millions of seismic waves—with more earthquakes and recordings happening continually—than humans can visually inspect.

Processing that much data is possible only with software, and so scientists are turning toward automation, machine learning, and AI to carry out analyses. Although that dramatically increases the number of usable measurements, it also introduces potential for error. Training algorithms to know the difference between high-quality and low-quality data is an active area of research.

Seismic imaging provides a present-day snapshot of Earth's interior. To put that in a context of the time evolution of the planet, with meaningful information about Earth chemistry and mineralogy, cross-disciplinary research is necessary. Geodynamicists use dynamical flow simulations to predict temperature and compositional patterns in Earth's interior. Mineral physicists investigate the mineralogy of the interior and reproduce those chemistries in high-pressure laboratory experiments. Combining those analyses with, for example, knowledge about the chemistry of erupted lavas, the generation and nature of Earth's magnetic field, and tectonic motions at Earth's surface, we continue to learn more about the origin and evolution of Earth's massive deep-mantle LLVPs and how they relate to important surface phenomena.

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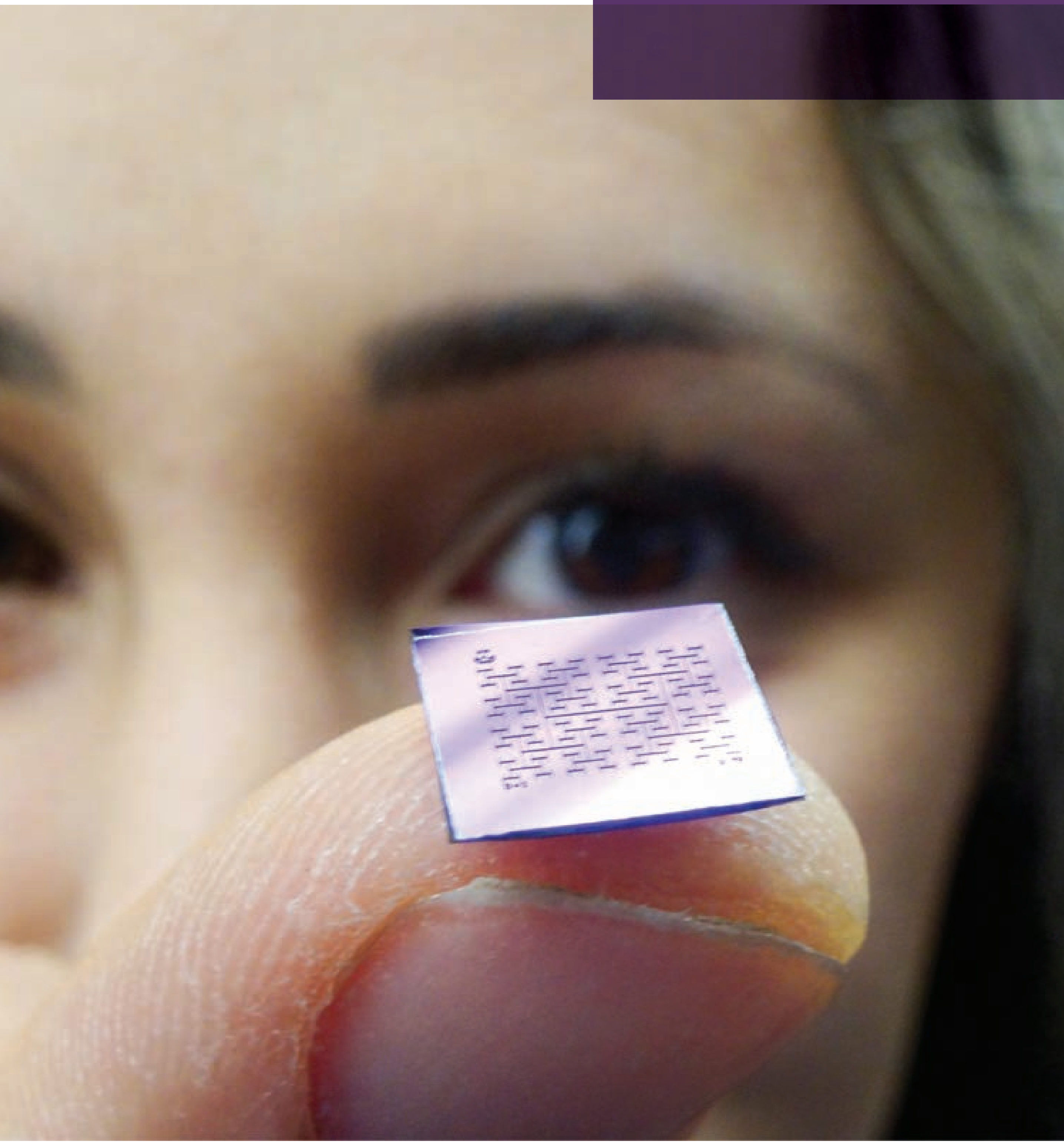
# The interdisciplinary journey to FRACTAL BIONICS

Richard Taylor

**The search is underway for the ideal electrode to pass signals from artificial implants to the body's neurons. Fractal shapes in biology could provide the solution.**

In the science fiction world of my childhood, damaged body parts were replaced by artificial implants that restored or even enhanced performance. I never tired of watching how the protagonists of 1970s TV shows like *The Six Million Dollar Man* and *The Bionic Woman* used their superior artificial eyes and ears to outwit villains.

**Richard Taylor** is a professor of physics, psychology, and art and the head of the physics department at the University of Oregon in Eugene. He investigates nature's patterns across diverse disciplines.



Fifty years on, that science fiction is transforming into science fact. Electronic devices have been implanted into eyes with the aim of restoring vision to patients with degenerative retinal diseases. Those diseases strike 1 in 10 people over age 50 and have no conventional cure. More than 160 000 brain implant surgeries have targeted neurological disorders such as Parkinson's disease. And people with amputated limbs can now receive interactive prosthetic implants that restore some mobility. Research continues to bring the capabilities of implants closer to those of my bionic heroes.

My journey into bionics began a decade ago when I was invited to the Pufendorf Institute for Advanced Studies. Located at Lund University in Sweden, the institute assembles eclectic teams to address diverse research themes. I was excited that my theme for the visit focused on vision because it united my backgrounds in physics and art. It also allowed me to listen to perspectives from those in other disciplines. My interests quickly gravitated to designing artificial neurons for the retina, inspired by the fractal geometry of the biological ones.

