PHYSICS TODAY

November 2022 • volume 75, number 11

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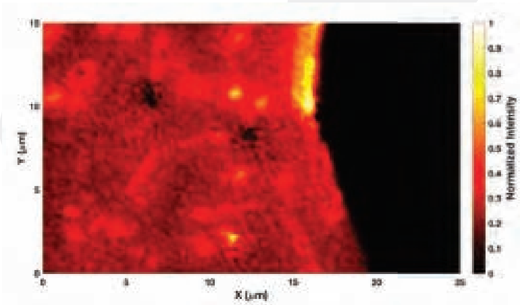

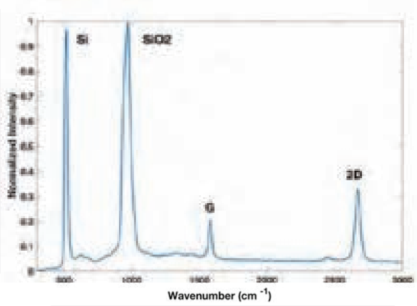

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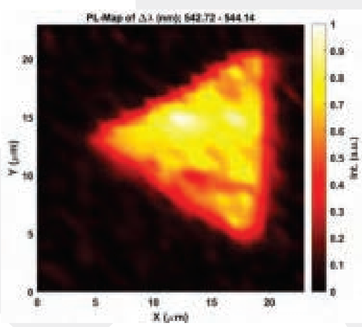

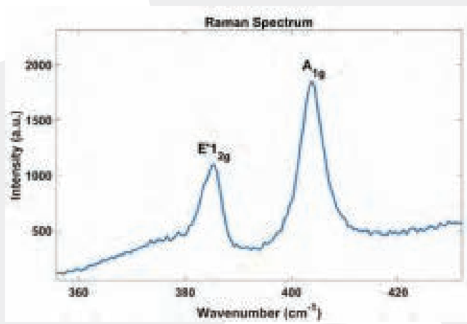

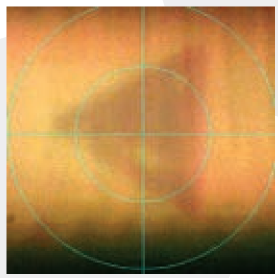

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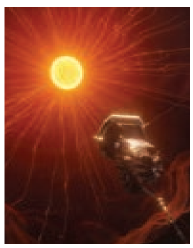
FEATURES



ON THE COVER: No spacecraft has traveled closer to the Sun than NASA's *Parker Solar Probe*. It is the fastest object ever built and will reach an orbit within 10 solar radii of the Sun by December 2024. On **page 28**, Nour E. Raouafi, the mission's project scientist, presents early findings about the Sun's coronal magnetic field, the solar wind, and energetic particles from solar activity. (Artist rendering courtesy of NASA/Johns Hopkins APL/Ben Smith.)

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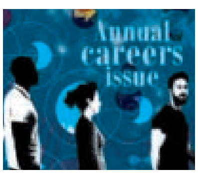

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Careers 2022

Curious about jobs in the public sector? Our expanded online edition of last month's careers issue includes a Q&A with a patent examiner, a profile of an organization that highlights opportunities in science policy, and a breakdown of where physical scientists work in the federal government.

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Geochronology

To determine the age of rocks that are millions or billions of years old, geologists use a radiometric dating technique that relies on a supply of radioactive isotopes. As Sarah Scoles reports, that supply comes largely from the production line that began during the World War II effort to build a nuclear bomb.

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#BlackInPhysics Week

Held on 24–28 October, the third annual #BlackInPhysics Week amplifies the work of Black physicists and reveals a more complete picture of what a physicist looks like. A new series of essays commissioned for this year's event explores the theme of joy and the difficulties in achieving it.

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Harvard SEAS values diversity among its faculty, is committed to building a culturally diverse intellectual community, and strongly encourages applications from women and underrepresented groups.

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Commentary

The benefits of being a maverick

Paradigm shifts start with revolutionary ideas. Thomas Kuhn, one of the most influential philosophers of the 20th century, coined the term "paradigm" as an agreed-upon state of knowledge and then went on to describe how that state is ruined as exceptions accumulate. In Kuhn's model,[1] emerging exceptions lead to the replacement of old paradigms with new ones, and as a result, knowledge leaps forward and progress is made. It is a process driven by mavericks and stemming from dissent.

THE PHILOSOPHER ANAXAGORAS, by Giovanni Battista Langetti, oil on canvas (c. 1660), Philadelphia Museum of Art. (Purchased with the W. P. Wilstach Fund, 1904/public domain.)

Dissent as part of the process

In science, dissent is not a drawback; it is a necessity. The mathematicians Edward Kasner and James Newman write that "the testament of science is so continuously in a flux that the heresy of yesterday is the gospel of today and the fundamentalism of tomorrow."[2] The courage to say no to scientific authority, to contradict widely accepted knowledge, to question and disrupt the status quo is essential to science's ability to move forward.

In a 1675 letter to Robert Hooke, Isaac Newton wrote the famous phrase "If I have seen further it is by standing on the shoulders of Giants." Newton paraphrased earlier uses of that sentence to make a point: Mavericks can produce transformative change only thanks to a vast body of incremental research done quietly, with no fame or recognition, and with no front-page news. In science, the incremental progress of many enables the transformative actions of individual mavericks.

And the history of science is rife with outstanding mavericks. In the fifth century BCE, the Greek philosopher Anaxagoras suggested heavenly bodies are made of stones snatched by a rotating ether. Arrested and sentenced to death for his claims about the Moon and the Sun, Anaxagoras was saved by his friend Pericles, a powerful statesman, and instead was exiled. The revolutionary progress made by Anaxagoras spurred some of humanity's earliest attempts at understanding the order of the universe and the transition from chaos to order through motion, an idea still in use today.

Nearly two millennia later, a different paradigm described Earth as a motionless object in the center of the universe. The work of Nicolaus Copernicus (1473–1543), embraced by Giordano Bruno (1548–1600) and supported by Galileo Galilei (1564–1642), provided a new "heliocentric," or Sun-centric, theory, backed up by hard evidence showing that the Sun is in the center of our solar system and Earth is one of the planets orbiting it. (See the article by Mano Singham, PHYSICS TODAY, December 2007, page 48.)

Such dissent is not exclusive to the early days of science. Scientists previously believed continents were unmoving bodies. Then to explain the matching large-scale features and outlines of separate continents, in 1912 Alfred Wegener (1880–1930) suggested that continents are, in fact, moving.[3] His claim, introducing plate tectonics to geology, was met with ridicule and hostility. Wegener was seen as proposing a "footloose" hypothesis that took "considerable liberty with our globe," as the prominent geologist Rollin T. Chamberlin of the University of Chicago wrote.[4] Despite the ridicule, Wegener's findings helped pave the way for modern geoscience.

The role of quantum mavericks

That trend continues. David Wick expertly describes a similar situation in his book *The Infamous Boundary: Seven Decades of Heresy in Quantum Physics* (1995). The prominent leaders of the field, such as Albert Einstein, refused to accept quantum theory in its entirety. Interestingly, one can find dissent, or at least strong polarization of opinions, in quantum physics almost continuously from the early 20th century to the present.

A good example is the surprising lack of a consensus—or fundamental understanding—of quantum mechanics. Among the currently discussed and often mutually exclusive interpretations of quantum mechanics that one can find are the Copenhagen, many-worlds, hidden-variable, spontaneous-collapse, informational, relational, and transactional interpretations, along with many others. Sessions on the topic at annual meetings of the American Physical Society are among the most attended, and they always lead to fascinating disputes and sometimes to heated debates. While debates about fundamentals continue, new areas of dissent are born, as scientists discuss answers to such questions as "Can we build a fully functional quantum computer that demonstrates an advantage over a classical one?" and "Can we use topological properties to build such a quantum computer?"

In the field, the coexistence of dissent and actual transformative progress is second to none. That excitement continues today, and it is fascinating to watch its overarching societal consequences, including the 2018 passing of the National Quantum Initiative Act; the fostering of quantum information science and engineering research; and the rise of the second quantum revolution, which targets the creation of quantum technology. Born out of—and continuously generating—dissent, coordinated by collaborative efforts, and enriched by the incremental work of many, the paradigm breaking and ongoing race in fundamental quantum research may one day change our lives the same way semiconductors have.

Paradigm-breaking revisited

The mavericks in the history of science may have paid their price, but they also provided necessary, transformative, and disruptive leaps in the progress of science. We owe them a debt of gratitude. We also owe such debt to their adherents, who explored the details of novel theories, filled the holes in reasoning, and pushed the boundaries of knowledge forward through the hard daily work of incremental research, which paved the way for the next great disrupters.

There is more to this story. Perhaps to improve the way we do science, we could find a way to break the paradigm of paradigm breaking and make better use of brilliant minds. Avoid the drama, use scarce resources wisely, and accelerate progress by coupling collaborative efforts with risky transformative ideas. Leadership in science and technology depends on the broad acceptance of risk and on our ability to elevate paradigm breaking to the norm.

Steps forward

Three steps are necessary to achieve such leadership: Create sustainable conditions for fundamental research that fuels translation into applications, accept scientific dissent and high risk, and embrace diversity.

On the tree of discovery, fundamental research forms the roots, and translation is the sweet fruit. We know beyond reasonable doubt that without fundamentals, characterized by lack of immediate application, there simply cannot be future applications. Examples of such a connection abound, including the transistor, the internet, and the smartphone. In a healthy science and engineering ecosystem, expanding and accelerating translational efforts is coupled with a careful and proportional treatment of fundamental and applied research.

Acceptance of risk is already practiced by several government agencies, including NSF, where I work and where the concept of high-risk, high-reward projects is openly embraced. Risk is difficult to assess, yet a discussion of what constitutes risk within a given structure is always the starting point, alongside identifying and selecting projects of high transformative potential while maintaining the ability to fund necessary incremental progress. It is a fine and complex balance that is under constant and careful adjustment.

The addition of a focus on diversity elevates the other two steps. Diversity is the source of rich, vibrant, and fruitful discussion, a cornerstone of modern science. Only through bringing together and connecting researchers from different backgrounds, cultures, disciplines, and views can we make progress. There is a tremendous and heavily underutilized potential residing in institutions that host groups historically underrepresented in the science workforce.[5] Such groups require and deserve well-planned and sustained support.

In the past, society would punish mavericks, only to later reap the benefits of their paradigm-breaking discoveries. In the future, we may choose to accept dissent, risk, diversity, and balance and thus nurture an army of mavericks to lead the way. The best time to break Kuhn's paradigm of paradigm breaking may be now.

Disclaimer: Any opinions, findings, and conclusions or recommendations expressed in this commentary are those of the author and do not necessarily reflect the views of NSF.

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LETTERS

More on the quantum measurement problem

Although I have neither an objection to nor an endorsement of David Mermin's major premise in his Quick Study, "There is no quantum measurement problem" (Physics Today, June 2022, page 62), I would like to make several contextual points.

Mermin's argument has an extensive history, along with a comparable history of rebuttal. Five decades ago Max Jammer wrote that "measurements in quantum mechanics are no more or less problematic than in classical physics, for the Hilbert space vector is only a purely formal device for relating the statistics associated with these arrangements to the physics of observations in classical physics." That seems like a condensed version of the argument Mermin presents. On the following page, however, Jammer notes that a "problematic aspect whose serious implications were only gradually understood was the fact that as long as a quantum mechanical one-body or many-body system does not interact with macroscopic objects, as long as its motion is described by the deterministic Schrödinger time-dependent equation, no events could be considered to take place in the system."[1]

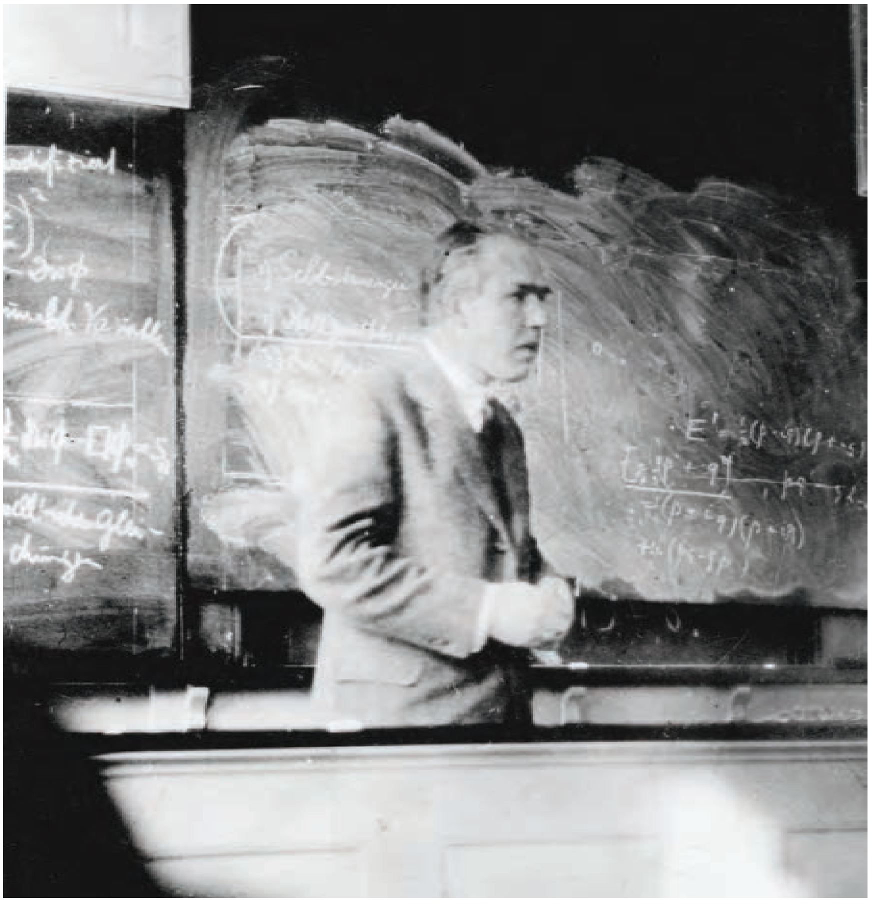
Regarding the quotations from Niels Bohr, Mermin's point is entirely valid and represents Bohr's position accurately, but Bohr's thought is always subtle and difficult to capture completely. Another quotation from Bohr, which is consistent with everything else he wrote, is, "The decisive point is that in neither case does the appropriate widening of our conceptual framework imply any appeal to the observing subject, which would hinder unambiguous communication of experience."[2] That quotation seems inconsistent with Mermin's paragraph that includes the passage "Why should I insist that *my* interpretation of science, which *I* use to make sense of the world that *I* experience, should never make any mention of *me*?" Bohr always insisted that his framework was a rational "generalization" of classical objectivity.

The last and most conceptually important point concerns the ontological status of probability. I don't necessarily disagree with Mermin and Bruno de Finetti, but it is by no means obvious that they are correct either. David Hawkins, for example, begins 50 pages of rigorous analysis with a brief statement of a major premise.

> The obvious and natural interpretation of probability in this context is that it introduces, not something that has to do with the nature of the physical system, but something that has to do with the incompleteness of our knowledge. . . .
>
> But this opinion turns out to be false. Ignorance of dynamical regularity may be a *motive* for resorting to probabilities, but it does not explain the probabilities to which we resort.[3]

Another example can be found in Jammer's well-known historical account of quantum theory: "For Einstein the notion of probability . . . was the traditional conception of classical physics, a mathematical objectivization of the human deficiency of complete or exact knowledge but ultimately a creation of the human mind. . . . For Born probability, as far as it was related to the wave function, was not merely a mathematical fiction but something endowed with physical reality."[4]

Of course, such examples don't mean that Mermin's position is incorrect, but I do think that they demand a better argument than a comparison to "Fairies and Witches." I am confident that Mermin has such an argument, and I look forward to reading it as I continue working toward a coherent position on the unresolved interpretational issues of quantum theory.



NIELS BOHR giving a lecture in Copenhagen in April 1929. (Photograph by Samuel Goudsmit, courtesy of the AIP Emilio Segrè Visual Archives, Goudsmit Collection.)

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In his June 2022 Quick Study (page 62), David Mermin argues that "the quantum state of a system expresses only the belief of the particular physicist who assigns it to the system." Applying that to quantum measurements, he finds that "the acquisition of further information by that physicist . . . can lead to an abrupt change in those probabilities and thus to an updating of the quantum state that the physicist uses to represent them. There is no quantum measurement problem."

But wavefunctions have been collapsing ever since the Big Bang, with no assistance from physicists. An apparatus's display of a measurement outcome occurs even if the experimenters happen to be out of the room. When a cosmic-ray proton strikes a sand grain on Mars and moves the grain, a quantum measurement occurs and the proton's wavefunction collapses regardless of the absence of humans.

Roger Carpenter and Andrew Anderson of the University of Cambridge performed a "Schrödinger's cat" experiment that demolishes Mermin's interpretation. Instead of connecting a Geiger counter to a cat-killing device, they mercifully connected it to a hammer that would fall without harm. Their strategy was to split information about the experimental result between two observers in such a way that neither observer can know the outcome. The observers learn the outcome later by sharing their information. The question is then, Did the hammer fall at the time of the experiment or later, when the observers became conscious of the outcome? The result: The hammer fell when the nucleus decayed, not later when the observers became conscious of the outcome. I think nearly all physicists would have predicted that. My hat is off to Carpenter and Anderson, who reported it with a straight face.[1]

Humans and their consciousness have nothing to do with quantum physics. Photons, electrons, and the like, as well as their states, are real configurations of fields that have existed throughout the universe since the Big Bang.[2]

Nevertheless, I agree with Mermin's title: There is no quantum measurement problem, because quantum physics, with no special interpretation and without a collapse postulate, logically implies that superpositions collapse nonlocally to a single definite outcome.[3]

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Sean Carroll's July Quick Study, "Addressing the quantum measurement problem" (page 62), brings up the following question: Does the wavefunction still obey the Schrödinger equation when a measurement is made? A system being measured (or interacting with its environment in any other way) is actually a subsystem, and a subsystem is properly described by a reduced density matrix. The density matrix for an entire system corresponds to a wavefunction—that is, to a pure state—but the density matrix for a subsystem does not necessarily correspond to a wavefunction. The reduced density matrix of a subsystem may correspond to an impure state, also called a mixture or an incoherent combination,[1] which does not have well-defined pure-state content.[2] In the words of Kurt Gottfried and Tung-Mow Yan, "systems in the real world are rarely in pure states."[3]

The proper way to discuss a measurement is not using a wavefunction but rather a reduced density matrix. The density matrix of a pure state evolves according to the Liouville–von Neumann equation, which is equivalent to the unitary evolution of the wavefunction by the time-dependent Schrödinger equation. For a subsystem (that is, for any system except the entire universe), the reduced density matrix evolves according to the nonunitary Liouville–von Neumann equation, which has an additional contribution causing decoherence and dissipation.[4] The nature of the measurement—or, more generally, the nature of the subsystem–environment interaction—selects a preferred basis, called the pointer basis, and the subsystem decoheres into an effectively classical mixture in the pointer basis. (See the article by Wojciech Zurek, PHYSICS TODAY, October 1991, page 36.)

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Among Art Hobson's and Gregory Derry's letters and Sean Carroll's July Quick Study (page 62), only Derry's letter addresses the point I was trying to make in my June Quick Study (page 62): Viewing probabilities as personal judgments eliminates the quantum measurement problem and enables one to make better sense of quantum mechanics.

Hobson's letter expounds his own realistic view of quantum states and their collapse. It belongs with the three examples I mention that eliminate the physicist from the story.

Carroll takes what I write about the consequences of a personalist interpretation of *probability* to be an example of an epistemic interpretation of *quantum mechanics.* That misses my point.

In 1926 Max Born noted that the content of quantum states was the probabilities that they enabled one to calculate. It is strange that after thus elevating probability to a new and foundational role, no physicists then or for the next three-quarters of a century thought it important to reexamine the meaning of probability. For most physicists, probabilities are user-independent frequencies, but for most statisticians, they are guides to action by the person who made the probability assignment. If physicists in 1926 had held a personalist view of probability, it would have *required* them from the very beginning to hold a personalist ("epistemic") view of quantum states. There would have been no need for an "interpretation."

I have comments on several issues raised by Derry. Max Jammer and many others have indeed written for over half a century that quantum states are nothing more than formal devices for encapsulating probabilities of observation. But nobody before Carlton Caves, Christopher Fuchs, and Rüdiger Schack ever added that *if* probabilities are viewed as personal judgments of the person who assigns them, then that same view *must* be taken of quantum states.

Derry quotes Niels Bohr's statement that he does not "appeal to the observing subject." Later in that paragraph, Bohr adds that "all subjectivity is avoided by proper attention to the circumstances required for the well-defined use of elementary physical concepts."[1] That does contradict my reading of the two Bohr quotations that appear in my Quick Study. By "experience," Bohr must have meant collective rather than individual experience. I doubt that Bohr took a personalist view of probability. That Bohr, however, *was* a personalist is argued interestingly by Ulrich Mohrhoff.[2]

I quote Bruno de Finetti on "Fairies and Witches" only to give a poetic statement of the unfamiliar view of probability that I am inviting physicists to examine. My point is that *if* de Finetti is correct, then it would profoundly affect our understanding of quantum mechanics. For me, the illumination it sheds on the interpretation of quantum mechanics is all by itself a compelling reason for adopting a personalist view of probability.

The expansion of my argument that Derry looks forward to reading can be found in the article of mine[3] cited in my Quick Study along with the rather more technical article[4] by Fuchs and Schack that inspired mine.

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I appreciate David Mermin's letter. There is, of course, an ongoing debate in the philosophy of probability about whether probability is best thought of as objective or subjective. Experts continue to disagree, which suggests that we might want to acknowledge a "problem" in that wider-than-quantum context, even if we think we have the right answer.

Whatever our stance is toward probability, we can still wonder about reality (ontology). People disagree about that too, and there are respectable but mutually incompatible possibilities—which represents another problem.

In particular, one can be a subjectivist about probability (as I am myself!) within different approaches to the quantum measurement problem. Both Everettian and Bohmian quantum theories invoke subjective probabilities, concerning which branch of the wavefunction you are on (Everettian) or the values of the hidden variables (Bohmian), although they treat quantum measurements differently. Taking a subjective stance toward probability does not by itself resolve the measurement problem.

Objective-collapse models, by contrast, sit more comfortably in (as the name suggests) an objective picture of probability. To the extent that such models are empirically viable, it seems wrong to deny the existence of the quantum measurement problem, since, again, they address it very differently than other models.

I am optimistic that the quantum measurement problem is solvable and will be solved, but I am wary about prematurely declaring victory.

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Polariton condensates show their nonequilibrium side

Although similar to ultracold atomic gases, fluids of quasiparticles in a solid have more in common with forest fires.

Can a Bose–Einstein condensate exist at room temperature? If it's made of atoms, not by a long shot. To coax a gas of bosonic atoms to pile up in their quantum ground state, researchers must cool the gas to within a few millionths of a degree of absolute zero.

More accessible condensates can be made by replacing the atoms with polaritons: light–matter quasiparticles that form when photons in an optical cavity couple to electronic excitations in a solid. Because the quasiparticles have such low effective masses, their quantum effects set in much more easily.

Polariton condensates form at standard cryogenic temperatures—around 4 K, the temperature of liquid helium—and under some circumstances, even at room temperature.[1] The warmer conditions make it easier to study the physics of Bose–Einstein condensation and to pursue potential technological applications (see the article by David Snoke and Jonathan Keeling, Physics Today, October 2017, page 54).

But polariton condensates aren't quite the same as atomic Bose–Einstein condensates. Unlike stable atoms, polaritons persist for only as long as their constituent photons remain trapped in the cavity—usually on the order of a few picoseconds. To keep a polariton condensate from decaying away to nothing, researchers have to keep repumping it with fresh photons. As a result, the condensate never thermally equilibrates; at best, it approaches a steady state.

Does it matter whether a polariton condensate is populated with new photons or old ones? Jacqueline Bloch (University of Paris–Saclay), Léonie Canet (Grenoble Alpes University), and colleagues have now shown that it does: Because of its nonequilibrium nature, a polariton condensate behaves in an observably different way from its equilibrium counterparts.[2]

The behavior follows the form predicted by the Kardar-Parisi-Zhang (KPZ) model, which describes a wide variety of nonequilibrium systems—but until now, only classical ones. The polariton condensate work is the first observation of KPZ physics in a quantum system. It also offers a new way to study phenomena in nonequilibrium statistical mechanics that have stymied theorists and experimenters alike.

