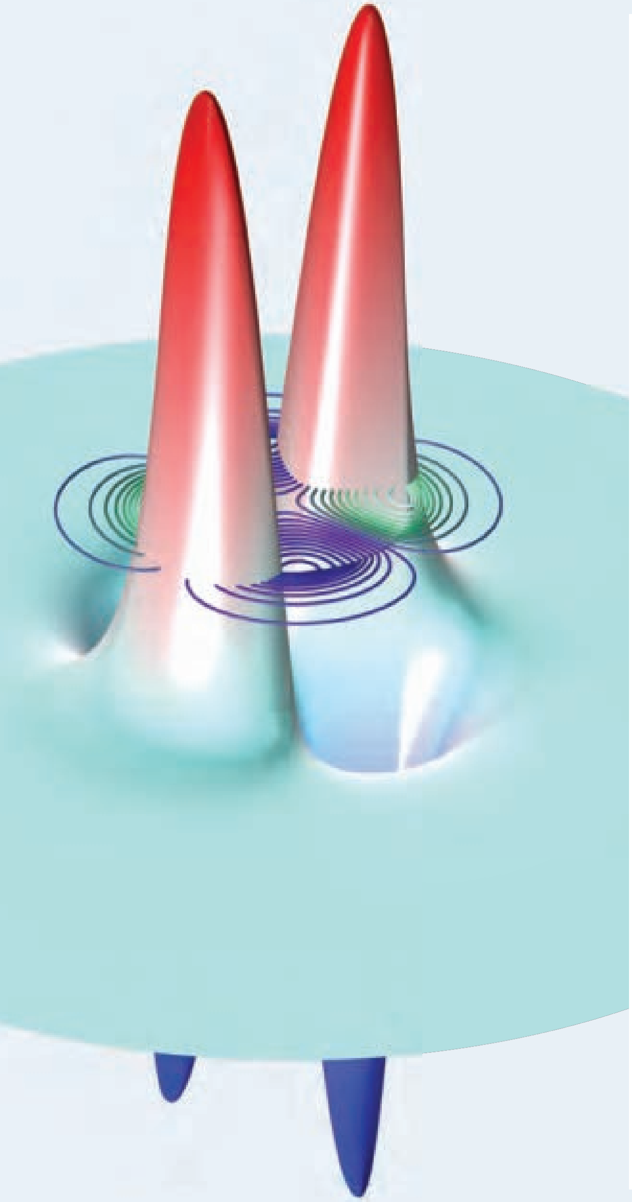

PHYSICS TODAY

October 2021 • volume 74, number 10

A publication of the American Institute of Physics

Annual careers issue

Martian seismology

Predicting how proteins fold

Integrated science programs

PHYSICS TODAY

October 2021 | volume 74 number 10

Careers issue

ON THE COVER: Our third annual careers issue focuses on the sector that employs the most graduates in physics and its related sciences: private industry. On **page 32**, Mike Tamor draws lessons from his career in research and research management at Ford Motor Company. On **page 42**, Physics Today's Christine Middleton reports on physics-based startups. And on **page 52**, Jorijn van Duijn recounts the history of the semiconductor company ASM International. (Image by Ana Kova, http://anakova.com.)

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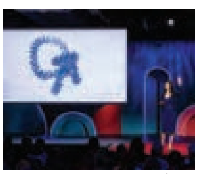

KARISSA SANBONMATSU/LANL

Switching fields

A new quantitative study finds a correlation between physicists who change areas of research and their new work's impact as measured by citations. Rachel Berkowitz reports on the results and several scientists' experiences making such shifts in research directions.

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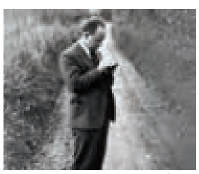

SAPIENZA/ESVA

Fermi's geophysics

Archival materials reveal that shortly after his arrival at Columbia University, Enrico Fermi offered a geophysics course in the spring semesters of 1939–41. The physicist's lecture notes highlight his famously clear and thorough style on the page and in class discussions.

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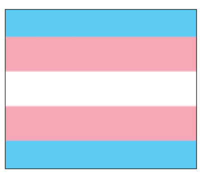

MONICA HELMS

Author name changes

A growing number of journal publishers are adopting policies to change authors' names on past academic papers. Physics Today's Toni Feder investigates the efforts of trans scientists who inspired the new policies and the positive impact they will have on trans scholars.

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Hidden physicists

Charles Day

Like me, my friend Vincent Kargatis earned a PhD in high-energy astrophysics and worked at NASA's Goddard Space Flight Center in Greenbelt, Maryland. Also like me, Kargatis left Goddard in the late 1990s to pursue a career outside of astronomy—in his case, computer programming. Now, 23 years later, he manages a team that ensures the quality of software produced by Oracle Utilities.

Since I joined PHYSICS TODAY in 1997, I've been obliged to keep up with developments in physics and to nurture contacts with physicists and their close professional relatives. Still, neither Kargatis nor I think of ourselves as physicists any longer.

Debbie Bard leads the data science engagement group at the National Energy Research Scientific Computing Center (NERSC) at Lawrence Berkeley National Laboratory. Before then, she worked at Imperial College London and SLAC. She earned a PhD in experimental particle physics at Edinburgh University in Scotland.

Bard's team helps researchers who need supercomputers for their data analysis and simulations. The job entails performing two translations: from what scientists need into what NERSC's systems engineers can provide and from what NERSC's hardware and software can do into what the scientists can implement.

"My work is very far from actual physics," Bard told me by email. "I'm mainly a manager of people and projects these days. But if someone asks me what I do, I still answer 'physicist.' It's pretty deeply ingrained in me."

I learned about Bard from Spotlight on Hidden Physicists, an ongoing series of articles in *Radiations*, the magazine of Sigma Pi Sigma, the physics honor society. Each article is about a person with a physics degree who, like Bard, Kargatis, and me, went on to do other things. The range of other things is wide. Among the 37 hidden physicists are a jazz singer, a Disney animator, a Wall Street analyst, and a theologian.

Kargatis qualifies as a hidden physicist. Indeed, people who work in computer software of one kind or another form the largest group in the *Radiations* series. Computer software is also the private-sector profession that employs the most PhD physicists, according to surveys conducted by the American Institute of Physics's Statistical Research Center. (AIP publishes PHYSICS TODAY and hosts Sigma Pi Sigma.)

Sigma Pi Sigma's Spotlight on Hidden Physicists succeeds in showing the variety of rewarding careers that people with a bachelor's, master's, or PhD in physics choose for themselves. High school seniors contemplating what subject to major in can be justifiably confident that a physics degree opens doors to careers beyond physics itself.

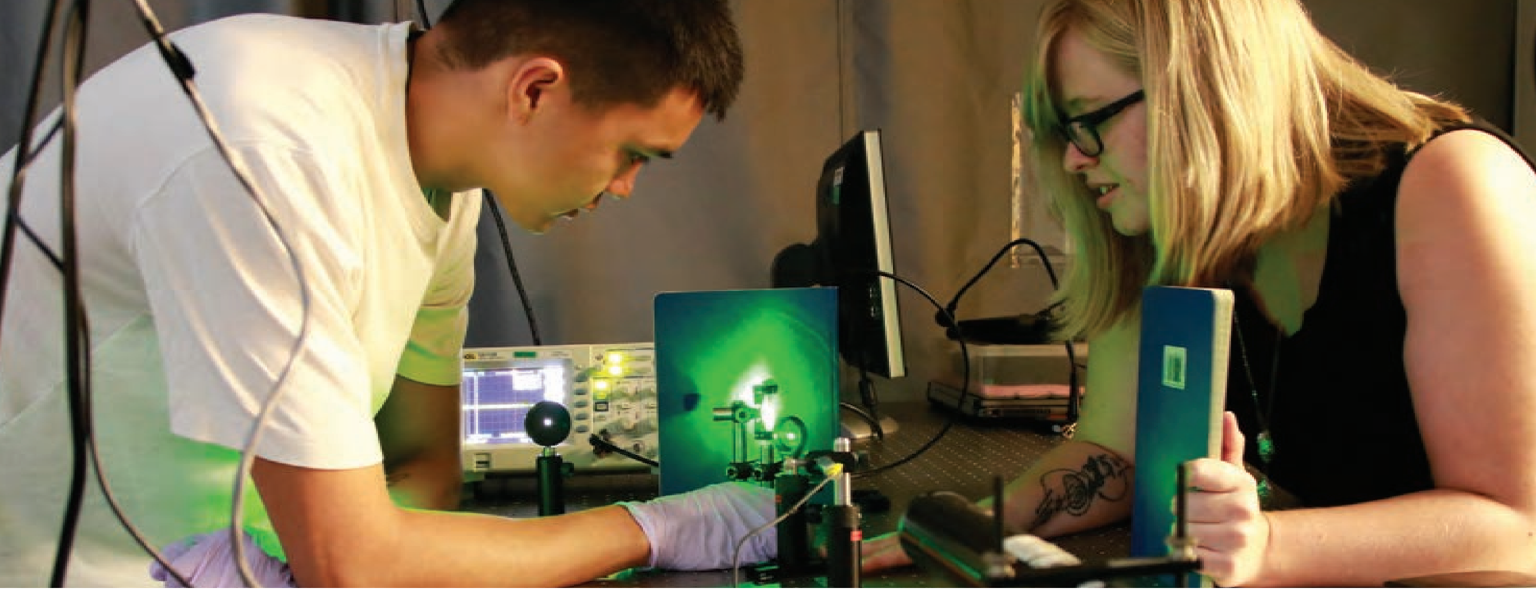
But when the professional physics community contemplates hidden physicists, it should be careful. Although Bard continues to think of herself as a physicist, Kargatis does not. When he and I get together, we talk mostly about music, food, and wine and occasionally about physics. He is not a prime candidate for becoming a PHYSICS TODAY subscriber or for rejoining the American Astronomical Society.

Of the physicists in the private sector, how many still consider themselves to be physicists? I don't know, but my hunch is that the answer has to do with whether they continue to do physics. This past May Google announced its intention to spend billions of dollars to build a quantum computer that can perform large-scale, error-free calculations by 2029. Out of curiosity, I looked up Google's jobs site. To accomplish that ambitious goal, the company sought to recruit just six additional physicists.

Two other companies in physics-flavored industries, IBM and Tesla, had no postings for physicists. That's not to say either company had no jobs for which physicists were qualified. Tesla is currently looking for someone to do computer-aided engineering and computational fluid dynamics. Some physicists meet the position's requirements, but so, too, do engineers and applied mathematicians.

If "hidden physicist" is intended to mean someone outside academia who identifies as a physicist and who does physics, some adjustment might be needed. There could be fewer of them than expected. PT

Jobs in the private sector is the focus of this year's annual careers issue.
Articles begin on page 32.



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Rutherford Adkins: Fighter pilot turned physicist

In his October 2020 column titled "Career choices" (page 8), Charles Day introduces three individuals whose obituaries appeared in different issues of PHYSICS TODAY in 1998. One of the themes was why the individuals selected the careers that they did, all of which grew out of their having doctoral degrees in physics.

One of the people mentioned was Rutherford Adkins, who after being drafted in 1941 became a member of the Tuskegee Airmen, the first African American aviator unit in the US armed forces. Adkins was a fighter pilot who flew the P-51D Mustang and completed 14 combat missions. But he and his fellow pilots and support personnel faced both Jim Crow laws and legal racial segregation in the US and at foreign military bases while fighting for "democracy" in Europe.

At the end of his column, Day notes that he doesn't know "why Adkins became a physicist after fighting the Luftwaffe," or why the other two physicists he mentions made the choices they made in their careers. "But," he says, "their lives remind us of the choices we have, even in difficult times."

I authored Adkins's obituary in PHYSICS TODAY (September 1998, page 90), and I write this letter to shine some light on the complex issue of why Adkins chose to be a physicist. The statements to come are based on my personal experiences and on my interactions with Adkins—who was one of my physics professors at Fisk University and, later, my colleague and friend.

Young Black girls and boys in the US have always been curious and sought various ways to understand the natural world. But in the 1930s, when Adkins was of school age, the realities of American society generally did not allow them to acquire the same education as white students. Many of them lived in states where Black children went to separate schools, which received far less funding than those for white children, and only a small percentage made it to high school.

RUTHERFORD ADKINS became a physics professor and university administrator after flying with the Tuskegee Airmen during World War II. (Fisk University, John Hope and Aurelia E. Franklin Library, Special Collections, Photograph Archives, Adkins008.)

But the Black children could still ask, "Why is the day sky blue, but the night sky black?" "Why can birds fly, but not humans?" "Why can water flow, but a stick cannot?" "Why?" "Why?"

Their elders told them that answers existed and that the mechanism to obtain, to comprehend, and to extend that knowledge was education. In 1930, when Adkins was five years old, few Black adults had received an education that taught them more than the skills necessary for domestic and agricultural work, according to a 2004 *American Educator* article by Peter Irons. But Black children nevertheless understood the power of education and how it could be used for the betterment of one's physical, mental, social, intellectual, and spiritual livelihoods and experiences. Not only was education valued, but educated Black individuals were considered to be of great importance to the community. From the Reconstruction era to the late 1950s, they talked to the "white power structure," helped secure jobs for other Black people, wrote obituaries and letters of recommendation, initiated voter registration drives, and generally acted as protectors of the Black community's interests.

Thus it is not surprising that Adkins wanted to be a physicist. As a child, he had taken apart radios and clocks, exploded ants with lenses using the light of the Sun, set his house ablaze in exploration of the properties of fire, and read and reread the articles on relativity in his ragged copy of the *Encyclopædia Britannica*.

After his graduation from high school, Adkins's physics education journey spanned nearly a decade and a half, culminating in his receiving a doctorate in physics in 1955 from the Catholic University of America in Washington, DC. That journey was initiated by two major factors: Adkins's desire to comprehend the physical world and his need to give back to and uplift the community from which he came. All of that was accomplished within the restrictions imposed by being Black in the US.

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It is not easy to summarize in one sentence a complex historical process like the Iberian Reconquest, which lasted almost eight centuries.

Knowledge transmission in medieval Spain

I enjoyed reading the article "Medieval weather prediction" by Anne Lawrence-Mathers in the April 2021 issue of Physics Today (page 38). But one aspect of the author's description of the transmission of knowledge from the Islamic world to Latin Europe caught my attention. She states, "Territorial conquests by northern European forces in the Iberian peninsula of al-Andalus made librarians, scholars, and translators available to the new Christian rulers."

It is not easy to summarize in one sentence a complex historical process like the Iberian Reconquest, which lasted almost eight centuries. But during that Christian reconquest, periods of peace and tolerance between Christians, Muslims, and Jews were more common than periods of war and confrontation. In fact, some Leonese and Castilian kings' tolerance of Muslims and Jews facilitated a cultural exchange that allowed the philosophical[1] and scientific[2] renaissance of the Iberian kingdoms and the entire Christian West.

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▶ **Lawrence-Mathers replies:** José Vaquero is correct that the processes by which scientific knowledge was transferred in Christian kingdoms like those of León and Castile were unusually open and positive. The contrast with, for instance, the attitudes of the Norman conquerors toward Anglo-Saxon culture in England is striking. My sentence was simply intended to recognize that those kingdoms would not have existed and lasted without the military side of what has been termed the Reconquest.

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Hackathon culture's maker potential

Toni Feder's item "Hackathons catch on for creativity, education, and networking" (Physics Today, May 2021, page 23) captures the lively ambiance of hackathons and sprints, which is familiar to those of us who have worked in engineering. It is provocative to see examples of that culture adopted by communities across the physical sciences, including quantum computing and astrophysics.

Hackathons signal a community's growing openness to rapid prototyping and iterative design as productive modes of inquiry. And when it comes to adopting that atmosphere in fundamental physics, I believe we're only seeing the tip of the iceberg.

First, while hackathons and sprints are bounded in time, their underpinning fast-paced and highly interdisciplinary culture—a staple of the maker movement—can be incorporated into an unbounded research agenda or even an entire institute. While each very distinctive, Arizona State University's Beyond Center, the Simons Foundation's Flatiron Institute (mentioned in Feder's article),

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JULIANA CHERSTON conducts thermal vacuum checks of an electronic-textile sensor soon to head to the MISSE (Materials International Space Station Experiment) Flight Facility, located on the space station's exterior, for early testing. (Courtesy of Juliana Cherston.)

and the Jet Propulsion Laboratory's Innovation Foundry are interesting scientific initiatives that can serve as inspiration. Second, the examples offered in Feder's story are largely grounded in software and data science; encouragingly, hardware-focused early prototyping is equally feasible and progressively more affordable.

Suppose the scientific community established the Center for Adventurous Inquiry—or something in that spirit—a hub for early instrumentation prototyping that would aim to build or adapt diverse technology to serve fundamental physics. Crucially, the institute would espouse the creative and iterative design approaches that commonly underpin hackathons, sprints, and rapid prototyping.

How would such an institute lure top talent from industry? Certain classes of physics instrumentation tend to take residence at the most exotic edges of Earth, whether in Japanese mines, Swiss tunnels, the Chilean desert, the Hawaiian mountains, Antarctic ice, the deep Mediterranean Sea, or the International Space Station. The latent appeal here is substantial—it would make for quite a hackathon prize to give winners the chance to further develop and eventually test early-stage hardware in one of those locales.

As an example from my own work, I aim to bring electronic textile technology to astrophysics. The intrinsically interdisciplinary rapid-prototyping effort leverages the International Space Station for resiliency testing. Scientific instrumentation that can be incorporated directly into a spacecraft's essential thermal blanket could find high adoption rates in comparison with traditional dedicated sensors. The research model used here, which focuses on bridging two fields and then testing out some early prototypes in an extreme venue, is driven by the same culture of making that inspires hackathons.

Of course, the cost, skill, time, and specialized laboratory access required to create certain types of precise and complex instrumentation can be prohibitive. But we ought to encourage a creative and flexible outlook. I welcome ideas for other potential projects under the umbrella of cross-disciplinary research or for places where such a scientific institute might find a home.

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Another use for liquid metals

Michael Dickey covered a number of interesting uses of liquid metals in his article "Liquid metals at room temperature" (PHYSICS TODAY, April 2021, page 30), but he left out one that has had great practical importance: the liquid-metal ion source (LMIS). Developed in the 1970s,[1] the LMIS revolutionized focused-ion-beam (FIB) technology by allowing usable currents (1–10 pA) to be focused to a diameter of only a few nanometers. Most FIB systems use liquid gallium because of its low vapor pressure at room temperature, its ability to stay liquid below the melting point, and its high surface tension.

Among other applications, LMIS-based FIB is used in semiconductor manufacturing. High-resolution FIB makes it vastly easier to do failure analysis on submicrometer-scale integrated circuits. The technology also enables the rewiring of integrated circuits in the development stage: Conductors can be cut and new ones added through the deposition of metallic compounds. That allows design engineers to make modifications to a circuit without needing to produce a new mask set each time. Hundreds of papers and at least three books[2–4] have covered LMIS technology and its applications.

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Deep learning opens up protein science's next frontiers

Computer models can now provide stunningly accurate predictions of proteins' three-dimensional structures. But what about their biological functions?

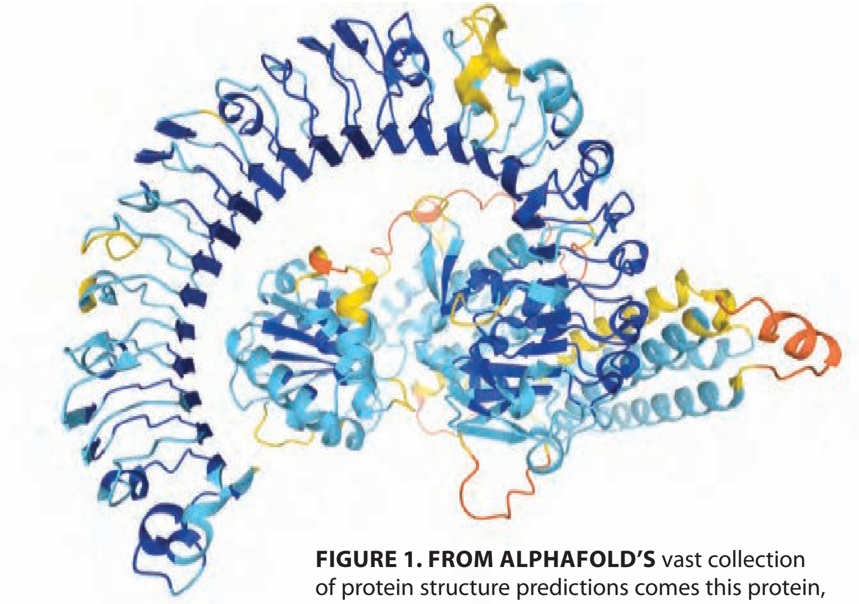

FIGURE 1. FROM ALPHAFOLD'S vast collection of protein structure predictions comes this protein, which may promote disease resistance in the Eurasian wildflower *Arabidopsis thaliana*. The colors represent regions of the protein predicted with high (blue) through low (yellow and orange) confidence. The structure has yet to be observed experimentally. (Courtesy of the AlphaFold Protein Structure Database, CC BY 4.0.)

At their heart, proteins are much like any other polymers: flexible linear chains of amino-acid monomers drawn from a library of just 20 or so building blocks. But unlike synthetic polymers, which tend to flop around stochastically, proteins reliably fold into characteristic three-dimensional shapes. The diversity of those shapes gives rise to the complexity of the biological world.

Uncovering the relationship between amino-acid sequence and folded structure has been a grand challenge of the past half century, with connections to cell biology, chemistry, biophysics, and medicine. To date, more than 180 000 protein structures have been made available to the world in the Protein Data Bank (PDB). But even that enormous resource barely makes a dent in the tens of millions of proteins known to be encoded by genes across all living species.