Brainstorming sessions with Lund ophthalmologist Maria Thereza Perez highlighted the medical challenge of fixing the retina's electrical wiring when it stops working. Perez described how electrodes were being used to stimulate electrical signals in neurons that no longer received messages from their damaged neighbors. The idea was far from novel, she said. More than two centuries earlier, Charles Le Roy had applied electricity to a patient's eyes, causing him to see flashes of light. Luigi Galvani had done the same to frog muscles, causing them to twitch. But those researchers knew little about the body's wiring. The concept of neurons arrived over a century later.

Now, it's known that electricity passes across synapses from neuron to neuron much like electricity flows between resistors in an electric circuit. And similarly to a faulty resistor, a damaged neuron will disrupt transmission through the circuit. To fix the circuit, today's surgeons can implant miniature electrodes into the body rather than relying on the crude external wires used by Le Roy and Galvani.

As I listened to Perez, I sensed the remarkable opportunity for interdisciplinary collaboration: Physicists could bring their knowledge of electrical networks; chemists, their knowledge of the materials needed to build the electrodes; and neuroscientists, their knowledge of the body's interactions.

Such a collaboration could potentially create artificial neurons that integrate seamlessly with their natural counterparts to form a hybrid system, just like the science fiction heroes of the 1970s took inspiration from biology and embraced bionics.

## The fractal nature of neurons

Human neurons vary in length from microns up to a meter. They form immense networks—humans have as many connections between neurons in a single cubic centimeter of their brain as there are stars in the Milky Way. Maintaining the health of those connections is important for daily tasks. In addition to brain connections facilitating thought, humans rely on neurons to connect to their eyes for sight and to their limbs for movement. The neurons' complex patterns contrast sharply with the simpler wiring of cell phones and computers.

Fractal branches are prevalent in nature. Bronchial trees and blood vessels in human bodies benefit from those structures. The branches and their gaps form two fractals sharing a huge interface that balances their operational performance with associated costs. Neurons exploit the fractal geometry of their branches and gaps to establish connections to their neighbors. The inset of figure 1 shows multiple views of a bipolar neuron that provides crucial connections between the eye's

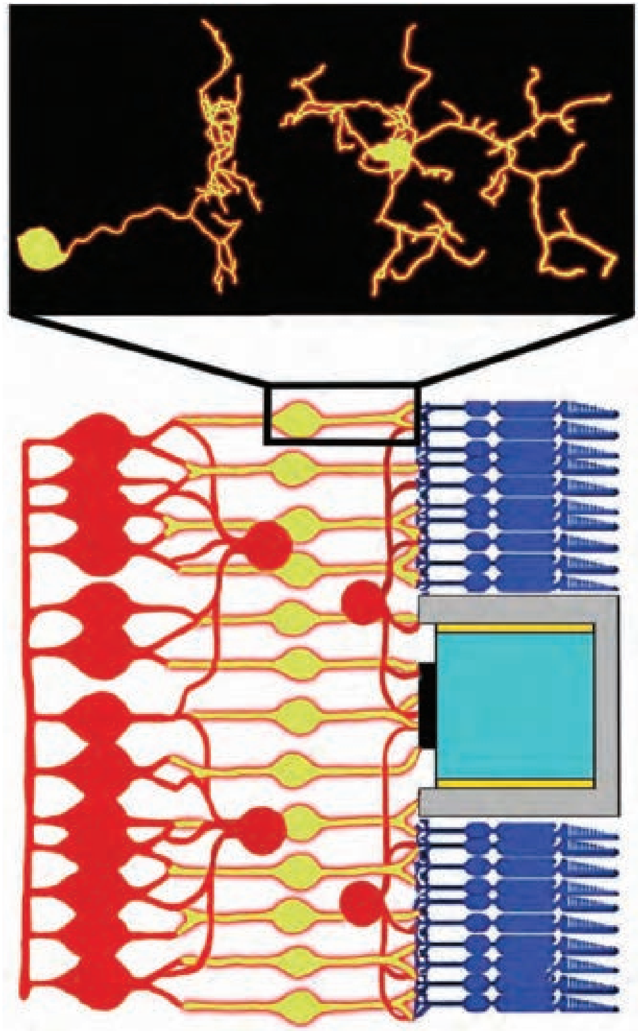


**FIGURE 1. A SCHEMATIC SIDE VIEW** of retinal wiring. Bipolar neurons (yellow) connect to other types of retinal neurons (red), photoreceptors (dark blue), and an implanted photodiode (the gray region and parts within). For simplicity, only one photodiode is shown. The inset shows a reconstruction of a real bipolar neuron from two angles. Dendrites branch out from its circular nucleus and spread 10–20 µm. (Data for the inset are from NeuroMorpho.org/CC BY 4.0.)