Universal fluctuations

When Mehran Kardar, Giorgio Parisi, and Yi-Cheng Zhang developed the KPZ model in 1986, they had in mind a specific type of system: the interface of a stochastically expanding or contracting classical object or region.[3] Although a large number of seemingly disparate interfaces fit the bill—including those of growing crystals, aggregating colloidal clusters, bacterial colonies, statues being eroded by acid rain, and burnt regions of forest or grassland—they're all fundamentally governed by the same physics. That is, they belong to the so-called KPZ universality class.

Kardar, Parisi, and Zhang formulated

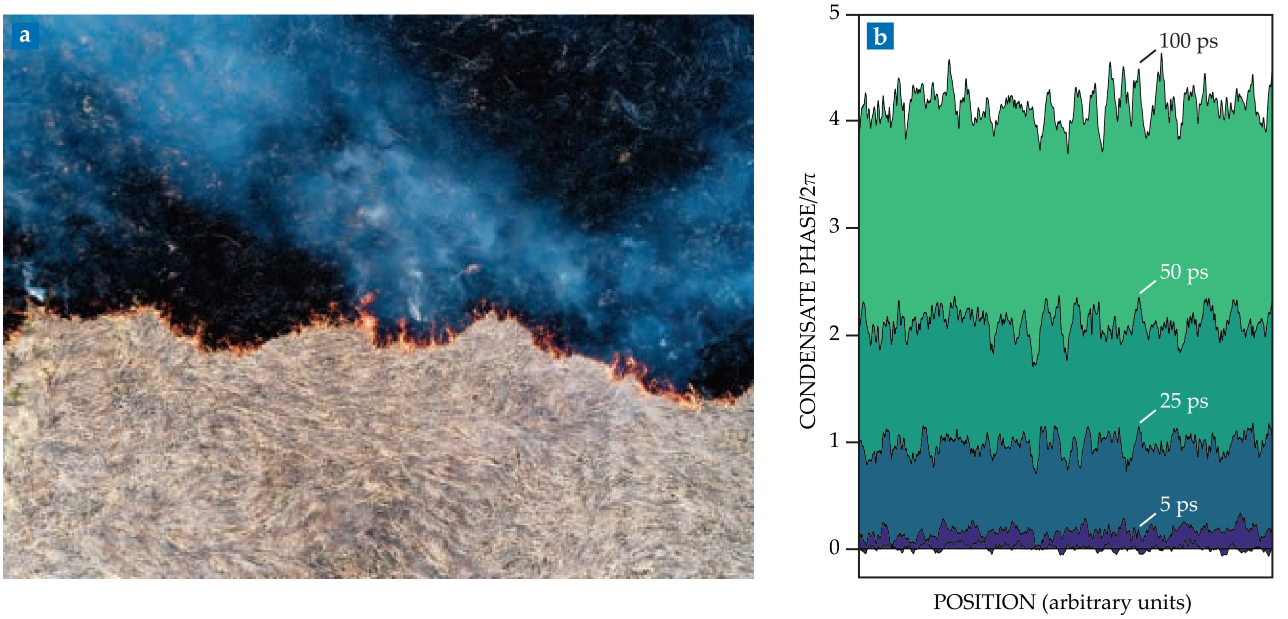

FIGURE 1. THE JAGGED EDGE of the boundary between burnt and unburnt regions of grassland **(a)** is a consequence of nonequilibrium statistical physics. The fluctuations' scale and shape depend crucially on the fact that the fire is expanding, not standing still. The evolving phase of a polariton condensate **(b)**, shown here as snapshots from a simulation, follows the same mathematical form, as described by the Kardar-Parisi-Zhang model. (Panel a by Nordroden/Shutterstock.com; panel b adapted from ref. 2.)

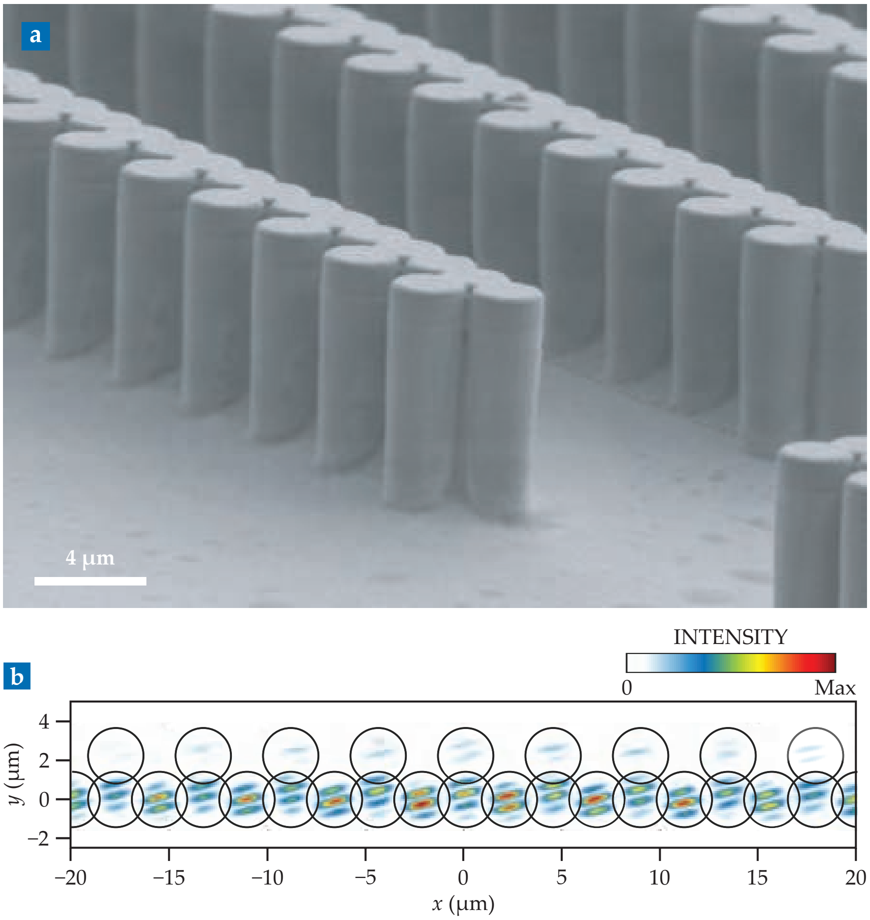

FIGURE 2. A ONE-DIMENSIONAL polariton condensate offers the best comparison to existing Kardar-Parisi-Zhang theory. **(a)** The condensate is confined to a row of semiconductor pillars. Each pillar is made of layers of different materials, some of which form the mirrors that trap the photons, others of which form the quantum wells that host the electronic excitations. **(b)** Michelson interferometry of the light emitted by the condensate yields a series of interference patterns like this one, from which researchers can extract the correlations in the condensate phase across time and space. (Panel a courtesy of C2N/CNRS; panel b adapted from ref. 2.)

a partial differential equation that describes the interface evolution as a competition between smoothing from diffusion or surface tension, roughening from random noise, and nonlinear growth normal to the surface. From that equation, they started to derive the mathematical properties of the interface shape. In particular, the lumps and bumps of a KPZ interface, such as the wildfire front shown in figure 1a, are characterized by certain power-law correlations that differ from those that arise in systems without the nonlinear growth term. The KPZ model therefore captures the distinctions between a dynamic, growing system and an equilibrium one.

But discovering all the implications of the KPZ model has taken a decades-long effort that's still not complete. On the mathematical front, the model's central equation wasn't even well defined: It's a differential equation, but the random noise it introduces is nondifferentiable. The analytical tools for dealing with stochastic noise in linear differential equations existed back in the 1980s, but it wasn't until 2013 that mathematician Martin Hairer found an approach that would work for the nonlinear KPZ equation. For his work, Hairer was awarded the Fields Medal in 2014.

On the experimental side, it's extremely challenging to measure an interface's time evolution—by its very nature, an irreversible and irreproducible process—in enough detail to compute its statistical properties. Although the characteristic power-law correlations were observed in many systems shortly after Kardar, Parisi, and Zhang's original work, only in 2010 did Kazumasa Takeuchi and Masaki Sano perform a comprehensive analysis of the scaling behavior and fluctuations of a growing interface in a turbulent liquid crystal.[4]

Today, the KPZ model is well understood in one dimension—that is, for a linelike interface working its way across a planar landscape—but in higher dimensions, little is known. Simulations have offered some insight into the 2D KPZ model. But despite numerous efforts, detailed experiments on 2D interfaces of growing 3D objects are almost entirely absent, and the 2D KPZ equation is unsolved.

Phase transition

Polariton condensates aren't characterized by interfaces, and they bear little resemblance to other systems in the KPZ universality class. But in 2015 two teams of theorists predicted that the mathematics of the KPZ model should describe the evolving phase of a polariton condensate wavefunction.[5] Figure 1b shows a simulation of what it might look like. As time progresses, the average phase advances at a constant linear rate. But the randomness introduced by the photon loss and repumping means that the phase picks up some local fluctuations, just like in any other KPZ interface.

The phase isn't directly observable, but its correlations can be measured through Michelson interferometry: The light emitted by the condensate is passed through a beamsplitter, one of the beams is sent down a delay line and back, and the beams are recombined. If the time to traverse the delay line is, say, 50 ps, the intensity of the recombined beam measures the correlation of the phase at time t with the phase at time $t + 50$ ps. The spatial correlations, meanwhile, can be measured directly from the spatially resolved interference pattern. By varying the length of the delay line, one can therefore study the functional form of the phase correlations and test it against the KPZ prediction.

That was the basis of Bloch, Canet, and colleagues' approach. To best compare with existing KPZ theory, they used a 1D polariton condensate confined to the row of micropillars in figure 2a. The pillars are made of layers of different semiconductor materials, some of which act as mirrors to trap the photons and others of which form the quantum wells that host the solid-state excitations. An example of the measured interference pattern is shown in figure 2b.

"The biggest challenge was mapping the observations onto the theory," says

Bloch, "to make sure we were measuring the right thing." Canet elaborates: "Polariton physics is quite far from statistical physics, and we needed to draw on expertise from various communities just to know what the relevant observables were and how to disentangle KPZ physics from other effects." With Bloch's experience with polariton experiments, Canet's expertise in KPZ theory, and collaborator Anna Minguzzi's knowledge of the theory of Bose–Einstein condensation, the team was able to confirm that the polariton condensate's phase correlations did indeed adhere to the predictions of the KPZ model.

Confounding vortices

A natural next step is to extend the work from one dimension to two. It's a lot easier to measure correlations in the phase of a 2D polariton condensate than in, for example, the 2D surface of a 3D expanding forest fire. Polariton condensates might seem to be a gift to the KPZ universality class to launch the model into the next dimension.

But before that can happen, researchers will need to fully understand a complicating factor that distinguishes polariton condensates from other KPZ systems. Whereas the height of a physical interface can be any real number, phase takes values only between 0 and 2π, so a phase of π is the same as a phase of 3π, 5π, 7π, and so on.

A 2D polariton condensate can therefore host phase vortices, where traveling around a closed loop picks up a phase change of some multiple of 2π. The condensate can undergo a phase transition (the Berezinskii-Kosterlitz-Thouless transition; see PHYSICS TODAY, December 2016, page 14) in which vortex–antivortex pairs form and separate. And the vortex dynamics can influence the measured phase correlations, potentially overwhelming the KPZ effects.

Because closed loops don't exist in one dimension, it might seem that the researchers haven't yet encountered any vortices. But to their surprise, they found that they have. When they simulated the phase dynamics in 1 + 1 dimensions (that is, one space dimension and one time dimension), vortex–antivortex pairs did show up—and the pairs didn't necessarily disrupt the KPZ dynamics. When the vortices are sparse enough, the signature KPZ fluctuations still shine through.

The researchers have some ideas for how to lessen the vortex effects in a 2D condensate by shaping the semiconductor lattice that hosts it. But because so little is known about KPZ physics in higher dimensions, it's hard for them to even speculate about what they might find. "The polariton condensate is really different from an equilibrium Bose–Einstein condensate, and it is far richer than a classical growing interface," says Canet. "It's essentially a new state of matter—a new object—and that could lead to some really different applications."

Johanna Miller

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The behavior of thin curved sheets is ironed out

Two simple geometric rules predict the wrinkle patterns of curved surfaces that are flattened.

Cartographers have long contended with the distortions in a map when the curved two-dimensional surface of Earth is projected onto a flat plane. The Mercator projection, for example, makes landmasses and other features far from the equator appear larger than they really are. Equal-area projections, on the other hand, distort the shapes of geographic features.

When curved surfaces are flattened, wrinkles form because of the mismatch in lengths on a curved surface and those on a flat plane. Nonlinear mechanics and tension-field theory do a good job of describing wrinkles made by tension acting on a shell—that is, a curved sheet. The tension partially stabilizes the crests and troughs of a wrinkle. But the approach fails to explain why wrinkle patterns appear when there's no external tension at all, such as when an elastic sheet that's just a few tens of nanometers thick is confined to a spherical substrate.

Ian Tobasco (University of Illinois at Chicago), Joseph Paulsen (Syracuse University), Eleni Katifori (University of Pennsylvania), and their colleagues recently considered the issue from a mathematical angle. The simple set of geometric rules they developed are an exact solution for the wrinkle patterns formed on flattened, curved sheets. Reassuringly, the rules' predictions agree with numerous experiments and simulations.[1]

FIGURE 1. RANDOM WRINKLES formed on this thin sheet with a diameter of 42 mm. It was cut from a curved elastic sphere with a radius of curvature of 77 mm before being placed on a flat liquid surface. Other shapes form ordered wrinkle patterns. Both types of patterns can now be predicted with a simple pair of geometric rules. (Courtesy of Monica Ripp, Paulsen Lab, Syracuse University.)

Isosceles triangles

For the last several years, the researchers had been independently studying wrinkle patterns in shells. In 2017, for example, Desislava Todorova and others in Katifori's group found that the wrinkle patterns that form on thin elastic sheets share similar physics to stripe-patterned liquid crystals.[2] Around the same time, Graham Leggat and Yousra Timounay, working in Paulsen's group, succeeded in manufacturing ultrathin curved sheets in the lab. And Tobasco was beginning to develop a mathematical framework to explain the phenomena.

"But the bigger story started to emerge once we crossed paths at a SIAM [Society for Industrial and Applied Mathematics] meeting in summer 2018," says Paulsen. "We realized that our ideas and results could be combined into something larger." The collaboration considered the wrinkles that would form on a shape that was cut out of a thin curved sheet and then confined to a planar liquid surface. Some regions of the sheets had ordered repeating structures and others, like those in figure 1, were more disordered.

Despite the seeming complexity of the wrinkles, the researchers found that the patterns could be predicted using two rules. For negative-curvature shells—think of a horse saddle, for example—the first rule predicts that wrinkles form along line segments perpendicular to the shell boundary, as shown in blue in figures 2a and 2d. The wrinkles meet along the medial axis, defined as the set of points that have two or more closest edge points. Notably, those segments make up the equal legs of isosceles triangles (figures 2b and 2e).

The second rule predicts that for globes and other positive-curvature surfaces (figures 2c and 2f), wrinkles form along the opposite legs (yellow) of the isosceles triangles. As a result, the wrinkle patterns in positively and negatively curved sheets are related: The pattern in one shell can be used to deduce that of its oppositely curved twin. "This reciprocal relationship was one of the most surprising observations," says Tobasco.

The isosceles triangles predict the location of the areas with ordered wrinkle patterns, even for nonuniformly curved surfaces, like an egg. The exact amplitude of the wrinkles' crests and troughs depends on the shell's specific curvature

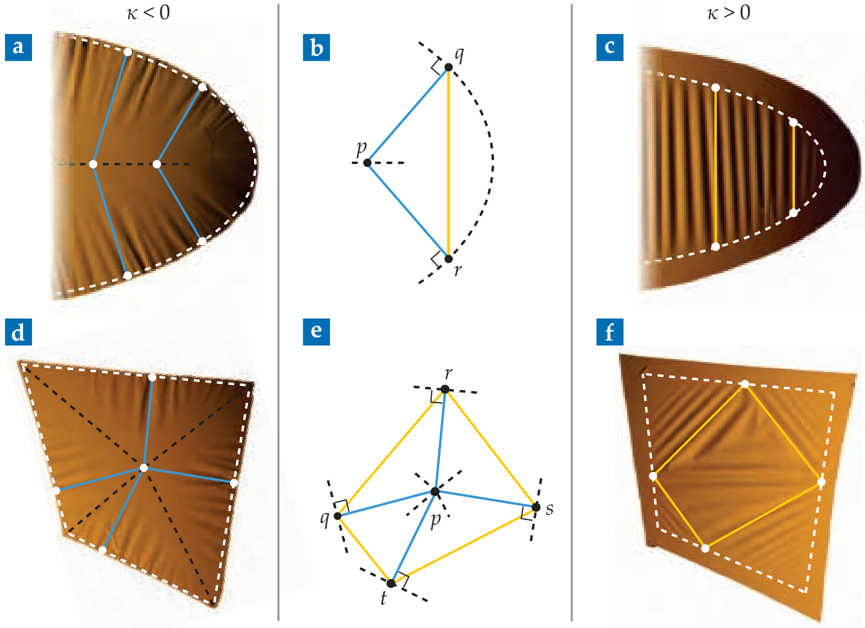

FIGURE 2. THIN CURVED SHEETS that are pressed onto a flat surface often exhibit ordered wrinkle patterns. **(a, d)** For sheets with negative curvature κ, wrinkles form along line segments (solid blue lines) that follow the shortest path to the sheet boundary (dashed white line) from a medial axis (dashed black line)—the set of points that have two or more closest edge points. **(b, e)** The line segments form the two equal-length sides of isosceles triangles. **(c, f)** Sheets with positive curvature produce wrinkles that form along the triangles' opposite legs (solid yellow lines). The area bounded by the yellow polygon in panel f is characterized by disordered wrinkle patterns. (Adapted from ref. 1.)

and some other parameters, but the overall layout of the wrinkle pattern depends only on the sign of the curvature.

Disordered wrinkle patterns also follow the rules. The disordered areas are reciprocally related to a point on the medial axis that has three or more closest boundary points, and the area is bounded by the yellow polygon in figures 2e and 2f. Although the statistics of the disordered patterns can't be predicted, the geometric rules do identify their locations on the cutout shape.

Smashed glass

To test the predictions of the new geometry-based rules, Paulsen, Leggat, and Timounay spin-coated polystyrene films onto curved glass surfaces. Then they observed the wrinkles that formed when curved sheets of various shapes were cut from the films and subsequently placed over a flat liquid surface.

"We started working with concave glass lenses, which are well controlled and could be purchased in a variety of curvatures," says Paulsen. "However, it turned out to be very difficult to separate the shells from these surfaces. So we had to develop a protocol for peeling the film off the substrate without tearing it or damaging it in any way."

Another challenge was making a negatively curved shell. "It seems simple at first—you can just spin-coat onto a saddle-shaped substrate. But we could not find a well-controlled glass substrate with uniform curvature," says Paulsen.

Once Tobasco predicted that the patterns depend only on the sign of the curvature, though, more substrate options became available. The spout of a laboratory beaker, for example, has negative curvature. Paulsen recounts that "Yousra put a glass beaker in a plastic bag, smashed it, and carefully selected a shard that could be used to spin-coat a film on. She formed films on this shard, floated them onto water, and the wrinkle patterns matched the theory beautifully!"

Coverage maximization

In a mathematical paper published last year, Tobasco showed that, in a limit where the wrinkles are infinitely fine, the wrinkle patterns could be derived as a consequence of the curved sheet trying to cover as much of the liquid surface as possible.[3] That coverage maximization is driven by energy minimization. "There's a trade-off between the amount of area you can cover by unfurling the shell and the amount of energy you have to spend by wrinkling," says Tobasco.

Physically, surface tension—the dominant role of the liquid in the experiment—acts to pull the sheet's edges as far apart as possible.[4] But gravity is also at play on the system, and its effect doesn't obviously lead to coverage maximization. "Before deriving the theory, I had no intuitive guess for how gravity would select the patterns," says Tobasco.

Katifori's group spearheaded the simulations. The team used a finite-element method to study how gravity may affect wrinkle patterns. Katifori and her colleagues found that gravity-driven systems were no different than ones driven by surface tension. The simulations with zero surface tension produced the same coverage maximization and the same wrinkle patterns as in the experiments.

The wrinkle patterns are similar to so-called locking materials. In fact, that similarity was what led Tobasco to the two rules for predicting the patterns. If one pulls at the end of a fitted bedsheet, for example, it initially stretches with only a negligible applied force. Eventually, however, locking materials experience an abrupt limit where they cannot stretch further unless there's a substantial increase in force.

Wrinkle patterns show more subtle locking behavior. If one pulls a wrinkled sheet perpendicular to the crests and troughs, then the wrinkles disappear. But pull the sheet along the crests and troughs, and the wrinkle pattern locks into place.

Although the new rules make predictions for wrinkles, they may be useful for understanding folds and other microstructures in bulk materials and thicker films. "Being ultrathin is not actually absolutely necessary," says Katifori. "People are working in more intermediate-thickness regimes, and you still see similar patterns. It seems that some aspects of it are true in a very wide range of regimes."

Alex Lopatka

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Time-reversed laser absorbs nearly all light

A simple design overcomes a substantial limitation on potential applications for coherent perfect absorbers.

Shine a flashlight at a cat at night, and its eyes will appear to glow. That's because cats—along with owls and many other nocturnal animals—have a reflective tissue layer behind their retinas. The adaptation increases their sensitivity to low levels of illumination by giving the retina a second chance to absorb photons.

A similar strategy can boost the amount of light absorbed by any material. For a material placed in an optical cavity, light passes through it many times. And under the right conditions, nearly all the light is eventually absorbed, even by a weakly absorbing medium. Such a system is an example of what's known as a coherent perfect absorber (CPA), which achieves its performance with the help of interference effects.

Absorption is essential for the efficiency of solar panels and of light detectors, for example, particularly when the targeted signals are weak. Maximizing that efficiency is tricky, however, because absorption and reflection generally go hand in hand: A highly absorbent material is usually also highly reflective and sends away much of the light. CPAs don't have that issue, and many of their designs could be incorporated into a detector without major alterations.

But until recently, CPAs worked only for a specific spatial mode and direction of propagation, both of which severely limit the eligible signals. Now Ori Katz of the Hebrew University of Jerusalem, Stefan Rotter of Technical University of Vienna, and their colleagues have demonstrated a CPA that overcomes those limitations.[1] Taking inspiration from an established laser design, their simple setup, shown in figure 1, widens the range of acceptable wavefronts for perfect absorption.

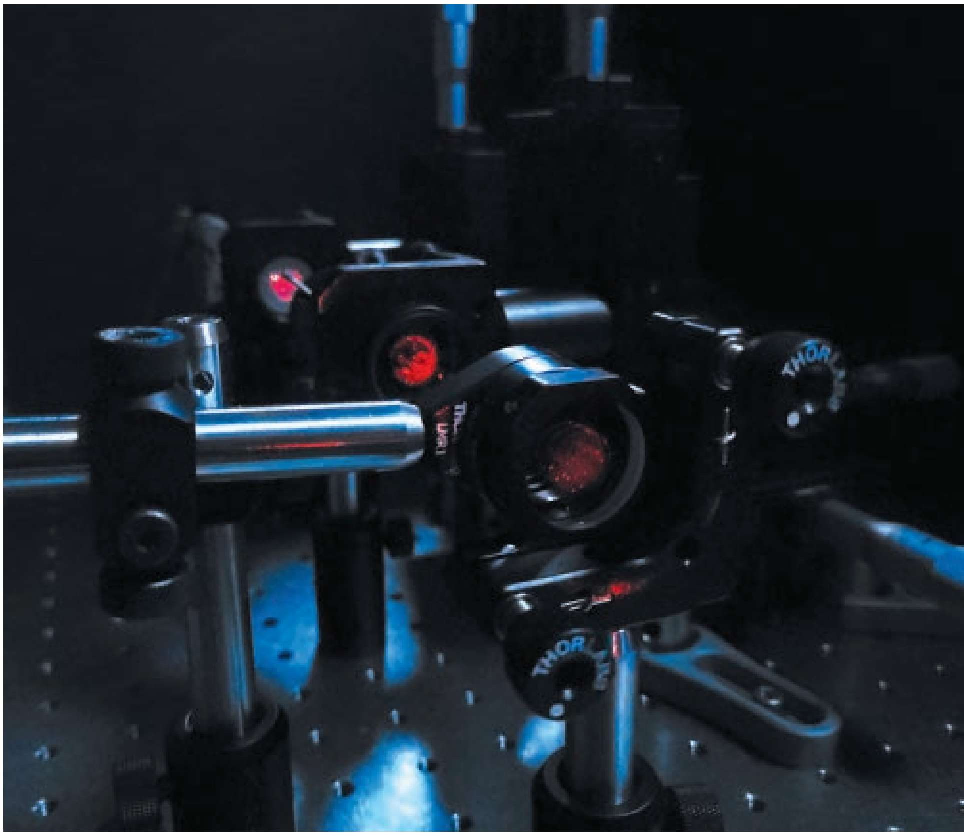

FIGURE 1. A SPECKLE PATTERN (red) comprises over a thousand distinct optical modes. For the right combination of mirrors, mirror spacing, and absorption properties of an inserted pane of colored glass (mounted here horizontally in the foreground and obscured by the mirror in front of it), all the light modes will be nearly completely absorbed by the glass. (Courtesy of Omri Haim, the Hebrew University of Jerusalem.)