Last November, as part of the Critical Assessment of Structure Prediction (CASP) project, researchers at DeepMind in London showed that their AlphaFold2 model had made astonishing progress. Given a protein's amino-acid sequence, AlphaFold2 could often predict its structure with most atomic positions correct to within an angstrom—less than the length of a chemical bond.[1] The team has now released its own database of predicted protein structures, including the complete human proteome and many nonhuman proteins whose structures, such as the one in figure 1, experimenters have yet to resolve.

Inspired by AlphaFold2 but with only a rough idea of the model's architecture, Minkyung Baek, in David Baker's group at the University of Washington, and her colleagues developed a similarly capable model, called RoseTTAFold, in time to publish their results concurrently with AlphaFold2's this summer.[2]

Both AlphaFold2 and RoseTTAFold use deep learning—a type of artificial intelligence—which means that their inner workings are largely a black box. But their guiding principles are some of the same ones that have been guiding structural biologists for years. And their success has researchers thinking about how to paint an even more complete picture of proteins and their biological environments.

A hard problem

Compared with the rest of organic chemistry, understanding of proteins came late. The first known protein structures, of myoglobin and hemoglobin, weren't discovered until 1958 and 1959, respectively—half a decade after the structure of DNA.

And unlike DNA's elegant double helix, protein structures were a mess. Linus Pauling, among others, had predicted years earlier that amino-acid chains could organize into orderly alpha helices and beta sheets. Indeed, those motifs do show up in protein structures, but they're interspersed with wild twists and turns that hadn't been anticipated. "There was a sense of, 'Holy cow, there's no symmetries here,'" says Ken Dill of Stony Brook University. But the structure wasn't disordered either: For any given protein, it was always the same.

The hemoglobin and myoglobin structures had been found through x-ray crystallography, the long-time gold standard for probing the atomic structure of any material, not just biomolecules. (See the article by Wayne Hendrickson, PHYSICS TODAY, November 1995, page 42.) But the powerful technique is beleaguered by a pair of challenges. First, it requires a crystalline sample—an unnatural form of matter for most proteins. Second, the x-ray diffraction pattern retains only half the crystal's structural information: The x rays' intensities are easily measured, but their phases are lost. Max Perutz, discoverer of the hemoglobin structure, solved the so-called phase problem by inserting various heavy-metal atoms into the protein to scramble the phases. (See Perutz's obituary in PHYSICS TODAY, August 2002, page 62.) But that trick doesn't always work.

In recent years, cryoelectron microscopy has started to rival x-ray crystallography in its ability to image proteins with atomic resolution. (See PHYSICS TODAY, December 2017, page 22.) It has the benefit of not needing a crystal—instead, the molecules are embedded in a thin sheet of vitreous ice—but it's still challenging. The folded proteins might unravel under the effects of surface tension, and one needs to computationally align many 2D images at random angles to convert them into a composite 3D structure. Finding protein structures experimentally by any method remains difficult and laborious.

What about theoretically? Although some proteins require chaperone molecules to fold correctly, most can solve their own folding problem using nothing but the laws of physics. It's tempting to try to reproduce their solutions in a computer simulation (see PHYSICS TODAY, December 2013, page 13), but the complexity of the system quickly runs up against the limits of computer power for all but the smallest proteins.

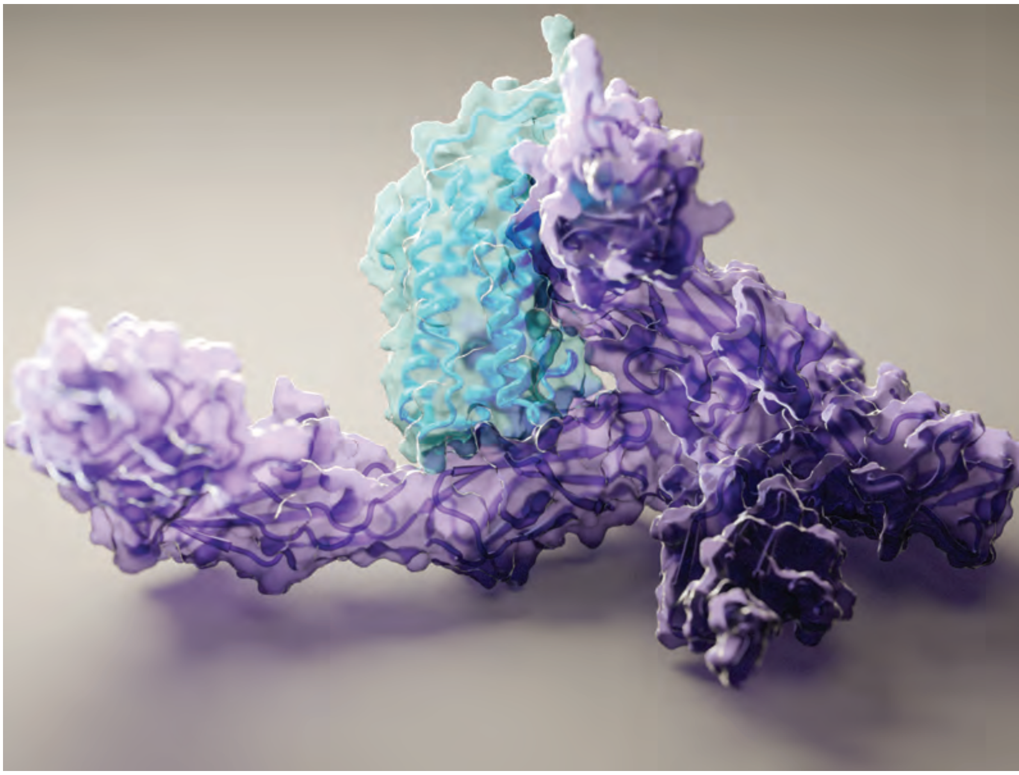

FIGURE 2. ROSETTAFOLD generated this structure of the human signaling protein interleukin-12 (purple) bound to its receptor (blue). Although the structures of molecular complexes are tougher to predict than those of single proteins, the structure here agrees well with one found experimentally through cryoelectron microscopy. (Courtesy of Ian Haydon, Institute for Protein Design, University of Washington.)

And the physics of folding is subtle. The folded structure is generally the thermodynamically favored one, but not by much, and the details of interatomic forces are extremely important. "If you don't know the forces, then a bigger computer doesn't help you get the right answers," says Dill. "It just gives the wrong answers a lot faster."

Biological shortcuts

Any successful approach to protein-structure prediction, including the new deep-learning models, needs to draw on insights from biology, not just chemistry and physics. "Protein sequences aren't random. They've been distilled by natural selection," says Temple University's Vincenzo Carnevale. Any given protein has thousands of evolutionary cousins from across the tree of life; that evolutionary context can provide hints about structure.

Proteins with similar sequences probably have similar structures. If the structure of a related, homologous protein is already known, it can be used as a template: The new sequence is fitted into the old structure, then adjusted accordingly. "That works in a stupendous way," says Carnevale, "but only because the community realized that to succeed with this approach, we needed not just to increase the size of the PDB but to explore the right regions of protein-sequence space."

From 2000 until 2015, the Protein Structure Initiative guided the discovery of thousands of new protein structures, chosen not haphazardly but with the goal of systematically exploring the possible structures proteins can adopt. By the end of the project, says Carnevale, "there was no longer anything novel being discovered in protein structural space. It had all been exhaustively mapped out." Although not every protein sequence has a sufficiently similar known structure to use as a template, the days of wholly unanticipated new protein structures were past.

Meanwhile, theorists were working on ways to glean information about a protein structure from its evolutionary context even when none of its relatives' structures are known. That surprising feat is possible because each protein in a family is the product of its own evolutionary optimization. When one amino acid in a protein randomly mutates, the mutation usually isn't enough to ruin the entire structure, but it does destabilize it. Evolutionary pressure therefore builds on the amino acid's neighbors in 3D space to mutate also and thus restore the structure's stability. If, in a list of many related protein sequences, two amino-acid positions show a tendency to mutate in tandem, they likely sit next to each other in the folded protein.

Structural revolution

Those methods and others were already being tried and tested at CASP before DeepMind entered the fray. Part computational experiment, part competition, CASP challenges hundreds of research groups every two years to reproduce protein structures that have recently been found experimentally but not yet published. Target structures are classified by difficulty, based in part on whether a homologous structure exists to use as a template. Structure predictions are graded on a scale from 0 to 100: A random guess might score below 20;

an atomically precise structure, above 90.

From the early days of CASP, models have been scoring above 80 for the easiest template-based predictions, while scores for the most difficult targets have been stuck around 40. So DeepMind's first CASP entry, the original AlphaFold model in 2018, shook things up by scoring above 70 for more than half of the most difficult targets.[3]

The power of deep learning is that it can recognize patterns, interpolate between known structures, and identify mutation correlations more keenly than human observers or more straightforward algorithms can. AlphaFold wasn't the first machine-learning model to be entered into CASP; its superior performance came, in part, from using the structure and correlation data to predict not just which pairs of amino acids are in contact but the full matrix of all their pairwise distances.

For the 2020 CASP assessment, the DeepMind team had revamped its model into AlphaFold2, whose predictions scored near 90 even for the most difficult targets—scores so high that they were probably limited by the imprecision of the experimental structures the predictions were graded against.

The AlphaFold2 code and method weren't made public at first; all that was released to the world was a 30-minute presentation that described a model that processed data on two parallel tracks. One carried the list of protein sequences thought to be related to the target protein; the other, a pairwise amino-acid distance matrix. By exchanging information between the two tracks, the model repeatedly updated both sets of data until it converged on a final prediction, from which a 3D structure was extracted.

Building on the ideas in the presentation, Baek and colleagues developed RoseTTAFold: a three-track model that iteratively updates the sequence data, distance matrix, and 3D structure itself. If it had been entered into CASP in 2020, its scores for the hardest targets would have averaged about 80.

Now that the AlphaFold2 details are published, Baek concedes that it's a better engineered method. "Almost every component is based on some physical insight," she says. For example, AlphaFold2 requires its amino-acid distances to satisfy the triangle inequality—two points can't be farther from each other than the sum of their distances to a third point—so it saves time by maintaining a degree of physicality even at intermediate steps.

Furthermore, while RoseTTAFold was trained on all the PDB structures, AlphaFold2's training data included additional structures predicted by the model itself. "Training data is very critical," says Baek, "so I think that more complete coverage of protein space helped them a lot."

Molecular interactions

Has deep learning solved the notorious protein-folding problem? That depends on how the problem is defined. Dill draws a distinction between predicting protein structures—what AlphaFold2 and RoseTTAFold do—and understanding protein folding. He considers the latter, which involves mapping the funnel-shaped energy landscapes that guide amino-acid chains into their folded structures, to be largely solved already by statistical physics.[4]

As far as structure prediction is concerned, the deep-learning models have reached a milestone, but they're far from the finish line. Proteins in nature aren't isolated structures. They interact with surrounding molecules, including water, and they combine with other proteins to build large molecular machines—and, ultimately, multicellular living organisms.

Deep-learning methods have made some headway toward solving the structures of multimolecular complexes: The structure in figure 2, found by RoseTTAFold, shows the signaling protein interleukin-12 (purple) bound to its receptor (blue). Multiprotein structures are much more challenging to predict than single-protein ones. The models rely heavily on structural clues from evolutionary context and mutation correlations. But amino acids don't always mutate in tandem if they're in different molecules—especially if those molecules come from different species, such as a pathogen and its host.

"Experimental methods are by no means obsolete," says DeepMind scientist Kathryn Tunyasuvunakool. "They can provide information that AlphaFold currently can't." The model's big advantage, she says, is that it produces structural starting points quickly—in minutes, rather than months or years—and in large numbers. "That's useful, for example, for generating hypotheses and planning experiments." The deep-learning models are already helping experimenters to fill in the missing structural data from their x-ray crystallography and cryoelectron microscopy experiments and to tackle ever more challenging structure problems.

New drugs

One of the most important uses of protein structures is in drug development. To stop a protein from performing some harmful action in the body, pharmaceutical scientists study the protein's structure, identify a nook or cranny that may correspond to the protein's active site, and design a molecule to plug it up like a cork in a wine bottle.

"But there's really no such thing as 'the' structure," says Carnevale, because proteins flex and contort. Focusing on fitting a molecule to one static structure ignores all the other conformations a protein can adopt or the transitions between them, any one of which might offer a more effective way to disrupt the protein's function.

In some cases, the dynamic approach to drug development might be the only viable one. In neurodegenerative conditions like Alzheimer's and Parkinson's diseases, amino-acid chains get tangled up and fold into the wrong structure, called an amyloid fibril. The fibril structure is known (see PHYSICS TODAY, June 2013, page 16), but the structure alone doesn't say much about how the fibril forms—or how to stop it from forming.

It would take a far more sophisticated model than the ones available today to predict a protein's entire conformational ensemble and range of motion. But as Carnevale points out, "Surely the sequence must encode that information, because nature knows what it is."

Another ambitious goal that's on Baek and colleagues' minds is to free their model from the need to consider evolutionary relationships at all and predict the folded structure based only on the amino-acid sequence. Evolution has produced a wondrous array of proteins and functions, but it hasn't come close to exploring every possible protein. The Baker lab's specialty is in designing proteins from scratch to do things that natural ones can't. (See PHYSICS TODAY, June 2020, page 17.) But those bespoke proteins don't come with millions of years of evolutionary relatives to analyze.

Says Dill, "The whole field is headed toward bigger, better, faster": bigger proteins, more complex actions, and more detailed information than has ever been possible before. Lately, modelers and experimenters alike have been working on understanding the spike protein of SARS-CoV-2—the virus that causes COVID-19—whose binding to a host cell involves a cascade of large conformational changes.[5] As Dill explains, "It's a huge protein that's part of an even huger complex, the virus, with all kinds of moving parts like a big Rube Goldberg machine."

Johanna Miller

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A seismometer maps Mars's anatomy

NASA's *InSight* is the first mission to explore seismic waves in a planetary body since *Apollo 17* in 1972.

On 26 November 2018, the *InSight* lander—whose acronym stands for Interior Exploration Using Seismic Investigations, Geodesy and Heat Transport—touched down on Mars's Elysium Planitia. Within two months on that flat, volcanic plain, the lander's robotic arm removed a seismometer from the lander deck and placed it on the ground (figure 1), where it started listening for vibrational signals. Eight orbiters currently survey the gravitational fields, magnetism, and atmosphere of Mars, and six rovers have explored its surface chemistry and geology. *InSight*'s seismometer is the only current direct probe of the planet's interior.

To date, the instrument has picked up more than 1000 distinct seismic events. Of the several hundred marsquakes it's recorded, the vast majority were small—none exceeded a moment magnitude of 4. A low level of seismic activity was not unexpected. Unlike Earth, whose sharply defined tectonic plates intersect at boundaries that wind around the planet like the seam of a baseball, Mars has a single, thick plate.

The Martian activity, however, is even lower than what some planetologists expected for the thousands of faults that populate the surface. Most may have formed from stresses on the planet as it shrinks while slowly cooling. Some could have arisen from internal dynamics—mantle convection and volcanism.

The outer part of Mars solidified from a magma ocean produced by accretion early in solar-system history. An iron-rich core formed as heavy, molten metal sank into the planet's center and lighter, silicate-rich material rose; part of that lighter material melted and refroze into a brittle crust. Orbital measurements of the planet's gravity, tidal response, and moment of inertia provided early hints of that differentiation.

An international collaboration of 65 seismologists and planetary scientists from 12 countries has now published three papers that describe the first direct observations of those distinct layers.[1–3] The teams' quantitative measurements of the structure set the stage for understanding how the planet evolved into its current thermochemical state.

Single seismometer

InSight isn't the first spacecraft to bring a seismometer to Mars. The two *Viking* landers each carried one when they landed on Mars in 1976. But uncaging mishaps and the seismometers' onboard installation prevented either from definitively detecting anything but the wind.

Working out planetary structure is largely a matter of interpreting shear (S) and compressional (P) seismic waves, which travel through the planet at different speeds and refract and reflect from the boundaries of the planet's layers. Those speeds vary with stiffness (or shear and bulk moduli, in geological parlance), density, and temperature. The difference in the waves' arrival times at the seismometer provides the distance to a marsquake but not its specific location.

To locate the quake's epicenter, seismologists normally resort to triangulation using at least three seismometers. The distance from the quake is represented as a circle around each seismometer, and the epicenter lies at the intersection of the three circles. Beginning with *Apollo 11* in 1969, the Apollo program established a four-station seismometer network on the Moon. But seismologists couldn't afford a network on more distant Mars.

What's more, although it's surrounded by a protective shield to filter out wind-induced vibration, *InSight*'s seismometer is still vulnerable to pressure vortices, daily temperature swings, and dust storms. Fortunately, Mars is naturally quiet. "Because it lacks oceans," says the Jet Propulsion Laboratory's Mark Panning, "it's at least two orders of magnitude quieter than any place on Earth in the 0.1–1 Hz frequency band that seismologists typically use." *InSight* is also sensitive enough that it can register vibrational amplitudes as small as an atomic width.

From the crust . . .

Marsquakes don't resemble the strong stick–slip interactions that take place at Earth's convergent plates. Rather, they mimic the slip along faults far from those boundaries. Tectonic fissures known as Cerberus Fossae (figure 2), which are located 1600 km from *InSight*, may account for the largest of that seismic activity.

Amir Khan of ETH Zürich and colleagues found that most marsquakes take place in the shallow crust.[1] But as on Earth, *P* waves can partially convert to *S* waves on being reflected or refracted from discontinuities. And those conversions make individual waves difficult to disentangle. A smaller number of quakes appear to originate below the crust. Of the marsquakes the team recorded, the collaboration analyzed the eight cleanest events. From that sample, they extracted *P*- and *S*-wave arrival times and polarizations, which revealed the waves' directions. Armed with that additional polarization data, the seismologists *can* determine epicenter locations.

The University of Cologne's Brigitte Knapmeyer-Endrun and colleagues found distinct layer boundaries in the crust below the *InSight* lander.[2] The first, as deep as 10 km below the surface, marks a change in rock lithology. Either the second or third, as deep as 25 km and 47 km, respectively, marks the bottom of the crust. The latter thickness is more consistent with previous estimates from orbital surveys.

Data from seismic-wave reflections indicate that Mars's crust is quite porous—"more like the Moon than Earth," says David Stevenson, a planetary scientist not affiliated with the collaboration. That may be a consequence of being heavily altered by the meteor bombardment it suffered during its first billion years. With the new measurements, Knapmeyer-Endrun and colleagues used the crustal thickness under the lander as a calibration for mapping the crust across the entire planet. Mars's lithosphere, the rigid outer part of the planet, reaches 400–600 km below the surface. That's more than twice as deep as Earth's continental lithosphere. And it's perhaps an indication of the upward migration of radioactive elements into the crust, which would reduce the average geothermal temperature gradient at depth.

. . . to the core

Simon Stähler of ETH Zürich and colleagues detected faint waves reflecting off the deeper core–mantle boundary.[3] From their analyses of those reflections, they derived a core radius of 1830 km, about 100 km greater than expected, based on Mars's moment of inertia and mean density. The large size means that the core's composition is less dense than expected. And that, in turn, implies that a greater concentration of light elements, such as sulfur, carbon, silicon, and hydrogen, are sequestered there.

The enrichment in light elements would have lowered the core's melting temperature, possibly to a point that sustains the entire core as a molten liquid. If that's the case—and the lack of shear waves passing through the core suggests that it is—the absence of a solid inner core is likely one of the reasons Mars's dynamo turned off billions of years ago. Earth's dynamo is driven by latent heat from crystallization of the inner core, an energy source that is not available on Mars. But that's speculation. No one has yet measured how much heat flows from Mars's core.

With no dynamo to sustain it, Mars

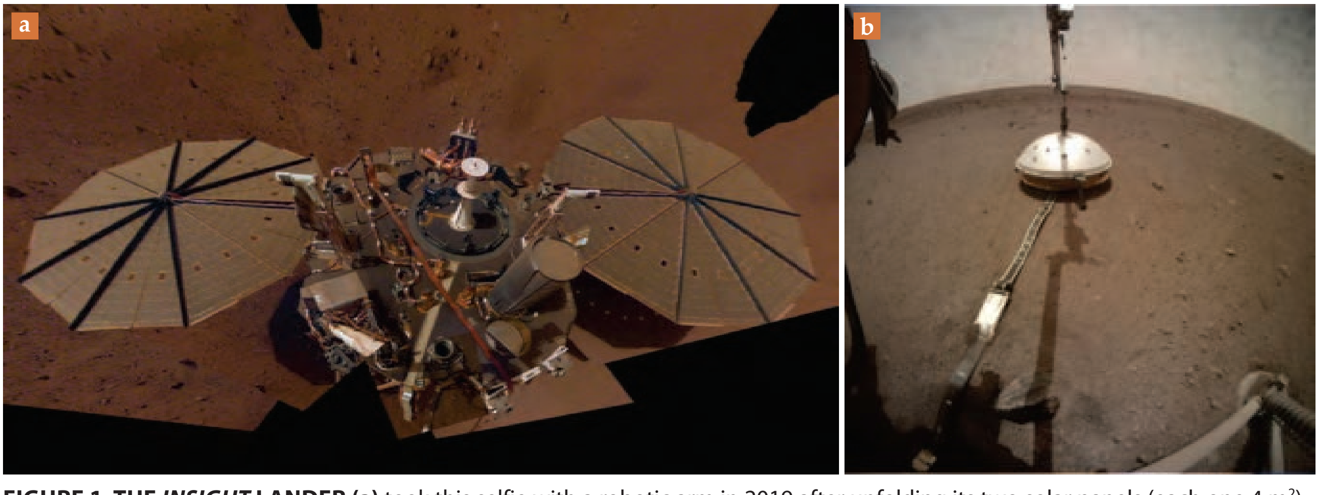

FIGURE 1. THE *INSIGHT* LANDER (a) took this selfie with a robotic arm in 2019 after unfolding its two solar panels (each one 4 m^2) and placing its seismometer on the Martian surface. **(b)** Attached to the lander by an electrical cord, the seismometer is protected in a vacuum under a wind shield. (Courtesy of NASA/JPL-Caltech.)