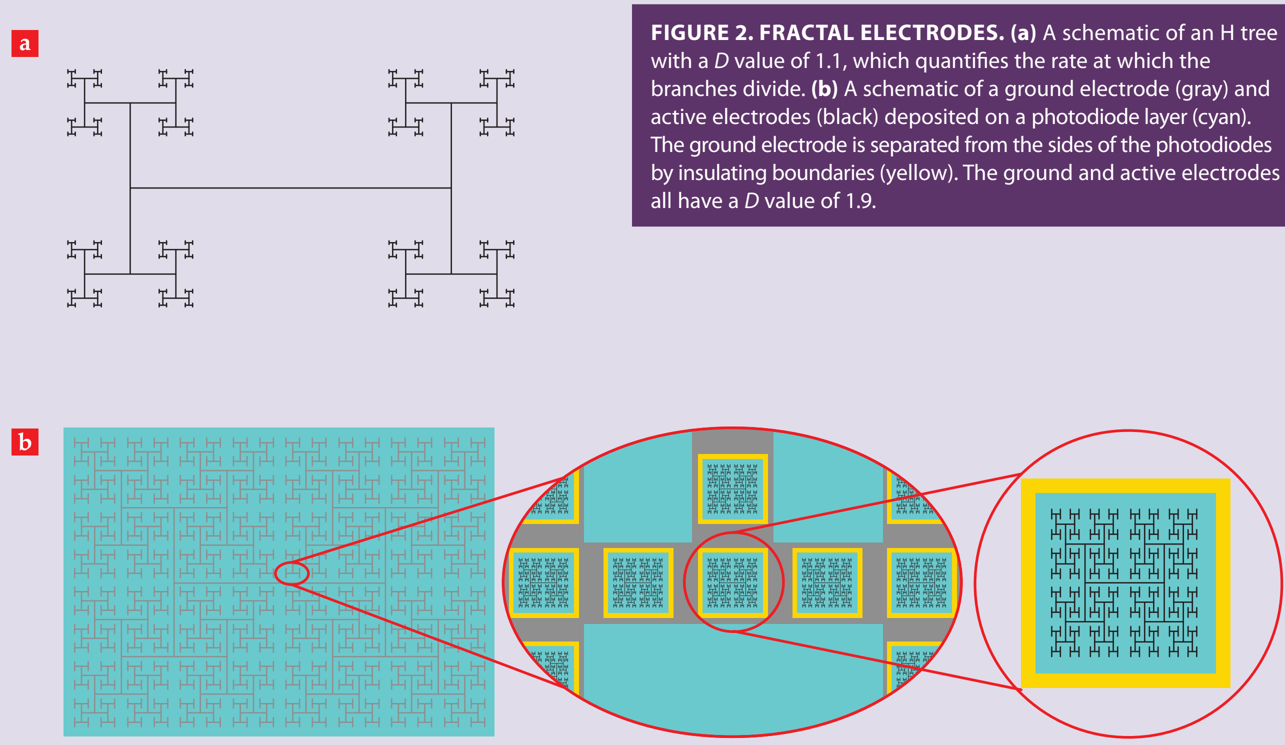



**FIGURE 2. FRACTAL ELECTRODES. (a)** A schematic of an H tree with a *D* value of 1.1, which quantifies the rate at which the branches divide. **(b)** A schematic of a ground electrode (gray) and active electrodes (black) deposited on a photodiode layer (cyan). The ground electrode is separated from the sides of the photodiodes by insulating boundaries (yellow). The ground and active electrodes all have a *D* value of 1.9.

photoreceptors and other retinal neurons that carry signals to the brain. The neuron's branching dendrites are fractal; they generate repeating patterns at different size scales as they grow out from its center.

An impressive piece in the story of nature's fractals is that only a few pattern repetitions are required to achieve that performance–cost balancing act. For some of nature's fractals, patterns typically repeat over a magnification factor of only 25. That is good news for bioengineers who want to replicate their geometry: Bioinspired electrodes will be less challenging to fabricate if their branches span a limited range of sizes.

Fractals fall into two families: exact and statistical. Mathematicians assemble exact fractals by repeating patterns precisely. Nature's randomness disrupts the precision, and only the pattern's statistical qualities repeat. Consequently, statistical fractals exhibited in systems such as neurons only appear similar at different scales.

The H-tree pattern shown in Figure 2a is an example of simpler exact electrodes. Most discussions of fractals quickly gravitate to the concept of the fractal dimension $D$. At each level of repetition, the number of branches $N$ is proportional to $L^{-D}$, where $L$ is the branch length. That power law generates the pattern's scale invariance, and its exponent $D$ sets the rate of shrinkage of $L$ between the levels. Higher $D$ values correspond to slower rates. Consequently, $D$ measures the relative contributions of coarse and fine structure in the fractal mix; fine structure plays an increasing role as $D$ rises. Nature's fractals maximize their functional properties by tuning their $D$ values, and our electrodes do the same.

## Heading into the retina

Figure 2b shows a design for using H-tree electrodes to collect charge from an array of photodiodes. One large H-tree electrode is deposited on a photodiode layer. That large electrode features an array of holes in its branches. Within each hole, an insulating interface separates the large electrode from the photodiode sides. A smaller H-tree electrode also nests in each hole. When the photodiode is illuminated, its charge migrates up to the surface to be collected by the smaller H-tree electrode. That active electrode then generates an electric field with the larger, grounded electrode.

Figure 1 demonstrates how the design might work in practice by showing a subretinal implant, which is a photodiode replacing a diseased photoreceptor. That strategy is feasible because common diseases predominantly attack the photoreceptors but leave the neighboring neurons sufficiently intact to interface with the photodiode's electrodes. In principle, the size of each of the active electrodes would match the photoreceptor diameter (about 5 μm), and the ground electrode would span the diseased region.

The subretinal implant celebrates the basic philosophy of bionics—that the hybrid system should maximize natural functionality. Signals from the subretinal implant pass through the retina's circuitry on the way to the optic nerve and in principle benefit from the image compression and processing functions performed by the millions of retinal neurons. Those functions are important for seeing. Even with the retina working, a billion signals pass down the optic nerve each second, requiring the brain to dedicate up to 30% of its volume to processing the incoming data. Without its retinal outpost, the brain's operation becomes strained.

To stimulate the targeted bipolar neurons, the electrical field generated by the electrodes changes the potential difference across ion channels that permeate the neuron's surface membrane. The induced ion flow through those channels triggers signals along the neuron's branches. Those signals then pass to neighboring neurons via synaptic connections on the neuron's surface.

Our team's electrical simulations of the photodiode–neuron operation highlight the advantage of adopting fractal designs: Significant amounts of charge reside on the H-tree sidewalls. Compared with Euclidean electrode designs, such as grids and squares, the large sidewall surfaces associated with the fractal's long boundaries generate enhanced capacitances and therefore larger stimulating fields. Our simulations show that the result is game changing: The fractal electrode stimulates all neighboring neurons, whereas the equivalent square electrode stimulates less than 10%. Along with translating to higher-resolution vision for retinal implants, the fractal advantage could also apply to brain and prosthetic limb implants.

## Fractal herding at the biophilic interface

Teaching my favorite course—Physics of Light, Color, and Vision—reminds me that implants are only as strong as their weakest link. Students often pull out their cell phones and, trying to be helpful, suggest that I should insert a phone camera into the eye. Indeed, there are high-end cameras that exceed the eye's pixel densities. Camera technology, however, isn't designed to interface with living systems. If an implant is rejected by the eye's cells, then its electrical performance becomes irrelevant. In particular, the superior fractal capacitances won't have a chance to shine.

Neuron biocompatibility, meaning its tolerance of a foreign implant, is therefore the driving force of any design. The design principles can be thought of as a three-legged stool. The two legs that have received the most attention are the chemical environment and physical texture provided by the electrode's materials. The third leg is the electrode's shape. Ultimately, bionics should be biophilic: Neurons should be attracted to, rather than simply tolerant of, the electrode. Fractal shapes could provide the key to that attraction.

Although bioengineers typically focus on neurons, glial cells also deserve their place in the research spotlight. Serving as the neurons' life-support system, glial cells provide the trophic and metabolic support for neurons to maintain their health and transmit their signals. To deliver the desired biophilic properties to our electrodes, we exploit the different reactions that neurons and glial cells have to artificial surfaces.