Run interference

A. Douglas Stone of Yale University and his colleagues introduced the theory behind CPAs[2] in 2010. Consider a laser hitting a slab of material. Some of the light is reflected, some transmitted, and some absorbed. If two antiparallel beams enter opposite sides of the material, they can interfere such that the transmitted and reflected light in each direction cancel. In that case, all of the energy is absorbed. In the first experimental demonstration in 2011, a silicon slab absorbed over 99% of the light from two counter-propagating lasers.[3] Total destructive interference requires matching frequencies, amplitudes, and phases and having the right material reflection and transmission coefficients.

The conditions for coherent perfect absorption can be reframed as those for lasing just run in reverse. With each round trip through a laser, the light amplification in the gain medium must balance the energy losses in the laser cavity. In a CPA, the light absorbed in each round trip must be equal to the light that enters the cavity during that time. If that condition is met—and if the cavity length is resonant with the wavelength—light that would be reflected at the cavity's entrance mirror is canceled out by interference, so all the light ends up in the cavity and bounces back and forth until it's absorbed.

Katz, who has long worked on novel imaging techniques, heard about the latest ideas for realizing CPAs at a February 2020 workshop on waves in complex media. Rotter's then graduate student Matthias Kühmayer presented the group's recent work showing coherent perfect absorption in a disordered medium, a feat that required devising a time-reversed version of what's known as a random laser.[4] As with other CPAs, the setup was limited to a single mode. Katz wondered if a time-reversed version of a laser that emits multiple modes simultaneously might overcome that single-mode limit.

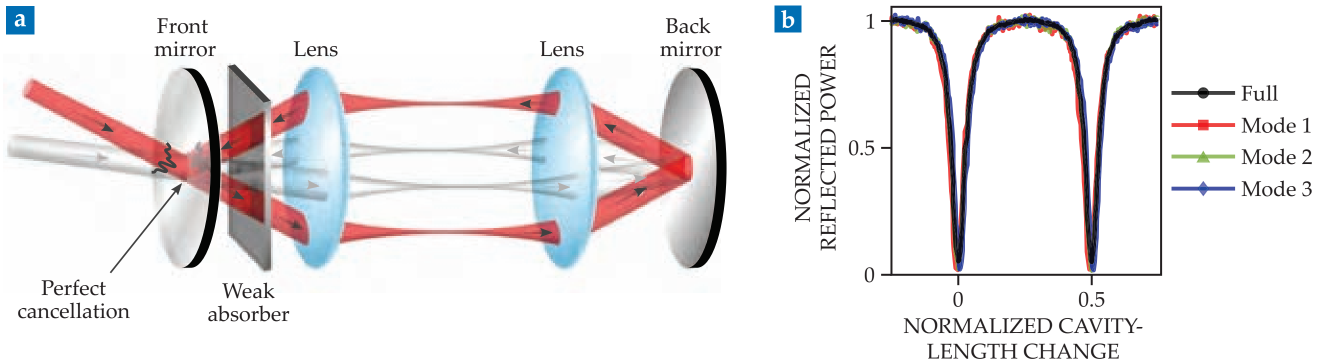

FIGURE 2. A DEGENERATE CAVITY enables near-perfect absorption of multiple light modes simultaneously. **(a)** The optical cavity has a partially reflecting front mirror, a nearly completely reflecting back mirror, a weakly absorbing material, and a pair of identical lenses arranged such that light travels closed loops in the cavity. Light entering at a large angle (red) or close to normal (light gray) is imaged onto itself after a round trip through the cavity, and the resulting interference can extinguish the reflected light at the front mirror. **(b)** The optical power reflected from the cavity depends on the cavity's length, with changes given here as fractions of the wavelength. Different light modes show identical reflection trends, including near-perfect absorption. (Adapted from ref. 1.)

Katz chatted with Rotter about the idea over one of the workshop's coffee breaks, and the two decided to collaborate. "The innovation the project introduces is primarily conceptual: bringing a well-known cavity design from laser physics to a different field," says Katz. That design came from a degenerate-cavity laser, a system he had worked on a few years earlier.

In a conventional CPA, light traveling perpendicular to the cavity's two mirrors bounces back and forth along the same path. Light at any other angle instead ricochets before eventually leaving the cavity. The degenerate cavity, shown in figure 2a, includes the addition of two lenses placed in a telescopic arrangement such that the light is imaged back onto itself after a round trip. Because light heading in any direction travels a closed loop, light at various incoming angles and with multiple spatial modes is trapped in the cavity. And because light ends up where it entered the cavity, it can destructively interfere with any would-be reflected light.

À la mode

Katz and two of his grad students—Yevgeny Slobodkin and Gil Weinberg—came up with a few possible designs for a CPA based on a degenerate-cavity laser. Meanwhile, Rotter's grad student Helmut Hörner did numerical calculations to verify that the idea was viable, particularly with any expected experimental imperfections. The predicted tolerance was enough that commercial optics were an option.

Bolstered by those promising calculations, Katz's group moved forward with an experimental setup: a thin slab of weakly absorbing colored glass with a partially reflecting entrance mirror on one side of it and two lenses and a nearly fully reflecting back mirror on the other. To get as close as possible to perfect absorption, the group members ferreted out misalignment and other sources of imperfections. In the end, spurious reflections from the lenses remained the main performance limiter; in the future, they could be reduced with better antireflection coatings or alternate cavity designs that swap the lenses for curved mirrors.

The researchers measured the spatial distribution of the reflected intensity when light impinged on the cavity. (The intensity transmitted through the cavity was consistently near zero.) They used two forms of illumination: a laser sent through a spatial light modulator to produce a speckle pattern of over 1000 modes, shown in figure 1, or the output from a multimode optical fiber that is shaken by airflows of various strengths and passes through turbulent air to produce a dynamic speckle pattern. The researchers found that absorption increased from 15% for the glass alone to nearly 95% in the cavity, with negligible differences between modes or airflow strengths.

The phenomenon could also be intentionally turned off—unlike more conventional forms of absorption—a feature that could be used for filtering or modulating. Changes of less than a micron in the cavity length altered the absorption dramatically. Dips in the reflected power occurred when the cavity length was resonant with the wavelength, as shown in figure 2b. When the cavity was detuned by fractions of a wavelength, the system's absorption was even lower than the colored glass alone. Modes from different spots in the speckle pattern all reached a minimum reflected intensity at the same cavity length, whose value matched numerical calculations.

Of course, the number of modes and incoming angles that experience perfect absorption is limited. Light incident at too great an angle or too far from the mirror's center hits the aberrant edges of the lenses and doesn't achieve the requisite self-imaging. The precise limits depend on the setup's specific optics and geometry. The researchers demonstrated consistent performance for more than 1000 modes covering a 3 mm × 3 mm area and with up to a 0.5° input angle.

The degenerate-cavity concept should work for all electromagnetic waves, for acoustic waves, and for other waves. "We believe that our results open up new ways to detect weak signals," says Katz, "even when they get perturbed by passing through the Earth's turbulent atmosphere," as is the case for faint starlight in astronomy, for example. But the current design is still limited to a narrow range of wavelengths for a given cavity length. Overcoming that limitation is Katz and his colleagues' current venture.

Heather M. Hill

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Philanthropy plays a growing role in funding US physical sciences

To buy equipment, build infrastructure, foster collaborations, and more, scientists are benefitting from—and relying on—private money.

A few years ago, Jonathan Feng was spreading the word about his idea for searching for light and weakly interacting elementary particles. One day after he gave a talk, a stranger approached him. It was Jochen Marschall, a science program officer at the California-based Heising-Simons Foundation. The foundation funded Feng's idea, and the Forward Search Experiment (FASER) was installed in a custom-excavated trench at the Large Hadron Collider in Geneva. It happened quickly—before the collider was turned back on in spring 2022—and FASER is now collecting data. At first, says Feng, a theoretical physicist at the University of California, Irvine, "it seemed like the money fell from the sky." But he came to find out that Marschall had heard him talk multiple times and researched the proposed experiment before they spoke.

Another example of private money for basic physical sciences research is the Mani L. Bhaumik Institute for Theoretical Physics at UCLA. In 2014 Mani Bhaumik funded a postdoc in Zvi Bern's group at the university. Two years later he expanded his gift to set up the institute; the endowment has grown to $20 million. Says Bern, who directs the institute, "We can hire about seven postdocs a year. We also fund graduate students, workshops, and lectures."

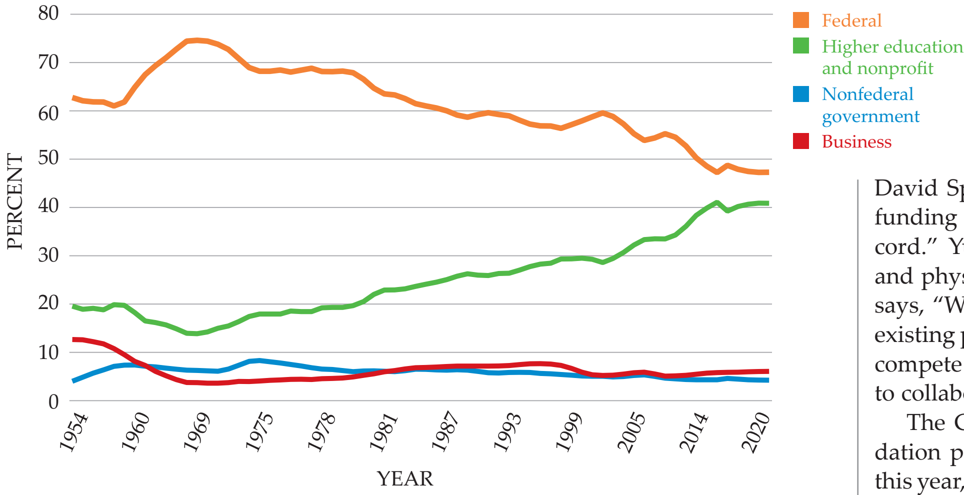
Without private money, says Bern, the US physics community "would be completely screwed. There is no way we could be as competitive in science as we are."

In the late 19th and early 20th centuries, private money was a mainstay for US science: Think of universities founded by the likes of John D. Rockefeller and Andrew Carnegie; telescopes, too, have a long history of private funding. After World War II, as the US government stepped up funding for science, private foundations took their money elsewhere. Government funding for science spiked after the Soviet Union launched *Sputnik 1* in 1957, but since the mid 1960s it's been decreasing as a share of research funding. (See the plot on page 25. See also PHYSICS TODAY, June 2018, page 26.)

The biggest source of private money in the US is from universities, largely in the form of startup funds, says Marc Kastner, a physicist and former dean of sciences at MIT. The numbers of foundations and ultra-wealthy individuals who

CERN

THE FORWARD SEARCH EXPERIMENT (FASER) at the Large Hadron Collider got off the ground in 2018. It has received several million dollars from the Heising-Simons Foundation and additional support from the Simons Foundation, CERN, and NSF. The experiment is designed to detect high-energy (TeV) neutrinos and other weakly interacting particles that are produced parallel to the beamline and that escape other detectors.



PHILANTHROPY'S INCREASING ROLE in funding US basic science. In 2020, higher education and nonprofit funding sources (green line) totaled $25.1 billion, or 42% of the total for basic research performed in universities and nonprofit research institutes. Gifts from private individuals are harder to track and are not included here. The importance of philanthropic investment has grown as the relative contribution by the federal government (orange line; $29 billion in 2020) has declined, according to the Science Philanthropy Alliance. (Courtesy of the Science Philanthropy Alliance, based on data from NSF.)

want to fund science is growing, with the bulk of philanthropy going to biomedicine. Kastner was the first president of the Science Philanthropy Alliance, which got started in 2013 with 6 member foundations and as of September had 37. The alliance guides philanthropists on best practices, helps them determine where to put their money, and encourages networking among them.

Traditions for science philanthropy vary by country, but most are weaker than in the US. Still, it's picking up in Europe too. An example is the CNRS Foundation, launched three years ago by its namesake; so far it is funded mostly through legacy giving by former CNRS employees.

Although philosophies and modes of operating vary, foundations generally share the aim of having impact by putting money where the government isn't, says France Córdova, former NSF director and the alliance's current president.

Filling the gaps

Foundations and individuals occasionally make enormous gifts to the physical sciences. Two notable examples are the $13 million raised by Jim Simons to rescue experiments at Brookhaven National Laboratory's Relativistic Heavy Ion Collider and T. Denny Sanford's $70 million gift to the underground lab named for him in South Dakota (see PHYSICS TODAY, March 2006, page 26, and February 2013, page 19). But for the most part, private money cannot fund major facilities. More often it focuses on funding people.

The Simons Foundation gave nearly $122 million to math and physical sciences in 2021, up almost threefold from a decade earlier. It has programs to fund institutions, individual investigators, collaborations, meetings, and conferences. It also funds projects, such as the arXiv preprint server, for which it covers half the budget, and the Simons Observatory in Chile, for which it's ponying up the bulk of the $108.5 million tab for construction.

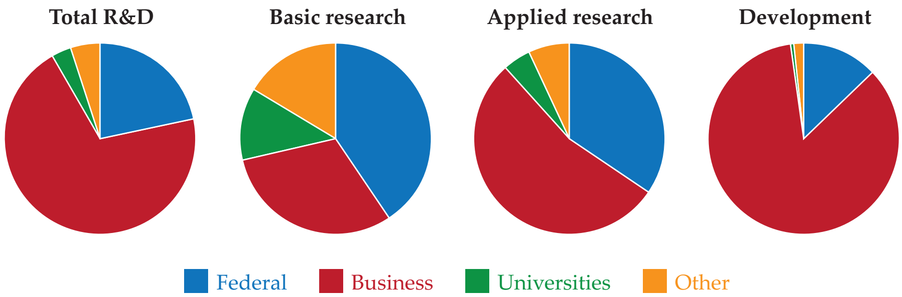
One Simons program provides grants for scientists to extend sabbatical leave. Another gives five-year awards annually to 140 mathematicians and physical scientists who do not have federal support.

A new program funds mid-career scientists who want to change research directions because, as Simons president David Spergel says, "it's difficult to get funding in a field without a track record." Yuri Tschinkel, director of math and physical sciences at the foundation, says, "We always aim at not replicating existing programs. And we don't want to compete with federal agencies. We want to collaborate with them."

The Gordon and Betty Moore Foundation plans to give about $420 million this year, of which $150 million will go to the sciences. Among its initiatives are calls for proposals in specific areas, such as tabletop experimental physics and emergent phenomena in quantum systems.

The Moore Foundation also funds standalone projects in areas it seeks out. Science program officer Gary Greenburg has funded projects from less than $100 000 up to $20 million. "I talk to experts and read broadly. My sweet spot is high-risk, high-reward projects," he says. One project was inspired by a *Physical Review A* paper that suggested that interaction-free quantum measurements could eliminate sample damage in electron microscopy. In another, an international collaboration has developed a dielectric laser accelerator that can drive electrons on a silicon chip at higher gradients than conventional accelerators.

The Research Corporation for Science Advancement holds "Scialog" workshops, often jointly with other foundations, in which early-career scientists from an array of disciplines are invited to brainstorm on a specified theme. Over the course of a couple of days, teams put together short proposals. A few get funded for a year at $56 500 per investigator. Recent topics include mitigation of zoonotic threats and negative emissions science. "The goals are to share ideas and enthusiasm, to get people to think more broadly, and to network," says Research Corp president Daniel Linzer. "Science has become ultracompetitive, and people



SUPPORT FOR RESEARCH in the US is presented by investment sector for 2018–19. The pie charts show the reliance of basic research on philanthropy, which is included in the categories "universities"—through institutional funds derived from endowments—and "other." These data include research performed by all sectors, including the business sector. (Courtesy of the Congressional Research Service, based on NSF data.)

do not play as nicely in the sandbox as they used to. Science should be fun."

A funding ecosystem

The foundations and individuals who fund science generally tout their nimbleness, flexibility, and risk-taking ability and contrast them with federal funding agencies, which are bound by procedures and accountable to taxpayers. "We can react quickly to changes," says Tschinkel. For example, early in the COVID-19 pandemic when many US universities froze hiring, the Simons Foundation stepped in to pay for 50 postdoc positions across the country. Heising-Simons's funding of the FASER experiment is another example of swift action.

Recipients of philanthropic gifts can typically redirect spending from, say, people to equipment. And if there is an abundance of outstanding postdoc applicants in a given year, says Hirosi Ooguri, director of Caltech's Walter Burke Institute for Theoretical Physics, "we can hire more that year. With federal funding, we wouldn't have that flexibility." It's also easier for a researcher with private money to pivot directions mid-grant. And private money can fund researchers in multiple countries.

Another advantage of private money is the freedom to fund unproven ideas or researchers. "Private philanthropy can take risks," says Adam Falk, president of the Alfred P. Sloan Foundation. "That means failing sometimes." The Sloan Foundation gives $90 million a year across programs, of which about $25 million goes to the physical sciences. As an example of a failure, Falk points to a project in the social sciences: "We funded a partnership between academic researchers and Facebook to study misinformation," he says. "The project didn't live up to its promise—the technical and legal problems were harder than we anticipated."

"Risk is a complicated topic," says Dusan Pejakovic, a science program officer at the Moore Foundation. Risk can come from outside, such as the travel and supply-chain difficulties that the pandemic wrought. Inherent research risk can be managed, in part, through diversification, notes Pejakovic. "If I have 20 or 30 investigators working on a topic, important discoveries will be made. The risk to the funders is minimal." If researchers have substantial funds and freedom, he says, "they almost always stumble on something exciting. The impact can be high even if the output is not what was expected."

One concern about private money that some researchers voice is that the review process can be opaque. Tschinkel notes that his division at the Simons Foundation gives proposals a thumbs up or down, but no reviews.

Thirty years ago, says UCLA's Bern, a US Department of Energy grant shared by three professors in elementary particle theory was sufficient to fund two postdocs and several students. "You need that type of funding to be a world leader in the field." On government grants nowadays, he says, "we can't even dream of funding students at anywhere close to the level we could 30 years ago." With researchers forced to look elsewhere for money, he adds, "private foundations have a huge influence on the direction of science. That makes transparency in their peer review important."

"It's an ecosystem, and there is room for both styles of funding," says Falk. In the federal system, the role of the wider scientific community "is critical and positive," he adds. "But it's nice to have that complemented by the philanthropic sector that has more freedom."

The philanthropists Bill Gates and Charles Simonyi contributed a total of $30 million for fabricating a new type of mirror for the Vera C. Rubin Observatory in Chile. After the technology was proven, NSF and DOE jumped in, says Kastner. "If it had been left up to the government, the observatory may never have happened." Likewise, Peter Graham, a Stanford University theorist, says that when he and colleagues wanted to build a low-frequency gravity-wave detector based on interfering atoms, they "needed someone to take a risk" on their idea. The Moore Foundation paid for tabletop proof-of-concept research and is covering the bulk of a scaled-up $15 million 100-meter vertical drop experiment under construction at Fermilab. The project also now has funding from DOE.

Moving from private to public money is a pattern, says Graham. "We build the first round thanks to private foundations. When it works like a dream, the government agencies step in."

Relationships

"Who gets to ask for private money?" says Lars Bildsten, director of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara. "The access question is important." Private philanthropy can be specific to an institution and rely on relationships, he notes, pointing to the $65 million that Charles Munger gave the institute for a building to house visiting scientists (see Physics Today, April 2017, page 32).

Relationships between several billionaire businessmen and some physicists are growing into the Quantum Gravity Institute in Vancouver, British Columbia, Canada. The form the institute will take is still in flux, with plans under discussion for fostering international collaborations, holding conferences, and having a physical space. "They are still feeling their way," says James Peebles, a Princeton University physicist who was among several Nobel laureates who attended the institute's launch conference in August. "But this institute will be prepared for a breakthrough in any direction." Terry Hui, one of the philanthropists behind the institute, earned his bachelor's degree in physics. "Contribu-

ABIGAIL VIEREGG (left) and Jessica Zebrowski, formerly an undergraduate in Vieregg's group, dig out the Askaryan Radio Array at the South Pole in 2018. Vieregg, a professor at the University of Chicago who develops instruments to detect ultra-high-energy neutrinos, is one of 16 inaugural awardees in the Gordon and Betty Moore Foundation's new Experimental Physics Investigators Initiative; they will each receive $250 000 a year for five years.

tions to physics are underrated," he says. "People don't see how basic research will help humanity. From my perspective, I think the impact is huge."

Bhaumik's gift to UCLA was also based on relationships: He was a postdoc at the university in 1959, and more recently he got to know Bern. During his career at Northrop Grumman, Bhaumik was involved in the development of the excimer laser, for which he received company shares that eventually grew into his fortune. "In India I worked with [Satyendra Nath] Bose. I had wanted to be a theoretical physicist," Bhaumik says. Having "suffered the agony of not really fulfilling that desire," he continues, seeding the UCLA institute has brought satisfaction and been "beneficial for me to understand the nitty-gritty of quantum field theory and meeting accomplished physicists from around the world."

Aligning goals

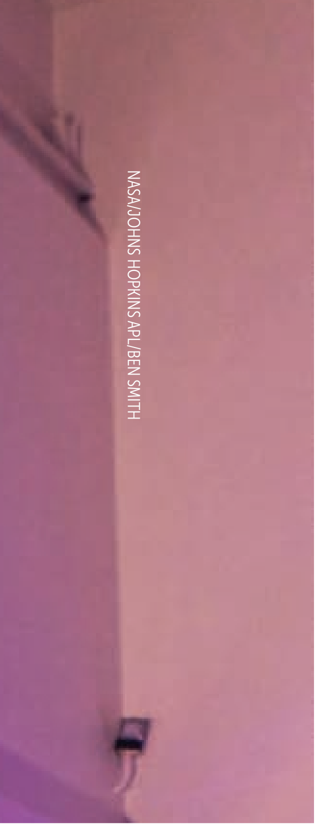
David Eisenbud was director of the Mathematical Sciences Research Institute in Berkeley, California, for nearly two decades. "You don't always get money for your top priority, but you don't take money for nonpriorities," he says. Among the traps to avoid, Eisenbud says, are money that is too restrictive, donors who want too much recognition, or situations where the donor feels they have the right to call the shots—such as the right to fire and hire or to select fellowship recipients.

As director of the Institute of Advanced Scientific Studies (IHES) on the outskirts of Paris, Jean-Pierre Bourguignon set to work in 1998 raising an endowment. For France, it was unusual to raise private money for science, he says, "and some in the science community disapproved." Still, he was successful, and the IHES now has an endowment of nearly €50 million ($49 million), of which about half is from donors in France. Contributions from individuals and companies in Japan and China, he says, are used to bring in mathematicians and physicists from those countries. Those type of strings are okay, he says. Also acceptable, he continues, is naming fellowships for companies that have made gifts. At IHES, for example, fellowships are named for Huawei and Schlumberger, but the companies have no say in who is invited to fill them.

The goals and expectations of the donor and recipient need to align. "If someone comes with money," says Caltech's Ooguri, "there may be a temptation to tweak the mission to match the money. That's a slippery slope."

Toni Feder PT

A JOURNEY to TOUCH the SUN



NASA/JOHNS HOPKINS APL/BEN SMITH

Nour E. Raouafi is a principal professional staff member at the Johns Hopkins Applied Physics Laboratory in Laurel, Maryland, and the project scientist for NASA's *Parker Solar Probe* mission.

Nour E. Raouafi

The *Parker Solar Probe* is braving extreme conditions to explore the mysterious solar corona, a region that harbors some of the most difficult-to-understand phenomena in astrophysics.