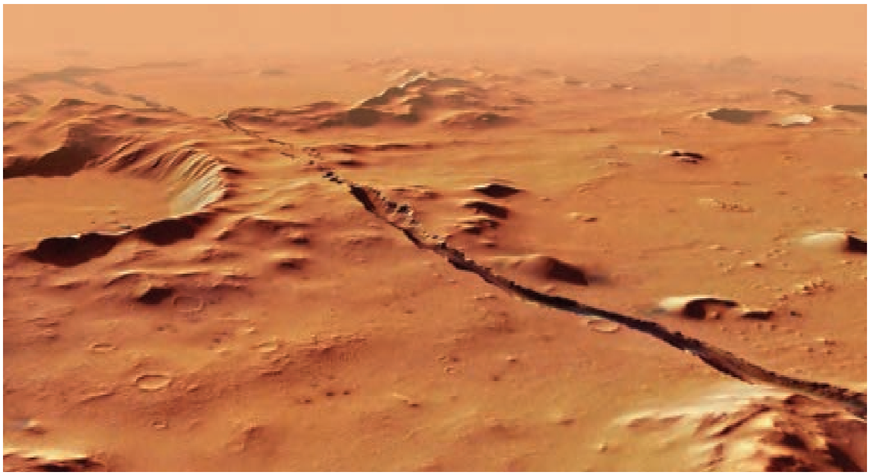

FIGURE 2. CERBERUS FOSSAE are a series of fissures on Mars formed by faults that are the source of several marsquakes. *InSight*'s seismometer sits about 1600 km west. This photograph, which shows just one fissure, was taken by the European Space Agency's *Mars Express* orbiter. (Courtesy of ESA/DLR/FU Berlin, CC BY-SA 3.0 IGO.)

has no global magnetic field today. But it did early on. In 1997 an orbiting spacecraft discovered localized magnetic fields that were frozen into the oldest crustal rock shortly after the planet formed 4.5 billion years ago. How or when the planet's dynamo turned off is unknown, but it must have done so when heat leaking from the core had diminished sufficiently. (See the article by David Dunlop, PHYSICS TODAY, June 2012, page 31.)

The enrichment also aligns with what is suspected about the planet's early evolution. Isotope evidence from Martian meteorites on Earth suggests that Mars formed early in the outer regions of the terrestrial planetary zone, where light volatile elements might have been more available and incorporated into the planet while it was still an embryo. Hafnium–tungsten isotope analysis suggests that Mars formed roughly 5 million years after the solar nebula did; Earth formed some 30 million–40 million years later. (See the article by Bernard Wood, PHYSICS TODAY, December 2011, page 40.)

The large core size also influences the convection of heat from the mantle. Being proportionally thinner as a result of the large core, Mars's mantle never reaches the high pressures required to produce a stable phase transition from ringwoodite—a high-pressure phase of olivine—to bridgmanite. Also known as magnesium perovskite, bridgmanite is the most abundant mineral in Earth. It is widespread in Earth's mantle deeper than about 660 km and circulates more sluggishly than the mantle above. On Mars, the absence of bridgmanite might have allowed the core to cool more efficiently.

Before the *Spirit* and *Opportunity* rovers finally died, dust devils occasionally boosted their power levels by scouring dirt from the rovers' solar panels (see the Quick Study by Ralph Lorenz, PHYSICS TODAY, July 2020, page 62). *InSight*'s lander has not enjoyed the same treatment—few devils appear in its vicinity—and its solar panels are producing just 27% of their dust-free power capacity. Mars is now close to aphelion, its farthest point from the Sun. Power is being shared among the spacecraft's science instruments, robotic arm, radio, and various heaters that keep everything working despite subfreezing temperatures.

Nevertheless, NASA expects the lander to survive the lower levels of sunlight and has extended the mission through December 2022. "We're still waiting for bigger quakes," says Panning. He and others are hoping for magnitude 5 events—larger signals would mean better resolution of core reflections, which would firm up constraints on deep structure. There's certainly more to learn. *InSight* has yet to detect any meteor impacts, for instance, despite predictions that it should see at least one a year.

R. Mark Wilson

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Metal cations drive carbon dioxide's chemical reduction

Experimental evidence confirms one long-standing hypothesis: Positively charged metal ions stabilize the reaction's intermediate molecules.

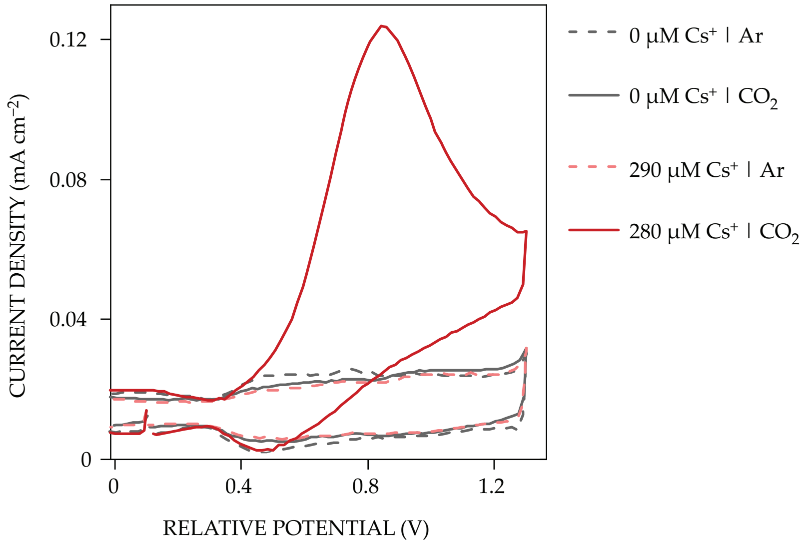

FIGURE 1. ELECTROCHEMICAL MEASUREMENTS of current density as a function of a gold electrode potential indicate that the reduction of carbon dioxide to carbon monoxide can proceed only with cesium or other metal cations in solution (solid red line). Baseline measurements in an argon atmosphere (dashed red and black lines) yielded no CO product, as expected. But the experiment without metal cations and a CO_2 atmosphere (solid black line) also failed to produce CO. (Adapted from ref. 3.)

The industrial production of ammonia, cement, and other compounds generates carbon dioxide as a byproduct. Those processes add some 1.3 gigatons of carbon emissions to the atmosphere per year. That's about two-thirds of the annual emissions associated with transportation.[1] A more sustainable system would redirect that industrial CO_2 waste stream to be an input for the synthesis of methanol, biofuels, and other useful chemicals.

One approach dissolves the CO_2 in an aqueous electrolyte solution and strips one of its electrons by using a metal catalyst and an applied current between two electrodes. If the catalyst is gold or silver, then the intermediate anion CO_2^- reacts with a proton from a water molecule to form carbon monoxide. Copper and other catalysts drive reactions that produce ethylene, ethanol, and other chemicals. The reaction could also be used to recycle the CO_2 from power-plant emissions.

To better understand the electrochemical reduction of CO_2, PhD candidate Mariana Monteiro at Leiden University in the Netherlands, her adviser Marc Koper, and their colleagues investigated how metal cations, such as cesium, in the electrolyte solution affect the reaction. Previous research hinted that they generate a local electric field near the electrode that boosts the reaction's effectiveness.[2]

The researchers have now found that the metal cations not only accelerate the reaction but are indispensable to it. Without them, the reaction doesn't yield the expected CO product.[3]

A simple solution

The most common way to improve the effectiveness of electrochemical CO_2 reduction, or any surface reaction, is to tune the catalyst. Tweaking a gold catalyst's crystalline structure, for example, changes the availability and nature of its active sites. Tuning can increase the catalyst's activity and selectivity—a measure of the formation of desired products relative to undesired ones. In 1959 Russian chemist Alexander Frumkin found that the specific composition of the electrolyte solution also affects the reaction's effectiveness.[4]

Since then, various studies have identified three possible mechanisms related to how metal cations, such as cesium and other alkali metals, in an electrolyte solution affect the reaction. One proposes that the cations drive the reaction by adsorbing to the surface of the electrode and generating a steep gradient in the electric potential between the electrode surface and the electrolyte bulk. The second possibility is that metal cations interact with water molecules close to the electrode and act as a buffer that regulates the pH to conditions more favorable for CO_2 reduction. The third hypothesis asserts that metal cations interact with nearby negatively charged intermediate molecules and electrostatically stabilize them long enough for the reaction to proceed.

Despite the progress in understanding CO_2 electrocatalysis, researchers still hadn't determined the primary contribution of the cations in the reaction when Monteiro and her colleagues started their research in 2019. To figure it out, they ran the reaction with and without metal cations in the electrolyte. "Everyone was surprised that no one had done this," she says. "I started super-complicated, with various species and mixtures. Then I came to my senses and thought, 'What if we remove the cation from the equation?'"

The researchers chose a polycrystalline gold electrocatalytic system for their experiments because of its stability and simplicity. In that system, CO and molecular hydrogen are the only two products formed from the reaction of CO_2 and water. Monteiro and her colleagues tested for the cation effect by running the reduction reaction with and without Cs^+ or other dissolved alkali metals in the electrolyte.

An aqueous electrolyte is, by definition, a solution with water, cations, and anions. The experiment without metal cations used a dilute electrolyte solution of sulfuric acid, whose only cations were hydrogen ions. But any impurities in the electrolyte could lead the researchers to misinterpret the results. Monteiro says that "everything you put in the experiment has to be ultraclean." That meant she had to carefully clean the glassware before every experiment. To remove any contaminants from the electrode surface, the researchers heated it to just below its melting point. All told, the cleaning and other preparations for each lab experiment took about half a day.

Sticking together

"All the main theories to explain the cation effect up to now were related to an electric-field effect," says Monteiro. The gold electrode in the electrocatalytic system is negatively charged. The metal cations in solution, the thinking goes, may produce an electric field near the electrode that helps nudge the CO_2 to undergo a reduction reaction. Even if the cations are removed, the electrode surface is still negatively charged. In principle, the reaction should therefore proceed.

However, the experimental results plotted in figure 1 clearly show that CO was generated only with metal cations in solution. Increasing the concentration of Cs^+ yielded more CO. The case with a CO_2 atmosphere and no metal cation in solution was statistically indistinguishable from the control experiments with an argon-only atmosphere.

The researchers also measured the effect of alkali metal ions lighter than Cs. The largest cation, Cs^+, showed the highest activity for CO_2 reduction, followed by progressively smaller cations, an observation that agrees with previous studies.

To uncover what the cations were up to, coauthors Federico Dattila, Rodrigo García-Muelas, and Núria López of the Institute of Chemical Research of Catalonia in Tarragona, Spain, modeled the experimental system using density functional theory and *ab initio* molecular dynamics simulations. Their calculations clarified that the Cs^+ pushes CO_2 to adsorb to the electrode surface and explicitly interacts with the adsorbed intermediate molecule CO_2, as illustrated in figure 2. The interaction stabilizes CO_2^- and allows for the next reaction steps to take place, which yield CO.

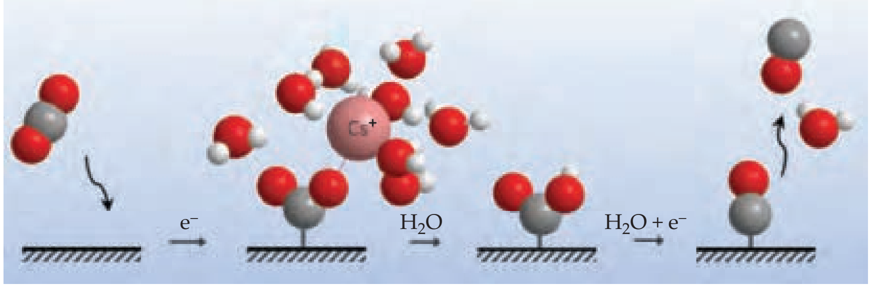

FIGURE 2. A CESIUM CATION in the electrolyte hosts several water molecules in its vicinity. Because of cesium's large ionic radius, each water molecule consequently has a weak attraction to the cation. That property allows Cs^+ to move close enough to the surface of an electrode and interact with an intermediate molecule in the reduction reaction of carbon dioxide to carbon monoxide. The interaction stabilizes the adsorbed molecule and is critical for the reaction to proceed to completion. (Adapted from ref. 3.)

Compared with other alkali metals, Cs^+ is the most effective. The ion is large and has only a +1 charge. Therefore, the water molecules from the electrolyte don't interact with it too strongly. With such a property, Cs^+ easily reaches the electrode surface unimpeded and stabilizes CO_2^-.

An engineering problem

Monteiro and her colleagues found that systems with copper and silver electrodes also need metal cations to enable the reduction of CO_2 to CO. That finding means that metal cations like Cs^+ are critical for reducing CO_2 in a wide range of electrocatalytic systems and for generating different chemical products besides CO.

The other two hypothesized mechanisms of the cations—increasing the electric gradient and regulating the pH—may still have some effect on the reaction. To achieve any future commercial applications, engineers of electrocatalytic systems should therefore consider not only the catalyst but also the electrolyte and the metal cations in it. Other species similar to Cs^+, such as multivalent cations and specialized surfactants, may have an even more pronounced stabilizing effect on the CO_2 reduction reaction.

The next step to recycling CO_2 via electrocatalysis is to further optimize the reaction for commercial settings. Several previous efforts have studied approaches in neutral pH conditions. In another paper, Monteiro, Koper, and two other colleagues from the chemical technology company Avantium in Amsterdam demonstrated a proof of concept for the first step in CO_2 electrochemical reduction in an acidic solution and at conditions similar to those of an industrial setting.[5] The laboratory-scale system demonstrated a 30% improvement in energy efficiency compared with a neutral pH system. According to Monteiro, "To scale it up to a real industrial scale is more of an engineering problem now than a chemistry one."

Alex Lopatka

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Undergraduate integrated science programs foster interdisciplinary and personal connections

Students and faculty thrive in programs that link the sciences; why aren't there more of them?

In the early 2000s, Derek Raine, a physicist at the UK's University of Leicester, spearheaded a program to immerse undergraduates in physics, math, biology, and chemistry in a setting that highlights commonalities across those fields. In the ensuing years, the program has changed with political and financial winds, but key elements persist: It experiments with new teaching methods, emphasizes teamwork, and embeds communication skills.

For several decades, researchers around the world have been encouraged to forge connections across disciplines; funding agencies, for example, commonly call for joint proposals from researchers in different fields. A smattering of programs, some founded earlier than the one at Leicester, introduce that philosophy at an earlier stage in people's education.

RUSS ELLIS

BLOOD SPATTER. For a module on forensic science, third-year students in the McMaster University integrated science program reconstruct the angle of impact, velocity, and distance traveled by blood in a mock accident scene.

Several Canadian universities have embraced integrated approaches to teaching science, and a few programs exist in the US and elsewhere. Some programs last four years, such as those at Leicester; at McMaster University in Hamilton, Ontario, Canada; and at Northwestern University in Evanston, Illinois. Others, including the Science One program at the University of British Columbia (UBC) in Canada, are intensive, nearly full-time programs for first-year students only. And some, such as at Harvard and Princeton Universities, represent a smaller portion of course credit but share similar aims of teaching students to recognize and make connections across fields.

"The workforce has a need for a wider cohort with interdisciplinary skills," says Raine, whose research has ranged from quantum field theory to biophysics. "We have to get that message across. It's hard."

Problem-solving

Meghan Scott has a year to go in the integrated science bachelor's program at Western University in Ontario. She took required classes she may have otherwise passed over—Big Data and Mathematical Modelling, for one. The courses were interdisciplinary and project-based. Learning how sciences can be applied to help address issues like world hunger, the pandemic, and climate change has been pivotal, she says. She credits the integrated science program with her choice to major in physics: "I came into university not liking physics, but I found I liked solving problems."

Darren Fernandes graduated from college in 2013 with the first integrated science cohort at McMaster. The program attracted him because he loved science but hadn't yet settled on a direction. In integrated science, Fernandes enjoyed working on open-ended projects and leveraging the strengths of partners in group assignments. "I was so enamored of the science I was learning," he says, "it was only in graduate school that I realized I had gained a huge advantage: I can communicate with scientists in many fields."

When he was a doctoral student in medical biophysics at the University of Toronto, Fernandes's ease in traversing disciplines proved useful. In trying to understand the social behavior of mice, he had an aha moment: Could he model mouse movements as an ideal gas with a tiny additional attractive force? The model described the mice well, he says. "You can find individual-specific traits over long times. Hopefully the approach will transfer to humans—for example, to help understand autism." He is now in his final year of medical school.

Fundamentals and friendships

Integrated science programs tend to function as small schools within their host universities. They typically enroll 20–80 students and have a high instructor–student ratio, often around 1:10. Julia Liu is an alumna of Princeton's integrated science program who majored in physics and is now an assistant professor of integrative biology and physiology at the University of Minnesota. "The main thing I got out of participating in the program was the feeling that I could learn anything," she says. "I have the foundational background, even if I'm not an expert. And the camaraderie of our class was tremendous."

In some programs students can graduate with a bachelor's degree in integrated science; others require a separate or double major. The McMaster and Leicester programs, for example, award degrees in integrated science, and many students choose an additional area of concentration. In the first year, the programs represent the lion's share of the students' coursework; in subsequent years the integrated science part of the curriculum goes down.

Early in the first year of the McMaster program, environmental geoscientist Carolyn Eyles introduces plate tectonics. In parallel, physicist Robert Cockcroft teaches about friction. "It matches beautifully," says Eyles, a founder of the university's integrated science program. In Canada, she says, most students don't learn about geosciences in high school.

PAUL JOSEPH

JIM BERGER at the University of British Columbia employs modeling clay to teach students in the integrated science program about meiotic recombination.

The integrated science program highlights that Earth sciences are a good vehicle to study topics such as how climate change will affect water supply and how geoscience applies to the exploration of other planets, says Eyles. "They get exposed to research and career opportunities."

On average, about 15% of students who continue on to graduate school from the McMaster integrated science program pursue an Earth sciences field, says Eyles. "It's a much higher uptake than I ever expected."

Northwestern University launched its integrated science program in the 1970s with the aim of attracting strong science students. Courses are offered by participating departments rather than being developed by a dedicated core team of instructors, as in many of the other programs. It focuses on neuroscience and geoscience in addition to math, physics, chemistry, and biology. Along the way, participants fulfill the university's general education requirements; elsewhere such requirements may be woven into the integrated science curriculum.

Northwestern integrated science students can graduate with a major in integrated science after three years, although most stay a fourth year and double major, says André de Gouvêa, who was program director until the end of August. The program draws 25–35 students a year.

The Princeton and Harvard programs each consist of a yearlong double course. Princeton's, which was established in 2004, began as a multiyear program aimed at life scientists but has morphed into a one-year program that serves all the sciences. The six-year-old Harvard program is geared to life sciences. "We emphasize the connections between quantitative and physical sciences and biology, which are becoming increasingly relevant to research in biology," says biophysicist Michael Desai, one of the course's founders.

Science One, the integrated science program at UBC, launched in 1993. Some 150–250 applicants vie for 80 spots each year. It covers physics, chemistry, biology, and math, says director James Charbonneau. Computer science, ethics, and scientific literacy are woven into the curriculum, partly through projects and student-led conferences. In nonpandemic times, incoming students take a four-day field trip to a marine sciences center, where they learn biology and biophysics and get to know each other.


NORTHWESTERN UNIVERSITY

STUDENTS IN NORTHWESTERN'S integrated science program enjoy a pre-pandemic picnic in front of the house where they study and socialize.

Often faculty sit in on each other's teaching modules, says Charbonneau. "We pipe up and have conversations in class. The students see scientists interact in real time." As an example of "de-siloing" the sciences, he says, students might apply computational methods to ecological questions such as how energy moves from one species to another. They build computational models that include the Sun, plant growth and death, and animal behaviors. Terminology for the same concepts—entropy, energy, work, gradients—can be different in different sciences. "We are breaking down communication barriers, translating," he says. "Typically, in the first year, students will not notice the connections unless you point them out explicitly."

Comparisons of performance in upper-division courses indicate that Science One alumni outperform their peers who had similar marks in high school. Faculty from the integrated science programs at various schools point to the success of their graduates. "They are well prepared, and they know how to think critically," says Sarah Symons, coordinator of McMaster's integrated science program.

"The way our integrated science program teaches is not just equations," Symons says. "We are trying to get at how to do science, how to communicate, how to accrete knowledge. You need to understand science's place in society, how science interacts with people's lives, and how scientists interact with one another."

Cost and commitment

"If these programs had been around when I was a student, I would have wanted to attend," says Cockcroft, who helped start the integrated science program at Western University in 2016 before rejoining McMaster in the summer of 2020. The appeal, he says, includes small class size, the bonds that develop between students and faculty, the close teamwork among faculty, the exposure to a wide range of sciences, and the confidence with which graduates are able to discuss ideas and present their work.

So why are there so few integrated science programs? And what do they need to succeed? One barrier is cost, especially at the development stage. "We were lucky to have external funds," says Raine; the Leicester program was initially funded through the UK's Institute of Physics in an effort to boost the number of physics students.

Startup costs aside, it's more expensive to support classes with student numbers in the low double digits than in the hundreds, as in many introductory math and science classes. And the multidisciplinary experiments can be pricier than those in traditional lab courses. UBC spends about twice as much on an integrated science student as it does on a traditional science major, according to "Are we doing any good? A value-added analysis of UBC's Science One program," by UBC faculty members in the December 2012 issue of the *Canadian Journal for the Scholarship of Teaching and Learning*.

Perhaps a bigger barrier is the investment needed. Setting up any new teaching program requires commitment from faculty members and buy-in from the university administration. These programs need someone to champion them, says Raine. "Not everyone is on board. Many academics think we are spoiling the purity of the disciplines."