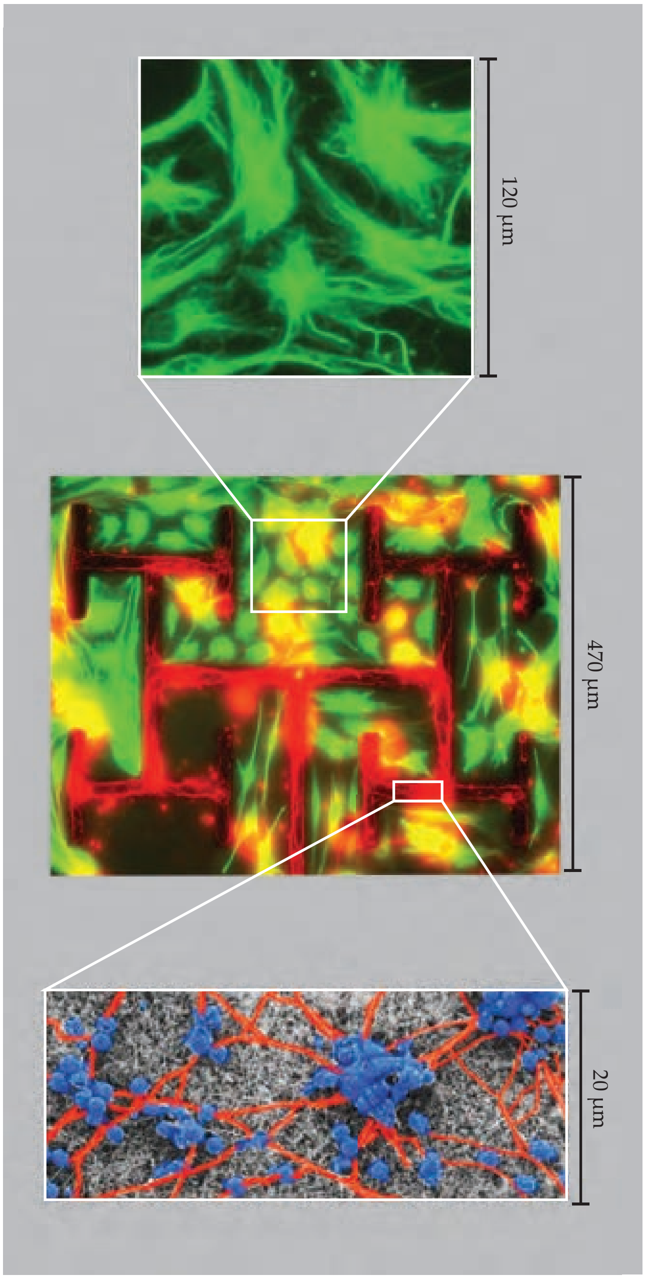



**FIGURE 3. FRACTAL HERDING.** A fluorescence microscope image **(middle)** shows neurons (red) growing on a carbon nanotube electrode, which is arranged in an H-tree branch pattern, and glial cells (green) growing in the surrounding gaps. The inset **(top)** provides a closer look at the arrangement of glia. A scanning electron microscope image **(bottom)** shows the neurons' nuclei and dendrites, which are false colored in blue and orange, respectively.

Figure 3 shows an electrode immersed in an *in vitro* culture of neurons and glia. We grow carbon nanotubes patterned into an H tree on a silicon dioxide substrate. When the nanotubes grow vertically from the substrate (out of the page in figure 3), they tangle into a conducting forest with a textured canopy. Neurons accumulate on the textured nanotube branches because they adhere strongly to surface textures that resemble the retina's multiscaled structural environment. In contrast, the glial cells proliferate in the gaps because the smoother $SiO_2$ surfaces encourage their division and growth. Once herded into the gaps, the glia can't physically hinder the neuron–electrode interactions but are still sufficiently close to provide their vital health support.

Herding increases with the amount of time for cell growth, and fractals outpace Euclidean electrodes significantly in the race. In particular, H trees with high *D* support vast colonies of glia because their multiscaled gaps provide the optimal balance between the glial cells' chemical need to be close to the neurons and their physical need to have open spaces in which to divide and grow. The neuron-rich branches also thrive because their long fractal boundaries with the gaps boost the health benefits of the glial colonies.

Those thriving neurons then optimize their network. Following an initial dendritic growth spurt to establish connections, the neurons collect into bigger clusters and prune some of those connections. Structurally, the optimization resembles small-world networks—efficient systems that link all locations using relatively few connections. You may have experienced small-world networks through the hub system used by airlines. There's no guarantee of a direct flight between any two airports, but you can get where you need to go by flying through major hubs. Fortunately, nature's neurons provide better service.

## Fractal resonance

Having herded neurons onto the electrodes, our collaboration proposed that fractal resonance would further help them thrive. Our hypothesis was that matching the electrodes to the neurons' precise fractal characteristics would induce greater connectivity between the two. Although the H tree shares the multiscale character of nature's fractals, the exact repetition of its straight lines and 90° turns are far from bioinspired.

By analyzing examples of neurons from both the retina (bipolar neurons) and the brain (hippocampal neurons), we found that the way their dendrites weave through space is crucial for generating their statistical fractal patterns. The neurons' attraction to that fractal weaving behavior raised a fundamental question: What are the negative consequences of deviating from the natural fractal form? If neuron functionality deteriorates, then fractal resonance should drive all electrode designs.

To deliver the answers, we created neurons that nature chose not to by imaging neurons using confocal microscopy and then mathematically distorting their dendrite weaving angles. In figure 4, the middle neuron is natural, and the left and right neurons are distortions created by straightening and curling the dendrites. The distortions cause the neurons' *D* values to deviate from the natural value of 1.42 in opposite directions. Continuing the curling process would ultimately produce a 3D sphere, with the increased fine structure filling that volume. In contrast, completely straightening the branches and lining them up end to end would produce a smooth, 1D line, devoid of fine structure.

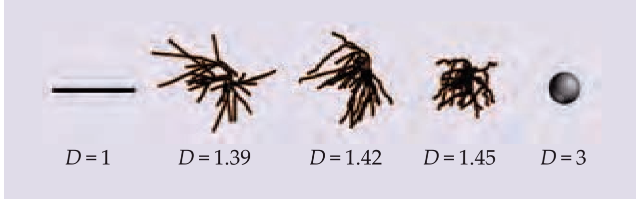



**FIGURE 4. NEURONS ARE OPTIMALLY SHAPED** to balance their connectivity with the cost of that connectivity. To demonstrate the range of *D* values, a natural hippocampal neuron—with a *D* value of 1.42—is compared with two distorted neurons and the Euclidean shapes that would emerge at low and high values of *D*.

Ramping up *D* increases a neuron's ability to communicate with its neighbors because of a rise in connectivity density. That quantifies the neuron's physical profile within a given volume and so measures the increased exposure of synapses on the dendrites' surfaces. Yet neurons need to balance increases in connectivity density with the costs of constructing and maintaining those connections. Construction costs include the amount of dendritic mass within a given volume. Maintenance costs include the energy to operate the ion channels, which increases with the dendritic surface area within a given volume.