The *Parker Solar Probe* (*PSP*) is exploring the Sun's atmosphere, one of the last unvisited and extreme regions in our solar system.[1] Launched on 12 August 2018, the *PSP* has flown closer to the Sun's surface than any other spacecraft. By 24 October 2022, the PSP had completed 13 of the 24 solar orbits scheduled for its seven-year mission. On 16 October 2021, the spacecraft flew by Venus for the fifth time. One month later, it achieved the closest approach yet—13.28 solar radii from the center of the Sun. It will use Venus for two more gravity assists to reach its ultimate perihelion on 24 December 2024: That closest point of 9.86 solar radii is about 4.5% of the Sun–Earth distance.

One of the phenomena the *PSP* is investigating is the solar corona, the most challenging region of the heliosphere because of its extreme conditions. From the corona, the solar wind flows to fill the whole heliosphere, which extends about 100 astronomical units (AU) from the Sun. The solar surface—the photosphere—is a million times as bright as the corona, yet the corona is more than 300 times as hot. The primary science objective of the mission is to determine the structure and dynamics of the Sun's coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and find what processes accelerate energetic particles.

Challenges of the mission

By 1958 the science case for a solar probe was already mature. It proved, however, very challenging to implement such a mission. The solar probe has been the top priority of several Decadal Surveys for Solar and Space Physics (Heliophysics) conducted by the National Academies of Sciences, Engineering, and Medicine. Yet five studies (1982, 1989, 1994, 1999, and 2005) did not culminate in the mission's execution. They were all predicated on using nuclear power to propel the spacecraft. Then a Jupiter gravity assist would slingshot it out of the ecliptic into a trajectory in which it would fly above one of the solar poles before plunging to the perihelion at about four solar radii. It would then be sent into the subsonic solar wind. Several scientific, technological, and cost factors, however, thwarted that concept: the short time during which data were collected at perihelion (16 hours pole to pole), the limited number of solar passes (two at most), the high probability that the sonic boundary is below four solar radii, and the lack of nuclear power available for public civilian spacecraft.

In 2007 NASA endorsed a new mission profile that uses seven Venus gravity assists so that the spacecraft can dive progressively closer to the Sun. Although the new orbit allows the spacecraft to fly only as close as 9.86 solar radii from the Sun's center, it permits a significantly lengthier mission, of seven years, to measure the solar wind's state through the major parts of the solar cycle—namely, from the minimum to the maximum.

Deep roots in coronal mysteries

During the 1869 total solar eclipse, William Harkness and Charles Augustus Young independently observed a new spectral line of the Sun's visible light at a wavelength of 5305 Å, the so-called green line. It did not, however, belong to any of the known elements. Anton Karl Grünwald named the hypothetical new chemical element "coronium." In the late 1930s, Walter Grotrian calculated the existence of an atomic transition that coincided with the green line, and Bengt Edlén confirmed it through laboratory spectroscopy experiments.[2] The spectral line belonged not to a new chemical element, as proposed five decades previously, but to the highly ionized Fe^{13+}, an iron atom stripped of 13 of its 26 electrons.

Scientists were then faced with a much more complex phenomenon. That Fe^{13+} can exist only in multimillion-degree hot plasmas is why the solar corona is so much hotter than the photosphere. That discovery has become known as the coronal-heating problem. More than eight decades later, it is still puzzling and controversial. To interpret the coronal heating, several theories have proposed various mechanisms, including magnetic field reconnection, Alfvén waves, and turbulence, but none can thoroughly explain the phenomenon.

Another solar mystery was identified in the early 1950s when Ludwig Biermann observed that comet tails flow away from the Sun at about 400 km/s. On a 1956 visit to the University of Chicago, he presented the results to John Simpson. Biermann suggested that some antisunward "corpuscular radiation" flow must affect the comet tails. Simpson refuted the idea by citing another great authority in solar–terrestrial physics, Sydney Chapman, who held that the solar atmosphere, much like Earth's atmosphere, was static. One of Simpson's colleagues, Eugene Parker—the namesake of NASA's *PSP*—showed that the Sun's atmosphere is highly dynamic and some flow could come out of what he called the solar wind. Against the advice of Simpson, Parker decided to publish the research.

Several journals rejected the single-authored paper.[3] One of Parker's critics suggested that he go to the library and do some reading before writing papers on the subject. But Subrahmanyan Chandrasekhar, the editor of the *Astrophysical Journal*, decided to publish the article. A few years later, the *Mariner 2* mission confirmed the existence of the supersonic solar wind. It was magnetized, hot, fast, and complex.[4] Since Parker's prediction, astronomers have been trying to figure out how the solar wind accelerated from a near-static state at the base of the corona to several hundreds of kilometers per second over a very short distance.

A final, critical mystery that astronomers hope the *PSP* will solve is the Sun's energization of particles. In 1859 Richard Carrington observed the first solar white-light flare,[5] followed by the most intense geomagnetic storm in recorded history. Telegraph communication failures occurred all over the world. Although some scientists suggested a connection between the solar event and the geomagnetic storm, the link between the ground-induced currents and the explosive solar activity was unknown then. The true nature of the solar activity and the solar cycle had to wait until George Hale observed strong magnetic fields in sunspots.[6] Chapman and Vincenzo Ferraro later explained the relation between solar activity and geomagnetic storms. The Sun–Earth connection, mainly driven by solar magnetism, became more evident after the 1957 launch of *Sputnik 1* and the advent of the space age. Whatever happens in the solar corona can affect Earth's environment, planetary systems, space equipment, and exploration.

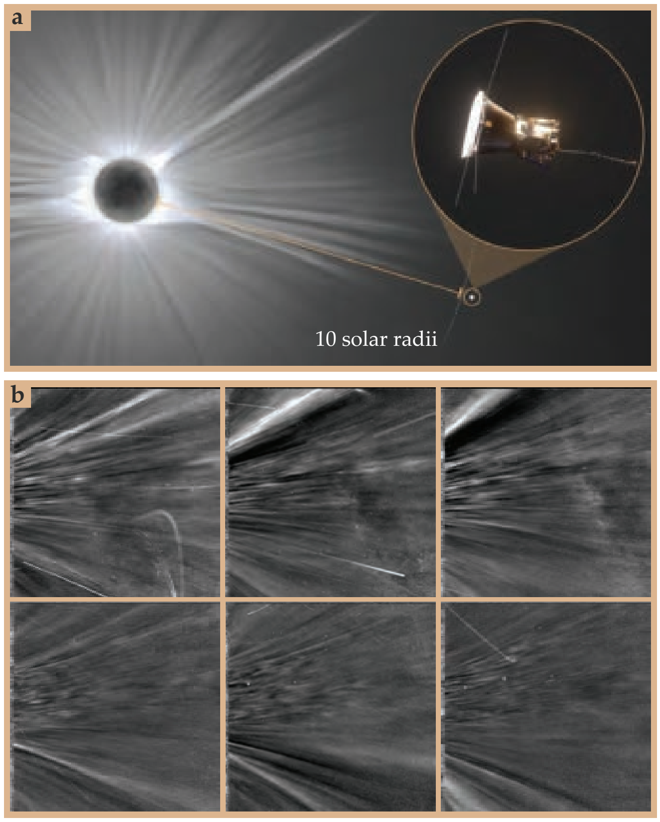


FIGURE 1. THE *PARKER SOLAR PROBE*, (a) as depicted in this illustration, flies through coronal structures like those visible during total eclipses. **(b)** Images from the spacecraft's WISPR instrument show the spacecraft gliding above and below the structures of the solar corona. That upward and downward motion of coronal features, however, is only apparent. (Courtesy of NASA/Johns Hopkins APL/Naval Research Laboratory.)

Why so close?

The Space Science Board of the National Academies of Sciences was appointed in spring 1958 at the request of the executive committee of the US National Committee for the International Geophysical Year to survey the scientific aspects of human and robotic exploration of space. The board chairman, Lloyd Berkner, appointed 12 committees to prepare reports on specific fields of space research, review proposals for experiments, and recommend a scientific program. The work of two committees—optical and radio astronomy, and physics of fields and particles in space—contributed to the nation's space science program and influenced NASA's process for selecting

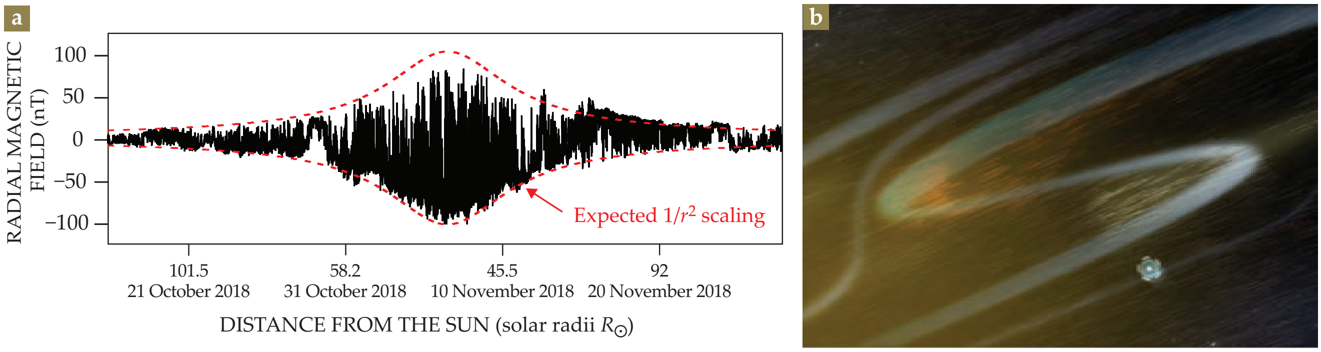


FIGURE 2. THE RADIAL COMPONENT (a) of the solar wind's magnetic field was measured by the *Parker Solar Probe*'s FIELDS suite during the first perihelion encounter. The measurement is peppered by high-amplitude fluctuations in which the field rotates almost 180° back to the Sun and out again. **(b)** The fluctuations appear as S-shaped switchbacks along the magnetic field lines and are grouped in periods of time separated by quiet spans of the magnetic field and other plasma parameters. (Adapted from ref. 13, S. D. Bale et al.)

space scientists. For the latter committee, Berkner designated Simpson as chair and James Van Allen as cochair. (To learn more about the Space Science Board, check out the NASA History Series Exploring the Unknown.)

The 1958 Simpson committee report recognized the need to fly a solar probe within the orbit of Mercury to sample solar-wind conditions and understand fundamental coronal phenomena. Beginning in the early 1960s, measurements of the solar wind around 1 AU revealed that it is impossible to trace the physical processes that create and accelerate the solar-wind plasma. During its journey to Earth and beyond, the solar wind is heavily affected by waves, instabilities, turbulence, and other physical phenomena. The only way to understand how hot plasma originates and flows is to sample it at its source, the solar corona.

The region where the solar wind's plasma acquires most of its heat and acceleration is below the Alfvén critical surface—where the solar-wind speed equals the Alfvén speed. The Alfvén critical surface defines the surface beyond which the plasma ceases to corotate with the Sun; that is, the magnetic field loses its rigidity to the plasma. Knowing the physical conditions below that boundary is essential to determine the solar wind's angular-momentum loss, the global heliospheric structure, and other large-scale properties. The physics of the solar wind also changes because the sunward and antisunward propagation of plasma waves affect the local dynamics, including the plasma's turbulent evolution, heating, and acceleration. In addition, velocity gradients develop between the fast and slow streams and set the initial conditions for forming corotating interaction regions, which are a major source of recurring geomagnetic storms.[7]

To make the necessary measurements, the *PSP* has four suites of instruments. The FIELDS suite measures electric and magnetic fields, waves, Poynting flux, densities, temperature, and radio emissions.[8] The Solar Wind Electrons Alphas and Protons (SWEAP) instrument measures velocities, densities, and temperatures of electrons, protons, and alpha particles of the thermal solar wind.[9] The Integrated Science Investigation of the Sun (IS⊙IS) suite[10] measures energetic electrons, protons, and heavy ions in the energy range between 10 keV and 100 MeV. The Wide-Field Imager for Solar Probe (WISPR) takes pictures of the solar wind, coronal mass ejections, shocks, and other structures as they approach and pass the spacecraft.[11]

Figure 1 shows a set of WISPR images around the perihelion of the ninth solar encounter—when the spacecraft flew through the solar corona. WISPR captures coronal structures moving upward in the upper field of view and downward in the lower part, although the motion is only apparent. The images also show various small structures that could not be seen from 1 AU. Those features reflect the highly dynamic nature of the young solar wind. The plasma data from both FIELDS and SWEAP confirmed that the *PSP* did cross the Alfvén critical surface, a significant milestone for the mission.[12]

Magnetic field switchbacks

Since the first solar encounter, the *PSP* has provided a dramatic close-up picture of the solar wind with features not seen in previous data. Although the magnetic field magnitude follows the r^{-2} behavior expected from flux conservation, the field is highly structured closer to the Sun and shows pronounced, ubiquitous high-amplitude fluctuations. Figure 2a delineates the measured radial component of the magnetic field vector, which comprises rapid, large-amplitude polarity reversals that are associated with jets of plasma. The magnetic field reversals, or switchbacks (SBs), are rotations of the field vector.[13] Rather than changes in magnetic-field polarity, the field lines fold over to form an S shape (see figure 2b), as shown by measurements of suprathermal electrons, the differential streaming of alpha particles, measurements of proton beams, and the directionality of Alfvén waves. The SBs are Alfvénic in nature, and the solar-wind velocity, therefore, is highly correlated with the magnetic field. Although SBs were observed sporadically in the solar wind before by the *Ulysses*, *Helios 1*, and *Helios 2* missions, their importance took center stage only after the recent observations by the *PSP*.

The SB occurrence rate, morphology, and amplitude and the fact that SBs are ubiquitously observed in slow, mostly Alfvénic solar wind made them one of the most intriguing aspects of the first few *PSP* perihelia passages. The magnetic reversals are grouped in spans of time separated by quiet periods during which the magnetic field and plasma parameters—velocity, density, temperature, and others—are devoid of large fluctuations. The reversals also carry excess energy, and their presence diminishes significantly farther out, as observed by the European Space Agency and NASA's *Solar Orbiter* and other space missions. Somewhere in the solar wind, therefore, the SBs must dissipate and release that energy to the plasma, likely in the form of heat and speed.

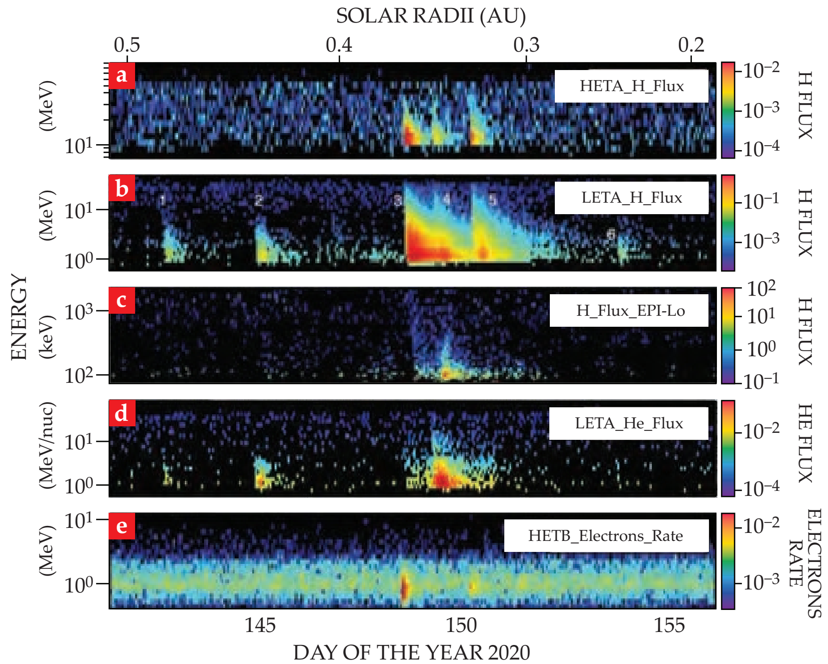


FIGURE 3. ENERGETIC PARTICLES near the Sun were observed by the *Parker Solar Probe*'s IS⊙IS suite. The spectrograms indicate the proton intensity (panels a, b, and c); the helium intensity (panel d); and the electron-count rate (panel e). High Energy Telescope (HET) A, Low Energy Telescope (LET) A, Energetic Particle Instrument-Low (EPI-Lo), and HETB are sensors of the IS⊙IS suite. (Adapted from ref. 15.)

The SBs' contribution to the heating and acceleration of the solar wind is not yet fully understood. There are, however, hints in the *PSP* data that after a certain point the SBs become unstable and shred themselves through turbulent mechanisms. If that is indeed the case, would they then be the smoking gun that scientists have sought for decades to explain the coronal heating and solar-wind acceleration? Solar scientists first need to understand and quantify their contribution to the thermodynamics of the solar wind's plasma.

Another controversial aspect of the SBs is their origin. Is there more than one flavor of SBs, such as some that form lower down in the solar atmosphere and are carried upward by the solar wind to *PSP* altitudes and beyond? And can SBs develop locally in the solar wind? Several models that may explain their formation can be put into two categories. The first favors SB formation through magnetic field reconnection at the base of the solar corona, and the second in the solar wind.

In other words, understanding the physical processes of SB formation could help researchers discriminate between the two most prominent solar-wind theories to explain the plasma heating and acceleration: magnetic field reconnection and turbulence. The most recent *PSP* observations seem to indicate a potential connection between the solar-wind SBs and magnetic field structures on the solar surface in the form of supergranules and magnetic field funnels at the base of the corona. SB observations hold promise as a way to better constrain our understanding of the solar wind.

Energetic particles

The energetic-particle environment closer to the Sun below 0.3 AU was not accessible until the *PSP* era. Previous studies, mostly from a distance of 1 AU, show that energetic particles originate from solar flares, shocks driven by coronal mass ejections, corotating interaction regions and stream interaction regions (both are interfaces between slow and fast solar-wind streams), coronal jets, and rarer smaller events. The energetic particles show a great diversity in composition—including electrons, protons, alpha particles, and heavier ions—and other properties. Among the fascinating phenomena discovered by the *PSP* IS⊙IS suite closer to the Sun are small solar energetic particle (SEP) events, which are radiation storms that result from small explosions at the solar corona's base.[14]

Figure 3 shows six of those SEP events over several days.[15] They're diverse in composition and origin but share some common characteristics with larger events. The triplet of events numbered 3, 4, and 5 in figure 3b is particularly interesting. They occurred within 24 hours of each other and seemed to originate from the same active region on the Sun. The composition of event 4, however, is quite different from the others. Events 3 and 5 show clear flux enhancements in the protons and electrons, whereas event 4 does not. Event 4 also has a helium-3 enhancement compared with the other two events. The cause of the compositional differences remains unclear. Event 4 may have originated from a different active region from that of events 3 and 5, which later produced event 6. The composition of event 6, however, is similar to that of event 1.

Solar activity is picking up as the current solar cycle progresses toward its maximum, so the *PSP* will have the opportunity to observe events of different intensities and distances from the Sun. The *PSP*'s new observations will help resolve fundamental questions about the origin, acceleration, and transport of SEPs in the heliosphere.

The dust-free zone

The zodiacal dust cloud consists of particles that orbit the Sun and fill the inner interplanetary space of the solar system. The thick circumsolar cloud of material is created mainly by asteroid collisions and cometary activity in the inner solar system. An excess of small-sized particles is observed in the inner heliosphere because of the grinding of dust grains. Small dust particles will lose angular momentum and gradually spiral toward the Sun because of the solar-radiation pressure, or more precisely, the Poynting–Robertson effect. The phenomenon mainly affects dust particles smaller than 1 mm in size, which are produced by catastrophic collisions, partial sublimation of larger particles, erosion through sputtering by solar-wind particles, and rotational bursting of grains.

Closer to the Sun, there could be a dust-free zone (DFZ). In 1929, in fact, Henry Norris Russell predicted that there should be such a region around all stars. Small dust grains in the vicinity of the Sun are heated to the point of sublimation. The resulting gaseous product is then washed away by the solar

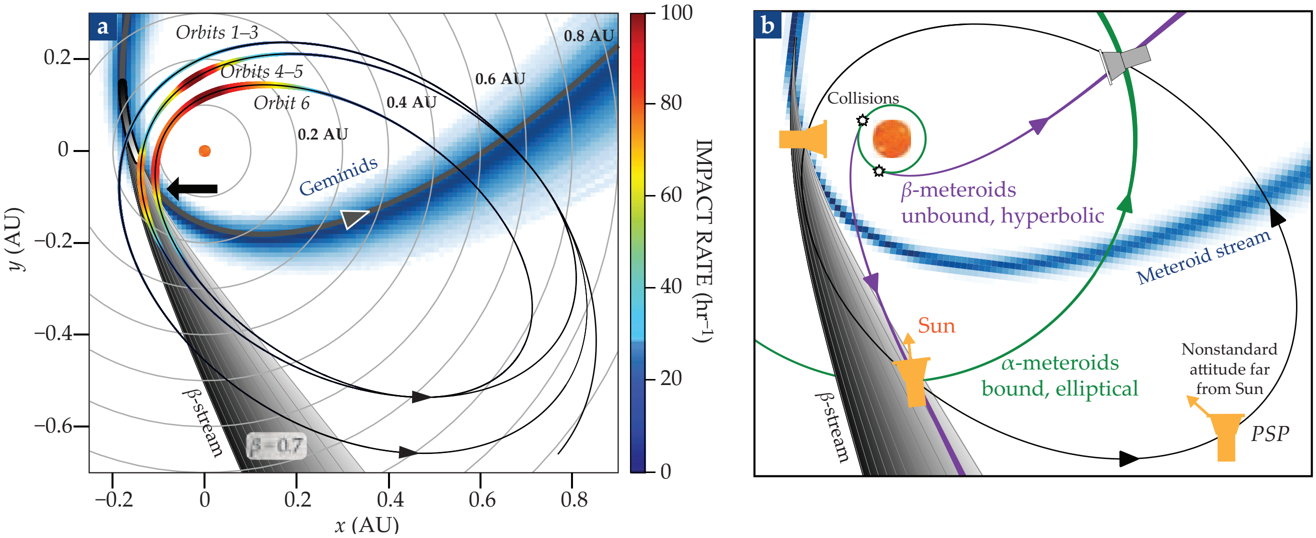


FIGURE 4. DUST IN THE INNER HELIOSPHERE and **(a)** dust-impact rates were measured by the *Parker Solar Probe*'s FIELDS electric antennas and are overlaid here on the *PSP* trajectory for orbits 1–6. **(b)** Several dust populations (not drawn to scale) were identified using the *PSP* measurements: gravity-bound α-meteoroids, unbound β-meteoroids, and a potential dust stream, known as a β-stream. The gray fanlike feature is a new dust stream produced by interactions between the Geminids meteor trail and the zodiacal dust cloud. (Adapted from ref. 17.)

radiation pressure and the solar wind, thus creating a depletion zone whose inner boundary marks the perimeter of the DFZ. Subsequent studies pointed to the same conclusion of a DFZ around the Sun and defined the boundary at about 4–5 solar radii. Observations, however, have failed for decades to provide any consistent evidence for the DFZ's existence.

Before the launch of the *PSP*, scientists expected to find hints of the DFZ late in the mission. To many people's surprise, sufficient evidence for its existence came during the spacecraft's first orbit. Observations from 1 AU before the *PSP* show that the brightness of the F-corona continues to increase linearly on a log–log scale all the way to the Sun, and the data do not indicate evidence for a DFZ. Data from the *PSP* taken closer to the Sun, however, show significant brightness decreases at small elongations from the Sun.[16] That can only result from a depletion of the dust-particle density closer to the Sun. More recent orbits with lower perihelia have confirmed the significance of the brightness depletion.

Dust in the inner heliosphere

In addition to solving the nine-decade historical DFZ puzzle, the *PSP* is revealing previously unknown phenomena related to dust dynamics in the innermost region of the heliosphere. Observations from previous space missions indicate the existence of several populations of zodiacal dust. The most prominent are α-meteoroids—gravity-bound particles on elliptical orbits around the Sun—and β-meteoroids, which are unbound grains on hyperbolic orbits that are likely the product of collisions of the α-meteoroids. Figure 4 shows indications of other dust populations too.

The dust environment in the innermost region of the heliosphere, however, has been unknown. Before the *PSP*, no spacecraft had flown into that region of space. To evaluate the risk to the mission, significant effort went into modeling that dust environment, which is particularly close to the Sun. The modeling results were only predictions, though, as there were no observations from that region of the heliosphere to compare with. Although the *PSP* lacks a dedicated dust sensor, the whole spacecraft can be used as a giant detector for measurable dust impacts. As fast dust particles hit areas of the spacecraft, they create a plasma cloud whose electric potential can be measured by the FIELDS electric antennas. Those impact rates carry critical information on the collisional environment of the inner solar system.