Thomas Gregor, a biophysicist at Princeton, says organizing courses for the integrated science program is a huge amount of work. "You have to coordinate something like 15 instructors."

And, of course, students have to sign up. Across all of the programs, students and faculty say that integrated science requires a bigger commitment from students than a traditional science path does. The one-year programs are aimed at freshmen, notes Gregor. "They are away from home and their parents for the first time, and they have to sign on to an intensive course. They have to give up extracurricular activities. They can't party more than one night a week or they'll fall behind."

The programs at UBC and McMaster are well known and oversubscribed. But high school students—and their parents—rarely recognize the value of "integrated science" and may prefer to stick with known quantities. It's easier for prestigious schools to risk launching such programs, notes Northwestern's de Gouvêa. They can afford the startup costs, and even an unfamiliar certificate from the likes of Harvard or Princeton looks good.

A program that integrated math, physics, chemistry, and engineering in the 1990s at North Carolina State University was dropped after four years because it overstretched faculty resources. Still, says Robert Beichner, a physicist and one of the program's founders, faculty "adapted the innovative teaching approaches to other settings." The most exciting research finding from those adaptations, he adds, is that they erase correlations between student demographics and performance. "All students benefit."

A six-year-old integrated science program at York University in Toronto was suspended this year because of declining student numbers. Despite a good start and enthusiastic leadership, it hadn't quite gotten off the ground when a labor disruption and then the pandemic took swipes at enrollment.

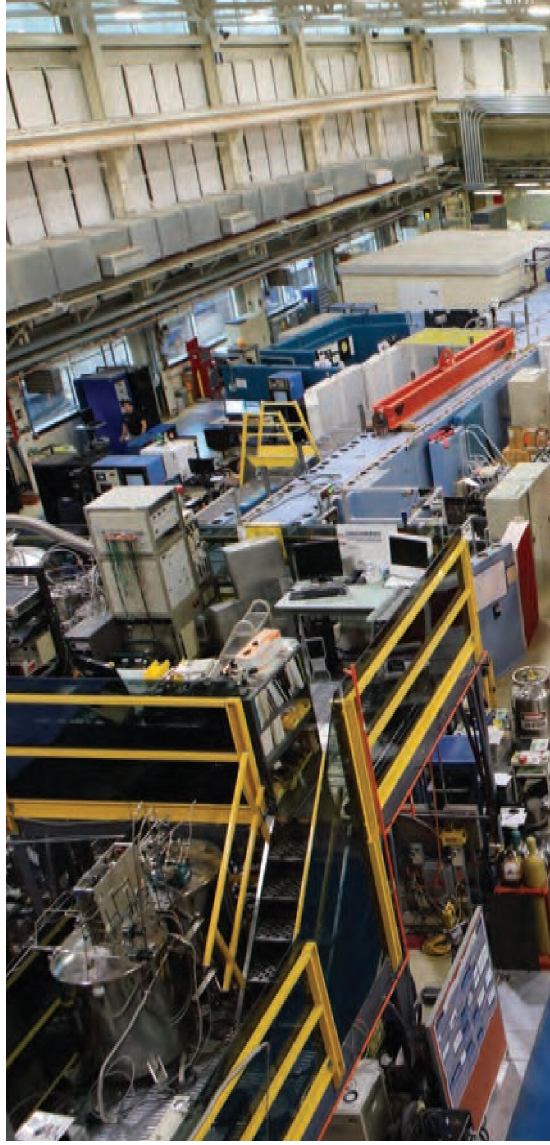
Integrated science programs are small and tend to serve as prestigious flagships for a university, notes Tamara Kelly, a founder of the York program. "We had to decide whether to do a small elite program or a larger one aimed at a broader range of students," she says. The dean's office opted for attracting top-performing students. But, she adds, "the approach is good for all students, particularly mid-performing ones who might not see the links between the fields."

Integrated science programs, says McMaster's Symons, are good for people who don't know what they want to do but love science. "They are good for people who like to ask questions—that's easier in small classes. And they are good for people who want a say in their education."

Toni Feder

Scientists dismayed by interruption at US's most productive neutron source

The unplanned shutdown of a NIST reactor following a February accident has taken out the nation's leading center for cold neutron research.



Scientists will probably never have enough neutrons available to satisfy their basic research needs. But they have had a lot fewer to work with since the closure of the NIST Center for Neutron Research (NCNR) in Gaithersburg, Maryland, nine months ago. And it's likely to be several more months before the research reactor that is the source of its neutrons can resume operations.

In the meantime, most researchers whose experiments were in the queue when the NCNR shut down have had their wait for beam time extended. "To say that it's been a tremendous loss to the neutron user community is putting it mildly," says Robert Dimeo, NCNR director. "We account for about 40% of US publication output in neutron science, and more than 300 publications from 3000 researchers annually."

The NCNR is one of just three major neutron user facilities in the US. The two others are located at Oak Ridge National Laboratory. The High Flux Isotope Reactor (HFIR), like the NCNR, is a fission source. The Spallation Neutron Source (SNS) is a proton accelerator that produces pulses of neutrons from a heavy-metal target. Even before the NCNR outage, each of the three was oversubscribed by a factor of two or more, says Dimeo.

The NCNR shutdown occurred on 3 February during a reactor restart, when an operator failed to properly latch a fuel element in the core. The reactor shut down automatically, but elevated temperatures created by the accident produced radiation that caused minor exposure of six control room operators and contamination of the reactor's primary cooling system. Monitoring of radiation levels outside the building showed that the public received no appreciable dose, the Nuclear Regulatory Commission (NRC) confirmed.

But the cleanup process is on hold until a shipment of special filters arrives, which should be this month. "Then we are hopeful we'll be able to clean up the primary coolant system relatively quickly, although that is an unknown until we actually do it," Dimeo says. But NIST also needs to complete a formal incident analysis and develop a corrective action plan for the NRC. "We're developing a comprehensive set of actions to make sure it never happens again," Dimeo says.

Neither Dimeo nor the NRC could provide a definitive date for resumption. In a statement, an NRC spokesperson said that in addition to the two reports required, NIST must make a formal request to the commission for authorization to restart the reactor. "We expect the root cause report soon, with the other documents to follow," the spokesperson said. "The agency continues its inspection of the event, and the findings from that inspection will also factor into the restart decision process."

The NRC staff has authority to approve restart without having the full commission consider it. Dimeo is hopeful that the NCNR will be operational within a few months.

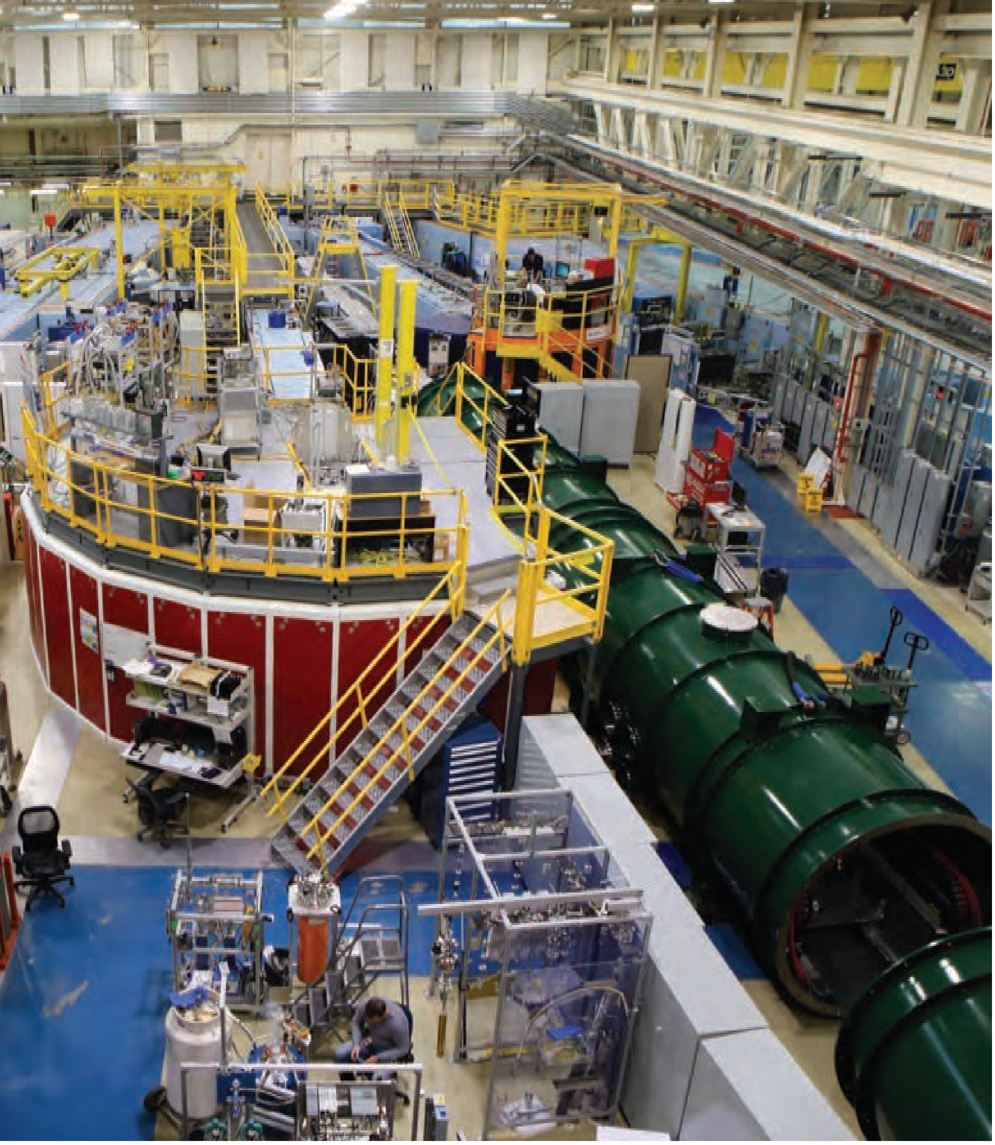
An unsatiated appetite

Starved of neutrons, some researchers have been analyzing data from previous experiments. Others have switched to using x rays or other probes. "The biggest interruptions are probably going to be for students who require neutron scattering data for their dissertations and theses," says University of Maryland chemist Efrain Rodriguez, who grew crystals and produced samples for neutron scientists while a postdoc at the NCNR. "In cases where we don't have neutron data, we've had to just move on and see what we can figure out with synchrotron x-ray data."

Despina Louca, a University of Virginia condensed-matter physicist, says her students are primarily working with in-house instruments, including x-ray machines in her lab and a nearby single-crystal diffractometer. "The basic stuff we can do here. We can't just sit here waiting; we would be out of business."

Still, Louca says, it will be difficult for her students to complete their theses without neutrons. "We do a lot of research on magnetic materials, and the neutron is the best probe when it comes to magnetism because of its intrinsic magnetic moment and the very high resolution that neutron techniques provide us with. Because they are highly penetrative, neutrons are also best for determining structures and dynamics in specialized environments, such as those involving magnetic and electric fields."

Collin Broholm, a condensed-matter physicist at Johns Hopkins University, is within commuting distance of the NCNR. He and his students were frequent users. He notes that neutrons are indispensable for probing a broad range of energy scales, from nanoelectron to electron volts. "You can't do that even with inelastic x rays. We gravitate toward other tools that access other materials proper-



YIMING QIU

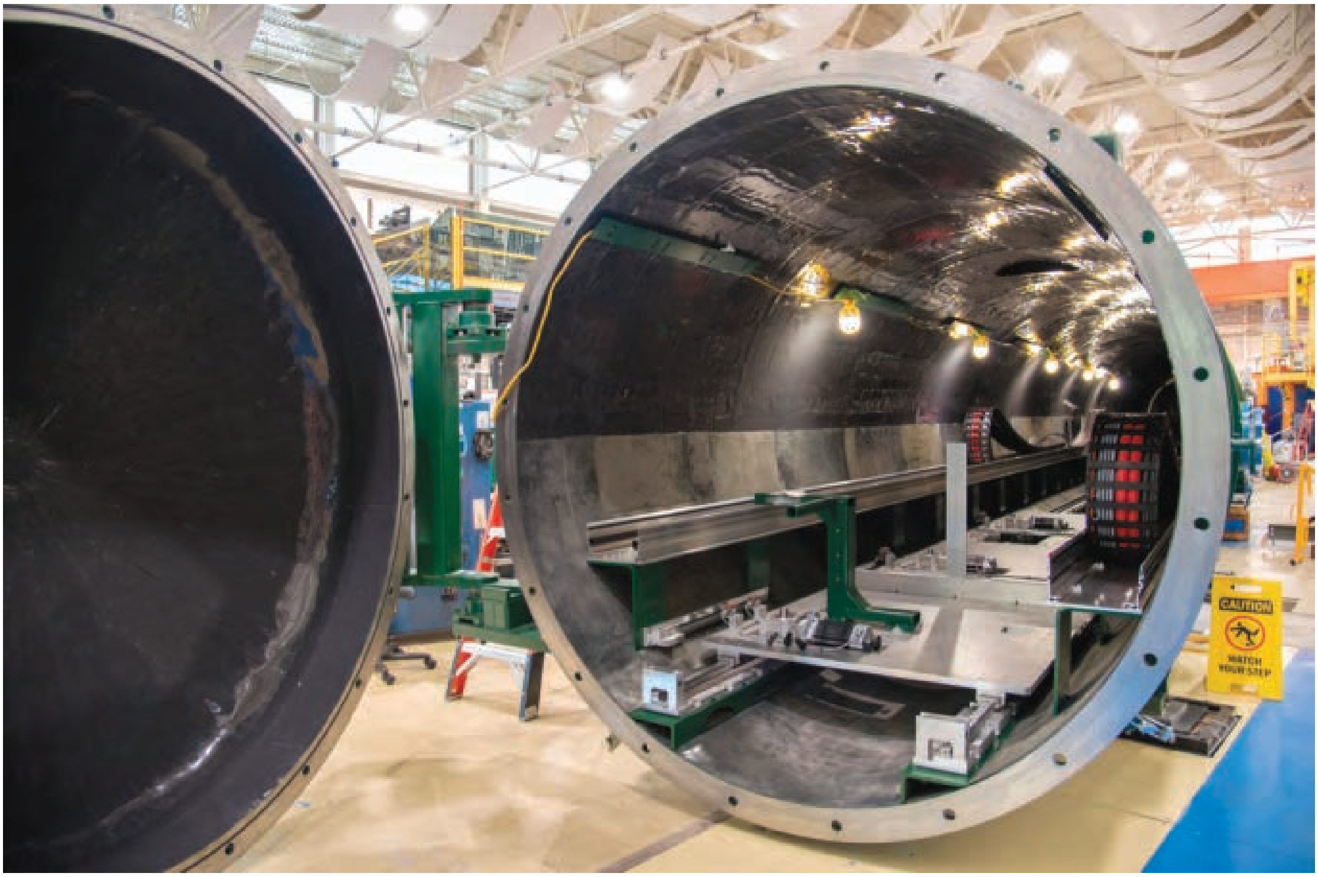
THE COLD NEUTRON guide hall at the NIST Center for Neutron Research shows the sample environment staging area in the foreground, with the disk chopper spectrometer immediately behind it. The very small angle neutron scattering (SANS) instrument is being assembled to the right, in front of the high-flux backscattering instrument. To the left, the mezzanine of the neutron-physics research station is visible, as are the SANS NG7 guide and the neutron interferometry cave.

ties and we've been able to make some progress, but some things we lack completely until NCNR runs again."

Broholm says it's not likely that he'll hold PhD students back. "We really try to have them graduate at the end of their fifth or sixth year. But they will leave with less hands-on experience," he says. They will also miss out on the camaraderie and the "buzz" that occurs at the NCNR when scientists rub shoulders and discuss their respective experiments.

The outage has prolonged the hiatus in experimentation that was created by the COVID pandemic. Travel restrictions have prevented US-based scientists from visiting neutron sources abroad. Experiments can be conducted remotely at other neutron sources by sending samples to be handled by local facility scientists and technicians. But remote access has its limitations. "It's definitely not the same," says Rodriguez, "because you just can't run the experiments you want to run." Adds Louca, "Many experiments are too complex and require the experimenter to be on-site."

Some of Broholm's students have managed to get remote beam time at other sources. "We had a very successful experiment at ISIS in the UK a month ago. We sent samples there, they put them on the instruments, and we talked online. We just finished an experiment at SNS for one of my grad students. It was a very important part of his thesis." The Paul Scherrer Institute in Switzerland also provided some remote-access beam



FRAN WEBBER/NIST

CUSTOM DESIGNED and built at NIST, the 45-meter-long very small angle neutron scattering instrument was put into operation in 2017 at the NCNR's Center for High Resolution Neutron Scattering.

time to his lab. Broholm estimated the success rate for beam-time requests to be similar to the chances of getting an NSF grant. To the extent that they can, the other US sources have been trying to accommodate postdocs whose research must be completed within a couple of years, he notes.

A spokesperson for the Institut Laue–Langevin, Europe's largest neutron source, says access is limited mostly to the 14 European countries that contribute to its operation; only 5% of beam time is awarded to outside researchers, including US users, through the lab director's discretionary time allotment. Some NCNR users have had their samples characterized at the University of Missouri's high-performance research reactor, which has some neutron scattering capability, and at the Australian Nuclear Science and Technology Organisation's research reactor.

A unique facility

NIST excels at generating and exploiting cold neutrons. They are particularly relevant for structural biologists and researchers who study soft matter, such as polymers and membranes. (See the article by David Hoogerheide, Trevor Forsyth, and Katherine Brown, Physics Today, June 2020, page 36.) Cold neutrons are produced by directing them through a cryogenic gas or liquid to reduce their energy.

Alan Hurd, former director of neutron scattering at the Los Alamos Neutron Science Center (LANSCE), rates NIST as the premier neutron scattering facility in the US and perhaps the world. LANSCE had been a neutron user facility until the Department of Energy's Office of Science cut off funding for that purpose in 2012. It currently operates principally for nuclear weapons R&D, though some nondefense collaborations take place between lab and outside scientists. In addition to an outstanding radiography setup, Hurd says, the NCNR's liquid reflectometer can probe thin films and monolayers of amphiphilic molecules that are of interest to drug development companies.

Funded over years primarily by NSF, the NCNR's experimental hall has been packed with instruments used for soft-matter and bioscience studies. "It's where NCNR shines as a leader in the US and the world," says Rodriguez.

"NIST has a long history of embracing cutting-edge ideas for spectrometers to do condensed matter," says Hurd. "They've broken a lot of ground on things like spin-echo techniques, which is like [nuclear magnetic resonance] on the fly."

The current outage is especially dismaying because experiments at the NCNR will halt again in 2023, when the reactor is scheduled for a year-long closure for installation of a new liquid-deuterium cold neutron source. Dimeo says the upgrade, which is expected to double the flux of long-wavelength neutrons, required years of planning. "It's a very cost-effective way to increase facility performance," he says. Several of the neutron guides—optical elements that transport neutrons from the cold source to the instruments—will be upgraded during the 2023 outage to further enhance instrument performance.

Dimeo says NIST plans to stick to the closure date, even if it means the NCNR operates for just a few months next year. "We are absolutely interested in delivering the maximum to the users and believe that will best be done by getting that outage over with." The installation can't be moved up to the current outage because of the long lead times required for acquiring some components.

The installation shutdown has backing from users. "It's really essential that the facility is always marching forward in its capabilities," says Broholm. Continuous improvements to the source, the guide network, and instrumentation "have kept NCNR fresh and moving into new areas of science."

The loss of the NCNR highlights the ongoing dearth of neutron facilities, says Louca. "There's a zero-sum game in the neutron world. When they build a new source, they shut down another." She points to the closures of the Intense Pulsed Neutron Source at Argonne National Laboratory in 2008 and the loss of LANSCE, which were offset by the SNS, the Oak Ridge facility that opened in 2007. (See the article by Thomas Mason, PHYSICS TODAY, May 2006, page 44.) A second target station for SNS has been green-lighted for construction, but it won't be completed for another decade.

Two other North American neutron user facilities were closed in the past several decades. The High Flux Beam Reactor at Brookhaven National Laboratory was shuttered in 1999 because of opposition from the surrounding community that was provoked by a tritium leak. Canada's neutron user facility was closed in 2018 when the National Research Universal reactor in Chalk River, Ontario, was retired.

A 2018 assessment of the NCNR by the National Academies of Sciences, Engineering, and Medicine (NASEM) said the US has fallen behind Europe and China in the "neutron enterprise" and warned that the US position will erode further as new facilities come on line in those regions and elsewhere. The assessment noted that the NCNR and the HFIR are both more than 50 years old and lack planned successors. Even if there were plans, it would take 15 years or more to build one.

According to the NASEM report, "Closure of either facility would have a major and instantaneous negative impact on U.S. capabilities for developing advanced materials that drive future innovation, as well as important research on fundamental properties of the neutron, like its lifetime or an upper limit on its electric dipole moment."

An aging source

The NASEM assessment called for planning to begin on a replacement for the NCNR reactor, which was commissioned in 1967. Dimeo says that the reactor's age played no role in the accident and that the NRC relicensed its operation for 20 years in 2009. Most importantly for users, he says, the reactor has continued to perform reliably, and the recent accident notwithstanding, safety hasn't been an issue. "When the reliability starts to diminish, we really need to think about a new source." Nonetheless, NIST has begun a rough preconceptual design for a new reactor, and both an upgrade of the current facility or one built from the ground up would be considered when the time comes.

The NCNR and the HFIR are among the five remaining US reactors that are fueled with highly enriched weapons-grade uranium (HEU). All other US research reactors, and all but a handful of foreign reactors that were supplied with US weapons-grade material, have been converted to low-enriched uranium (LEU), which doesn't present a proliferation concern. (See PHYSICS TODAY, April 2016, page 28.) The American Physical Society's Panel on Public Affairs in 2018 urged the timely conversion of the NCNR and the others, but it added that "any transition from HEU to LEU reactor fuel must not compromise neutron research and engineering capabilities, especially those that cannot be duplicated using spallation sources."