Crucially, connectivity and its costs increase at different rates as *D* rises, and that allows the neurons to balance those competing factors. That balance can be quantified using balanced connectivity, which considers the ratio of the connectivity rate and cost rate. As expected, natural neurons have *D* values that cluster around the peak in the balanced connectivity curve; nature found the optimal amount of fine structure.

The distorted neurons have *D* values that lie away from the peak, and the drop-off in balanced connectivity quantifies the deterioration associated with deviating from the neuron's natural form. The Euclidean shapes also lie well away from the optimal balance, demonstrating why neurons follow fractal rather than Euclidean geometries. The lack of gaps in the sphere generates a large profile, but the heavy price paid for its large mass density explains why neurons aren't that shape. Simple, straight lines use little mass at a given location, but they pay the price of spreading their profile over expansive regions.

If the electrode's *D* value is matched to that of the neurons, the neurons can preserve their natural weave during the adhesion process. They will then benefit from being at the peak in their balanced connectivity when interacting with their neighboring neurons and the electrode. In contrast, requiring neurons to grow along the straight lines and turn the tight corners of Euclidean electrodes, such as grids, will force neurons down the slope of the balanced connectivity curve.

Fractal resonance can be compared to an aircraft on final approach. Whereas pilots prefer to fly straight when approaching 1D, straight runways, neurons like to maintain their weave as they land on our electrodes. Ultimately, different neuron types might be guided to different electrode runways depending on their *D* values. Using the equivalent of autopilot, we are

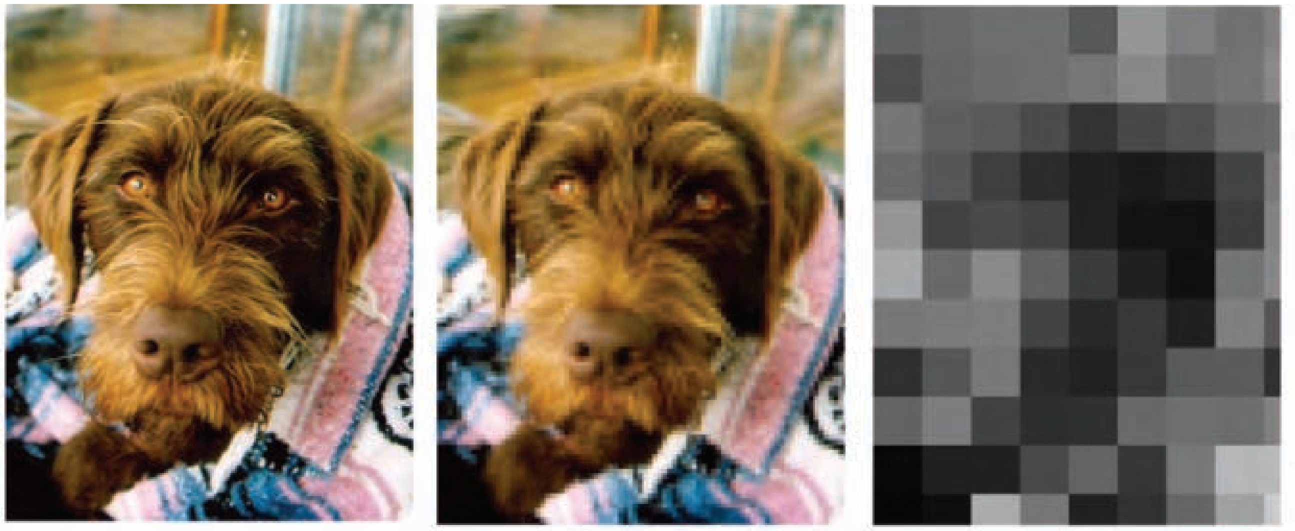


**FIGURE 5. PHOTOGRAPHS OF GRIFFON,** my German wirehaired pointer, with their resolutions adjusted to symbolize different levels of acuity in comparison with 20/20 vision: 100% **(left)**, 25% **(middle)**, and 4% **(right)**. Legal blindness corresponds to 10% acuity. Subretinal implants previously provided 4% acuity, but new designs using fractal structures to better match the design of the neurons they connect to are expected to provide 25% acuity.

developing software to predict the electrode shape that provides large overlaps with the dendrites while minimizing their distortion. Those statistical fractal electrodes will be constructed using 3D printers for future clinical trials.

## The brave new world of fractal bionics

How far do the fractal advantages get us? The pioneering implants used to replace damaged photoreceptors have 4% of typical visual acuity. That's worse than the legal blindness level of 10%, below which tasks like driving safely are impossible. The square electrodes in those original subretinal implant experiments had a low capacitance. They didn't generate large stimulating fields, and the few neurons that adhered to their surfaces were likely distorted, which prevented them from effectively passing signals to their retinal neighbors.

In contrast, our simulated fractal implants are expected to have roughly 25% acuity. We created 20 μm photodiodes, which we made larger than photoreceptors to accommodate for their poorer performance, and the resulting vision is accurate enough to perform many daily tasks. Figure 5 compares those two acuity levels against natural vision using photos of my old friend Griffon that progressively reduce in pixel density.

I recently returned to the Pufendorf Institute and reminisced with Perez about our bionic adventure. We agreed to relabel our artificial neurons as "interconnects" to capture their multiple functions that go beyond the electrical performance suggested by calling them "electrodes." For example, the multiscaled branching properties that allow trees to sway in the wind without breaking can translate to mechanically flexible electronics—the interconnects could conform to the retina's shape, and surgeons might even curl them up for delivery through less obtrusive insertions. Advances that use fractal shapes to manipulate light on the nanometer scale might even allow wavelength tuning for color vision.

Building on the solid-state chip revolution, electronic strategies continue to be an obvious approach to retinal repair. Although my research focuses on interconnects, other advances—such as improved photodiodes or supplemental implantable batteries—could come from the implant's power source. Alternative long-term strategies focus on fabricating organic artificial photoreceptors or growing new biological systems using stem cells. Regardless of the approach, future advances will require collaboration between bioengineers and neuroscientists to foster a greater understanding of the interactions between the natural and introduced systems. The interdisciplinary endeavors undertaken already emphasize how far the field has come since Le Roy and Galvani's pioneering experiments.