Figure 4 illustrates the dust-impact rates measured by the *PSP*. Dust-impact rates during the spacecraft's first three orbits show a single peak occurring slightly before the perihelion followed by a gradual drop-off after the perihelion (figure 4a). Subsequent orbits show two peaks: one before and another after the perihelion. Modeling indicates that preperihelion peaks are consistent with the α- and β-meteoroids populations. The *PSP* dust-impact data also show that the collisions producing β-meteoroids occur in a region that's 10–20 solar radii from the Sun. The postperihelion peaks could not be reproduced by the models unless a third population, known as a β-stream, is considered (see figure 4b). If the *PSP* is observing a β-stream, it would be the first direct observation of asteroidal and cometary debris trails collisionally eroding as they transit the zodiacal cloud.[17]

As the mission progresses, it could reveal additional meteoroid streams that would be difficult to detect via other means. The potential β-stream is likely related to the Geminids meteor stream, associated with the mysterious 3200 Phaethon asteroid. It brightens close to sunlike comets that have a dust tail 2.5×10^8 m long. What remains puzzling is how a rocky asteroid can leave behind a trail of debris that sparks the Geminids meteor shower.

Venus's circumsolar dust ring

The *PSP* collected science data during an extended campaign from 12–23 January 2020 before the fourth perihelion encounter. The spacecraft traveled from 0.5 AU to 0.25 AU and rolled

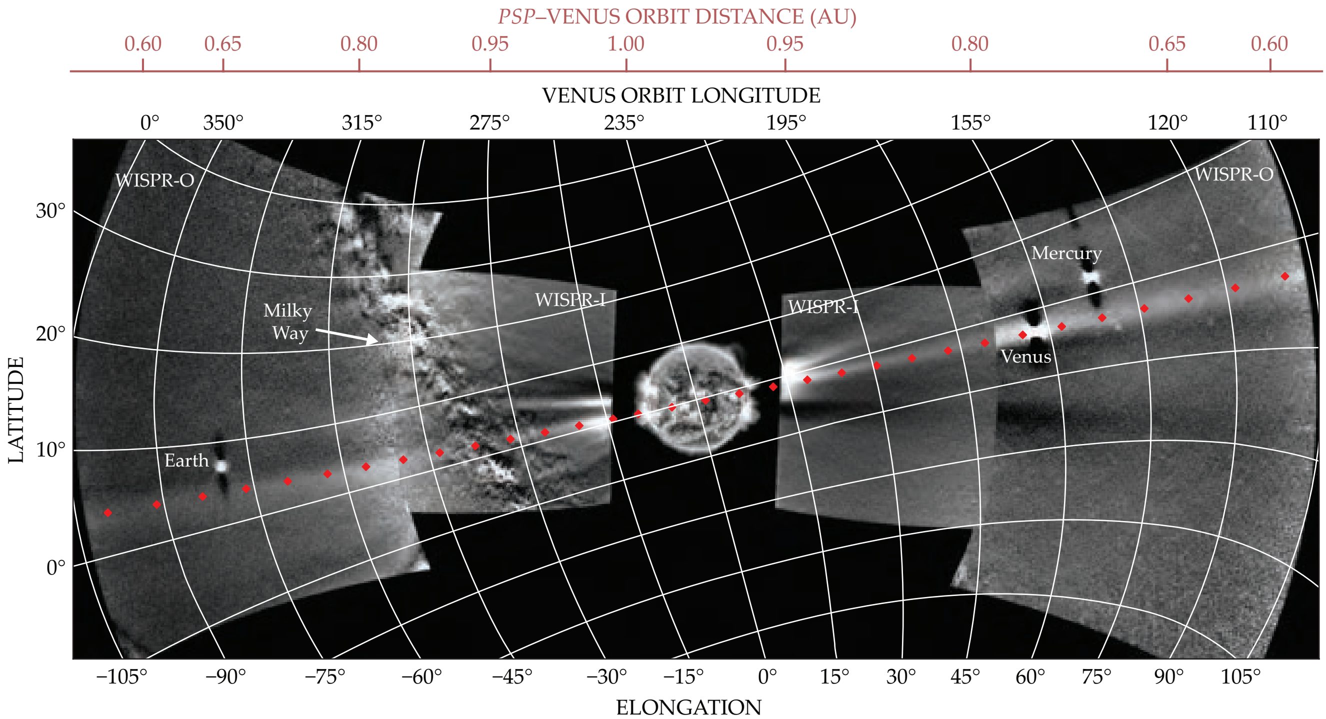


FIGURE 5. A CIRCUMSOLAR DUST RING, identified by the faint emission along the orbit of Venus (red dotted line), was first observed by the *Parker Solar Probe*. The spacecraft's WISPR sensor collected the images during the extended campaign that preceded the fourth perihelion encounter. The Sun—not to scale and masked by the spacecraft's heat shield—is the disk at the center. The images on the right- and left-hand sides are in the direction of the spacecraft's motion and the opposite motion, respectively. (Adapted from ref. 18.)

180° back and forth to communicate with Earth and manage its own momentum. Those maneuvers are not performed during solar-perihelion encounters, when the WISPR imager is always looking in the spacecraft's direction of motion, known as the ram direction. During the extended campaign, the WISPR imager was recording images in the ram and antiram directions. Figure 5 shows a composition of WISPR images projected onto the surface of a sphere.

The data required a new processing technique different from the one used during the first two perihelion encounters, when WISPR was imaging along the spacecraft's path of motion. The new data show a faint emission that extends through the instrument's entire field of view with an excess brightness of about 1% above the background zodiacal light. The emission is clearly not an artifact and cannot be of coronal origins, because coronal structures do not extend that far from the Sun.

The emission coincides precisely with Venus's orbit (see figure 5). The *PSP* imaged the full extent of the circumsolar dust ring along the orbit for the first time.[18] Previous and subsequent data analyzed with the new processing technique confirmed the existence of the ring. Now the question is, How can such a dust ring form? There are two competing theories: resonant gravitational trapping of dust by the planet and co-orbital asteroids along the Venusian orbit. Either theory could be correct, or perhaps another interpretation could better explain the dust ring.

The *PSP* is four years into its primary mission. So far, it has uncovered numerous phenomena. Most of those discoveries were about phenomena occurring during solar minimum. But the Sun's activity level is rising toward solar maximum, predicted to occur in 2025. Solar scientists will undoubtedly discover other aspects of the solar corona and inner heliosphere. They are eager for the spacecraft to fly through many of the most violent solar eruptions, the data from which may reveal how particles are accelerated to extreme levels. The *PSP* is rewriting the textbooks on our understanding of the Sun, the solar wind, and, more generally, stars and their winds.

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MEMCOMPUTING: When memory becomes a computing tool

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Massimiliano Di Ventra

A physical system that retrieves information from the past and acts on it appropriately can efficiently solve difficult combinatorial-optimization problems.

> *"The theory of computation has traditionally been studied almost entirely in the abstract, as a topic in pure mathematics. This is to miss the point of it. Computers are physical objects, and computations are physical processes. What computers can or cannot compute is determined by the laws of physics alone, and not by pure mathematics."*
>
> —David Deutsch, *The Fabric of Reality: The Science of Parallel Universes—and Its Implications*

In that 1997 book, David Deutsch has a fascinating perspective.[1] It's one that I share, and it goes against the prevailing understanding of most computer scientists, mathematicians, and pretty much anyone who has even a minimal background in the theory of computation. For them, computation was defined more than 80 years ago by Alan Turing.[2] The edifice researchers have built on it—which has led, among other things, to our modern computers—is quite impressive. Those researchers would tell you that the only physics necessary in the field of computation is the one that makes Turing's ideas practical. That is, physics is just a tool to realize in practice the mathematical concept that Turing envisioned: With better transistors, engineers can make our modern computers faster, more energy efficient, and smaller.

What if instead we take Deutsch's viewpoint more seriously? In that case, what physics should we use to compute? Deutsch most likely would say quantum mechanics! He was, after all, one of the first proponents of quantum computers. And despite serious roadblocks, they are frequently hailed as the future of computation.[3] But can we go even further and understand computation as more than a mere physical process? Indeed, can we interpret *any* physical process as some type of computation?

The equivalence of information and computation

To answer that question, consider a pinball machine (figure 1). As a ball is dropped from the top of the machine, gravity drives it toward the bottom. Along the way, the ball scatters off bumpers and, provided it doesn't get stuck, exits at the bottom. It has no other choice!

The question is, Can you compute the path the ball follows from the top entrance to the bottom exit? Because I used the word "compute," you might think of using Newtonian mechanics to calculate the path that an ideal pointlike ball, starting from a given position and velocity, would take while scattering elastically off rigid disks along the walls. You might then turn to modern computers to numerically integrate the equations of motion of the system. And there you have it: You have calculated the ball's trajectory.

But was it necessary to use modern computers to answer the question? Why not just observe the ball's trajectory by putting fresh paint on the machine's surface? After all, the information you want to extract is its trajectory. It does not matter whether that comes directly from the physical system, the ball in the pinball machine, or traditional computation. The actual physical system can calculate its own trajectory infinitely better than the approximate equations used to describe the trajectory. The system includes all possible effects, and the ball doesn't know or care if such a calculation is difficult. It simply acts according to natural laws. In the process, you would interpret the result as a path or a trajectory.

Indeed, any physical system performs some type of computation, with the observers providing meaning to it. I call that process the equivalence principle between physical information and computation.[4] We apply that principle in countless instances without even realizing it—when a thermostat computes the temperature of a room, say, or a speedometer computes a car's relative speed.

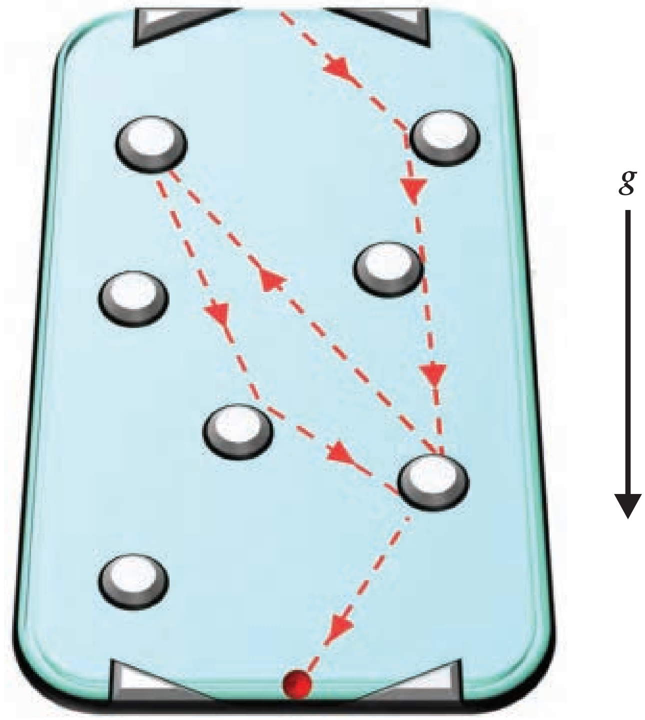


FIGURE 1. A PINBALL MACHINE as a metaphor for a computer. The ball calculates its own trajectory (the red dashed line) from entrance to exit in the machine, as driven by gravity.

Analog versus digital

You might think that what I have just described is an analog machine—one that, like the temperature on a thermometer or the position of a pinball, operates with real numbers. And analog machines are not efficient at solving combinatorial-optimization problems, such as factoring numbers into their constituent primes. That's because analog machines are not easily scalable. If you wanted to linearly increase their size—and, correspondingly, the size of the problem to solve—you would need to increase your resources, such as time, space, or energy, exponentially. Because analog machines are sensitive to noise, one would need a digital machine, which maps one finite string of zeros and ones into another finite string of zeros and ones, to solve a combinatorial-optimization problem.

Modern computers operate in real time and manipulate currents and voltages of actual physical devices, such as transistors, with the unavoidable noise and imperfections they carry. Those devices cannot represent mathematical symbols, such as zero and one, with absolute precision. Yet no one would argue that our modern computers are analog machines and hence not scalable. In fact, many scientists believe they are best described as Turing machines, though that is not exactly accurate.

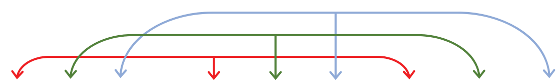
What really distinguishes an analog machine from a digital one is our ability to write the input and read the output of the computation with finite precision—that is, with a finite number of bits. That's what Turing had in mind, and it's how our modern computers work. Even though a single transistor cannot exactly represent the mathematical zero (with a low current, say) or one (with a high current), it can represent those values to within an error, or current threshold, that is independent of the size of the machine or the problem to solve. What happens between the input and the output—the so-called transition function in computer-science jargon—is not important for the scalability of the machine, provided the map does not destroy the output of the computation if it is subject to noise or perturbations.

The need for a collective approach

The choice of what physical phenomena should be used to represent the transition function between input and output must be dictated by the goal. If the goal is to solve combinatorial-optimization problems, such as prime factorization, you need to first understand why they can be difficult.

Take, for instance, the Boolean formula in figure 2. It consists of three variables, v_1, v_2, and v_3, related to each other by a logical OR, thus forming a clause, and three different clauses related by logical ANDs. Those variables can take the Boolean values of zero or one. If you ask what logical assignment I need

Collective allocation of variables



$$1 = (\neg v_1 \vee v_2 \vee v_3) \wedge (\neg v_1 \vee \neg v_2 \vee v_3) \wedge (v_1 \vee \neg v_2 \vee \neg v_3)$$

FIGURE 2. THIS BOOLEAN FORMULA has three logical variables v_1, v_2, and v_3—each taking the values zero or one—that are related to each other by a logical OR (symbol ∨) and clauses (in parentheses). The three clauses, in turn, are connected by a logical AND (symbol ∧). The symbol ¬ indicates negation. The goal is to determine the values of the variables that satisfy all the clauses so that the formula is true, represented by the value one. The ideal way to solve the problem is to assign the variables' values collectively—that is, at the same time.

for v_1, v_2, and v_3 to satisfy such a formula—that is, when all the clauses are logically satisfied—then I could randomly assign an initial value to the three variables and sequentially check whether each clause is satisfied.

If any are not satisfied, I could change the value of v_1, say, and try again until I find a combination for v_1, v_2, and v_3 that works. That's easy to do if the number of variables and clauses is just three. But if the number grows to thousands or even millions, as it can in many real-life problems, that approach is not efficient. One may come up with clever algorithms to speed up the process, but for some problems even that approach struggles: The computation time increases exponentially when the size of the problem increases linearly.

The reason for that scaling is that all algorithms are perturbative approaches to computation. They change the value of one or more variables in the problem in a sequential way. Ideally, one would have a machine that assigns the values of a large number of variables collectively, all at once. That collective behavior is nonperturbative. As such, it is reminiscent of strongly coupled systems. And because the machine has to act on a collective number of variables at once in a correlated way, it should have some type of long-range order.

That behavior is typical of continuous phase transitions. Indeed, in the 1990s the theorist Chris Langton suggested that "computation at the edge of chaos"—in the proximity of a critical state of the phase transition—is the optimal condition for processing and storing information.[5] But it's not at all obvious how to practically build a machine that operates at such a sweet spot. In addition, although long-range order is a feature of continuous phase transitions, it may emerge even without a phase transition.

MemComputing paradigm

How can a system self-tune into such a long-range ordered state during computation? The key to that process is memory. By memory, however, I don't mean storage, but rather time nonlocality—the ability of a physical system to remember its past dynamics in order to perform necessary tasks. I call that computing paradigm MemComputing.[6]

Time nonlocality may induce spatial nonlocality and drive the system into a long-range ordered state.[3] The process can be intuitively understood with a story. If, for example, I leave pebbles on a trail—forming a "memory trace"—someone else can retrace my path, even if I've never met that person and so long as the memory is not somehow displaced. Thanks to that memory trace I can now interact with that person at long distances in a correlated way.

How does that work in practice? Suppose you want to solve a combinatorial problem like the one outlined in figure 2. The idea is to transform the logic gates of the problem into physical systems, such as electronic or optical circuits with specific properties, and then put them together into a single unit. For instance, take the logical OR gate, shown in figure 3. It has only four possible logically consistent states. Then transform the logical variables into continuous ones, which could be the voltages or currents of an actual physical circuit.[7] As with transistors, you could set a threshold to some voltage that identifies a logical zero or one, irrespective of how many units you put

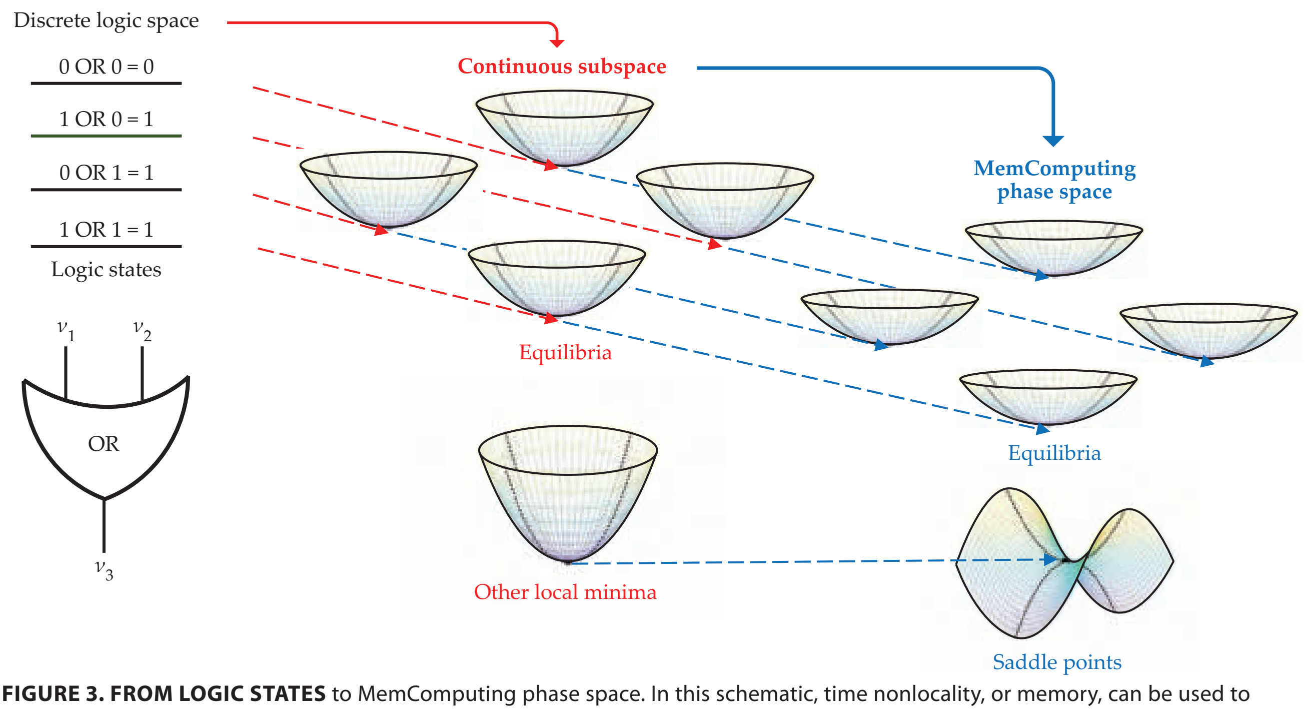


FIGURE 3. FROM LOGIC STATES to MemComputing phase space. In this schematic, time nonlocality, or memory, can be used to transform a logic gate into a physical system whose only equilibria are the logically consistent states of the gate. The OR gate has three terminals that take three discrete variables, v_1, v_2, and v_3, each either zero or one, and four possible logic states. The discrete variables of the gate are first transformed into continuous variables. That subspace (red) may contain local minima in addition to the equilibria corresponding to the four logic states. Memory variables can then be added so that those additional local minima are transformed into saddle points. The MemComputing phase space (blue) is the space of continuous variables plus the memory variables. It contains only saddle points and equilibria, or solutions to the problem. (Adapted from ref. 4.)

together. You would then have a digital MemComputing machine, a subclass of the much more general concept of MemComputing.[8]

I have now transitioned from the discrete space of logic states to the continuous phase space of dynamic variables. And I can map the four logically consistent states of the OR gate into four distinct equilibrium points of the system's dynamics. But if I stop here, the phase space may have additional local minima beside the four equilibrium points (figure 3, middle). And if the system ends up in one of those additional "wrong" local minima, it will not be able to get out and hence not solve the problem.

Here is how memory, in the form of additional dynamic variables, helps to solve that problem. If I add memory variables, which one could think of as additional degrees of freedom, I can extend the phase space of the original variables—from which I read the solution—to a larger phase space. That way, if I add the memory variables appropriately,[4] I can transform the local minima I don't want into saddle points, thus opening up directions in phase space from which the system can move toward the solution (figure 3, right). It is in that enlarged phase space, containing only saddle points and equilibria representing the solutions of the problem, that the machine performs its computation.

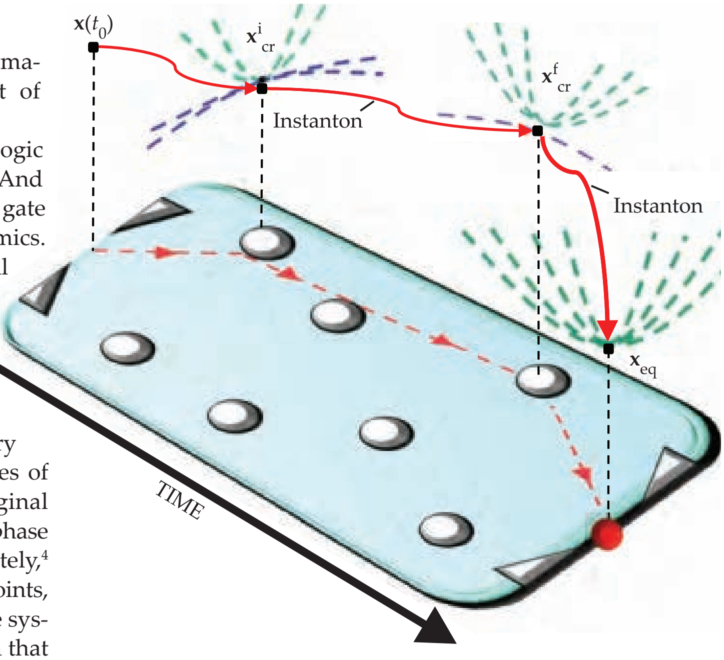


FIGURE 4. THE PHASE-SPACE TRAJECTORY, illustrated by analogy to a ball traveling down a pinball machine, is the path a digital MemComputing machine follows in phase space to solve a given problem. The trajectory $\mathbf{x}(t)$ starts from an arbitrary initial state $\mathbf{x}(t_0)$ and reaches the closest saddle point, or pinball bumper, at an initial critical point $\mathbf{x}^{i}_{cr}$, which has some unstable directions (negative-curvature parabolas) and stable directions (positive-curvature parabolas). From there, the system tunnels to another saddle point with fewer unstable directions along an instanton, the trajectories connecting the saddle points. That process repeats until the machine reaches a stable equilibrium point $\mathbf{x}_{eq}$ representing the solution, if one exists. (Adapted from ref. 4.)

Topological nonquantum computing

How does that computation occur? Unlike the Hilbert space of quantum computers,[3] the dimension of the phase space in a digital MemComputing machine grows linearly with the number of degrees of freedom of the system—the number of original variables v_i plus the additional memory variables. Suppose that the location of those variables is indicated with the state vector $\mathbf{x}$. That dimension, in turn, grows polynomially (linearly, typically) with the size of the problem being solved.[7] The dynamics are then dictated by some equation of motion of the type $d\mathbf{x}/dt = F(\mathbf{x})$, with F being some appropriate function.[4]

If that were the whole story and the dynamics were simply a random walk in phase space, the computation would not be efficient. Instead, the system can only go from one saddle point with a certain number of unstable directions—along which the machine can move toward the solution—to another saddle point with fewer unstable directions until its dynamics end in equilibria. The equilibria, which are the solutions to the problem, don't have any unstable directions, as shown in figure 4. (Notice the lack of any downward-pointing parabolas there.)