Alan Kuperman, coordinator of the Nuclear Proliferation Prevention Project at the University of Texas at Austin, says NIST has committed to conversion but has maintained that it will require an ultra-high-density uranium–molybdenum fuel, the development of which has been delayed for decades because of technological challenges. Other high-performance research reactors—including the HFIR, which officials had once said required uranium–molybdenum fuel—have since committed to converting to high-density silicide LEU. That fuel, says Kuperman, has been available since the 1980s.

David Kramer PT

Washington University in St. Louis

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Candidates should have a Ph.D. in Physics or a closely related field at the time of appointment, significant research achievements, and an aptitude for teaching physics at the graduate and undergraduate levels. For a list of duties and application requirements please refer to the Interfolio application: **https://apply.interfolio.com/94448**

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Applicants should provide a cover letter, a curriculum vitae with a list of publications, a research plan, a teaching statement, and arrange for at least three letters of recommendation to be sent (all in PDF format) to: cmtsearch@physics.fsu.edu. Review of applications will begin on **November 29, 2021** and will continue until the position is filled.

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Department of Mathematics & Physics
North Carolina Central University, Durham, NC 27707, USA

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Mike Tamor is an adjunct professor at Arizona State University in Tempe. From 1982 to 2017 he worked as a researcher at the Ford Motor Company in Dearborn, Michigan. In 2013 he was promoted to Henry Ford Technical Fellow, the top executive-scientist position at Ford.

Lessons from 35 years in industry

Mike Tamor

Physicists working at private-sector companies must learn quickly and adapt as needs evolve.

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The way I started my industrial career is virtually unheard of today. I earned my PhD in solid-state physics at the University of Illinois at Urbana-Champaign in 1982 and was hired directly by the Ford Scientific Research Laboratory in Dearborn, Michigan. The early 1980s marked the end of the era of great industrial research labs whose departments bore academic names. Through them, corporations sought to "own" the R&D pipeline from fundamental discovery to product execution.[1]

The near disappearance of corporate basic research does not mean that no one does physics in industry anymore, nor that the capabilities and outlooks of physicists are not valuable, even to a century-old consumer-products company. Rather, it means that physicists in industry must learn to operate differently from their forebears, and they must learn quickly. A physicist leaving academia today is expected to pick up in a matter of months the knowledge and skills I had many years to absorb.

Here I attempt to capture a few key lessons that might ease the jarring transition from academia and promote, even in some small way, a successful industrial-physics career. In that regard, I hope this article will provide some useful guidance to younger physicists starting or considering careers in industry. The lessons are best understood in terms of my own career path, which could be viewed more as three careers because each position differed significantly in the nature of my research and the scope of my responsibilities.

Career 1: Materials scientist

Although the automobile industry has not been seen as high tech since the 1920s, it is rich with new technologies and innovations. I was hired by John Reitz (1923–2014), coauthor of the well-known textbook *Foundations of Electromagnetic Theory*, into the physics department of what was then the Ford Scientific Research Laboratory. On my arrival in Dearborn, I was given a modest equipment budget, the able assistance of one-half of a lab technician, and a partially renovated lab that had once been occupied by Albert Overhauser, best known for his theory of dynamic nuclear polarization. With a silicon micromachining facility nearing completion, my assignment was to "do something with silicon."

The search for relevance began immediately. My absurdly vague mandate morphed into a materials-characterization project to help find a more robust replacement for mercury cadmium telluride in thermal imaging systems. (At that time, Ford was making thermal imagers and seekers at its aerospace division in Newport Beach, California.) Although none of the alloy and superlattice systems we studied proved suitable for IR detectors, the work led to interesting physics. For example, in some disordered materials, the Hausdorff dimension describing transport of electric charge could become temperature dependent.[2]

In those early days, my only responsibilities were to build up the lab and get results. Although I had to justify equipment budgets and present progress reports, I did not have to manage many people or write proposals. Even so, I had opportunities to influence major corporate decisions.

The electronics content of vehicles was growing rapidly in the 1980s. But denser packaging and improved aerodynamics made finding cool, dry locations for system control modules increasingly difficult. Auto manufacturers worried that silicon-based devices were reaching their limits, and gallium arsenide, with its wider bandgap, was emerging as a potential solution to the temperature problem. Suspicious of that simplistic argument, I conducted a study of the limitations of silicon-based electronics in the automotive environment and the prospects that other semiconductors could overcome those limits. The study identified packaging and connections as the real challenges and concluded that with modest changes to circuit design and materials choices, the anticipated—and extremely expensive—shift to wide-bandgap semiconductors was unnecessary.

In 1985 "diamond fever" broke out. Although immediately overshadowed by breakthroughs in high-temperature superconductors, vapor-deposited thin-film

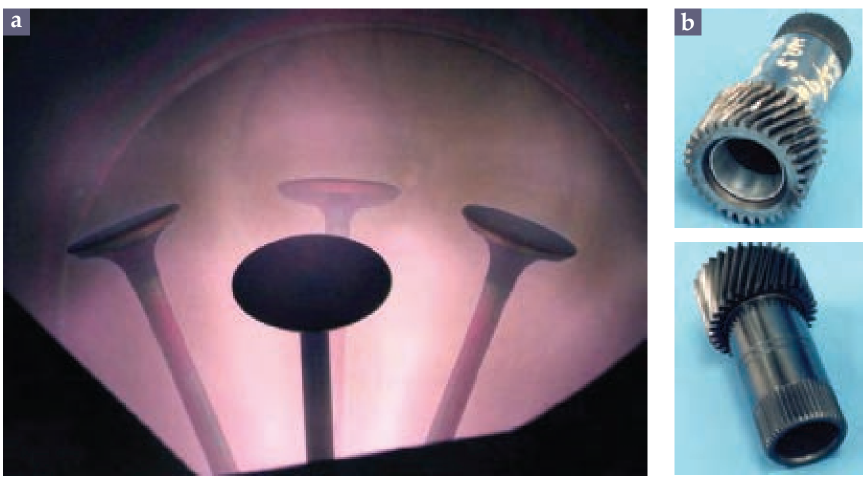

FIGURE 1. DIAMOND-LIKE CARBON (DLC) thin films greatly reduce friction and wear. **(a)** These engine intake valves receive a conformal plasma coating of silicon-stabilized DLC. **(b)** A transmission sun gear (top) that failed a durability test shows wear and spalls. A DLC-coated sun gear (bottom) that passed an extended durability test shows essentially no wear. (Photos courtesy of Ford Motor Company.)

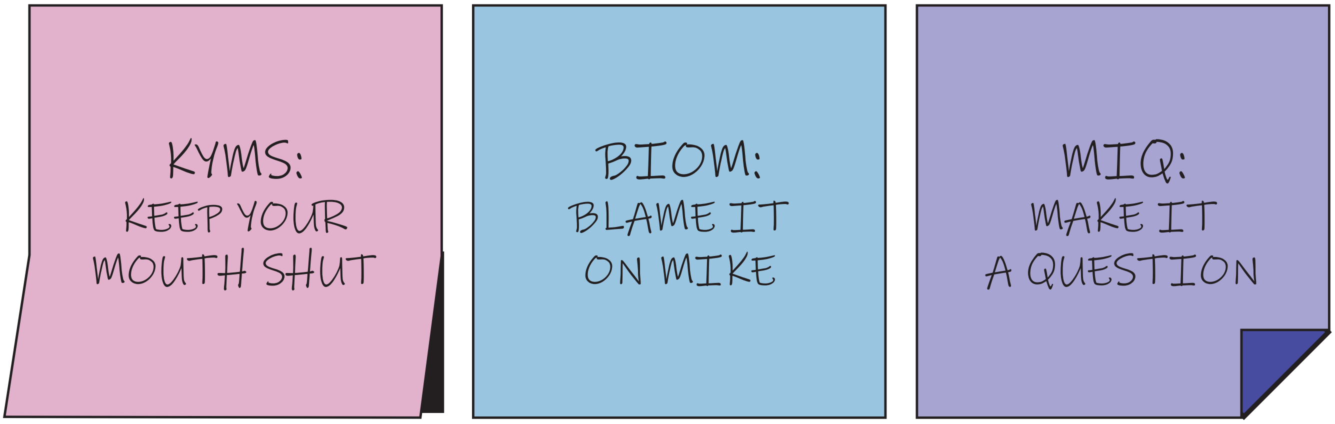

FIGURE 2. RESPECTFUL COMMUNICATION is critical to working in industry. Notes in the author's office served as reminders that a more successful approach involves listening to others, taking responsibility for missteps, and making an effort to understand other perspectives in a disagreement.

diamond was promoted as the solution to all friction and wear problems and as the ultimate high-temperature semiconductor.[3] In response, I assembled and led a team of scientists and technicians exploring synthesis, properties, and applications of crystalline diamond and amorphous diamond-like carbon thin films. Figure 1 illustrates how the silicon-stabilized diamond-like carbon films we developed improved the performance of engine components and tools. Although leading that larger team entailed greater management responsibilities, the learning curve for managing like-minded scientists was easy compared with what was to come.

Career 2: Power-train researcher

My leap into advanced propulsion-system research began almost by accident. After attending a seminar on the complexity of the design space for hybrid-electric vehicles—a novelty in 1993—I proposed an optimization method that combined an adaptive energy management strategy with scalable, physics-based models of system-architecture options. The goal was to maximize efficiency while minimizing system cost.

The resulting lash-up of Visual Basic models and the existing Fortran-based vehicle simulation program worked well as a design platform. In the early 1990s, conventional engineering wisdom held that a hybrid vehicle was in essence a short-range electric vehicle with a small "range-extender" engine that would run at a single, optimal operating point while the battery delivered the varying power for driving. The headline finding of the self-optimizing model was that the recommended system have a large engine that would generally follow the driving load, and that the battery—the costliest part of the system—could be surprisingly small.

When I presented the results to the engineering team, it was clear that a physicist with no vehicle experience flying in with counterintuitive recommendations had little credibility. If I was going to convince them to accept my findings, I had to be all in. To my managers' horror, I asked to transfer into the power-train laboratory. I was expecting to be assigned a nonleadership role, but to my horror, the "reward" for finding an optimal design that maximized fuel economy while meeting essential performance criteria was to be placed in charge of the engineering team and, later, all research on hybrid-electric and fuel-cell vehicle technology. The new position entailed significant managerial responsibilities for budgets, personnel, and reporting to funding agencies.

My transition from working with a small group of PhD scientists to leading a growing engineering team was a near disaster. In graduate school, physicists are trained in hand-to-hand combat. Every assumption, every method, and every step are subject to scrutiny and occasional shaming. As one colleague put it, a successful seminar was one in which the speaker did not leave in tears. It is a tacit—and usually wrong—assumption that such grilling will not be taken personally.

Although that meticulous combativeness might be good for scientific integrity, it can be a social and professional disaster. Engineers are accustomed to working in teams, often large ones, and they rely on tested tools and methods to achieve predictable, robust outcomes. Antagonistic dialog that many physicists understand as a customary means of communication comes off to engineers (and most other humans) as arrogant, insensitive, and often insulting. (For more about the value and dangers of arrogance, see the Commentary by J. Murray Gibson, PHYSICS TODAY, February 2003, page 54.) Navigating that transition required a conscious and systematic revision of my communication habits.

As a constant reminder, I posted a few simple rules in my office (see figure 2): KYMS, or keep your mouth shut until others have said what they need to say; BIOM, or blame it on Mike, meaning be prepared to share responsibility for discouraging missteps and dead ends; and MIQ, or make it a question, a reminder that any disagreement can be rephrased as a question. It should come as no surprise that the rules can apply to any social interaction.

Career 3: Sustainability guru

Historically, the mobile and stationary energy economies have been essentially disconnected; things that move run on oil, whereas those that don't rely on a menu of other energy resources. Early in the development of hydrogen fuel-cell vehicles, researchers pointed out that they could not be considered "zero emission" if making their fuel produces carbon dioxide. Of particular concern was black hydrogen made from coal-fueled electricity. The same holds for charging battery-electric vehicles.

By 2010 it was clear that moving to a carbon-neutral economy would entail making every vehicle electric where practical and providing renewable chemical fuel for the remainder—mainly aircraft. The strategic need to map out the role of a carmaker in an emerging, highly integrated energy economy brought me to my third career in energy systems and sustainability. The transition can best be described as a switch from a conventional leadership role—the "commander in chief" of four departments comprising more than 200 engineers and technicians—to one of "convincer in chief" with only two direct reports.

The fun part of my transition was the opportunity to dive deep into other sectors of the energy economy and their regulatory systems. The challenge was to integrate into corporate strategic planning the findings from multiple studies of personal vehicle usage, the electricity grid's evolution, prospective renewable fuel pathways, and government policy choices. In a large organization, that is not as simple as it sounds. Understanding how decisions are really made, no matter how arcane it might seem, is essential. Having a real effect on strategy requires identifying who is making key decisions, what they need to know, when they need to know it, who else must be convinced to bring the decision makers on board, and what form the findings and recommendations should take for each audience.

It is true that I enjoyed the rare privilege of (usually) choosing my own research directions. However, the choice was not made in a vacuum and was never based on pure scientific curiosity. Rather, each of my three careers began with the identification of a void in corporate understanding of the underlying science, technology, or potential business impact of an important area of development. The task at hand, then, was filling that knowledge void and building new capabilities so the company could respond as needed.

The capacity to adapt to changing needs is certainly not unique to physicists, but they do seem to use it often. A few examples of technologies that arose from Ford's "physics" labs as a result of that mindset include applications of neural-network computing, x-ray tomography, acoustic profilometry, autonomous vehicles, applications of simulated annealing, human–machine interfaces, virtual reality, and big-data analytics. I believe adaptability is what makes physicists so valuable to industry and is the hallmark of a successful industrial career. In other words, the best way to get a new and better job, in reward or advancement, is to invent that job and start doing it!

My career and those of many of my friends and colleagues have consisted of distinct phases. As a new hire, your boss tells you what to do and how you will do it. Then, after achieving a degree of confidence-building success, you will advance to a stage where your boss tells you what to do and you figure out how to do it. With a broader understanding of the business's needs and greater confidence in your abilities, you can graduate to where you tell your boss what you are going to do and how you are going to do it. If you join the ranks of the most successful industrial researchers and ascend to the final phase, you tell your bosses what they are going to do and how they are going to do it.

Figure 3 illustrates the direct mapping of my own career path and responsibilities in the four phases. Although the wording may sound a bit silly, the progression reflects an increasing understanding of the enterprise's needs and direction combined with the development of managers' and colleagues' confidence that you can and will continue to deliver on those needs. Figure 4 shows that organizational authority is not a measure of career progression or business impact. In fact, your technical contribution is often enhanced by deliberately shedding managerial responsibilities.

Words of wisdom

Described with deliberate and, hopefully, humorous overstatement, here are a few important lessons learned over the course of 35 years in industry. The first set relates to expectations for your role. Corporations don't have physics departments and don't hire physicists to "do physics." Physicists are technology stem cells—they're expected to mold themselves to fit specialized roles that inevitably arise. It is startling to see how often physicists are the first to dive into new areas and develop them until the areas have new names and the pioneers get matching

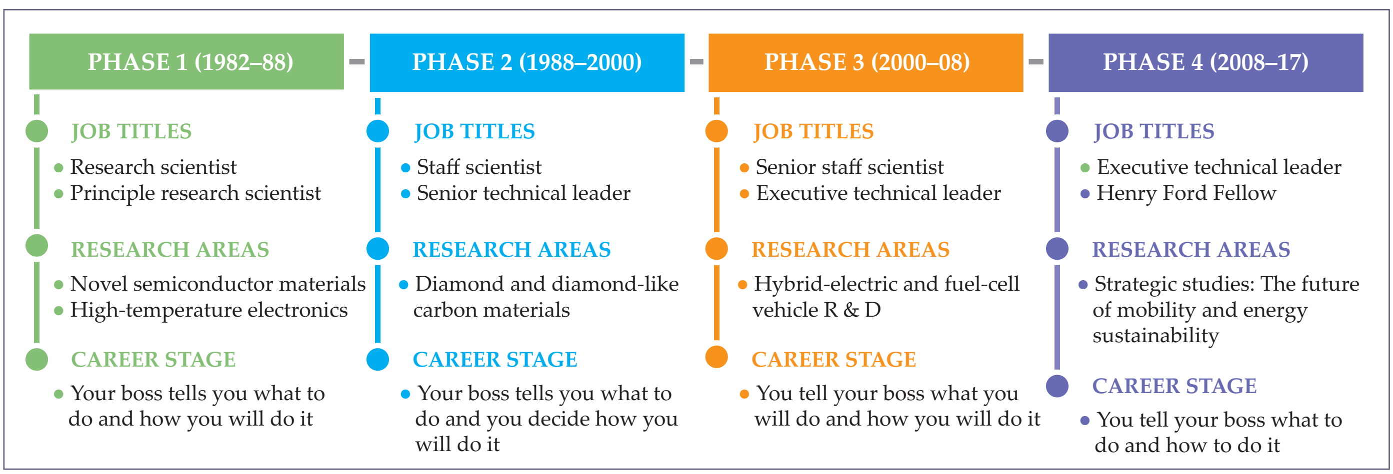

FIGURE 3. THE CAREER PATH of an industrial physicist can be divided into four phases. Here, the author's career illustrates the evolution from a new hire to a high-level executive.

job titles. In other words, a successful industrial physicist is unlikely to be called a physicist at work.

Physicists are trained to revere new knowledge. The two happiest moments in a scientist's life are when they realize they know something nobody else knows and when they convince an appreciative but skeptical audience that they're right. But in the business world, new knowledge is not an objective. (Don't take it personally.) The job of the physicist is to initiate the process of converting that knowledge into new competitive capabilities; where the knowledge came from might even be irrelevant. New capabilities are the real objective.

But capabilities have no value unless they are applied, which leads to another lesson: Focus on decisions. The competitive advantage of a new capability is lost without a timely decision to use it. But who makes the key decisions? When and where do they make them? What data will they need? Just ask! At the same time, it is essential to find out what customer experience, rather than what physical product, the company seeks to deliver. When should we deliver it? Will we know how to deliver it by then? What must we learn now to be ready in time? Figuring out what data are needed to make decisions and what must be learned before they can be implemented is the essence of outcome-based research.

As for behavior, I have shocking news: Physicists can be arrogant. If asked how you know something, answers such as "it's trivial" or "conservation of momentum" may be amusing to other physicists but are highly offensive to engineers and incomprehensible to management. As I mentioned above, a simple and disarming strategy is to recast every statement in the form of a question. Everyone enjoys feeling respected for their expertise and opinion, even when you are in the process of showing that they are mistaken.

Next, and closely related: The physicist is not Moses. Findings handed down will not be immediately understood, applauded, and implemented. A useful aphorism is that engineers design to the edge of the page, whereas physicists make the page bigger. Because engineers rely on deep discipline and validated tools to ensure quality and consistency of results, they can understandably be nervous about new principles and functionalities. You must join the team and be prepared to teach and reteach what you have learned.

That leads to another lesson: Communication is everything. Think of an Olympic event in which half the points are awarded for technical merit and the other half for artistic merit. Being right—getting perfect technical marks—is of no value without conveying the potential benefits, or the artistic merit. There is no trade-off; you must be excellent at both.

The challenges of communication with management are as great as those with engineers. Management is rarely interested in how smart you are—at least, not in public. Just because executives may have difficulty understanding your work or immediately appreciating its implications does not mean that they are unqualified or unintelligent. In a large organization, there are many routes to senior positions. Executives are intelligent people, and they can be taught! Your greatest success will be marked by an executive lecturing on what you taught them, often without attribution, and sometimes back to you.

Finally, be patient and build trust. When engineers and executives see that you understand their needs and have a record of delivering on them, your influence and freedom to take initiatives will increase accordingly.

When it comes to professional success in industry, you might ask, what's in it for me? Although the money is usually quite good, don't count on being the next tech billionaire. In modern, flat organizations, it is difficult to use promotions as rewards. Most companies have internal recognition programs for patents and technical achievements. Some are quite generous, but others are more symbolic. Technical societies, including IEEE, SPIE, and Optica (formerly The Optical Society), offer prestigious recognitions, and the American Physical Society recognizes important contributions to industrial and applied physics. But there is no Nobel Prize, Fields Medal, or equivalent for industrial physics.

Your greatest pride and satisfaction will come from positive societal impacts that the new functionalities you develop bring to the world. The scale of those impacts can be large: Replacing a million gasoline-powered vehicles with hybrids avoids 30 million tons of carbon dioxide emissions over the vehicles' lifetimes. When approached, or reproached, by environmental activists, I can honestly say, "I gave at the office."

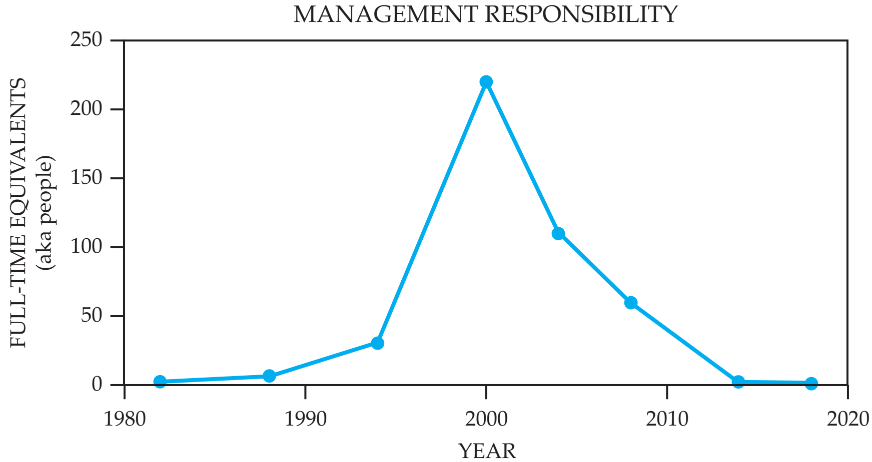

FIGURE 4. MANAGERIAL RESPONSIBILITIES are not always a measure of career advancement. As evidenced by this graph of the author's reports over the course of his career, being responsible for fewer people can free up time to make big-picture contributions.