*I thank my collaborators Benjamín Alemán, John Dalrymple-Alford, Bruce Harland, and Maria Thereza Perez, and my current and previous PhD students Bret Brouse, Aiden Dillon, Saumya Keremane, Rick Montgomery, Saba Moslehi, Sam Philliber, Conor Rowland, Julian Smith, and Bill Watterson.*

## ADDITIONAL RESOURCES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# NEW PRODUCTS

## Focus on cryogenics, vacuum equipment, materials, and semiconductors

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

**Andreas Mandelis**

### Dry claw vacuum pump

Leybold's Clawvac CP B rough vacuum pump, a new addition to the company's Clawvac B dry claw vacuum pump series, offers precise, trouble-free operation under harsh conditions. It is suitable for use in robust procedures such as food processing, materials handling, and environmental industries, especially in processes involving particles, vapors, and contaminated gases. Due to its functional design, the powerful, energy-efficient pump is easy to handle and clean. It features a pair of stainless-steel claws that rotate in the cylinder without coming into contact or causing wear. The housing and claws can be disassembled without the need to readjust the gear control afterward. The coated, corrosion-resistant vacuum chamber is easy to clean, and a separate gearbox prevents oil from contaminating processes. A silencer reduces the noise level and allows the condensate to drain off through the opening. The Clawvac B ensures short downtimes and long service intervals: 20 000 h between oil changes and up to 48 000 h between general overhauls. ***Leybold GmbH**, Bonner Str 498, 50968 Cologne, Germany, www.leybold.com*

### Silver-filled silicone adhesive

Master Bond MasterSil 323S-LO is an addition-cured silicone that is electrically and thermally conductive and meets NASA's low outgassing specifications. Designed for bonding applications in which low stress is critical, MasterSil 323S-LO is suitable for use in vacuum environments and the aerospace, electronic, optoelectronic, and specialty OEM industries. MasterSil 323S-LO offers flexibility and toughness, with a Shore A hardness of 35–55, a low tensile modulus of less than 800 psi, and an elongation of 50–100%, measured at 24 °C. Those features allow the product to withstand aggressive thermal cycling and mechanical shock, while offering a wide service temperature range from −62 °C to 204 °C. The two-part, silver-filled compound with a volume resistivity of less than 0.003 Ω-cm has a thermal conductivity of 1.30–1.59 W/mK at room temperature. It bonds well to many substrates, including metals, composites, glass, ceramics, rubbers, and many types of plastics. MasterSil 323S-LO has an easy-to-use 1:1 mix ratio by weight and features a paste consistency with minimal flow. ***Master Bond Inc**, 154 Hobart St, Hackensack, NJ 07601, www.masterbond.com*

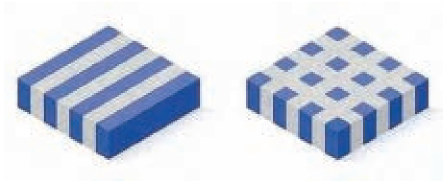
### Compact hybrid-bearing high-power turbopump

Pfeiffer has launched the HiPace 30 Neo turbopump, a vacuum pump for compact analysis systems and portable applications. According to the company, the HiPace 30 Neo is the smallest hybrid-bearing high-power turbopump on the market and has the lowest vibration level. Because of its high gas throughput and compression, the HiPace 30 Neo is suitable for light gases and has excellent critical backing pressure. The patented laser balancing technology and the good balancing quality of the rotor, which runs at up to 1500 rps, make the pump suitable for vibration-sensitive applications. It is environmentally friendly: Its compact design allows for the reduction of $CO_2$, and its intelligent sensor technology ensures the pump operates with the best possible energy input. The intelligent control system facilitates the easy interconnection of pumps: Upstream pumps and turbopumps can interact and thereby realize a complex, internet-of-things-capable vacuum system. To ensure safety and improve aging resistance, the HiPace 30 Neo also incorporates a new high-performance lubricant. ***Pfeiffer Vacuum Inc**, 24 Trafalgar Sq, Nashua, NH 03063, www.pfeiffer-vacuum.com*

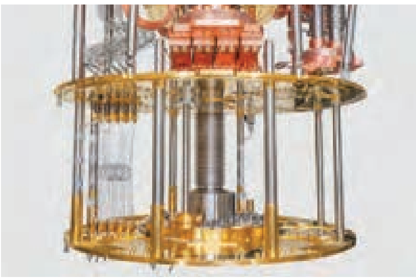
### Diaphragm gas pumps

The NMP 830.1.2 and NMP 850.1.2 configurations of KNF's NMP series of diaphragm pumps feature new direct current brushless integrated (DC-BI) pump drive technology. The DC-BI motors, manufactured in-house by KNF, allow for a compact and lightweight pump design and, according to the company, a long lifetime. KNF pumps feature extensive customization and parameterization options that, combined with the DC-BI motors, enable energy-saving features that meet the needs of various operations. Depending on the specific configuration, the state-of-the-art diaphragm gas pumps deliver flow rates up to 8.5 L/min, pressure up to 3 bar (relative), and ultimate vacuum down to 55 mbar (absolute). The NMP 830 and NMP 850 series pumps provide the fast, reliable, and accurate measurement results essential for portable gas measurement systems. Since their unique technical characteristics make them suitable for transferring hydrogen and conveying ambient air for complete energy conversion, they can be used for hydrogen fuel cell technology. ***KNF Neuberger Inc**, 2 Black Forest Rd, Trenton, NJ 08691, https://knf.com*

## Piezoelectric ceramic composites

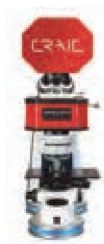


PI Ceramic has introduced a new product category, piezoceramic composites. In this technology, piezoelectric ceramics are embedded in filling polymers. The basic functionalities of piezoceramics—ultrasonic conversion and actuator technology—can thus be combined with the properties of the filling polymers. That allows for better adaptation to application-specific conditions and requirements, such as complex shapes and adjustable acoustic, mechanical, and electrical properties. To enable the best adaptation to the application, PI Ceramic offers two types of filling polymers: epoxy resins for rigid composites and softer, silicone-free polymers for highly flexible composite structures. By suppressing cross contraction and the associated vibration modes, the composites improve focusability, sensitivity, and resolution. The new composites are suitable for applications in medical technology—for example, high-intensity-focused ultrasound applications and diagnostic imaging—and in industrial applications such as flow-rate metering and nondestructive measurement. ***PI Ceramic GmbH***, *Lindenstrasse, 07589 Lederhose, Germany, www.piceramic.com*