The phase-space trajectories between the saddle points—and from the last saddle point to the equilibria—have the fancy name instantons.[9] That's because they connect two distinct critical points in the phase space (those where $F(x) = 0$), and they occur in a very short, but finite time—an instant. Instantons are the classical equivalent of tunneling between two states. And because they connect two inequivalent critical points, they are topological objects: They cannot be destroyed without changing the phase-space topology.[10] The dynamics of the MemComputing machines are thus quite robust against noise and perturbations.[4]

In fact, the dynamics are quite similar to those of the ball in a pinball machine, in which the bumpers are saddle points and the trajectories between them are the instantons, as shown in figure 4. If one were to shake the machine, the ball might take a different path and hence follow different instantons, but it will always exit at the bottom as driven by gravity. What's more, instantons are the type of nonperturbative phenomena that are key to compute hard problems efficiently. In fact, a single instanton can involve a large number of variables simultaneously—that is, collectively.[10]

A physical system (a digital MemComputing machine) computes even difficult combinatorial-optimization problems efficiently. Every time the machine tunnels from one saddle point to another, more stable one—that is, one having a smaller number of unstable directions—via an instanton, it sheds unstable directions. The instanton brings the machine to a more stable saddle point, a process that repeats until the machine reaches the most stable point, which is the solution of the problem.

Because the number of unstable directions is at most equal to the dimension of the phase space, and the latter grows linearly with the number of degrees of freedom, the number of instantons the machine needs to reach the solution can grow at most only polynomially with the size of the problem. That statement is true even in the presence of moderate noise and perturbations.[10]

Hardware and software

The physical hardware that makes up the machines can include electrical, optical, spintronic, and superconducting circuits.[4]

Some realizations may be more advantageous than others in terms of their spatial footprint, energy consumption, and ease of integration. But in many cases, the machines' equations of motion are ordinary differential equations. As such, they can be efficiently programmed in software so that one can test the machines' performance by simply simulating them on a traditional computer.

Testability is a major advantage of MemComputers over quantum computers. A wide variety of combinatorial-optimization problems have already been tackled by simulating the equations of motion of the machines.[4] The simulations have shown considerable advantages over traditional algorithms and strongly suggest that building the machines' hardware is achievable. In fact, for some applications of interest to industry, a software solution is sufficient.[11]

Epilogue

MemComputing is a physics-based approach to computation radically different from both the traditional Turing paradigm and even quantum computing. It uses time nonlocality (memory) as a tool to navigate a complex phase space efficiently. And because it relies on nonquantum dynamic systems, not only can a digital MemComputing machine be built using solid-state hardware, but it can also be efficiently simulated in software, which makes it easier to deploy in industry. The machines were originally designed to tackle combinatorial-optimization problems, but their application range also covers machine learning and quantum mechanics, which open new and interesting research directions.[4]

The physics of the machines shares several remarkable features with nonabelian gauge theories, such as quantum chromodynamics,[12] and the calculation of how many instantons are required to reach the solution of a given problem is an exercise in algebraic topology.[13] Those ideas suggest an intriguing duality between that field of mathematics and computational-complexity theory—which focuses on how one can solve combinatorial-optimization problems more efficiently—and that is worth exploring further.

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PAUL LANGEVIN, U-BOATS, AND ULTRASONICS

Dazzle camouflage was used by the Allies during World War I in an attempt to make it difficult for German U-boats to detect a target ship's position and speed. Arthur Lismer's 1919 painting *Olympic with Returned Soldiers* depicts the *Olympic* (the *Titanic*'s sister ship) in dazzle camouflage at a dock in Halifax, Nova Scotia. (Courtesy of the Canadian War Museum, public domain.)

Francis Duck is a retired medical physicist, based in the UK, who now writes books and articles about the history of medical physics.

Francis Duck

Created in 1917 to detect German U-boats, Paul Langevin's piezoelectric quartz transducer remains the foundation of all modern ultrasonic techniques.

The Panthéon in Paris is the final resting place for the most honored citizens of France. Four notable physicists lie there: Pierre Curie, Marie Curie, Jean Perrin, and Paul Langevin. In life, that scientific quartet formed an intimate group that was united by their love of science, humanity, and one another. Unlike his three compatriots buried in the Panthéon, Langevin never received a Nobel Prize. Perhaps for that reason, he never achieved the iconic status of Marie Curie.

But in the early 20th century, Langevin contributed prolifically to such fields as electromagnetism, diamagnetism, birefringence, and relativity.[1,2] In honor of the 150th anniversary of his birth, this article focuses on another aspect of his work: His discovery during World War I that the piezoelectric properties of quartz could be used to generate and receive ultrasound. Although aspects of that story appear in historical reviews of piezoelectricity,[3] electroacoustic transduction,[4] and underwater detection,[5] Langevin's wartime studies of ultrasound are worth recounting on their own merits.

Early life

Langevin was born on 23 January 1872 in Paris in a small house close to where the Sacré-Cœur Basilica is located today. The Parisians were just emerging from the trauma of the city's occupation during the 1870–71 Franco–Prussian War and the bloody suppression of the short-lived Paris Commune in May 1871. A beneficiary of France's introduction of free public education in 1881, Langevin remained committed to the social importance of universal education throughout his life.

When World War I broke out in August 1914, Langevin's scientific reach was already international. He had represented France at the 1904 International Congress of Arts and Science in Saint Louis, Missouri, and, as a competent linguist, had conversed easily with the eminent group of international physicists who attended the first Solvay Conference on Physics in Brussels in 1911 (see figure 1). A close friend of Albert Einstein, Langevin had colleagues in both Germany and the UK. Fighting Germans made no more sense to him than fighting his friends in the UK: As a pacifist, he did not believe warfare was a means to resolve conflict. So when war broke out, he joined the territorial reserve as a sergeant, where he carried out noncombat duties in Versailles.

Marie Curie believed that was a huge waste of his creative and active mind. By the end of 1914, she was already operating her first x-ray van on the front line. Langevin, on the other hand, was forced to cope with the loss of his staff and students at the ESPCI Paris, where he was a professor. As Curie wrote in a January 1915 note to Langevin, "We are going through such a hard time that a man like you must urgently offer the services that only he can give. You can and must do much."[6]

Underwater detection using ultrasound

Shortly thereafter, a report appeared on Langevin's desk. Written by Constantin Chilowski, a young Russian engineer, it proposed using the echoes of pulses of high-frequency sound to detect underwater objects. Although the idea of echo detection was not new, Langevin realized that Chilowski was suggesting something original. Sound from a

FIGURE 1. THE ATTENDEES at the first Solvay Conference on Physics, which took place in Brussels from 30 October to 3 November 1911. Paul Langevin stands farthest to the right; next to him is Albert Einstein. (Photograph by Benjamin Couprie, public domain.)

low-frequency source usually spreads in all directions. But if the source is large and of high-enough frequency, a beam of sound analogous to a searchlight can be made.

It all depends on the sound's wavelength in seawater, λ. At 1 kHz, a frequency audible to humans, λ is about 1.5 m. But as it happens, a source needs to be five wavelengths or more in diameter to generate a sound beam underwater, which means that a 1 kHz emitter would need to be at least 7.5 m in diameter—far too large to mount at sea. But at the ultrasonic frequency of 100 kHz, where λ is about 15 mm, a practical echo-detection system can fit on board a ship. So little was known about the properties of sound in water that Langevin initially considered several frequencies from 15 kHz to 174 kHz. The scheme also depended, of course, on how far sound waves would travel at any frequency before they become too attenuated to be detected. That needed to be determined.

Were there any alternative ultrasound sources that could produce sound beams underwater? Immediately after the sinking of the *Titanic* in 1912, Lewis Fry Richardson, a physicist and meteorologist, had suggested using ultrasound to detect icebergs by placing an underwater whistle at the focus of a mirror to create a beam. Chilowski, on the other hand, imagined a large underwater loudspeaker. After some consideration, Langevin rejected both of those options. What he believed was needed was a device with very low inertia that could operate with low loss and be driven at a voltage that could be sustained underwater.

At Langevin's request, in March 1915 the French Navy began funding a program of practical research in his ESPCI laboratory. Working with Chilowski, he designed an ultrasonic transmitter known as a singing condenser. They used a thin sheet of mica as a dielectric, which was held in place by a vacuum on a metal sheet that acted as one electrode of the capacitor. Water formed the other electrode. The navy lent Langevin an experimental arc transmitter for generating the high-frequency driving voltage, and by July 1915 he had generated ultrasonic intensities of about 100 mW/cm^2. He confirmed the emission of ultrasonic waves by observing how the radiation force displaced a thin membrane.

Langevin had imagined an integrated pulse-echo system but failed to make the condenser work as a receiver. Chilowski and Marcel Tournier, also an engineer, designed a special carbon-granule hydrophone based on carbon microphones that were used to receive audio frequencies in air. To increase the sensitivity, they mounted the microphone at the focus of a parabolic mirror. Langevin put Tournier in charge of building and testing a working system. Successful tests in the Seine River led to a transfer of work to the naval base in Toulon in April 1916.

"A piece of stone, two plates of tinfoil"

Although the French were interested in underwater detection, the matter was perhaps more pressing for their UK allies, whose supply lines were threatened by German U-boats. Langevin's counterpart in the UK was the physicist Ernest Rutherford, whom the Royal Navy tasked with, among other things, improving submarine detection methods. Although Rutherford preferred to use hydrophones as listening devices, he remained open to other options.

In May 1916 a small contingent from Rutherford's team was invited by the physicist Maurice de Broglie to visit Langevin's ultrasound research group in France. The visit went well: By August Rutherford was instructing Robert Boyle, a Canadian physicist working with him and the British Admiralty, to explore the potential of ultrasound techniques. Concentrating first on the receiver, Boyle made and tested several microphone designs in fall 1916. But he struggled to make a reliable source of ultrasound.

In early 1917 Langevin submitted a progress report to de Broglie, who brought it to the UK that February. In the report, Langevin described the progress he had made on his ultrasound project. Realizing that a large-area flat carbon microphone might prove more effective than a smaller one, he had employed one with his singing condenser and two additional components that were used in radio receivers: an audio amplifier and a heterodyne detector. But he admitted that his design still needed a few technical tweaks. For example, the transmitters often failed because of sparking through the 1 μm mica film, and hydrostatic pressure generated noise in the carbon-granule microphones if ocean conditions weren't calm. Despite those issues, Langevin recommended that UK scientists pursue his approach.

Nevertheless, he soon began using quartz in place of the carbon granules. Quartz is a common crystalline form of silicon dioxide; its crystals are hexagonal prisms with dissimilar ends. As the brothers Jacques Curie and Pierre Curie discovered in 1880–81, it also has piezoelectric properties: When a quartz crystal is compressed or stretched, an electric charge is created on its faces. Conversely, applying a voltage across a crystal causes it to change dimensions slightly.[7]

Polar charge is greatest in three specific directions, each of which are parallel to the crystal's three pairs of prismatic faces and in a plane perpendicular to the prismatic axis. When quartz is used as a piezoelectric device, electrodes are always placed in planes perpendicular to one such polar axis, which is defined as the x-axis. The Curie brothers got Ivan Werlein, a Paris optical instrument maker, to cut two specific slices of quartz for them. The first, later termed the x-cut, which appears as the cylinder in figure 2, is done in such a way that the direction of compression or tension is along the x-axis. The second, now known as the y-cut, is depicted in figure 2 as the rectangular prismatic rod. It has a pair of electrical faces perpendicular to the x-axis but is oriented so that the stress is applied along the y-axis.

As his colleague Tournier later recalled, Langevin asked for one of the Curie brothers' original x-cut crystals. Setting it down on a bench, Langevin connected the electrodes to the radio receiver they had developed for the carbon microphone. When he placed a watch on the crystal, Langevin heard its tick through the loudspeaker. That was the vital breakthrough: Within a few days, Langevin and his team had constructed a prototype ultrasonic receiver that employed the Curies' x-cut quartz plate as a transducer.[8]

Soon a new 10 cm by 10 cm x-cut quartz transducer was cut from a large display crystal provided by Werlein. Despite Langevin's concern that the piezoelectric properties of quartz might diminish at high frequencies, the device proved to be both sensitive and stable. With no evidence of a frequency-dependent loss factor, Langevin delighted in his elegantly simple solution, which he described as "a piece of stone, two plates of tinfoil."[9]

Boyle went to France in April 1917 to learn more about cutting quartz and visit the naval dockyard in Toulon. A joint Anglo–French mission presented a full account of their progress in Washington, DC, on 15 June, which prompted several US laboratories to begin researching the technology as well. By November Langevin's piezoelectric quartz receiver was being successfully tested for underwater echo detection and communications, although it still employed a mica transducer to generate the ultrasound beam.

The quartz transmitter

As Boyle arrived in France to visit Langevin that April, the French physicist was beginning to investigate using quartz as a piezoelectric transmitter. He soon found that x-cut quartz could successfully transmit ultrasound. Exciting a 16 mm slice of pure quartz crystal at its thickness resonance, Langevin estimated that he could generate an acoustic power of about 1 kW. A visiting US physicist, Robert Wood, later noted that Langevin's beam killed small fish that swam through it and caused "an almost insupportable pain" to anyone who put their hand in its path.[10] Langevin had established the basis on which all later developments in ultrasound followed.

In a major step toward modern ultrasonic circuitry, Langevin's team replaced the arc transmitter with a tunable oscillator. He then realized that the most efficient transfer of electric energy to acoustic energy occurred when the driving frequency was

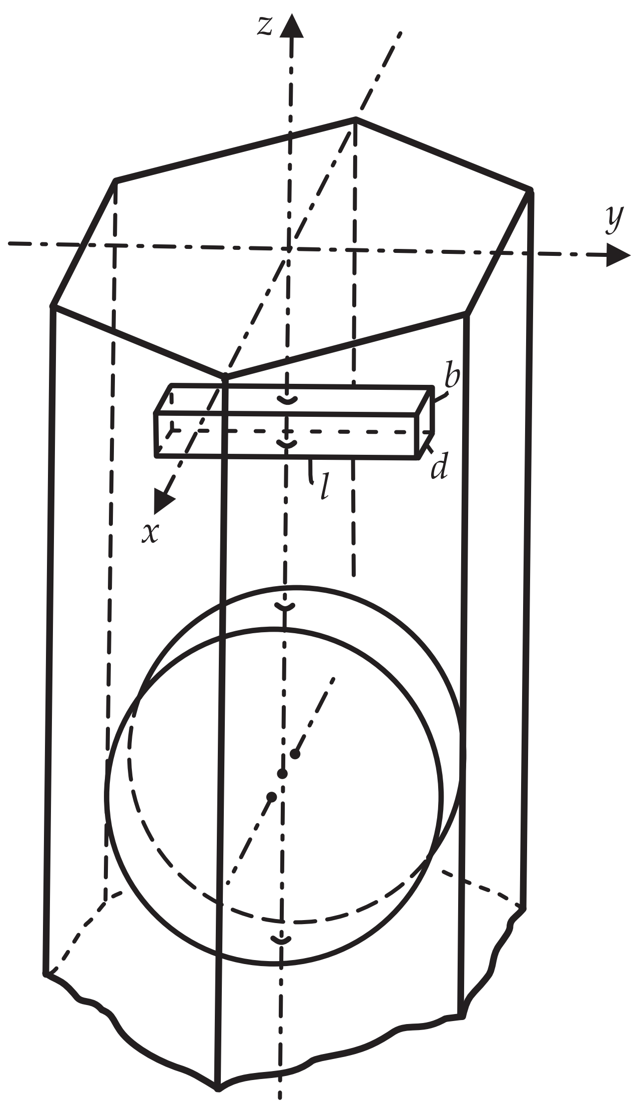

FIGURE 2. A DIAGRAM of x- and y-cut quartz. The cylinder at the bottom of the crystal is an x-cut plate of the type employed by Paul Langevin in his quartz transducer. The rectangular prism, $l \times b \times d$, on the other hand, is a y-cut plate. (Adapted from E. Hiedemann, *Grundlagen und Ergebnisse der Ultraschallforschung* [*Principles and Results of Ultrasound Research*], Walter de Gruyter, 1939, p. 4.)

FIGURE 3. A RESONANT QUARTZ SANDWICH TRANSDUCER previously owned by the French Navy. The instrument, which has a diameter of 10 cm, is now on display at the ESPCI Paris. It has been opened to show the quartz mosaic attached to the quarter-wave steel plate on the right.

the same as the natural resonant frequency of the quartz—analogous to the ringing of a bell. After experimentation, he determined that primary resonant frequency occurred when the thickness of the quartz slice was exactly half the wavelength of a sound wave in the elastic medium of the quartz.

But Langevin could only estimate the speed of sound, whose value he needed in order to set the correct thickness. The first crystal he tested resonated at about 150 kHz, which was a higher frequency than he wanted. He estimated the frequency of the ultrasonic wave by measuring the wavelength from the interference between the acoustic and electromagnetic signals in the beam. That direct measurement then allowed him to precisely relate crystal thickness to resonant frequency.

Langevin then focused on the extra gain that would result from operating the crystal at its mechanical resonance and would be added to the resonant gain from the tuned amplifier. But there was a looming problem: The higher the frequency, the more absorption resulted from thermoviscous effects in the water. A 100 kHz frequency was too high, and Langevin calculated that reducing it to 40 kHz would result in a sixfold increase in range. But the quartz crystal necessary to produce that frequency would need to be more than 50 mm thick. Naturally forming crystals of that size are rare, so that approach began to seem impracticable.

Langevin had another problem. To maintain a directional beam, the diameter of the transducer had to increase in inverse proportion to the frequency. That implied that the transducer's overall mass would need to increase approximately as the inverse cube of the frequency. Scaling up from the laboratory to the ship would not be easy.

To solve those problems, he developed what became known as the Langevin sandwich transducer (see figure 3). Bonding a 4-mm-thick sheet of *x*-cut quartz between two 3 cm plates of steel, he created a device in which the resonant frequency was set by the whole structure and not the quartz alone. He managed to create a transducer of sufficient area for a 40 kHz directional beam by building a mosaic of smaller quartz pieces into an area 10 cm in diameter. Close liaison continued between Boyle, Langevin, and their teams, who were all searching desperately for difficult-to-find quartz. Eventually, the French naval attaché tracked down a chandelier supplier in Bordeaux, where Boyle was astonished to find a warehouse full of natural quartz crystals piled up like coal.

Ultrasound between the wars

An open exchange of ideas occurred in Paris in October 1918 at an interallied conference on supersonics.[11] Ever the innovator, Langevin proposed a fan-beam design for use in shallow waters and discussed the challenges of refraction and acoustic cavitation. By then, plans were in place to install ultrasonic systems of Langevin's design on 7 French ships and of Boyle's design on 12 UK ships.

The war ended before either navy could detect enemy submarines ultrasonically. In that sense, the work of Langevin was an operational failure. The modest financial investment in the development of the novel technology saved no lives and failed to prevent, for example, the Allies' loss of roughly 6 million tons of shipping to U-boats in 1917. But ultrasound slowly began to attract the attention of scientists from academia, industry, and the military.[5]

Langevin declined an invitation to move to the US and instead turned his attention to peacetime applications of the technology he had invented. In collaboration with Charles-Louis Florisson, an electrical engineer, he developed and patented the first commercial ultrasonic depth-sounding equipment.[12] The first sounding took place off Nice in October 1920. By the late

Paul Langevin (1872–1946)

1872: Born on 23 January in Paris.

1888: Began studies at the ESPCI Paris, where he was taught by Pierre Curie.

1894: Began studies at the École Normale Supérieure in Paris.

1897: Received a fellowship from the city of Paris, which he used to study at the Cavendish Laboratory at Cambridge University.

1900: Named a research assistant in the faculty of sciences at the University of Paris (today's Sorbonne University).

1902: Completed his PhD thesis on the ionization of gases.

1905: Chosen to succeed Pierre Curie as a professor of physics at the ESPCI Paris.

1909: Appointed a titular professor at the Collège de France.

1911–27: Attended the first five Solvay Conferences on Physics.

1920: Named scientific director of the *Journal de Physique et le Radium* (*Journal of Physics and Radium*).

1925: Appointed director of the ESPCI Paris.

1930–33: Chaired the sixth and seventh Solvay Conferences on Physics.

1934: Elected to the French Academy of Sciences.

1940–44: Held under house arrest during the German occupation of France.

1944: Named president of the commission on education reform in postwar France.

1946: Died on 19 December in Paris.

1920s, their ultrasonic depth sounder was widely licensed and installed on merchant and passenger ships. By the 1930s, Langevin's original discovery was being used to produce thin, small quartz plates that generated ultrasonic beams at frequencies in excess of 1 MHz and did not require bonded substrates or mosaic fabrication.

Langevin's patents on ultrasound technology were soon challenged in UK and US courts. Although the US case dragged on for 20 years, his intellectual property was ultimately defended in both instances. The decision to contest the cases has attracted attention from scholars because it seems to conflict with his belief that science was a shared endeavor and that its outcomes should be communal assets.[4,5,7] But it seems likely that Langevin's patent applications were motivated as much by the aspirations of his partners as by his own: Chilowski wanted to promote his career outside Russia; Florisson needed commercial protection for his depth-sounding equipment; and Langevin's wife, Jeanne, may have sought improved financial security.

Generously, Langevin assigned some of the income associated with the patents to Jacques Curie and to Pierre Curie's daughters, Irène and Ève. In that way, he acknowledged his debt to the Curie brothers for their discovery of the piezoelectric reciprocity of quartz, which was crucial for its use in ultrasound detection.

All ultrasound work in the immediate aftermath of World War I was derived from Langevin's breakthrough.[13] Boyle returned to Alberta, Canada, where he continued investigating ultrasonic metrology and ultrasonic cavitation. In the UK, one of the physicists Boyle had worked with, Frank Lloyd Hopwood, with St. Bartholomew's Hospital in London, carried out numerous biophysical experiments based on Langevin's work.

Perhaps the most notable researcher inspired by Langevin's work was Wood, who became interested in ultrasound during his wartime visit to the French physicist's Toulouse laboratory.[10] After the war, he was approached by the US financier Alfred Lee Loomis, who offered to fund a laboratory. When Loomis asked about ideas to study, Wood remembered Langevin's work and suggested that they explore "supersonics."[14] Using simple quartz transducers driven at very high powers, Wood and Loomis achieved spectacular results and brought publicity to Loomis's newly established laboratory in Tuxedo Park, New York.

Although Wood learned of Langevin's results in France, most other scientists and industrialists in the US got wind of Langevin's breakthrough during the June 1917 Anglo–French visit to Washington, DC. That visit spurred Alexander Nicolson's investigations into the properties of the piezoelectric crystal known as Rochelle salt and Walter Cady's work on the quartz piezoelectric resonator. Nevertheless, interest in ultrasound gradually waned as the war receded from memory. It was not until World War II that scanned sonar became widely used to locate submarines.

In the interwar period, Langevin became one of the most senior and well-respected physicists in Europe. During the 1920s he gave a series of physics courses at the Collège de France on such topics as ultrasonics, quantum physics, magnetism, and relativity. In recognition of his seniority, he was elected to lead the sixth and seventh Solvay Conferences, the crucible for international physics debate at the time.

During the German occupation of France during World War II, Langevin was held under house arrest in Troyes because of his prewar anti-fascist activities. Upon his return to Paris, a delayed 73rd birthday ceremony was organized for him on 3 March 1945, which was attended by senior scientists, political leaders, educators, and representatives of wartime resistance movements.[15] Delegates or messages of goodwill poured in from nations across the ideological spectrum, including the UK, USSR, Greece, Yugoslavia, and China. Upon his death on 19 December 1946, Langevin was widely loved and respected (see figure 4).

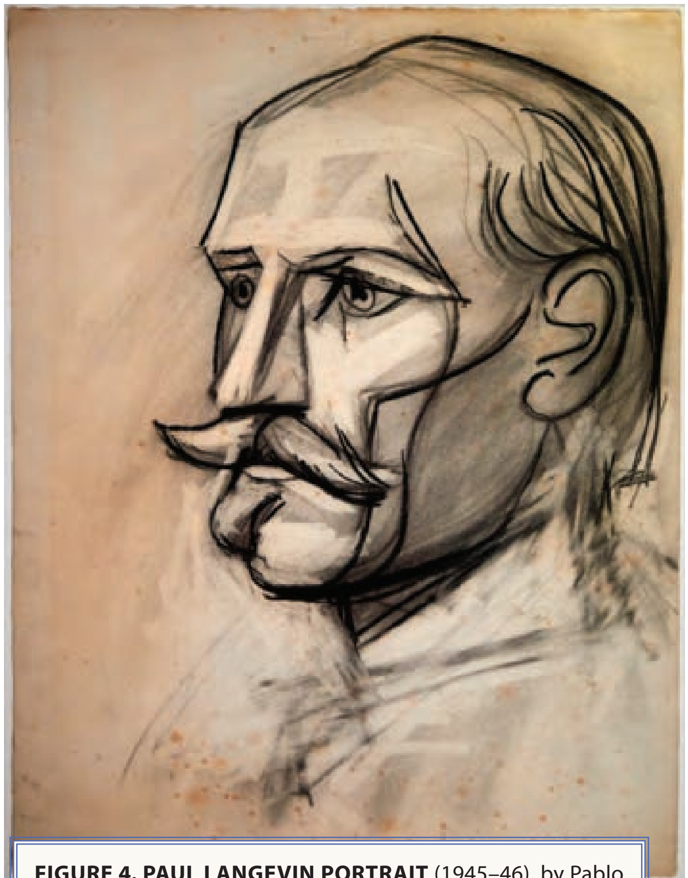

FIGURE 4. PAUL LANGEVIN PORTRAIT (1945–46), by Pablo Picasso, Army Museum, Paris. (Image from agefotostock/Alamy Stock Photo.)