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3. R. Pool, *Science* **249**, 27 (1990).

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RICE

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The Department of Physics & Astronomy invites applications for tenure-track faculty positions in areas of experimental quantum science and technology, including quantum information, sensing, communication, opto-mechanics, and quantum simulation in photonic, atomic/ionic, quantum-material, and other solid-state platforms. We seek outstanding scientists whose research will complement and extend existing activities within the Department and across the University.

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The Department of Physics and Engineering at Westmont College invites applications for a tenure-track faculty position at the Assistant or Associate rank in Physics and Astronomy to begin in August 2022. Candidates must have a PhD in physics, astronomy, or astrophysics, a commitment to excellence in teaching a broad range of undergraduate physics and astronomy courses, and a passion to mentor undergraduate research. Although a variety of research specializations will be considered, preference will be given to candidates who demonstrate a willingness and proficiency to utilize our modern campus observatory in the department curriculum, student research, and public outreach. Westmont College is a national liberal arts college in the evangelical Protestant tradition, seeking faculty with a vital and informed commitment to the Christian faith. We continually aim to diversify the faculty and strongly encourage applications from historically underrepresented groups. Questions may be addressed to Dr. Robert Haring-Kaye at rharingkaye@westmont.edu. Review of applications will begin in September 2021 and will continue until the position is filled. Apply at **https://www.westmont.edu/office-provost/open-positions**

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The Department of Physics at The Pennsylvania State University (University Park campus) invites applications for faculty to start in Fall 2022. We are seeking to hire in quantum-related areas, including AMO and condensed matter physics, and in biological physics. We will also consider applicants in any of the department's other areas of research, which include astro-particle physics, cosmology and gravitation, and particle physics. Applicants should have a Ph.D. and an outstanding research record. A successful candidate will be expected to build a world class research program, teach graduate and undergraduate courses, and perform university service and public outreach. Rank will be commensurate with qualifications and experience. Application details can be found at https://science.psu.edu/physics/hiring . Applications completed by **November 15, 2021** will be assured of full consideration.

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UAB

THE UNIVERSITY OF ALABAMA AT BIRMINGHAM

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The University of Alabama at Birmingham (UAB) is a comprehensive urban university with the nation's third-largest public hospital, which has rapidly evolved into a world-renowned research university and health care center that ranks in the top ten nationally for student diversity. With over 22,500 students and 2,459 full-time faculty members, and a campus covering more than 100 city ranks in the top 20 public universities for federal research funding and is the major research and teaching university in Alabama. Interdisciplinary scholarship and teaching are prominent. UAB was recently named America's No. 1 Best Large Employer and America's No. 4 Best Employer for Diversity (Forbes, 2021). Times Higher Education has ranked UAB No. 1 Young U.S. University for two years in a row, top 10 worldwide. The College of Arts and Sciences (CAS) treasures the rich diversity of our student body, and we are committed to their success. Members of the CAS community are expected to reflect our value for inclusive excellence in both our work and learning environment as well as in our efforts to serve and engage the community. We are also a founding partner of Innovation Depot, the largest high-tech incubator in the southeast, whose economic impact between 2010 and 2015 was $1.38 billion. UAB research funding is at an all-time high of over $600M, while the Physics footprint continues to grow with the new state-of-the-art Science and Engineering Complex that will host the Department. The Department of Physics is experiencing growth fueled by its focus on Advanced Materials, Optics, and Computation, as well as using emerging technologies to remove existing barriers and provide equal opportunities for high-quality education across geographical, social, economic, and gender boundaries. Birmingham is the largest city in Alabama, noted for its vibrant music scene, fine dining, warm weather, excellent schools, and a culture embracing diversity within driving distance to Atlanta, Memphis, Nashville, and New Orleans.

UAB is an Equal Opportunity/Affirmative Action Employer committed to fostering a diverse, equitable and family-friendly environment in which all faculty and staff can excel and achieve work/life balance irrespective of race, national origin, age, genetic or family medical history, gender, faith, gender identity and expression as well as sexual orientation. UAB also encourages applications from individuals with disabilities and veterans.

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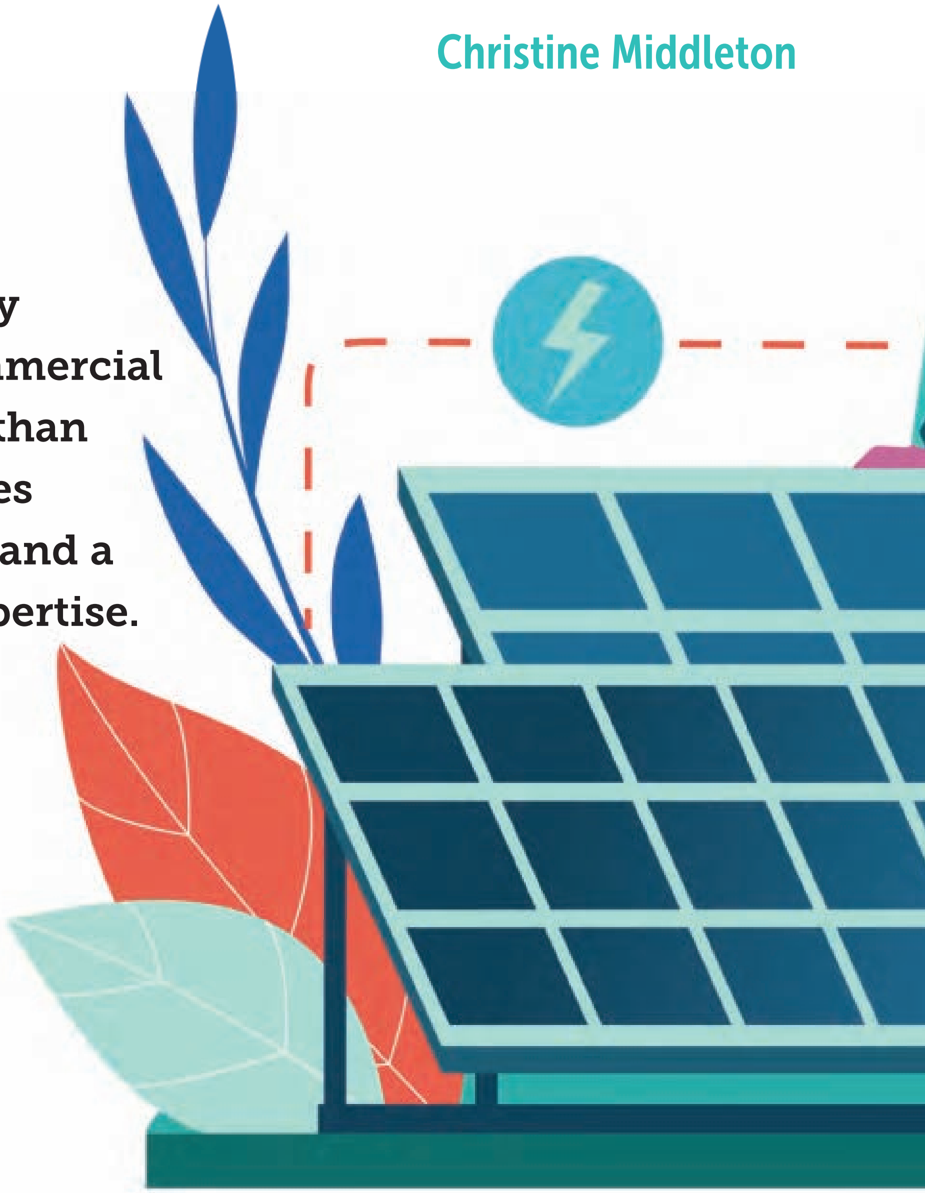
Christine Middleton is an associate editor at Physics Today.

The road from academia to entrepreneurship

Christine Middleton

Developing laboratory innovations into commercial products takes more than a great idea. It requires financial investment and a team with diverse expertise.



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University researchers are responsible for nearly half of all basic research performed in the US[1] (see figure 1). But what happens when that research yields a discovery or invention that could have practical applications? If a technology is going to be of use, it has to make its way out of academia and into a company that can bring it to market.

Startups are an increasingly popular route for commercializing academic research; more than 14 000 startups based on academic research were formed from 1996 to 2017, and more than 1000 per year were added[2,3] in 2018 and 2019 (see figure 2). But pursuing that route requires expertise in areas such as business, marketing, development, and manufacturing that are likely not covered in most scientists' PhD programs. It also requires money. For a potential first-time entrepreneur, it can be difficult to envision what the process entails—who should be involved, what funding sources are available, and how to handle intellectual property—or where it begins.

Early days

Any new invention or discovery should be discussed early on with the university's technology transfer office (see figure 3), which helps researchers pursue intellectual property protection and commercialization (see PHYSICS TODAY, February 2021, page 24). The first step is usually to complete a disclosure form or notice of invention. That information will help the office's staff decide whether the concept is novel enough to be patented and whether it might have some commercial value.

If an invention or discovery passes both tests, the tech transfer office facilitates the patent process. An attorney, likely one who specializes in the appropriate scientific area, will handle the filing process, which can require multiple exchanges with the patent office and take more than a year. The tech transfer office also typically covers patent filing fees, which can be $10 000–$20 000, and the maintenance fees due every three to four years. Disclosures based on federally funded research must be reported to the funding agency within two months, another task the office usually handles.

Tech transfer offices need money and experts to run, which is why considerable disparities in resources can be found across academic institutions. Large universities with a history of successful tech transfer and commercialization are able to provide more specialized guidance and may even host their own startup incubators or entrepreneur training programs. Researchers from smaller universities that don't generate many patents may need to look for additional support from people and programs outside their institutions.

The patent process highlights an important difference between the incentives for academics and for entrepreneurs. University researchers are generally excited to share their new work with others in the community through seminars, conference presentations, journal articles, and other means. That sharing, however, can be a death knell for the patenting process. Once the information has been presented or published, it may no longer be eligible for patent protection. Consulting the tech transfer office at the first inkling that a discovery might be patentable can help prevent disqualifying disclosures.

The current system for protecting university-developed intellectual property was born out of the Bayh–Dole Act of 1980. Prior to its enactment, the federal government owned the rights to technologies developed with federal funding. At the time, however, less than 5% of the government's 28 000 patents from federally funded research had been licensed for commercial use, compared with nearly 30% of patents that the government had allowed companies to retain.[4]

Bayh–Dole allows universities to retain ownership of the intellectual property developed in their laboratories with federal funding. It was intended to help research results progress into useful products. By giving universities a financial stake in the successful licensing of their patents, the government incentivizes both universities and researchers to patent their work and to pursue and facilitate the licensing of those patents. Universities are required to give inventors a share of any royalties generated by the patent, but the percentage varies widely between universities; it typically falls in the 25–75% range and may decrease when profit thresholds are reached.[5]

Has the Bayh–Dole Act been successful? It depends on the metric. For most university tech transfer offices, the revenue they bring in through licensing doesn't cover their operating costs. In 2019, however, more than 7500 patents were issued based on academic research and close to 10 000 licenses and options were executed for the use of existing university patents.[2] Such licensing can be credited with creating hundreds

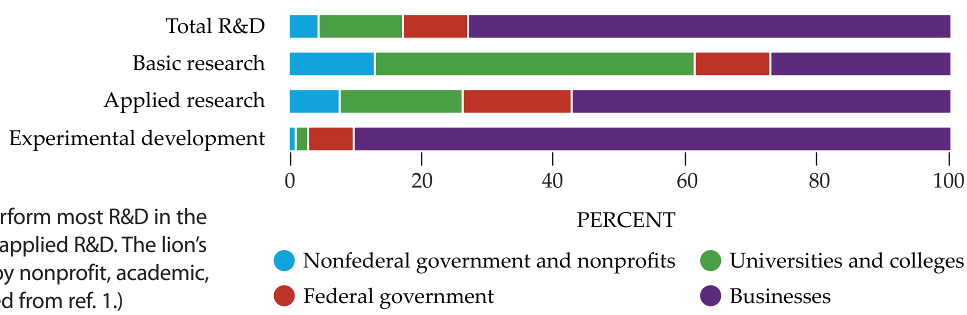

FIGURE 1. PRIVATE COMPANIES perform most R&D in the US. Much of that work, however, is in applied R&D. The lion's share of basic research is performed by nonprofit, academic, and government institutions. (Adapted from ref. 1.)

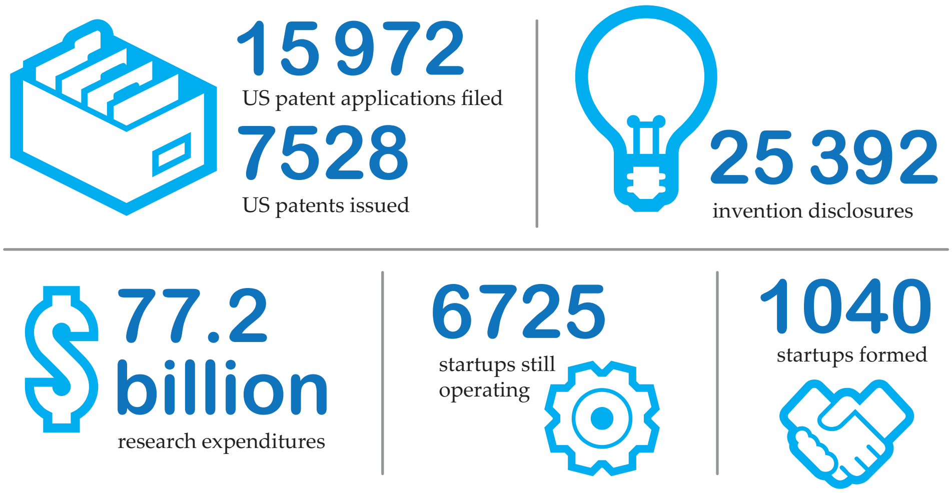

FIGURE 2. TECHNOLOGY TRANSFER continues to bring ideas from academic labs to commercial settings. These numbers reflect the state of tech transfer in 2019. (Adapted from ref. 2.)

of thousands of new jobs and adding up to $30 billion to the annual US GDP.

Diving in

When a new technology based on academic research is patented, it typically has a technology readiness level (TRL) of around a 1 or 2. A widely used measure of how mature a technology is, the TRL scale ranges from 1 (a basic principle is observed) to 9 (operational in a target environment), as shown in figure 4. The new technology is cutting-edge research, which makes it exciting, but that novelty also means that it's not quite ready for prime time. A large company is therefore unlikely to swoop in and license a new patent. It will want to see that the science works, which can take time, and that the technology has an application for which there is a market.

Startups can help bridge the gap between basic research and commercial readiness, sometimes referred to as the "valley of death."[6] (See the article by Orv Butler and Joe Anderson, PHYSICS TODAY, December 2012, page 39.) From 1996 to 2017, about two-thirds of university patent licenses went to startups and small companies with fewer than 500 employees. A so-called deep-tech startup—one based on advancing a scientific or engineering innovation rather than, say, delivering a service or developing software—would typically get an exclusive license for the patent so it could use the technology for a potential product. (The term "product" is used loosely here; it could mean a standalone device or something that gets incorporated into a consumer product. See the box on page 46 for examples.)

The people who found startups are typically those who know the underlying technology intimately: the researchers who developed it. In that case, they're likely also named on the patent and therefore have a preexisting financial stake in the startup's success. More importantly, however, researchers' deep understanding gives them a clearer picture of what the technology could be used for; they're likely to be the first to see its potential and the most excited about sharing it with the world.

Even if the founders of a startup are the inventors of the underlying technology, they generally still have to license any relevant patents from the university. A 2018 update to the Bayh–Dole Act requires researchers to assign ownership of federally funded inventions to the university where the research was performed. An inventor usually has no guaranteed right to a license. But individual rights vary depending on the researcher's contract with the university, and an inventor may, for example, retain some priority status over third parties in licensing negotiations. The updated act also generally requires that licensing preference be given to small businesses.

Deciding whether and how to pursue commercialization requires more than just vision and excitement. That's where incubators come in—they provide researchers with the mentorship and tools needed to set and refine development goals, create a business plan, and take other essential steps. Not all incubators target deep-tech startups, which have different needs than companies based on, say, services or algorithms. But many do, and they're often hosted by universities or potential investors.

NSF's Innovation Corps (I-Corps) is an incubator-stage federal program designed to help researchers evaluate the market opportunity for their technology and fill any skills or knowledge gaps associated with turning their basic research into a commercial venture. Piloted in 2011, the program is based on the Lean LaunchPad methodology developed and taught by Steve Blank at Stanford University. It applies the scientific method to starting a business and pushes participants to quickly test their ideas in the "real world." Applicants must have previously received an NSF grant for related research or have participated in local I-Corps training.

I-Corps has proven effective: Through 2020 the program has spawned more than 1000 startups, which have attracted $760 million in investments.[7] Federal agencies, including NASA, the Department of Defense, and the Department of Energy, now also host I-Corps cohorts. Although it's not the only model for developing a business, it introduces questions and steps that are important for any potential entrepreneur.

Teamwork

I-Corps applicants begin by assembling a team of three people: an entrepreneurial lead, who will spearhead the business's development and is often a late-stage graduate student or postdoc; a technical lead, who is typically the inventor and often the research's principal investigator (PI); and an industry mentor who can provide independent advice and feedback. The mentor should have a background in the relevant technical area, and it helps if they have entrepreneurial experience or have previously been an I-Corps mentor.

The makeup of the team highlights a few important roles in a startup. The entrepreneurial lead should be passionate about securing funding for the company and helping it grow. They'll therefore need to be able to communicate clearly and concisely with nonscientists. The entrepreneur must be able to tell a story that not only conveys the function and importance of the new technology but also creates excitement and presents a clear path to success.

Graduate students and postdocs who contributed to the invention can be natural fits for an entrepreneurial role. They have a deep understanding of the underlying technology, and they may already be interested in moving away from academia: A 2017 survey found that about half the people with physics PhDs work in the private sector (see the article by Anne Marie Porter and Susan White, PHYSICS TODAY, October 2019, page 32). Joining a startup can be a particularly exciting entry point into an industrial career because it involves building something new and playing a myriad of roles. It is riskier, however, than taking a position at an established company. Fewer than half of deep-tech startups become profitable,[8] and only a small fraction of those develop into "unicorns"—wildly successful startups worth at least $1 billion.

The technical lead's scientific expertise and vision drive the continued R&D at the heart of the startup. They may be less directly involved than the entrepreneurial lead in building and marketing the company, though, and the company's first employees are likely to be scientists who will also facilitate technical development. The technical lead can therefore be a sensible role for a PI.

Some professors may want to dive headfirst into a startup and embrace its new challenges; those so inclined are well positioned to eventually take on a full-time role as chief technology officer. But in the long run, many will choose to remain in their faculty positions.[9] So how does one find the time to start a company? Many universities allow professors to use up to 20% of their time, or one day per week, on consulting or other related professional activities. A sabbatical can be dedicated to getting a company up and running, as can a temporary leave of absence. In the long term, however, a professor will devote the majority of their working time to the university, which means serving the company only in a part-time consulting or advisory capacity.

The industry mentor is essential in part because graduate students, postdocs, and university professors are unlikely to have training or experience in business. Like the scientific community, the business world has its own jargon, procedures, and norms that can make communication and collaboration with outsiders challenging. Alumni offices, incubators, and advisory boards at universities can be good places to look for potential mentors. Local and regional professional societies and previous I-Corps participants can also provide guidance.

Working in industry requires a different mindset compared with academia, where research often happens on longer timelines and can be redirected by intellectual whimsies. Scientists at a startup must be goal oriented and focused on probing the details of the technology being developed, understanding why things go wrong, and directly addressing issues that arise. The work can't get sidetracked, and problems have to be solved in a robust way on the timeline laid out by the business plan.

Circumstances vary, of course, so the roles—and who should fill them—aren't set in stone. More important is recognizing the different kinds of contributions that will be essential to a startup's early success: clear communication and storytelling to generate excitement and investment, technical expertise to quickly advance the product's TRL, and guidance from the private sector to help facilitate the business's nontechnical progress. Although certain people may be able to contribute in multiple areas, building a strong team is important; starting a business is a lot of work, and it doesn't have to rest on a single person's shoulders.

The real world

When a team is selected to participate in the I-Corps program, the members are tasked with evaluating the market opportunity for their new product. Most startups fail not because the technology doesn't work but because a market for their product doesn't exist.[7] So the team approaches potential customers, partners, and stakeholders to understand the product's potential value. Through those discussions, they try to answer various questions: Who would be interested in the product and why? How might they want to use it? Does it represent a significant enough advance to be worth incorporating into an existing product?

I-Corps teams are required to have at least 100 such meetings over the course of seven weeks. That number may sound daunting, but the information gathered from those meetings is crucial for understanding whether a startup can be successful and, if so, how it should proceed. (In fact, many teams take more than 100 meetings.) Importantly, potential investors will want to see that kind of market research when they're deciding

DEEP-TECH STARTUP SUCCESS STORIES

▶**E Ink** was founded by MIT researchers in 1997. The company's low-power displays generate images by manipulating microparticles using electric fields. The now widely used technology is perhaps best known for its application in e-readers such as the Kindle and Nook.

▶**Alien Technology** was founded by researchers at the University of California, Berkeley, in 1994. The company's fluidic self-assembly process enables high-speed manufacturing of RF identification (RFID) chips. Alien is a leading manufacturer of RFID-based devices and has relationships with Walmart, Hewlett Packard, and the US Department of Defense, among others.