## High-power system for 1 K experiments

Bluefors has announced its XLDHe high power (XLDHehp) system, a cryogen-free measurement system that is powered by helium-4 and delivers high cooling power for experiments in the 1 K temperature range. The XLDHehp is suitable for demanding applications such as spin-qubit quantum computing devices and single photon detectors for photonic quantum computers. The system generates high cooling power between 200 and 700 mW at 1–1.2 K and features side-loading ports for the fast exchange of experimental wiring. A large, 540 mm experimental flange and height options of 175 mm or 776 mm support a wide range of experiments. Fast turnaround options make it possible to scale up the number of experiments carried out. Powered by either two or three pulse tube cryocoolers, XLDHehp systems reach a base temperature of less than 900 mK in 12–16 h. Additional options can reduce the time to 9 h and can decrease the system warm-up time between experiments. ***Bluefors Oy***, *Arinatie 10, 00370 Helsinki, Finland, https://bluefors.com*



## Confocal Raman microscope

Craic Technologies designed its Apollo M confocal Raman microscope to characterize the composition, structure, and properties of materials with high precision at the microscale. Offering high spatial resolution and depth profiling capabilities, the Apollo M's confocal imaging system captures high-resolution 3D images of materials. Its advanced Raman spectroscopy capabilities deliver high sensitivity and signal-to-noise ratio. The microscope supports multimodal imaging techniques, including confocal Raman spectroscopy, fluorescence imaging, and color microscopy, and its intuitive software interface and automated analysis workflows streamline data acquisition, processing, and interpretation. The Apollo M confocal Raman microscope is suitable for materials research across a wide range of disciplines, including semiconductor technology, pharmaceuticals, nanomaterials, and biomaterials. ***Craic Technologies Inc***, *948 N Amelia Ave, San Dimas, CA 91773, www.microspectra.com* PT

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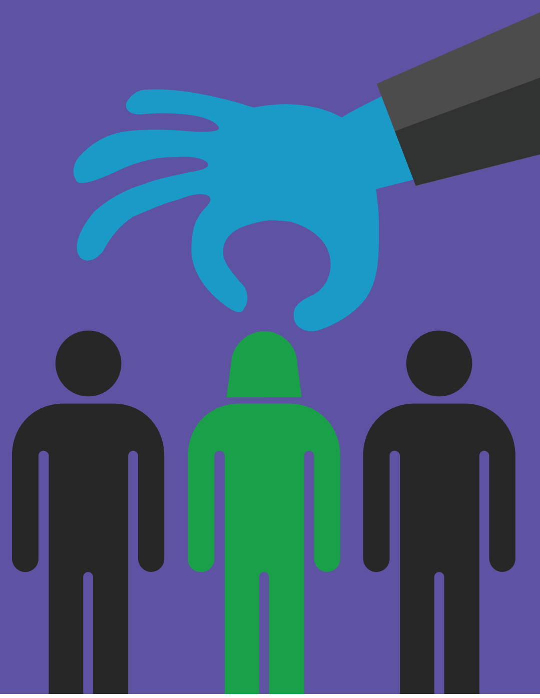

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# QUICK STUDY

**Savannah Gowen** is a graduate student and **Sidney Nagel** is an experimental soft-matter physicist and Gowen's research adviser in the department of physics at the University of Chicago. **Thomas Videbæk** is an experimental soft-matter physicist in the Martin A. Fisher School of Physics at Brandeis University in Massachusetts.



# Going with the flow in unstable surroundings

**Savannah D. Gowen, Thomas E. Videbæk, and Sidney R. Nagel**

A colorful technique allows us to better understand the development of branching patterns in fluid flow.

As children, we learn to stack simple symmetrical shapes and use them to create patterns. A sense of order and repetition sways our ideals of perfection. But, as English writer W. Somerset Maugham wrote in *The Summing Up*, "But perfection has one grave defect: it is apt to be dull."

Nature, though, is rarely dull. It is full of patterns that are imperfect or disordered. Although patterns appear at different scales and in different contexts, they often have underlying rules that govern their growth. For example, tree branches, plant roots, and river networks share similar branching features. As experimentalists, we aim to uncover the physics that governs the branching observed in nature by reproducing patterns in the controlled environment of the lab.

For branching patterns, the archetypal system of study is an unstable fluid-flow phenomenon called viscous fingering. It occurs when a less viscous fluid, such as water, invades a more viscous fluid, such as honey, in a confined space—for example, the thin gap between two plates. The inner, low-viscosity fluid contacts the outer fluid at an interface that is initially smooth. But the flow is unstable: Any small distortion, caused by a molecular-level pressure variation or even a mote of dust, becomes amplified. Those initially small perturbations eventually cause undulations to form along the interface. Small, protruding sections of the inner fluid grow faster than neighboring regions and form long fingers.

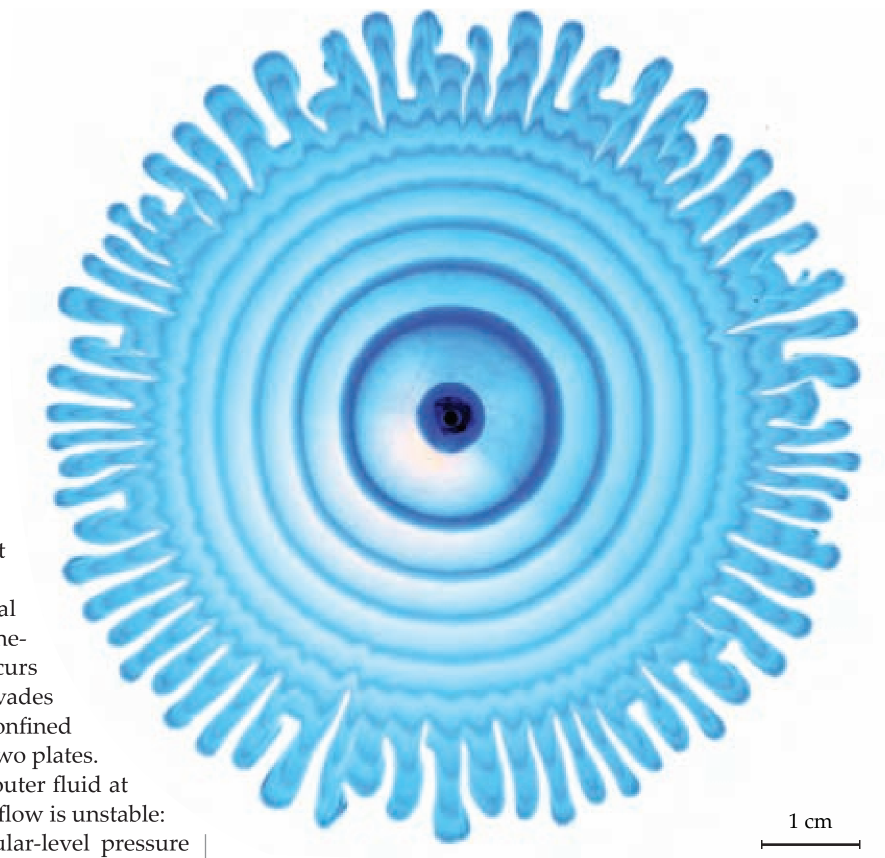


**FIGURE 1. BRANCHING PATTERNS** formed by viscous fingering. Low-viscosity inner fluid, visible in shades of blue, is injected in alternate rings into a more viscous, transparent outer fluid. Fingers grow at the unstable interface between the two fluids. Undulations along the rings of dyed fluid reveal the influence of local pressure gradients.