Langevin's legacy: Ultrasound in medicine

The medical use of ultrasound—both diagnostic and therapeutic—is Langevin's most tangible legacy today. In 1949, more than 30 years after Langevin's first work on ultrasound, the first-ever conference on medical ultrasound was convened in Erlangen, Germany. At the conference, Florisson, Langevin's colleague, recalled that Langevin had predicted that ultrasound might someday be used for medical therapy.

Ironically, it was not in France but in Germany that ultrasound therapy took flight. As with the pulse-echo system, quartz transducers—operating at about 1 MHz—were the key to the technological breakthrough. The scientific rationale for therapeutic ultrasound was developed by Reimar Pohlman, a physicist working for Siemens in Berlin, who in 1939 demonstrated that ultrasound exposure at moderate powers could be beneficial without doing damage. By the time of the Erlangen conference, there were at least 10 European companies selling equipment for ultrasound therapy. All but one of them used x-cut quartz piezoelectric transducers. Diagnostic ultrasound,[16] on the other hand, emerged in the 1950s. (See the article by Carr Everbach, Physics Today, March 2007, page 44.) The initial transducers used were, again, quartz, although they were quickly replaced by ceramic ferroelectrics.

Echoes of Langevin's work still pervade the field of medical ultrasound. Piezoelectric transducers remain the dominant technology used in ultrasound devices. Acoustic power is still measured using radiation force, just as Langevin did. Transducer delamination, a major problem for Langevin, is still an issue. Artifacts caused by refraction and absorption still need to be identified. And harmonic imaging remains based on an understanding of finite-amplitude propagation, which was first taught by Langevin in the 1920s.

Cady, a fellow piezoelectricity pioneer, described Langevin in 1946 as "the originator of the modern science and art of ultrasonics."[17] Langevin's scientific genius lay in unlocking the piezoelectricity of quartz to act simultaneously as an ultrasound source and receiver and in developing the first working ultrasound pulse-echo system. His quartz emitter opened the path to ultrasonic cleaning, sonochemistry, and surgery; his pulse-echo system enabled the development of proximity detectors, nondestructive testing, and medical scanning. Today, worldwide sales of medical ultrasound scanners total about $8 billion per year. Ultrasound scanning is a cost-effective, safe, portable, and noninvasive medical technology. The pacifist Langevin would surely have approved.

Tom Szabo's comments on an earlier draft of this article are greatly appreciated.

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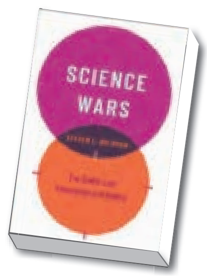
JOACHIM WTEWAEL/PUBLIC DOMAIN

This painting, *The Battle Between the Gods and the Giants*, dates from around 1600 and was created by the Dutch artist Joachim Wtewael.

A history of philosophy of science

Science Wars
The Battle over Knowledge and Reality
Steven L. Goldman
Oxford U. Press, 2021. $35.00



In Plato's dialog *The Sophist*, a character known as the Eleatic Stranger describes an ongoing battle between the gods and the giants—that is, between rationalist philosophers who believe that unchanging immaterial ideas are the ultimate reality and empiricist sophists who believe that the material world is all that truly exists.

Steven Goldman, a philosopher and professor emeritus at Lehigh University in Pennsylvania, takes that conflict as the starting point and organizing principle of his engaging new survey of the history of modern Western philosophy of science. Since its inception in the 17th century, he argues, modern science has been a conscious and contradictory effort to have it both ways: embracing the empiricist methodology of the "Giants" while claiming the deductive certainty of the "Gods."

Science Wars: The Battle over Knowledge and Reality consists of a brief introduction and 16 relatively short chapters arranged largely chronologically. The first chapter describes the Gods–Giants conflict in antiquity. Chapters 2–4 consider how the competing ideals of knowledge and method were defended by the major figures of the so-called Scientific Revolution. Chapters 5 and 6 review a range of philosophical responses to natural philosophy in the 17th and 18th centuries, and chapters 7–9 cover challenges to and defenses of 19th-century scientific theories.

Chapters 10–16 cover the 20th century. In chapter 10 Goldman surveys conventionalist, pragmatist, and logical positivist attitudes toward scientific knowledge, and in chapter 11 he describes how the rise of quantum mechanics led to controversies over the nature of reality. The 12th chapter uses the question of who thinks scientifically to discuss the history of psychology and the relationship between individuals and collectives in scientific thinking. Chapters 13–15 are devoted to Thomas Kuhn's *Structure of Scientific Revolutions* (1962), French postmodernist theories, and the academic debates that ensued in their wake. Postmodernist critiques of modern rationality aligned with a widespread reading of *Structure* (with which Kuhn himself was uncomfortable) that saw scientific consensus as a political and ideological achievement that could never be truly objective.

In chapter 16, "The Science Wars Go Public," we arrive at the Sokal hoax and its aftermath. In 1996, the theoretical physicist Alan Sokal submitted a paper intentionally consisting of nonsense sprinkled with postmodern jargon to the journal *Social Text*, which at the time was nonrefereed. The editors had their reservations, but they mistakenly believed it to be a good-faith effort by a respected physicist to engage with postmodern philosophy. When Sokal refused to revise his manuscript, they decided to publish the paper. Upon publication, Sokal announced his prank and declared it to be proof of the intellectual bankruptcy of the entire so-called academic left.

As Goldman observes, "The Sokal hoax proved nothing at all about the validity of postmodern criticism of science, including the claim that scientific knowledge was socially constructed." He goes on to describe the furious reactions to the hoax on all sides, as well as the ironic development that, in their efforts to establish "creation science" and intelligent design in the science curricula of public schools, fundamentalists on the religious right adopted the leftist critiques of science publicized by the Science Wars.

Goldman's exposition is consistently strong. He describes many complex philosophical positions with impressive accessibility, nuance, and an admirable evenhandedness. But that balance does not prevent him from explicitly articulating a stance of his own at the end of the book. He places his hopes in promoting an image of science more akin to common images of technology. Contemporary Americans are comfortable with the idea that a technology can become obsolete without rendering its past period of ascendancy an error or fraud. He suggests that the public must learn to see a similar process of replacing scientific models with better ones as something expected rather than problematic.

Although Goldman is generally sympathetic to theories that emphasize so-called external factors—those pertaining to the social interests and identities of relevant people and institutions—in understanding how science works, his own method is largely "internalist": He deftly explicates ideas and arguments but only occasionally discusses their contexts in detail. One can only do so much in a book that covers so many scientists and philosophers, so that observation is not necessarily critical.

Instead it underlines that *Science Wars* should be read as a history of Western philosophy of science rather than a history of science. The reader should not expect to examine material practices of experimentation or the social and political forces that shaped the emergence of modern science as a profession. Goldman's aim is to explore the question of how scientific knowledge works by charting several past efforts to answer that question.

The book's structure and title prioritize the *Social Text* fracas as the story's culmination. But given its centuries-long scope, I would have preferred Goldman devote more space to the ongoing ramifications of the tension he traces. Only in the final pages does Goldman briefly sketch the persistent societal stakes of his story: "The public, abetted by scientists, *does* misunderstand the natures of science and of scientific knowledge."

Because scientists act as though science produces certain truth, science loses public credibility whenever a previously "certain" truth is overturned. If we are ever to achieve sound science policy in a democracy, Goldman argues, "the public needs to understand the intrinsically conjectural, contingent, and corrigible nature of scientific knowledge," and it must understand that science nonetheless offers "the best experience-validated accounts of experience available to us at a given time." The urgency of the problem is clear. To anyone seeking a lively historical tour of the problematic nature of scientific knowledge and our unending struggle to pin down what makes it so valuable, I recommend *Science Wars* enthusiastically.

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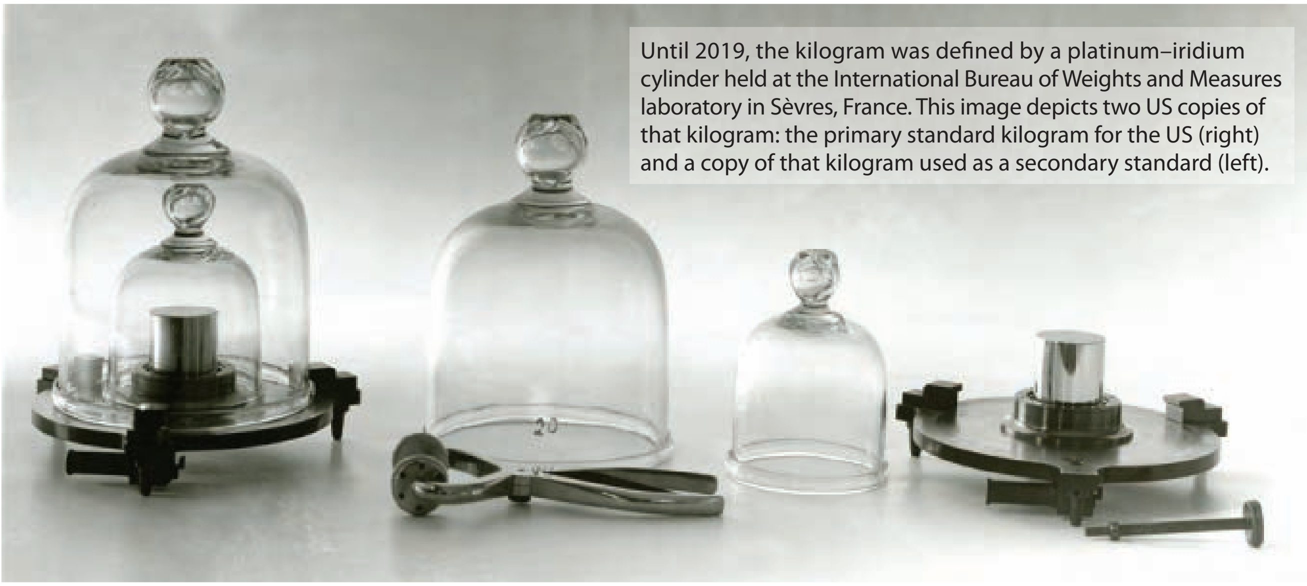
Philadelphia



Until 2019, the kilogram was defined by a platinum–iridium cylinder held at the International Bureau of Weights and Measures laboratory in Sèvres, France. This image depicts two US copies of that kilogram: the primary standard kilogram for the US (right) and a copy of that kilogram used as a secondary standard (left).

NIST/PUBLIC DOMAIN

The deeper power of dimensional analysis

In the preface of his new book *Fundamentals of Dimensional Analysis: Theory and Applications in Metallurgy*, Alberto Conejo notes that the "full potential" of dimensional analysis will always be circumscribed if it is introduced solely "as a tool to reduce the number of variables." That sentiment will undoubtedly ring true for all physicists who teach or use scaling and dimensional analysis daily to produce profound insights. *Fundamentals of Dimensional Analysis* purports to demonstrate the deep power of those methods in metallurgical applications.

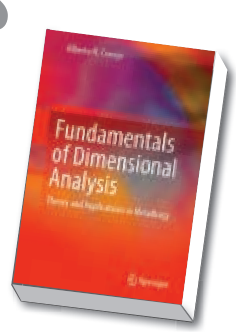
Chapter 1 provides a terse overview of the significance of dimensional homogeneity and the power of dimensional analysis. Chapter 2 traces the origins of that approach by detailing the early ideas of Galileo Galilei, James Clerk Maxwell, and others. The third chapter offers a quick tutorial on the history of units from antiquity to the present day. It also outlines how the standard meter, kilogram, and other SI base units have gradually evolved over time (see the article by David Newell, Physics Today, July 2014, page 35). Conejo ends that chapter by discussing dimensional homogeneity, or the so-called fruit-salad law—as the saying goes, "You can't add apples and oranges unless you want fruit salad."

Familiar dimensionless quantities like the Reynolds, Prandtl, and Froude numbers, which are encountered in transfer processes, are introduced in chapter 4. Although other books contain more complete lists of those dimensionless numbers, that chapter does contain interesting brief biographies of the scientists associated with those quantities. Conejo then outlines the various methods to deduce relevant dimensionless groups in a given situation. He discusses the familiar Rayleigh method in chapter 5, but for some strange reason, it is only in chapter 6 that he introduces the formalized version of the method known as Buckingham's theorem, which determines the number of dimensionless parameters to expect in a given application.

Chapters 7–9 expose readers to the Ipsen, matrix, and inspection methods of dimensional analysis. Those techniques are not mutually exclusive, so it is unfortunate that Conejo doesn't elucidate the connections between them. That could easily confuse uninitiated readers. On the plus side, he uses the same example of heat transfer from a sphere in each of those chapters to illustrate different methods of extracting dimensionless numbers.

Chapters 10 and 11 explain how experimental results must be combined with dimensional analysis to establish quantitative relationships between dependent and independent variables that can be used for predictive purposes. In chapter 10 he uses a gas bubble rising in a quiescent liquid as the model flow, alongside a few other familiar examples. The bubble's shape, Conejo notes, is determined by a balance among the inertial, viscous, and surface-tension forces. Chapter 11, on

Fundamentals of Dimensional Analysis
Theory and Applications in Metallurgy
Alberto N. Conejo
Springer, 2021. $139.99



the other hand, concentrates exclusively on modeling metallurgical operations like slag foaming, bubbles, and gas injection in steelmaking. Some of the discussion in that chapter—which, at almost 200 pages long, makes up more than half the book!—develops valuable insights by prudently blending dimensional analysis with available experimental data.

Chapter 12 addresses the issues dealing with the similarity (geometric, dynamic, kinematic) and scale-up of lab-scale data. The 13th and final chapter deals mainly with the scaling of the familiar Navier–Stokes and energy equations used to describe the flow of Newtonian fluids, a topic covered in many other books.

Even though the book's title includes the words "fundamentals" and "theory," it is more of a "how-to" book. For that reason, aside from some examples from the discussion of metallurgical nonreacting systems in chapter 11, it is likely to be of limited interest to both students and practitioners of dimensional analysis.

Strange inconsistencies and omissions

hamper the book. When Conejo considers the flow through a tube, for example, he does not include the fluid density ρ in one list of pertinent variables early in the book but adds it to a similar list later without any explanation. Similarly, in the chapter on Buckingham's theorem, Conejo does not mention that one of the requirements when selecting repeating variables is that a subgroup should not be able to form a dimensionless group. Another serious omission is the lack of discussion of chemical and material similarity in chemical reactions encountered frequently in metallurgical processes.

Several typos also slipped through the cracks. At one point, for example, Conejo mentions the physicist Osborne Reynolds when he surely means Lord Rayleigh. Later in the book, the discussion of the Navier–Stokes equations contains several errors: The x-component of the equations should contain g_x and not g, the expression for the so-called total derivative is incorrect, and no distinction is made between scalar and vector quantities. Neither the equations nor the tables presented in the book are numbered, which makes it rather tedious to read.

Fundamentals of Dimensional Analysis is a curious book. It isn't a textbook, but neither does it present the state of the art in dimensional analysis. For that reason, it isn't clear who its target audience is. But the book does contain some interesting and novel applications of dimensional analysis (although similar works do too), and the historical sections at the beginning of most of the chapters are effective. On those counts, it is a worthwhile addition to the existing literature. But I continue to prefer other books on the subject like Don Lemons's 2017 textbook *A Student's Guide to Dimensional Analysis*.

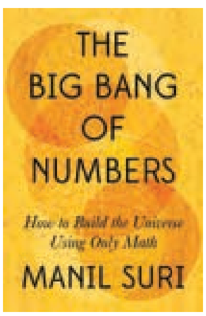
Raj Chhabra
Indian Institute of Technology Ropar
Rupnagar, India

NEW BOOKS & MEDIA

Good Night Oppy

Ryan White
Prime Video, 2022

During the 1990s, NASA lost three Mars missions: *Mars Observer*, *Mars Climate Orbiter*, and *Mars Polar Lander*. So a lot was riding on the rovers *Spirit* and *Opportunity* when they launched in 2003. Originally intended to survive 90 Martian days on the planet's surface, both rovers remained active for years: *Spirit* until 2011 and *Opportunity*, remarkably, until 2018. In *Good Night Oppy*, the director, Ryan White, uses archival footage, interviews, and artistic renderings to compose a love letter to *Opportunity* and the scientists and engineers who worked on it. It's touching to see how attached the NASA team became to *Opportunity*, which overcame dust storms to reach Endeavour Crater after a three-year trek. Although the film falls firmly in the inspirational-documentary genre, it is a fun watch. —RD



The Big Bang of Numbers

How to Build the Universe Using Only Math

Manil Suri
W. W. Norton, 2022. $32.50

Inspired by the popularity of his 2013 *New York Times* opinion piece, "How to fall in love with math," the mathematics professor Manil Suri has expanded on the topic of math appreciation with *The Big Bang of Numbers*. Aimed at math novices and enthusiasts alike, the book begins with the titular Big Bang, an "origins" story in which Suri shows how to create math's basic building blocks—numbers—out of nothing. He then goes on to discuss how those numbers can be used to devise arithmetic, geometry, algebra, and physics, and ultimately to construct the entire universe. By limiting the formulas and equations, the author has created a very readable tour of mathematics that emphasizes ideas over calculation. —CC PT

Washington University in St. Louis

Cluster Hire in Quantum Information, Materials, Sensors, and Applications

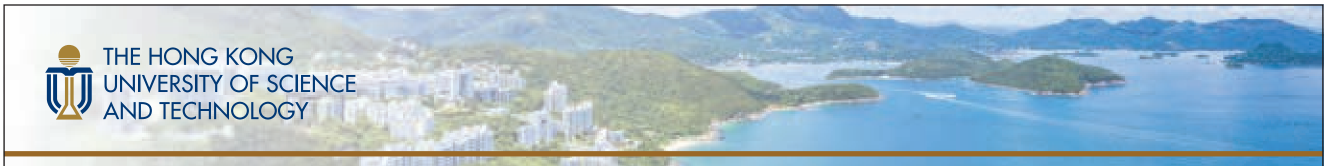
Washington University in St. Louis

Washington University in St. Louis invites applications for a cluster hire of four faculty positions in the broad area of quantum sciences, including two positions in the Department of Physics (expt or theory; one Asst/Assoc, one open rank), one in Electrical and Systems Engineering at McKelvey School of Engineering (open rank), and one in Cell Biology & Physiology at the School of Medicine (open rank). We seek candidates working in topical areas including quantum information, materials, and sensors; quantum optics, advanced spectroscopy and microscopy; and applications to biophysics or other physics, engineering, or medical fields.

Information can be found at https://physics.wustl.edu/, https://ese.wustl.edu/, and https://cellbiology.wustl.edu/. Faculty will be associated with the Center for Quantum Leaps (https://quantumleaps.wustl.edu/), and are encouraged to pursue interactions with the Institute for Materials Science and Engineering (https://imse.wustl.edu/), the McDonnell Center for Space Sciences (https://mcss.wustl.edu/), and the Center for Cellular Imaging (https://wucci.wustl.edu).

Candidates should have a Ph.D. in Physics, Engineering, Biology, or closely related field. Joint applications with a high degree of research synergy will be considered. Candidates for the rank of associate or full professor should have outstanding teaching, service, and publication record commensurate with tenure at that rank. Duties will include conducting research, teaching, advising students, and participating in departmental governance and university service. Diversity and inclusion are core values at Washington University, and we seek to create inclusive classrooms and environments in which a diverse array of students can learn and thrive. Applications consisting of a cover letter; detailed curriculum vitae; statements of research directions (3 pages) and interests in teaching, outreach, and diversity (2 pages); and contact information for at least three references should be submitted to **https://apply.interfolio.com/112603** by **Nov. 14, 2022** to receive full consideration.

Washington University in St. Louis recruits, hires, trains, and promotes persons in all job titles without regard to race, color, age, religion, sex, sexual orientation, gender identity or expression, national origin, protected veteran status, disability, or genetic information.



TENURE-TRACK FACULTY POSITIONS IN PARTICLE PHYSICS AND COSMOLOGY

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

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

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

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

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

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

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

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

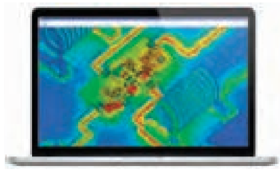
NEW PRODUCTS

Focus on software, data acquisition, and instrumentation

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

Software for RF and microwave design



Keysight's integrated design and simulation software, PathWave Advanced Design System (ADS) 2023, addresses increasing design complexity and higher frequencies in the RF and microwave industry. It includes improvements to electromagnetic (EM) simulation for circuit designers and streamlines integration of multitechnology circuit assembly and simulation into EDA (electronic design automation) workflows. Simulation performance enhancements in RFPro, the interactive EM simulator integrated with PathWave ADS, enable rapid design tuning and optimization. Error vector magnitude (EVM) distortion specification is required when designing for digitally modulated signals in RF and microwave applications; PathWave ADS incorporates Keysight instrumentation algorithms for compact test-signal generation and rapid EVM distortion calculations. It delivers EVM-simulation support for any modulated signals at the circuit level. ***Keysight Technologies Inc***, *1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Langmuir probes for plasma diagnostics

Hiden's ESPion Langmuir probes are a series of bolt-on plasma process analyzers for fast-response, high-sensitivity analysis of plasma parameters for characterization and uniformity measurements. The ESPionSoft multilevel software package controls the ESPion system and gives detailed information on plasma stability and reproducibility. A wide range of plasma parameters are calculated, including plasma potential, electron temperature, electron energy distribution, ion density, and ion flux. ESPion systems are offered with standard sampling options to suit various plasma applications, including electron cyclotron resonance, high-power impulse magnetron sputtering, pulsed plasma thrust, and laser ablation. Probes are supplied with Hiden's multi-inductor chain for wideband RF blocking. For high-temperature applications, probes feature integral gas cooling. ***Hiden Analytical Inc***, *37699 Schoolcraft Rd, Livonia, MI 48150, www.hidenanalytical.com*

Microwave lock-in amplifiers

The GHFLI and SHFLI microwave lock-in amplifiers from Zurich Instruments extend the advantages of lock-in detection—such as noise rejection, phase sensitivity, and frequency tracking—to the gigahertz range. With measurement frequencies of up to 1.8 and 8.5 GHz, respectively, the instruments are suitable for measuring periodic signals in such applications as RF MEMS and NEMS characterization and control, spin qubits, ultrafast laser spectroscopy, spintronics, and electronic-devices failure analysis. Each of two independent lock-in channels can measure multiple signals in parallel and generate multitone waveforms, and a full microwave measurement suite includes an oscilloscope, spectrum analyzer, and parametric sweeper. Eight demodulators allow users to simultaneously measure up to eight harmonics—or eight arbitrary frequencies with the multifrequency option—and provide signal amplitude and phase outputs for each harmonic or frequency. The demodulator filters reveal the best trade-off between noise rejection and measurement speed, with a time constant tunable between 14 ns and 21 s. ***Zurich Instruments AG***, *Technoparkstrasse 1, 8005 Zürich, Switzerland, www.zhinst.com*

Phase-noise tester and signal-source analyzer

The 7000 series from Berkeley Nucleonics is an all-in-one solution that offers a set of low-noise functions for basic phase measurement. According to the company, having both absolute and additive residual measurement capabilities makes the 7000 series the most flexible tool of its kind on the market. It comprises a two-channel cross-correlation system with two internal, tunable reference sources; it also allows measurements with externally sourced references. The 7000 series can measure down to −190 dBc/Hz and evaluate signal sources ranging from VHF to microwave frequencies. Three platform options are available, each covering a different frequency range: the 7070, from 1 MHz to 7 GHz; the 7300, from 1 MHz to 26 GHz; and the 7340, from 1 MHz to 40 GHz. Applications include high-speed production testing of phase noise; voltage-controlled oscillator testing and characterization; additive phase-noise characterization of amplifiers, transmitters, and mixers; ultralow phase-noise oscillator analysis; and time stability analysis of clocks. ***Berkeley Nucleonics Corporation***, *2955 Kerner Blvd, San Rafael, CA 94901, www.berkeleynucleonics.com*