▶**Peregrine Semiconductor**, now pSemi, was founded in 1990 by researchers at the US Naval Ocean Systems Center in San Diego, California. The company's high-performance RF CMOS integrated circuits, which implement silicon-on-sapphire and silicon-on-insulator technology, are used in a wide range of devices, including some Samsung Galaxy phones and Apple products.

▶**Eden Park Illumination** was founded in 2007 by researchers at the University of Illinois at Urbana-Champaign. The company's UV lamps produce 222 nm radiation that reduces pathogens but is still safe for human exposure. The coronavirus pandemic has spurred their installation in retail and dining spaces.

whether to fund an endeavor. But making professional connections is important not just for identifying funding sources and potential customers. The new contacts will also have valuable expertise, and having so many meetings gives team members an opportunity to practice their pitch and hone their ideas.

Through all that effort, teams may learn that pursuing commercialization is unlikely to yield success, and that's okay. Not every idea is going to be successful, and it's better to find out early. The teams that do receive promising feedback will have gained a deeper understanding of both their product's value and their potential customers and investors.

Before a startup can move on to securing funding, the company needs to be incorporated. For a startup, that process achieves two primary goals: It details how equity is divided among the partners and enables the company to license any necessary intellectual property from the university.[10] Although it's possible to pursue a do-it-yourself approach using online tools, the process can be complicated. Hiring a lawyer to facilitate it is generally prudent to make sure everything is done correctly. A common legal structure for startups is a C corporation, which separates the owners from the company both legally and financially, and for tax reasons, they're frequently incorporated in Delaware.

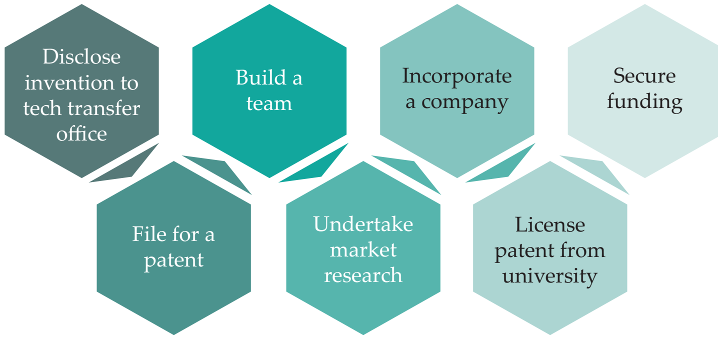

FIGURE 3. BUILDING A COMPANY from a basic discovery involves many logistical steps before the R&D can start. Although not comprehensive, this sequence captures some important benchmarks.

Show me the money!

New startups can benefit from federal funding specifically targeted at the development and commercialization of basic research. The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs issue grants expressly for that purpose. The primary difference between them is that to get an STTR grant, a company must partner with a research institution that will receive at least 30% of the funds. That model is well suited to startups using technology that came from academia because the company has a natural partner—the university lab that spearheaded the research. The partnership can provide continuity and facilitate a smooth transition of the research from the university to the company.

SBIR and STTR grants are awarded by 11 federal agencies, including DOD, DOE, and NSF. The grants come in three phases. Phase 1 awards support six months of exploratory research (1–3 on the TRL scale) and can provide up to \$250 000, although they typically don't exceed \$150 000. If the results are promising, the researchers may apply for a phase 2 award, which would be used to expand on the initial results and start moving from the research into the development stage (TRL 4–6). Phase 2 awards last for up to two years and can provide up to \$1 million.

The awards given in phase 3 are different in that they don't come with additional funding. Rather, they "derive from, extend, or complete" work done under a prior SBIR grant and must use funding from an external source. Although an award without funding may seem unusual, its value comes from the 20 years of SBIR/STTR data-rights protection that it bestows.[11] The government has access to the data produced under the award, but the data can't be disclosed to outside agencies. The protection therefore safeguards the company's value and provides a right to sole-source contracts.

SBIR and STTR grants are important examples of what's called nondilutive funding, in which owners don't have to give up equity in their company in exchange for financial support. But they're not the only examples—some government agencies have other small-business grants, and financial support can also come from, say, foundations or startup competitions.

The structure of a phase 3 award, however, hints at an important point about startup funding: Deep-tech companies often need private financial support to get up and running. Grants can be a good starting point, but eventually the company will almost certainly have to secure outside money. The sources of those investments broadly fall into two categories: angel investors and private-equity firms.

Angel investors are high-net-worth individuals who provide startup funding in exchange for equity in the company, meaning the funding is dilutive. Because the money is coming from an individual, they may be looking for a project that will not only provide them a return on their investment but also feel exciting or influential. Securing investment from an angel can hinge on the entrepreneur's ability to develop a personal relationship with that individual. Angels are more likely to invest at an earlier stage than a firm might, and they're usually more hands-on regarding the company's development.

Private-equity firms pool capital, such as pension funds, from high-net-worth individuals and from institutions. They then invest that money in private companies to generate returns for their contributors. Startup funding typically comes from venture capital (VC), a type of private equity that focuses on higher-risk investments in less mature industries. Still, the firm may want to see a technology at a higher TRL than an angel investor would (perhaps a 6 or 7 rather than 3–5).

VC funding is also dilutive, and the firm may require a majority stake in the company in exchange for its investment, thereby leaving the founders with less control over their company's future. The firm may also set ambitious goals for the company's development to speed up the return on its investment. That heavy hand, however, comes with an upside: Whereas angel investments are typically around a few hundred thousand dollars, VC investment is often more than a million dollars.

Navigating the landscape

Although personal relationships may be less important for attracting VC investment, translating the science into language

BASIC RESEARCH	1	Basic principle observed
	2	Technology concept formulated
	3	Proof of concept established
DEVELOPMENT AND INNOVATION	4	Small-scale prototype in the lab
	5	Large-scale prototype in the intended environment
	6	Prototype system verified at near-intended performance
DEPLOYMENT	7	Pilot demonstration at precommercial scale
	8	Technical and manufacturing processes in place
	9	Product commercially available

FIGURE 4. AN INNOVATION'S MATURITY can be characterized by its technology readiness level (TRL). Research at low TRLs (1–3) is typically performed at universities and funded by grants from foundations and the federal government. Work on technologies at high TRLs (7–9) is often funded by corporations. Startups can help bridge the gap between those development levels.

that investors can understand is still crucial. The entrepreneur will have to convince the firm that the idea is groundbreaking and in demand enough to eventually make the investors a profit—their primary focus—while also assuring the VC fund managers that the startup has the technical capabilities to develop the product. Scientists often focus too much on an invention's uniqueness rather than its market potential, and that can weaken their argument. Assembling a strong team that combines business and technical expertise is critical for convincing investors that the company is poised for success and can achieve its goals.

Researchers coming from academia can struggle to manage investors' expectations. Many academic seminars or conference talks end with broad statements about a technology's potential, but investors can hear them as assertions about what the company plans to accomplish. Setting and communicating realistic goals is critical for ensuring that everyone is on the same page. And building some wiggle room into any proposed timeline can help with meeting deadlines. In academia, progress often happens on a more flexible schedule; at a startup, missing deadlines costs investors money.

Technologies born from research in the physical sciences can be a harder sell for investors than, say, service- or algorithm-based ones because they require more time and money. Whereas a tech startup founded on applying artificial intelligence may be able to create its product within a year, the R&D behind a manufactured product often takes five to seven years and sometimes more. It may also involve multiple rounds of investment totaling tens or even hundreds of millions of dollars. Cutting-edge deep technologies can also be difficult to explain, which makes it challenging to convince investors of the potential value—and important that the entrepreneur is an adept communicator and salesperson for their idea.

On the bright side, physical-sciences technologies can be easier to bring to market than medical and pharmaceutical products, which typically require years of clinical testing and wading through red tape. But regulations may still govern a deep-tech startup's eventual product—for example, a new rechargeable battery would have to be proven safe for consumers and the environment. If regulatory hurdles exist, someone with the appropriate expertise should be part of the team.

One characteristic that many startups have in common is their end goal. Success usually means being bought by a larger company. At the outset, entrepreneurs might imagine their company growing, becoming self-sufficient, and flourishing. Although that trajectory is possible, it's not the only picture of success. Selling is the fastest and easiest way for investors to get their return on investment and move on to the next opportunity. Another option is an initial public offering, which enables them to realize their gains by selling stocks to public investors. But that process is arduous and expensive, so a sale is most investors' preferred route.

Deep-tech startups based on university research are high-risk, high-reward endeavors. But when they succeed, they enable cutting-edge, undeveloped technologies to realize their potential in commercially viable products (see the box on page 46). And the researchers behind the company reap more than just financial benefits. They also get the satisfaction of influencing people's lives with their work.

Thanks to David Grier and Andy Kent for sharing their experiences and continuing to teach me outside the classroom, and to Dan Pisano, Steve Blank, and Steve Weinstein for sharing their insights.

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PT

UNIVERSITY of DENVER

PHYSICS AND ASTRONOMY

Assistant Professor Tenure-track Position—Experimental Condensed Matter/Quantum Science

The Department of Physics & Astronomy at the University of Denver (DU) invites applications for a tenure-track assistant professor position to begin in September of 2022. We seek candidates with research interests in experimental condensed matter physics whose research and teaching will support a new initiative in Quantum Materials and Information Science. All areas broadly related to quantum materials and information sciences will be considered, with potential for collaboration with existing research areas on campus and in the surrounding areas a particular plus. The successful candidate will possess enthusiasm for teaching both undergraduate and graduate courses, and demonstrate promise of developing an independent extramurally funded research program that involves both Ph.D. and undergraduate students. A bachelor's degree in physics and Ph.D. in Physics or a related field is required. We are especially interested in qualified candidates who can contribute to diversity, equity and inclusion through their teaching, research, and service. More information about the department can be found at **https://physics.du.edu**.

Applications for this position must be submitted through **https://jobs.du.edu** and should include a cover letter, CV, statements of teaching philosophy and research plans, one-page statement of how the applicant can contribute to DU's values, practices, and actions regarding diversity, equity and inclusivity, and names and contact information for at least three references. Applications completed before **January 15, 2022** will be assured full consideration, but the selection process will continue until the position is filled.

The University of Denver is committed to enhancing the diversity of its faculty and staff. We are an Equal Opportunity/Affirmative Action Employer. All qualified applicants will receive consideration for employment regardless of age, race, color, national origin, religion, sex, sexual orientation, gender identity, disability, military/veteran status or any other status protected by law.

All offers of employment are based upon satisfactory completion of a criminal history background check.

https://physics.du.edu

浙江大学 物理学系

Faculty positions available in the Dept of Physics, Zhejiang Univ, P. R. China

The Dept of Physics, Zhejiang University, is expanding its research scope and seeking a number of candidates to fill faculty positions at all professor levels in all subfields of experimental & theoretical physics. Applicants must have a Ph.D. in physics or closely related fields and a distinguished record of scholarship. The successful applicant is expected to develop an innovative research program and participate in teaching at the graduate and undergraduate levels. Zhejiang University offers a generous start-up fund, a competitive salary and an attractive housing benefit with the opportunity to purchase an affordable university apartment.

We invite scholars who seek positions to attend the "Zhejiang University Qizhen Youth Forum—Dept of Physics" during **Dec 18–19, 2021**. This forum will be held online, details will be announced in due course. Interested scholars should apply by sending full CV to the HR Office, Dept of Physics (wangdn@zju.edu.cn, with subject "applicant's full name + Physics Forum 2021") before **November 30th, 2021**. Approved applicants will receive a formal invitation letter from the forum organizers.

http://phy.zju.edu.cn/

BU Arts & Sciences Astronomy

TENURE TRACK ASSISTANT PROFESSOR POSITION

The Department of Astronomy at Boston University (BU) invites applications for a tenure track Assistant Professor position to begin July 1, 2022. The successful candidate will have a PhD and postdoctoral experience in a relevant field, will develop and lead a research program affiliated with the Center for Space Physics, will participate in the department's teaching mission, and may benefit from BU initiatives in computing and data sciences. All areas of Earth, Planetary, and Heliospheric Space Physics will be considered. The Department is committed to inclusion, equity, and diversity in all settings through building a collegial and supportive community. For more information and to submit an application, please visit: **https://academicjobsonline.org/ajo/jobs/19408**.

BU is an equal opportunity employer, and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability status, protected veteran status, or any other characteristic protected by law. BU is committed to building a culturally, racially, and ethnically diverse scholarly community. Applications from women and underrepresented minorities are strongly encouraged.

https://www.bu.edu/astronomy/

TENURE-TRACK ASSISTANT PROFESSOR, PHYSICS EDUCATION RESEARCH

Western Washington University — MAKE WAVES.

Full-time, tenure-track assistant professor, beginning September 2022. Western Washington University (WWU) invites applications from candidates with research specialization on the learning and teaching of physics and/or astronomy. This is a joint appointment in the Department of Physics and Astronomy and the Science, Mathematics and Technology Education (SMATE) program.

The successful applicant will enhance existing strengths in undergraduate education and science teacher preparation and will contribute actively to identifying and responding to new challenges and opportunities in these areas. Teaching assignments (typically five courses per academic year) will be distributed evenly between courses in the Department of Physics and Astronomy and courses in SMATE. An active research program on the teaching and learning of physics and/or astronomy is expected, especially one that engages undergraduate research assistants and supports collaborations within and between SMATE and Physics. Service activities include departmental committees and student advising. The successful applicant will work to close existing gaps in student retention and success and to provide equitable and inclusive learning opportunities for all students.

Applications must include (1) a detailed cover letter describing the ways in which the applicant's background addresses the required and preferred qualifications, (2) a statement of teaching philosophy, (3) a statement outlining proposed research plans, specifically addressing plans for undergraduate involvement, (4) a statement that addresses how your cultural, experiential, and/or academic background has prepared you to support the success of students with backgrounds or identities that are underrepresented in STEM fields as well as your commitment to these issues, and (5) a full curriculum vitae including the names, addresses, e-mail addresses, and telephone numbers of three professional references. Do not send letters of recommendation; they will be requested only for semi-finalists. Review of applications will begin on December 3, 2021, and the position will remain open until filled. All application materials must be uploaded at **http://www.wwu.edu/jobs**.

Inquiries may be addressed to the search committee chair, Dr. Ken Rines, at kenneth.rines@wwu.edu or (360) 650-7944.

Western Washington University is a primarily undergraduate institution in the beautiful Pacific Northwest. The Department of Phyiscs and Astronomy offers a bachelor of science degree and a bachelor of arts degree in math/physics education. More information can be found at http://www.wwu.edu/physics.

https://physics.wwu.edu/

Georgia Tech — Physics — College of Sciences

The Position of Chair and Professor of Physics

The School of Physics at the Georgia Institute of Technology ("Georgia Tech") invites applications for the position of Chair and Professor of Physics. The Chair is expected to develop and pursue an ambitious strategic plan with emphasis on research in core areas and cross-disciplinary directions, innovative and empowering training at all levels, and inclusive governance. Applications from members of groups underrepresented in the sciences are particularly welcome.

For details, please visit: **https://physics.gatech.edu/chair-search** Consideration of applicants will begin in September 2021, and will continue until the position is filled.

Georgia Tech provides equal opportunity to all faculty, staff, students, and all other members of the Georgia Tech community. Georgia Tech complies with all applicable laws and regulations governing equal opportunity in the workplace and in educational activities. Georgia Tech prohibits discrimination, including discriminatory harassment, on the basis of race, ethnicity, ancestry, color, religion, sex (including pregnancy), sexual orientation, gender identity, national origin, age, disability, genetics, or veteran status in its programs, activities, employment, and admissions.

https://physics.gatech.edu/chair-search

National High Magnetic Field Laboratory

Dirac Postdoctoral Fellowship in Theoretical Condensed Matter Physics

The National High Magnetic Field Laboratory offers the ***Dirac Postdoctoral Fellowship***, a two-year postdoctoral fellowship in condensed matter theory. The program is designed for Ph.D.'s with a research interest in any of the condensed matter areas represented by the three sites of the NHMFL. Successful applicants are expected to demonstrate high aptitude for theoretical research as well as to draw on the close connection with the ongoing experimental program.

The expectation is that upon appointment the successful 2022 candidate will be located at the NHMFL in Tallahassee. The appointment includes a competitive salary and benefits, $5000 annually in discretionary funds to cover research and/or travel expenses, and the opportunity to travel to the other two NHMFL sites at Los Alamos and the University of Florida at Gainesville. Minority applicants are encouraged to apply.

Applicants should submit the following: (1) A statement of prior research activities and future research interests that will be pursued at the NHMFL if granted a fellowship. (2) Curriculum vitae including publications. (3) At least three letters of reference in support of the application. (Official undergraduate and graduate transcripts will be required from successful applicants to whom offers are extended).

Application review will begin on Nov. 15, 2021 and continue until the position is filled. The appointment will commence on or about Sep. 1, 2022. All application packets should be submitted, preferably by email in PDF electronic format to: *Mr. Arshad Javed <ajaved@magnet.fsu.edu>, Administrative Specialist, Condensed Matter Sciences, A300 NHMFL FSU, 1800 E. Paul Dirac Dr., Tallahassee, FL 32310-3706.* The Florida State University is an Equal Opportunity, Affirmative Action employer, committed to diversity in hiring, and a Public Records Agency.

https://nationalmaglab.org/

UNIVERSITY OF NOTRE DAME | COLLEGE OF SCIENCE DEPARTMENT OF PHYSICS

Tenure-track Faculty in Experimental Condensed Matter Physics

The Department of Physics at the University of Notre Dame invites applications for a tenure-track faculty position in Experimental Condensed Matter Physics. Applications from tenured/senior researchers will also be considered. The CM group at ND consists of 6 experimental and 4 theoretical faculty, doing research in hard condensed matter, quantum materials, complex networks, and biophysics. The newly established Stavropoulos Center for Complex Quantum Matter, headed by László Forró, the Aurora and Thomas Marquez Chair Professor of Physics, adds additional strength and expertise to the current CM group. The Center's mission is to synthesize materials of interest for novel technologies and to study them with cutting-edge experimental and theoretical methods. We seek faculty members committed to developing and sustaining an environment of inclusive excellence in research, teaching, and service. The successful candidate will be part of the CM group and the Stavropoulos Center as well, and must demonstrate the ability to develop a highly successful research program, attract independent research funding, teach effectively at both the graduate and undergraduate levels, and engage with students from diverse backgrounds. Applicants must have a Ph.D. or equivalent advanced degree. Salary and rank will be commensurate with the successful applicant's experience and research accomplishments. The expected start date is August 2022.

Link to apply: https://apply.interfolio.com/93408

Tenure-Track Faculty in Experimental High Energy Physics

The Department of Physics at the University of Notre Dame invites applications for a tenure-track faculty position in Experimental High Energy Physics. Applications from tenured/senior researchers will also be considered. The HEP group at ND consists of 6 experimental and 5 theoretical faculty, doing experimental research with CMS, DUNE, MINERνA, EMPHATIC, and NA61, along with instrumentation R&D. Our theory group does research on low-energy, collider, and astrophysical tests of the Standard Model and its possible extensions. We seek faculty members committed to developing and sustaining an environment of inclusive excellence in research, teaching, and service. The successful candidate must demonstrate the ability to develop a highly successful research program, attract independent research funding, teach effectively at both the graduate and undergraduate levels, and engage with students from diverse backgrounds. Applicants must have a Ph.D. or equivalent advanced degree. Salary and rank will be commensurate with the successful applicant's experience and research accomplishments. The expected start date is August 2022.

Apply at: https://apply.interfolio.com/93005

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

Applicants should submit a curriculum vitae, list of publications, detailed research plans, and a statement of teaching and mentoring. Candidates must also arrange for at least three letters of recommendation. Review of completed applications will begin on November 1, 2021, with a final deadline of December 31.

The Department of Physics at Notre Dame has 39 tenured and tenure-track faculty; 21 research, teaching and concurrent faculty; more than 100 graduate students; and ~120 undergraduate physics majors. Additional information about the department and the College of Science can be found at http://physics.nd.edu and http://science.nd.edu.

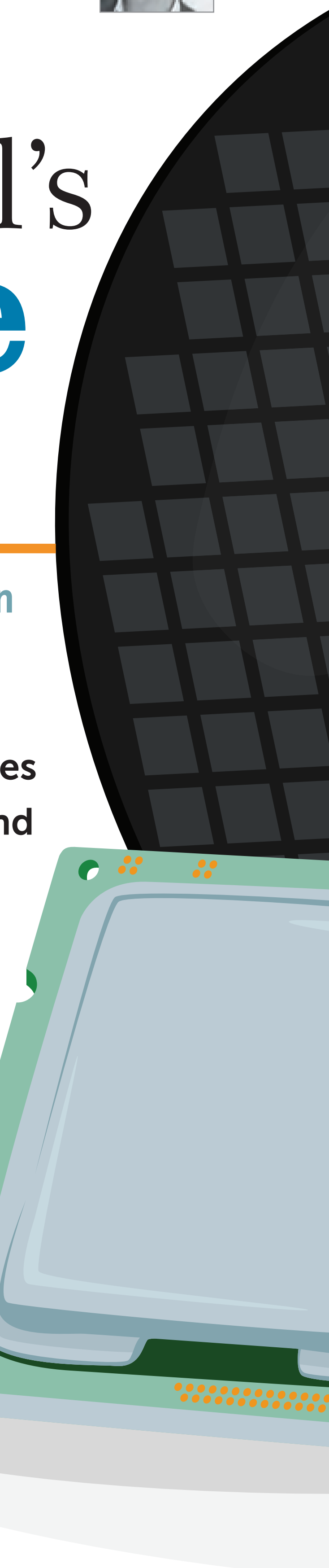
The University of Notre Dame seeks to attract, develop, and retain the highest quality faculty, staff and administration. The University is an Equal Opportunity Employer, and is committed to building a culturally diverse workplace. We strongly encourage applications from female and minority candidates and those candidates attracted to a university with a Catholic identity. Moreover, Notre Dame prohibits discrimination against veterans or disabled qualified individuals, and requires affirmative action by covered contractors to employ and advance veterans and qualified individuals with disabilities in compliance with 41 CFR 60-741.5(a) and 41 CFR 60-300.5(a).

physics.nd.edu

Jorijn van Duijn is a historical consultant in Utrecht, the Netherlands. He received his PhD in innovation studies, business history, and technology history from Maastricht University in 2019. This article is based on his book *Fortunes of High Tech: A History of Innovation at ASM International, 1958–2008* (2019).