We can re-create such finger patterns using an experimental apparatus called a circular Hele-Shaw cell, which consists of two flat, round glass plates separated by a thin gap. The size of the gap determines the fluid confinement. In our experiments, we use two fluids that are miscible with each other so that there is negligible surface tension between them. The more viscous fluid, followed by the lower-viscosity one, is injected through a small hole in the center of the top plate. The resulting radial flow is imaged from below the plates. By dyeing one of the fluids, the boundary between the two is visible.

For decades, researchers have largely restricted themselves to observing how finger patterns form at the interface. Few have examined what happens beyond it—namely, how the

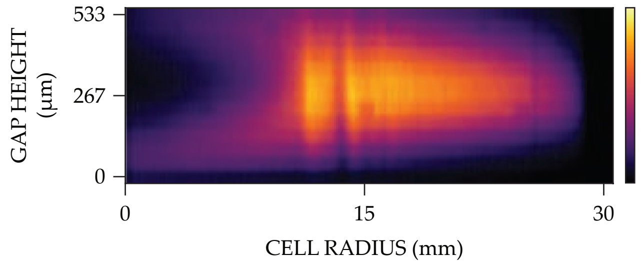


**FIGURE 2. CONFOCAL IMAGING** of a dyed fluid ring in the gap of a Hele-Shaw cell. Fluorescently dyed fluid is injected alternately with undyed fluid between two glass plates. The fluid between the gap is imaged using a confocal microscope. The aspect ratio has been exaggerated along the *y*-axis because the height of the gap is much smaller than the radius of the cell. The highest pixel intensity is observed at the center of the gap, where the dyed fluid is most concentrated.

flow of the incoming and the outgoing fluid interacts with the branching finger structures. Understanding those interactions requires probing the fluid flow everywhere in the cell. We therefore redesigned our experiments to allow us to peer at the fluid behind and the fluid beyond the patterns forming at the interface.

## Designing the technique

It can be difficult to measure flow in confined systems like the Hele-Shaw cell. In our technique, we first inject into the cell the more viscous, transparent outer fluid, which appears as the white outer region in figure 1. Then, using two syringe pumps, we alternately inject a dyed and undyed version of the less viscous inner fluid, which propagates radially outward. The two versions of the inner fluid appear as the alternating light and dark blue rings in the figure. We still see the interface between the two fluids at the boundary between the white and blue colors, but now we also see alternating rings of colored fluid behind the interface. Following the rings as they propagate outward allows us to measure the flow velocity throughout the inner fluid.

Not only does the technique create an elegant visualization of the patterns shown in figure 1, but it also allows us to isolate the flow velocity across the vertical gap between the two plates. We can use confocal microscopy to understand why that is true. A confocal microscope focuses light on a single region in the fluid to capture one pixel and then scans across the gap to create the full image. It allows us to visualize the distribution of dye at different heights in the gap. The amount of dye determines the intensity of each pixel.

Figure 2 shows a confocal image of what happens in the gap when we inject a small volume of fluorescently dyed fluid, preceded and followed by undyed fluid, between two glass plates. Drag between the fluid and the plate walls causes the dye to stretch into a parabolic shape. The highest intensity, and thus the highest concentration of dye, appears at the middle of the gap. In other words, by tracking where dye is most concentrated, we are measuring flow along the midplane of the gap. With our technique, we can observe and interpret how flow, even far from the interface, is influenced by the pattern growth.

## Memorably perturbed

Figure 1 shows something exciting: Not only do we observe the branching patterns at the interface between the fluids, but we also see an echo of that structure in the next ring of dyed fluid behind it, a smaller echo in the one behind that, and so on, until every hint of a pattern is lost in the inner rings. To understand how that happens, we follow the trajectory of dyed fluid along its journey toward the interface. The fluid emerges at the inlet and propagates radially outward as a ring with increasing circumference. Its smooth circular contour is initially unperturbed. Then, somewhere between the inlet and the interface, the perfect symmetry of the circular ring is disturbed by wavy structures that grow dramatically as the ring propagates outward.

The appearance of those imperfections indicates local pressure gradients that, although seeded at the interface, can affect flow up to several centimeters behind it. We can characterize that length and observe how it evolves dynamically with the patterns. The same persistence of local pressure variations is revealed in the outer fluid when we employ an alternate injection technique, in which the outer fluid is dyed.

The technique we developed allows us to measure the flow dynamics for a system that is otherwise hard to access by simulation or experiment. As it turns out, the tiny pressure perturbations that seed the instability cause increasing flow distortion long after the patterns first emerge and reveal a hidden length scale over which local pressure gradients matter. We suspect that may be relevant to understanding other branching phenomena.

In the end, our unstable system looks a lot more enticing than its stable counterpart, a perfect circle. All the small perturbations and disturbances added together form a natural beauty perhaps more memorable than mere perfection.

## Additional resources


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# BACK SCATTER

## Measuring violin resonances

Carleen Maley Hutchins, a mid-20th-century science teacher and luthier, sought to quantify the historically qualitative craft of violin making. This photo shows a moving-coil electromagnetic transducer applied to the wooden plate of a violin. The transducer allowed Hutchins to measure the vibrating plate's resonant frequencies. She determined that the best-sounding violins, including the ones played by famous violinists, have top and bottom body plates characterized by resonances that are within a whole tone of either of the instrument's two middle strings—on a traditional violin, the A string is tuned to 440 Hz and the D string to 294 Hz.

When building a stringed instrument, a luthier can change the resonances of the instrument's top or bottom plate by shaving wood from its underside. When two plates are paired to create the body of the instrument, their resonances either complement each other to create a rich, full tone or work against each other to deaden the tone. Rather than pairing plates by ear through trial and error, Hutchins measured and tuned the target resonances of each plate. She applied her deep understanding of the instrument to develop the violin octet (see the article by Hutchins, Physics Today, February 1967, page 23). The family of violins—from the largest, a contrabass, to the smallest, a treble violin—spans the tonal range of the piano, and the instruments have acoustical properties different from the viola, cello, and bass. (Courtesy of the AIP Emilio Segrè Visual Archives, Physics Today Collection.) —EMW