Integrated patch clamp amplifiers

Sutter Instrument's family of integrated patch amplifiers (IPAs) enable efficient, low-noise, whole-cell recordings in electrophysiology applications. Available in either single- or dual-headstage versions, the amplifiers combine state-of-the-art technology with fully integrated digital-to-analog and analog-to-digital conversion and a high-speed USB interface. Data are managed using the bundled SutterPatch data acquisition and analysis software, which is built on the foundation of Igor Pro from WaveMetrics. The IPA system, in combination with the SutterPatch software, automatically captures and stores all amplifier settings, stimulus information, and external experiment parameters and associates them in time with the raw data traces. The scope window supports multiple view modes in both a 2D and a novel 3D display, which is useful during assay development. ***Sutter Instrument***, *One Digital Dr, Novato, CA 94949, www.sutter.com*

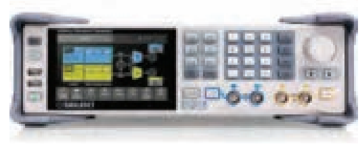
Motion-control platform

Aerotech has added new products and features to its Automation1 software-based precision machine and motion-control platform. The number of compatible hardware products has increased, so more systems can use Automation1 as their core motion controller. Servomotor drives now include the XC6e higher-powered pulse-width-modulation model and the XL5e and XL2e linear amplifier servo drives. With the new MachineApps tool, users can quickly build and deploy graphical user interfaces for machines and motion systems. The Automation1 iSMC (software-based machine controller) connects with broader factory and laboratory automation systems via the new Python application programming interface and LabVIEW virtual instruments. The Studio development software now offers tools to streamline the development process. Those include configuration checklists, homing and motor-phasing helper modules, and parameter comparison and copying tools. Upgraded servo tuning and data visualization tools come standard. ***Aerotech Inc****, 101 Zeta Dr, Pittsburgh, PA 15238-2811, www.aerotech.com*

High-performance oscilloscope

Rohde & Schwarz has upgraded its R&S RTP (real-time processing) high-performance oscilloscope. According to the company, the compact, flexible instrument is not only easier to use but also delivers the fastest possible acquisition for real-time signal-integrity analysis. The R&S application-specific integrated circuit enables an acquisition rate of 750 000 waveforms/s, which helps users more easily spot, isolate, and analyze design defects in circuit boards. The new models are offered in bandwidths of 4–16 GHz with a sample rate of up to 40 Gs/s. To reliably capture and analyze long events or sequences, the standard acquisition memory has been increased to 100 megapoints per channel; 3 gigapoints per channel is optional. The R&S RTP-K39 user-defined math option expands the possibilities for analysis of captured data. Users can call a Python script for complex calculations and display the results as a math signal on the oscilloscope. ***Rohde & Schwarz GmbH & Co KG****, Mühldorfstraße 15, 81671 Munich, Germany, www.rohde-schwarz.com*

Arbitrary waveform generator



The latest addition to Siglent's Performance Series, the SDG7000A, is the company's most powerful family of arbitrary waveform generators to date. Excellent output performance and flexibility make the SDG7000A suitable for use in the development of embedded electronics. The generators are offered in three bandwidths: 350 MHz, 500 MHz, and 1 GHz. Their two independent channels can be combined to simulate interference on the main signal or easily generate complex modulated signals. In addition to standard waveforms such as sine, square, triangle, and pulse, the SDG7000A generators can output Gaussian noise with device-specific or limited bandwidth. All are equipped with 512-megapoint memory for creating custom signals. User-defined signals can be generated with Siglent EasyWave software or directly on the device display; arbitrary curves can also be imported from text or comma-separated-values files. ***Siglent Technologies America Inc****, 6557 Cochran Rd, Solon, OH 44139, https://siglentna.com*

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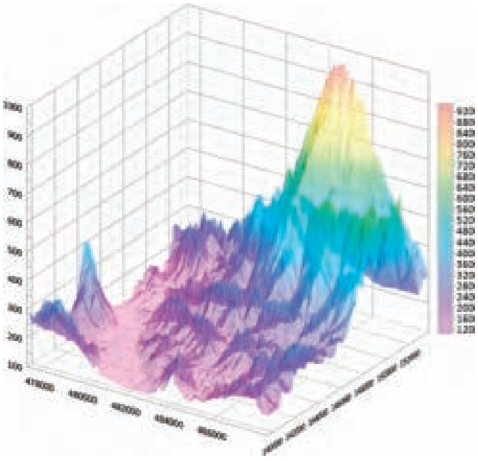
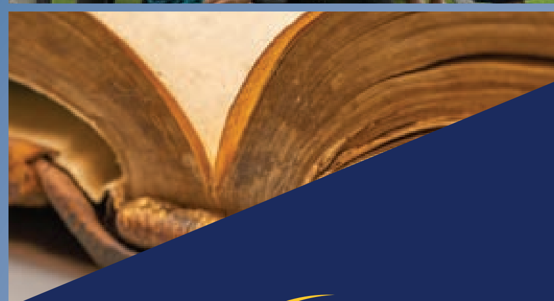


Scientific graphing software

Golden Software has released the latest version of its Grapher software for visualizing and analyzing diverse data sets. Grapher is used by scientists and engineers in academia, climate research, environmental services and consulting, and exploration. Enhancements to the software include improvements in axes and plots: Users can now add as many breaks as needed to a single axis, format the breaks with various symbols, and position them as desired on the axis. Inverse relationships, such as the Arrhenius plot relationship between temperature and activation energy, can now be plotted by linking the axes to each other. To easily compare distributions between data sets, such as changing patterns on periodically collected data, users can plot multiple histogram sets together by means of stacked or adjacent bar charts. To improve the appearance of exported 3D graphs, plot transparency is now supported in all 3D plot types, including surface and bubble. ***Golden Software LLC***, *1301 Arapahoe St, Ste 105, Golden, CO 80401, www.goldensoftware.com*

Data loggers

CAS DataLoggers has made available the sq16 and sq16-plus from Grant Instruments. They build on the capabilities of the previous Squirrel data loggers and feature updated SquirrelView software, a built-in Bluetooth communications interface, and the new SquirrelView mobile app. The data loggers provide universal analog input channels to measure current, voltage, resistance, temperature, humidity, pressure, flow, wind speed, and concentration of species. Digital channels can be set to automatically trigger or stop logging if an event occurs. Both the sq16 and the sq16-plus offer eight differential channels that can accept up to 16 sensors. The sampling rate is up to 8 Hz in the sq16 and 100 Hz for two channels in the sq16-plus. The sq16 provides support for two-wire resistance measurements; the sq16-plus offers three- and four-wire resistance. Multiple loggers may be linked, which saves space and enables measurement and monitoring of up to 128 channels of data at once. ***CAS DataLoggers***, *8437 Mayfield Rd, Unit 104, Chesterland, OH 44026, www.dataloggerinc.com* PT



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

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PHYSICS TODAY | JOBS

Stephen Howard Davis

Stephen Howard Davis, Walter P. Murphy Professor Emeritus of Engineering Sciences and Applied Mathematics at Northwestern University, died in Chicago on 12 November 2021 following complications from cardiac bypass surgery.

Born in New York City on 7 September 1939, Steve moved with his family to Long Island when he was three years old. At age 16 he elected to head upstate to attend Rensselaer Polytechnic Institute (RPI). He earned his bachelor's degree in electrical engineering in 1960 and his MS and doctoral degrees in applied mathematics in 1962 and 1964, respectively. At RPI at the time, applied mathematics was a storied department with a heavy emphasis on continuum mechanics, given the presence of Richard DiPrima, George Handelman, and Lee Segel, among others. Steve's dissertation research on Bénard convection was done under Segel. In addition to receiving an excellent education, Steve adopted several of RPI's traditions—notably, a lack of academic stuffiness, which he carried with him throughout his life.

Steve's first position after earning his PhD was at the Rand Corp in California. In Santa Monica, he met Suellen Lewis, and over the course of their 56 years together, she became known nearly as well as Steve throughout the fluid dynamics community. After a lectureship at Imperial College London in 1966–68, he accepted a position in the department of mechanics at the Johns Hopkins University. In January 1979 he moved to Northwestern.

At Johns Hopkins, Steve established his presence in the fluid dynamics community among such colleagues as Owen Phillips, Francis Bretherton, Kim Parker, William Schwarz, and, especially, Stanley Corrsin. He also established his reputation as both an outstanding researcher and an excellent teacher. Stan and Steve had a daily tradition of hosting a 10:00am coffee with a collection of faculty, students, visitors, and staff—all addressing one another on a first-name basis. Conversations covered science, politics, sports, humor, and more, creating a collegiality unmatched in other academic departments.

At Northwestern, Steve's open-door policy and willingness to meet and discuss any topic—especially his beloved New York Yankees—established a relaxed and friendly atmosphere in the department. When visiting his office for the first time, one was introduced to experimental photographs that provided the spark for much of his theoretical work. Attracted by Steve's presence, internationally renowned visitors constantly flowed into the department. Wherever he went, he built a collegial community.

Steve's renown as a researcher in the field of fluid dynamics was for pioneering work on contact-line dynamics; the stability of time-dependent flows; flows in thin films, including rupture; and the stability of flows driven by temperature-induced surface-tension variations. Later in his career, he became interested in problems in materials science, particularly those in which flow processes played a role. A worldwide leader in the dynamics of crystal growth, he made contributions to rapid solidification, anisotropic-material effects, mushy-zone convection, and nonlinear evolution of cellular growth. His unique ability to apply mathematics to important problems in materials science is captured in his 2001 monograph, *Theory of Solidification*.

Among his many awards and honors, Steve received the American Physical Society's Fluid Dynamics Prize and a Humboldt Research Award in 1994 and the 2001 G. I. Taylor Medal from the Society of Engineering Science. His many accolades, however, do not begin to encompass Steve's impact on his fields of study, nor do they do justice to his well-known personality. As a professor, his courses were always popular because he delivered complicated material in a clear, understandable way. As an adviser, Steve was able to suggest relevant, timely problems, saw the end from the beginning, and knew that the proposed topics would yield important results. When a research student encountered the inevitable brick wall, Steve would suggest a work-around that ultimately led to the problem's successful completion.

Stephen Howard Davis

Steve's influence on fluid mechanics worldwide cannot be overstated, and many consider him to have been one of the world's foremost fluid dynamicists in his time. A two-time chair of the American Physical Society's division of fluid dynamics, he was also the editor of the *Journal of Fluid Mechanics* (*JFM*) and *Annual Review of Fluid Mechanics*. He was the first to hold both editorships concurrently. His service on the editorial board of *JFM* spanned more than 40 years, and he served as its first, and to this day only, editor not affiliated with Cambridge University. Although his office was sparsely appointed, his bookshelves were lined with his *JFM* collection, and one would frequently find him sitting in his office reading the current issue.

To his academic family and his many friends who did not understand the complexities of his work, Steve will always be remembered for his warm consideration of others, his ever-engaging sense of humor, and his love of travel and fine dining. Regardless of how one knew him, when conversing with Steve about any aspect of life, he had a joke to fit the situation. He will be greatly missed.

Michael J. Miksis
Northwestern University
Evanston, Illinois
G. Paul Neitzel
Georgia Institute of Technology
Atlanta
William W. Schultz
University of Michigan
Ann Arbor

Bruce Lee is a professor of biomedical engineering at Michigan Technological University.

Mimicking mussels in the lab

Bruce P. Lee

Materials scientists increasingly turn to the sedentary mollusks for inspiration when developing glues that adhere to wet surfaces.

Human beings use more than 6 billion pounds of glues and adhesive tapes every year. Widely applied in the automotive, aerospace, furniture, electronics, and construction industries, they are pervasive. Unfortunately, most of them are not degradable; many pile up in landfills, and some even release toxic gases into the atmosphere.

Adhesives have become indispensable in sealing tissues and dressing wounds after surgical procedures. Yet water makes up 60% of our bodies, and most synthetic adhesives cannot bind tightly to wet surfaces. Physicians must usually dry a wound before applying a bandage. To stick to any surface, those adhesives rely on a combination of ionic and van der Waals interactions with surface elements and on mechanical interlocking. Yet the large dielectric constant of water compromises the bonds made from those interactions; water molecules bind tightly to surfaces and prevent adhesives from displacing them.

To mitigate such problems and design better-performing adhesives, scientists have taken inspiration from nature. Many underwater creatures such as mussels, barnacles, sandcastle worms, and octopuses use different strategies to bind themselves to surfaces in an aquatic environment. Although biologists have only begun to study how some of those organisms perform their underwater magic, they have attempted to mimic the adhesive strategies of mussels for more than two decades.

A protein's sticky solution

Ordinarily, marine mussels cling to rocky shorelines in turbulent intertidal zones, as shown in figure 1. But they are notorious foulers of ships. Underwater equipment becomes insidiously difficult to remove or repair once a colony of mussels has latched on to it.

To attach to a surface, mussels secrete liquid proteins that solidify within seconds to form surface-bound adhesive plaques. Those proteins are made of the uniquely modified amino acid 3,4-dihydroxyphenylalanine, or DOPA. The amino acid contains a catechol group—a benzene ring with two hydroxyl groups attached to adjacent carbon atoms—that has two main purposes. It forms strong bonds with a surface and quickly solidifies the adhesive proteins through chemical cross-linking.

The adhesive chemistry of catechol underlies its ability to form strong bonds with metals, polymers, and even biological tissues. That chemistry is quite diverse: Catechol can form either permanent (covalent) bonds; reversible bonds, such as cation–π interactions with positively charged surfaces; or hydrogen bonds with polar molecules on surfaces. And when catechol is oxidized—either chemically or enzymatically—it transforms into its highly reactive form, known as quinone. In turn, quinone can cross-link with another catechol molecule that cures the adhesive proteins.

Nurture over nature

Although it is feasible to directly harvest those adhesive proteins from mussels, it would take more than 10 000 of the animals to produce a mere gram of the protein. That makes scaling

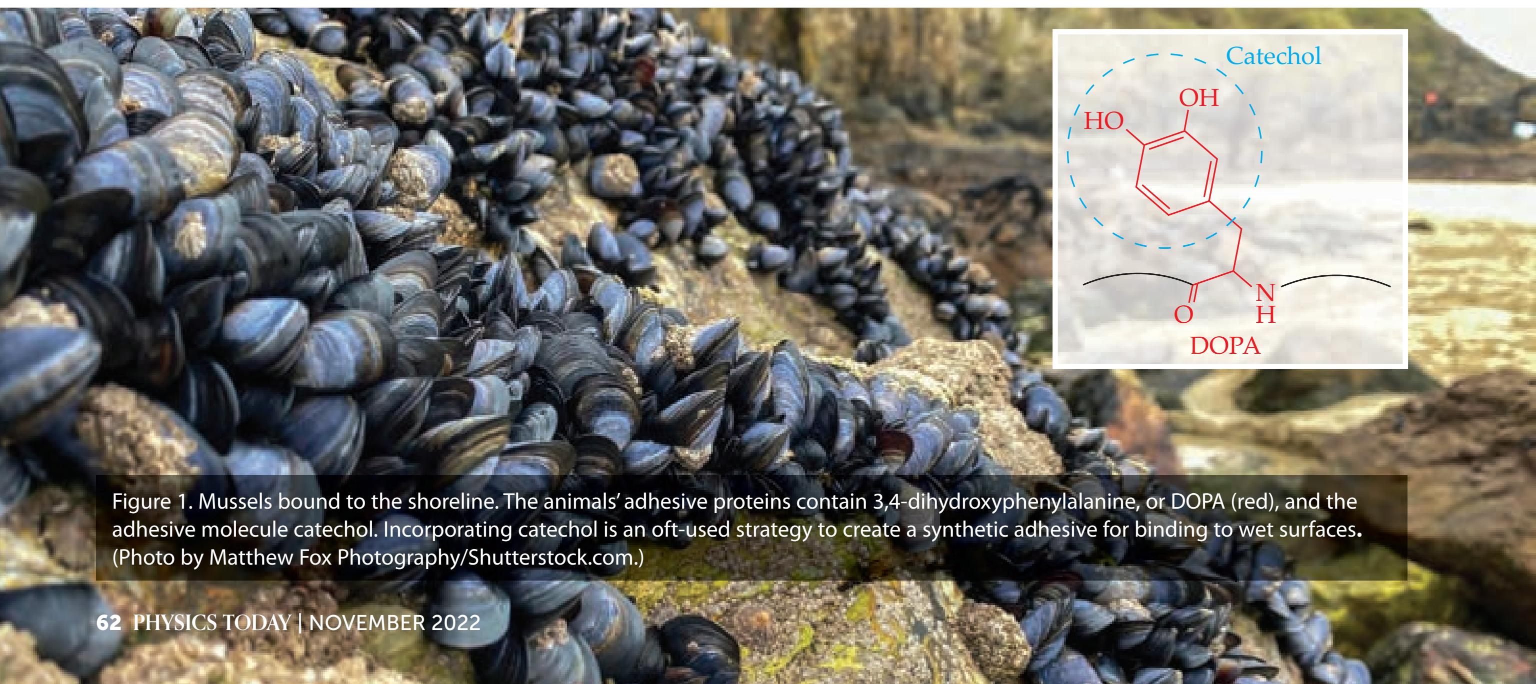

Figure 1. Mussels bound to the shoreline. The animals' adhesive proteins contain 3,4-dihydroxyphenylalanine, or DOPA (red), and the adhesive molecule catechol. Incorporating catechol is an oft-used strategy to create a synthetic adhesive for binding to wet surfaces. (Photo by Matthew Fox Photography/Shutterstock.com.)

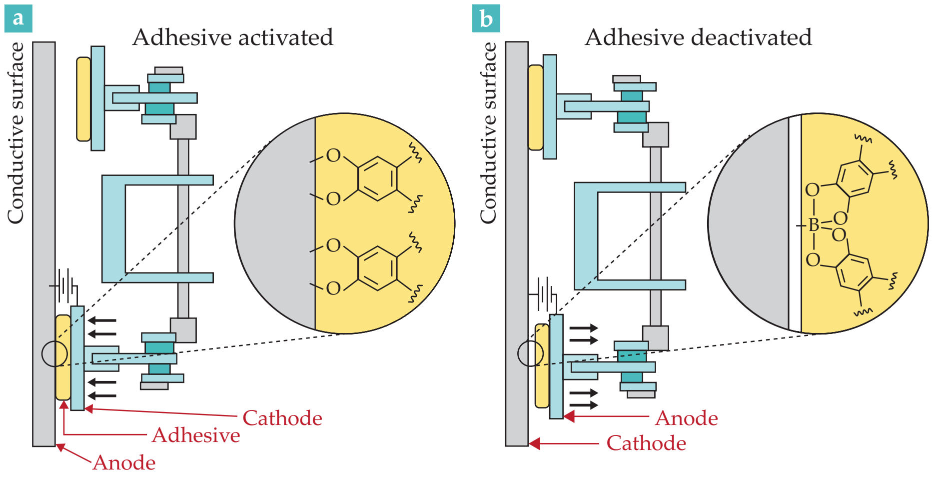

FIGURE 2. A CLIMBING ROBOT in action. **(a)** With electric pads made of adhesive hydrogel as its feet, the robot adheres to a vertical, conductive metal surface. When a current runs through the adhesive, it becomes bound to the metal surface. The inset shows the chemical structure of bound catechol. **(b)** Reversing the current—so that anode and cathode switch places—weakens the adhesive enough for the robot's foot to detach. The black arrows indicate its direction of movement. The inset shows the chemical-structure change. (Adapted from B. P. Lee, *Sci. Robot.* **6**, eabh2682, 2021.)

up the natural production of the adhesive difficult and impractical. Instead, most scientists focus on synthetic approaches to produce it.

When catechol is chemically attached to a polymer intended as one of those mussel mimics, it makes the polymer sticky. Fortunately, it's possible to tune the polymer's composition—and thus control its adhesive strength, degradation rate, and biocompatibility. The simplicity and versatility of that approach enable materials scientists to design adhesives for a variety of applications, including stopping bleeding, repairing tendons, and sealing incisions usually closed by sutures, staples, and tacks.

Part of catechol's lure is its ability to bind to metal and metal ions. Scientists can sequester antimicrobial nanoparticles and silver ions into the adhesive matrix, where they are released over time to prevent infection. What's more, reactive oxygen species (ROS) such as hydrogen peroxide are generated as by-products of the oxidation of catechol.

Those ROS generated from catechol turn out to be antimicrobial and antiviral. That's appealing because our bodies generate ROS as part of their normal immune response, and ROS naturally degrade into water and oxygen. Alternatively, one can chemically modify catechol using a halide atom such as chlorine, bromine, or iodine. Researchers have found that such halogenated catechols can kill many strains of antibiotic-resistant bacteria.

On-off switches

Natural mussel proteins attach to a surface permanently. But the adhesive characteristics of catechol, more generally, respond when the pH of any liquid surrounding it changes or when catechol is exposed to an electric current. For instance, forcing an electric current through a catechol-containing adhesive that is already attached to a surface prompts the adhesive to detach.

That switchability arises from the adhesion difference between the natural form of catechol and its oxidized form, quinone. The latter is only 20% as adhesive as catechol. And by controlling its state using pH or electrochemical oxidation, one can effectively tune the adhesion. But the reactive nature of quinone also renders it unsuitable for repeated bonding. Fortunately, a protective chemical group of boronic acid prevents the oxidative cross-linking of catechol and can preserve its reversibility in redox reactions.

In 2021 Conghui Yuan and Lizong Dai (both polymer scientists at Xiamen University in China) and their collaborators integrated a catechol-containing polymer—a hydrogel in this case—onto the feet of a 50-gram climbing robot, pictured schematically in figure 2. Electric signals turned the adhesive on and off within seconds and allowed the robot to "walk" on vertical and inverted surfaces, much like a gecko grabbing hold of a surface and releasing it repeatedly. It is potentially feasible to develop such robots for the surveillance, inspection, and maintenance of submarine and ship hulls.

Deactivating bound adhesives would also be an appealing option for physicians removing wound dressings. It would minimize pain and avoid damaging skin. Moreover, the ability to deactivate an adhesive on command would allow scientists to more easily disassemble bonded components prior to recycling them.

Currently, catechol chemistry is mostly used to design mussel-mimetic adhesives that bind to wet surfaces. But those mimics pale in comparison with the performance and complexity of natural proteins created by the mussels themselves. The animals rely on many types of proteins to construct adhesive plaque, with each protein having a different function. Some work as a surface primer, some provide mechanical strength, and others offer a protective coating.

Additionally, mussels are tethered to their surface-bound plaque via stretchable "byssal" threads that act as shock absorbers and soften the impact when the mussels are repeatedly pulled by pounding waves. That integrated design is incredibly difficult to replicate and exploit. Chemists and materials scientists have a long way to go to fully duplicate the strong underwater adhesion of mussels. But they're working on it.

Additional resources

▶ W. Zhang et al., "Catechol-functionalized hydrogels: Biomimetic design, adhesion mechanism, and biomedical applications," *Chem. Soc. Rev.* **49**, 433 (2020).

▶ H. M. Siebert, J. J. Wilker, "Deriving commercial level adhesive performance from a bio-based mussel mimetic polymer," *ACS Sustainable Chem. Eng.* **7,** 13315 (2019).

▶ B. Liu et al., "Antimicrobial property of halogenated catechols," *Chem. Eng. J.* **403**, 126340 (2021).

▶ M. S. A. Bhuiyan et al., "In situ deactivation of catechol-containing adhesive using electrochemistry," *J. Am. Chem. Soc.* **142**, 4631 (2020).

▶ J. Huang et al., "Electrically programmable adhesive hydrogels for climbing robots," *Sci. Robot.* **6**, eabe1858 (2021). PT

A six-year galactic portrait

Andrew Resnick, an associate professor of physics at Cleveland State University in Ohio, and his family have seen some spectacular views of the Milky Way during their annual one-week vacation at the beach in North Carolina. This image is the culmination of a six-year effort by Resnick to photograph the Milky Way and was made from about 2500 individual photos taken at a single location. Resnick says that on one or two nights of his vacation each year, the sky gets sufficiently dark and clear for at least an hour or so—the conditions needed to see the galaxy.

Being on vacation, Resnick didn't use a motorized telescope mount or other specialized equipment. He took all the images using a DSLR camera with a 105 mm lens, a shutter speed of 1 second, and an f-stop of f/2, which allows for the aperture to take in a lot of light, even at night. Resnick stacked and assembled the photos into a composite image using the Astro Pixel Processor application. Such a spectacular view of the galaxy is rare: An atlas of artificial night-sky brightness published in 2016 found that the Milky Way is not observable for 80% of people living in North America. (Image courtesy of Andrew Resnick.) —AL

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