ASM International's innovative divisions

Jorijn van Duijn



The company's history under founder Arthur del Prado illustrates the semiconductor industry's trend toward specialization—and the risks of tying a firm to one charismatic individual.

ISTOCK.COM/LEMONO

Increased specialization has been the name of the game in the semiconductor industry since its birth in 1947. The $439 billion business is made up of firms of all stripes.[1] Some design and manufacture chips in-house. Others specialize in manufacturing or design. Still others fabricate parts of chips. Then there are equipment manufacturers, material suppliers, and component subcontractors—and research centers that drive innovation.

The industry's specialization is an example of a bedrock principle of economics: the division of labor, or the separation of work into its component tasks. Perhaps best exemplified by the late-19th-century assembly line, it was first described by Adam Smith in his 1776 treatise *The Wealth of Nations*, which outlined how the division of labor improves workers' skills, saves time, and enables further technological advancement. In the case of the semiconductor industry, it accelerated the development of more advanced chips, which in turn enabled new applications, increased growth, and stimulated further specialization that kept expanding as the semiconductor industry grew.[2]

The history of ASM International, one of the industry's juggernauts, serves as an illustrative lens for understanding specialization. Founded in 1964 by Dutch entrepreneur Arthur del Prado (1931–2016) as Advanced Semiconductor Materials, ASM is a global leader in the production of semiconductor manufacturing equipment. Under Del Prado, who retired in 2008, ASM pioneered manufacturing techniques, such as atomic layer deposition, and successfully brought them to market. The company, which Del Prado registered as private in 1968, casts a large shadow over the industry: Three other major semiconductor companies, ASML, Besi, and ASM Pacific Technology, originally started as divisions of ASM.

Del Prado's beginnings

ASM's history is closely tied to Del Prado, seen in figure 1. As founder, CEO, and majority shareholder, Del Prado was Mr. ASM. All lines of communication led to him. His personal convictions about how to lead and run a business defined ASM's organizational structure and management. Those principles can be traced back to his early days as a salesman hawking silicon in the late 1950s and early 1960s.

Born in what is now Jakarta, Indonesia, Del Prado had a tumultuous early life. During World War II, he was detained in a prison camp on the island of Java when the Japanese occupied what was then the Dutch East Indies. Raised in the Netherlands after the war, he moved to the US in 1954 after graduating from college. He ended up in the San Francisco Bay Area, where in 1957 he bumped into engineer Dean Knapic, who had recently established a new venture called Knapic Electro-Physics (KEP).

FIGURE 1. ARTHUR DEL PRADO holds a silicon wafer in front of ASM International's headquarters in Bilthoven, the Netherlands, in 1996. Del Prado founded ASM in 1964 and was its CEO until 2008. (Photo by Fotopersbureau Dijkstra.)

Knapic had formerly worked with semiconductor innovator William Shockley at Shockley Semiconductor Laboratory. He left that firm as an expert in the Czochralski method, one of the most effective techniques to create monocrystalline silicon.[3] It involves mounting a thin seed of silicon on a rod, dipping it in molten polysilicon, and then withdrawing the rod while slowly rotating it. That process creates a monocrystalline silicon shaft (see figure 2). By exploiting that technique, KEP became the first company to sell silicon crystals commercially. Knapic hired Del Prado, then 26 years old, as KEP's European marketing manager.

That proved to be the turning point in Del Prado's career. When he returned to the Netherlands in 1958, Del Prado spearheaded the development of the European market for silicon crystals. In those days international calls were still extremely expensive, which meant that he was able to communicate with KEP headquarters in Palo Alto, California, via only airmail and telegrams. Because of the geographic separation, Del Prado built trust with the company through his sales. He wrote to businesses across Europe and built a customer base that spanned the continent. Most of his clients were semiconductor manufacturers whose names are long lost in memory. Customer satisfaction was critical to Del Prado, who never gave no for an answer, even if he was unsure if KEP could fulfill the clients' demands. His sales increased from $9000 in 1958 to $249 300 in the first nine months of 1960. By 1963 Del Prado served 40% of the European silicon market.

FIGURE 2. KNAPIC ELECTRO-PHYSICS was one of the first companies to sell silicon crystals. It produced them using the Czochralski method, which required machinery like the crystal puller pictured here. (Courtesy of the Arthur del Prado Collection.)

But KEP did not last long. It faced increasing competition in the silicon crystals market in the early 1960s. Silicon was rapidly becoming the standard material from which semiconductors were made, and more semiconductor manufacturers began producing silicon crystals internally. Another manufacturing technique called float-zone refining also began gaining popularity. That method involved slowly melting a polysilicon rod and allowing it to crystallize into monocrystals. Even though the Czochralski method would again become predominant when the size of silicon wafers increased, at that time float-zone refining was more economical because it enabled manufacturers to control for silicon impurities more easily.

KEP also faced increasing demand for silicon wafers coated with an epitaxial film of silicon. Such a film offered more control over the material's conductive and crystalline properties. But Knapic refused to pursue any of those innovative techniques and insisted that KEP stick to the Czochralski method. As a result, the company's sales declined in the early 1960s. Investors attempted to revive KEP's fortunes by sidelining Knapic and installing new management, but that proved fruitless. KEP closed in early 1964.

Del Prado was now a free agent, and he quickly founded a new company called Advanced Semiconductor Materials—now ASM International. He drew two major conclusions from KEP's demise. First was that a founder could lose control of their company if it had external investors. Having been responsible for his own success so far, Del Prado was determined to secure maximum elbow room for himself. He would not face Knapic's fate. The second was that it was crucial for a business like KEP to diversify its operations. The rise of float-zone-grown silicon had quickly undermined Knapic's business. An expanded product portfolio formed a hedge against such surprises. Moreover, in good times, diversification allowed a company to leverage a successful business to develop a new one.

Following that strategy drove ASM's growth. The business began as a sales agent for a range of semiconductor technologies. It grew rapidly, to the point that Del Prado could no longer oversee everything by himself. He hired extra hands and began expanding in Europe, Asia, and the US. Because he had been successful working independently at KEP, he granted his managers significant autonomy.

Del Prado's business decisions at ASM were reinforced by the management and business principles of the day. He was a voracious reader of trade magazines like *Harvard Business Review*, *Businessweek*, and *Electronics Weekly*, and they helped shape his ideas. In those days, prominent management scholars, such as Peter Drucker and Igor Ansoff, advocated pursuing long-term strategies, diversifying a company's business, and decentralizing its organization into smaller units that would empower employees.[4] Although Del Prado's business philosophy was based primarily on his own experience, his entrepreneurial instincts were in line with the academic zeitgeist.

Building a diversified company

Two structural drivers fostered ASM's growth after its founding as a one-man sales agency for silicon. The first was people: Young, inventive, and ambitious engineers brought along promising ideas and skills. They were the innovators around which new ASM ventures and businesses could be set up. The second was leveraged innovation, in which earnings from one profitable enterprise were used to cultivate a new one. The new business might supplant the old one, but if both flourished, their combined profits could be used to build yet another new division. Two individuals illustrate how those drivers helped ASM grow into a diversified enterprise.

The first was engineer Martin van Beest, hired as ASM's first employee in 1965 (see figure 3). His resourcefulness and curiosity helped the company transform from a semiconductor middleman into an equipment manufacturer. Van Beest was hired at age 23 to install and service ASM's technologies across Europe. His skills and knowledge grew in tandem with ASM's rapidly diversifying product portfolio, which soon came to include gas dryers, diffusion furnaces, and wire bonders. In 1969 he began to install and service chemical vapor deposition reactors sold by Silicon Valley start-up Applied Materials. In those devices, vapors react and successively decompose onto a silicon wafer.

In the early 1970s, after a market downturn caused Applied Materials to withdraw from a planned joint venture with ASM to assemble such reactors in Europe, Del Prado decided to produce them internally. Van Beest was put in charge of that operation. He ordered the necessary components from companies across Europe and assembled the deposition reactor in fall 1971 in the attic of ASM's headquarters in Bilthoven. Dubbed the SOX 10-2 because it could process 10 wafers, each with a 2-inch diameter, the reactor was ASM's entry into the field of semiconductor equipment manufacturing.

Plasma-enhanced furnaces

In the 1970s Del Prado began to leverage the international appeal of Dutch technology and established ASM subsidiaries abroad. In 1975 ASM Asia was established in Hong Kong, and a year later ASM America was set up in Phoenix, Arizona. Those branches had to cultivate business autonomously from their Dutch parent. ASM America quickly hired several engineers who had formerly worked at Motorola, the largest US semiconductor company of the day. By 1978 ASM America succeeded in making limited inroads into the US market for horizontal chemical vapor deposition furnaces, which attracted the attention of the ambitious and hands-on engineer George Engle.

In the early 1970s, Engle was working for Applied Materials when he began using his spare time to tinker with chemical vapor deposition furnaces in his garage. At that time, researchers were increasingly interested in a new silicon nitride deposition process called plasma-enhanced chemical vapor deposition, which allowed the passivation of the latest chips at low temperatures. Yet such methods often produced impurities in the silicon or were uneconomical. Engle's new type of horizontal deposition furnace proved to be just the solution. Instead of laying the silicon wafers flat in a heated tube, as was done in previous deposition furnaces, Engle stood them upright and placed them against graphite plates positioned longitudinally in the tube. He then ignited a plasma between the plates. His technique allowed the deposition of silicon nitride for passivation films to be carried out in large quantities.

FIGURE 3. MARTIN VAN BEEST (left) talks with colleagues in the 1970s. (Courtesy of ASM International.)

Convinced of his machine's success, Engle peddled his ideas to his employer, but it turned him down. A rival firm, Pacific Western Systems, helped Engle build a few furnaces, but he was quickly dissatisfied by the company's failure to market them aggressively. He soon took his patented idea to a more ambitious and audacious party: ASM America. Engle's furnace was introduced by the subsidiary in 1979 as the Plasma I (see figure 4), and it proved to be a hit in the US, Japan, and Europe. Sales boomed as doors opened to prestigious customers like IBM. The horizontal plasma furnaces' success paved the road to Wall Street: In 1981 ASM International—as the combined operations in the Netherlands, the US, and Hong Kong were now called—made its initial public offering on Nasdaq. ASM was now a worldwide name.

In accordance with Del Prado's management strategy, the funds from both the initial public offering and a subsequent flotation of shares in 1983 were leveraged to expand the company further. Time and again, ASM reinvested the capital it accrued from investments or profits into skilled and dedicated groups of engineers, who produced new innovations that fueled the company's growth. In 1982 ASM Japan was established with a workforce of ambitious service engineers who knew the country's market intimately. ASM Lithography (ASML), a joint venture with Philips, followed in 1984. That subsidiary was staffed with former Philips employees and complemented with an influx of intrepid and enthusiastic young engineers.[5]

A year later a group of experienced engineers in ion-implant technology convinced Del Prado to fill a gap in that market, which led to the founding of ASM Ion Implant in Beverly, Massachusetts. More new divisions and subsidiaries followed. By the end of 1985, ASM had revenues of 351 million Dutch guilders (approximately $321 million in today's dollars), a huge sum at the time. With 1870 employees across 13 divisions worldwide, the company was an international powerhouse in semiconductor equipment technologies.

Del Prado structured his company and its subsidiaries in decentralized divisions that operated autonomously. ASM was not one monolithic company; it was ASM Japan, ASM America, ASM Europe, ASM Fico, ASM Assembly Automation, ASML, ASM Microelectronics Technology Center, and more—all managed by a small, agile parent company called ASM International, of which Del Prado was the majority shareholder. Each new branch or subsidiary added to the plethora of ASMs.

Imperial overreach

Yet ASM's expansion could not be sustained indefinitely. In the latter half of the 1980s, the company began to flounder. Following an industry downturn in 1984 and 1985, the dynamics of the international semiconductor market changed. As manufacturers began to specialize in specific market segments, such as

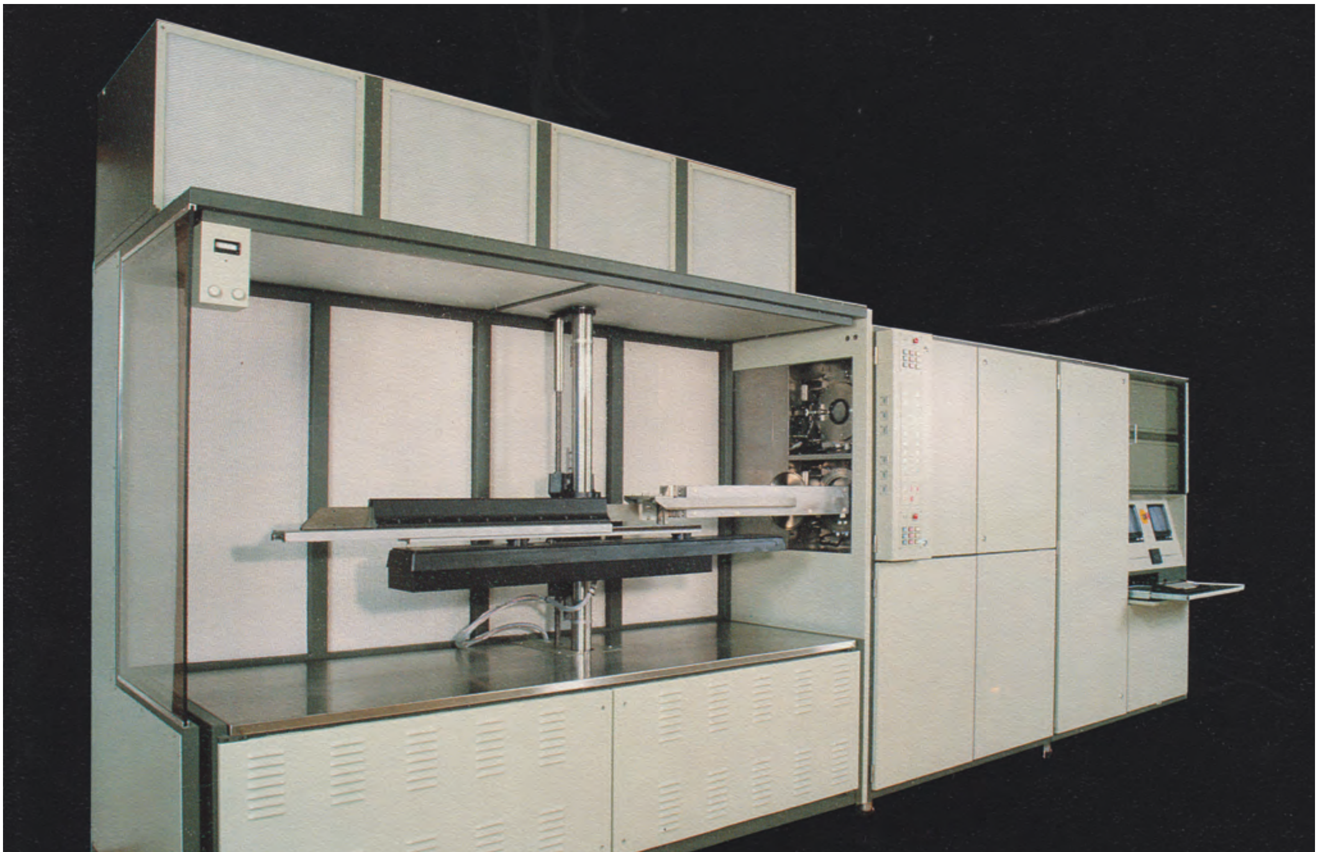


FIGURE 4. ASM AMERICA INTRODUCED the Plasma I reactor, designed by George Engle, in 1979. Shown here are the horizontal plasma furnace (right) and its loading station (left). (Courtesy of ASM International.)

microprocessors or memory, their needs diverged. Before, they had all sought the same technology—horizontal deposition furnaces—but now manufacturers wanted equipment tailored to the specific semiconductors they built.

Demand for types of semiconductor equipment was correlated with regional market tendencies. Memory producers in Japan, for example, requested vertical batch furnaces, which would maximize productivity in increasingly expensive clean rooms with limited floor space. Microprocessor and application-specific chip producers in the US, on the other hand, demanded single-wafer reactors that processed only one silicon wafer at a time but allowed for the higher process qualities needed to produce such chips.

Because of that market divergence, ASM's organizational structure became increasingly obsolete. The multiplier effect resulting from selling horizontal deposition furnaces to manufacturers worldwide was gone. ASM's various business units had to reinvent themselves while maintaining revenue. In doing so, they often found themselves interfering and competing with the business of other ASM divisions. Costs increased dramatically, which meant that less revenue remained to sustain leveraged innovation in lithography, in ion implantation, and at the company's new research center.

ASM's capability to organize promising engineers and technology proved to be too closely tied to a single person. Del Prado's personality was a hindrance to the company's ability to address changing market dynamics. He was unable or unwilling to impose a cohesive direction on ASM and rein in the company's headstrong divisions. Moreover, he refused to relinquish complete control over the enterprise, which hampered its finances. To gain an influx of capital, Del Prado used conventional short-term loans to fund ASM rather than selling some of his shares, which would have dropped his stake in the firm below 50%. That decision could have worked only if all of ASM's money-draining ventures quickly transformed into moneymakers—but they did not.

By 1988 the bleeding at ASM had to stop. The company began selling off some of its developmental ventures to improve its finances. It divested its share of ASML that summer and sold ASM Ion Implant to Varian Associates around the same time. In December the Hong Kong division was floated as an independent subsidiary on the Hong Kong Stock Exchange under the name ASM Pacific Technology, with ASM initially retaining a 75% stake in the venture.

Even that was not enough. As horizontal deposition furnaces became increasingly obsolete and ASM failed to develop profitable successors, the company's finances continued to deteriorate. Between 1991 and 1993, practically all its remaining assets were up for sale. The research center was closed. ASM Fico, the European division that produced semiconductor encapsulation equipment, was eventually sold to Berliner Elektro Holding in fall 1993 and renamed BE Semiconductor Industries. Now known as Besi, the venture is one of ASM Pacific Technology's main competitors.

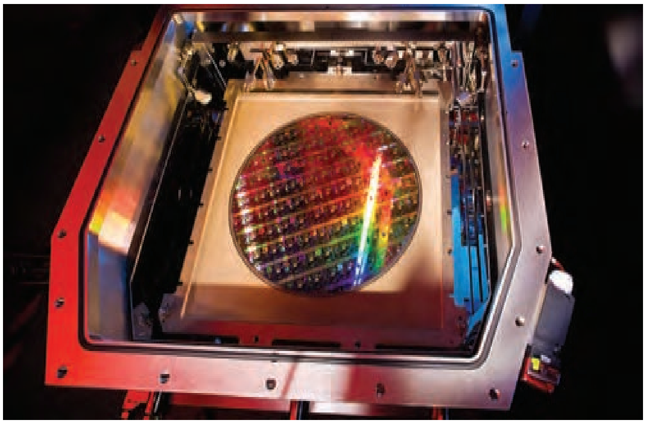


FIGURE 5. ASM INTERNATIONAL'S RESURGENCE in the late 2000s was fueled by its investments in atomic layer deposition technology. This image depicts a wafer in part of a reactor that uses the technology to fabricate semiconductors. (Courtesy of ASM International.)

ASM's fragmented structure proved to be a blessing in disguise for its divested divisions. They had already operated with considerable independence, and now that they no longer needed to share funds with unprofitable divisions, the ventures prospered and grew. ASML is now the world's leading supplier of lithographic equipment, and Besi and ASM Pacific Technology are market leaders in semiconductor assembly and packaging technologies. Del Prado's ASM children continue to dominate the industry.

The tumultuous 1990s

Even though Del Prado's leadership was partially responsible for the company's failings in the late 1980s and early 1990s, he remained ASM's founder, CEO, and majority shareholder. But he was forced to make changes. An interim manager, Ray Friant, was installed as chief operating officer to help with decision making. To turn around the company's fortunes, Friant argued in a report that Del Prado, whom he acknowledged was a "visionary," needed to be complemented by "practical business personnel who are focused on making money each month."[6]

Although some argued that Friant needed to streamline and centralize ASM's operations, he chose to keep the fragmented structure that the company had developed under Del Prado. Instead, under his and Del Prado's keen eyes, ASM retained its stake in the increasingly profitable ASM Pacific Technology while simultaneously focusing its business around three novel deposition technologies. Each of those methods were championed by one of ASM's divisions: ASM Europe developed a novel vertical low-pressure deposition and diffusion furnace, ASM America offered customers a single-wafer epitaxial reactor, and ASM Japan marketed a single-wafer plasma deposition tool.

That allowed ASM's fragmented structure to again work in the company's favor, because it meant that each division could focus on a different product and therefore a separate market. Friant's business acumen saved the company—and it was just in time, for by 1997 ASM needed to settle an escalating legal dispute with Applied Materials over epitaxial technology for the daunting sum of $80 million.

But a leopard can't change its spots. With the lawsuit settled, Del Prado returned to his old playbook during the late 1990s dot-com bubble. Once again, he began to expand ASM into new markets. Now it was in the equipment segment for deposition technologies. In 1999 ASM acquired the Finnish company Microchemistry, which had developed promising atomic layer deposition technologies, processes, and tools. Such methods enable the layer-by-layer formation of thin films with nearly perfect conformality and step coverage across complex nanoscale geometries. Microchemistry's engineers and scientists lacked practical experience in semiconductor manufacturing, but they were intimately familiar with the chemical processes it involved. Teaming up with in-house experts at ASM, they began a decade-long endeavor to commercialize atomic layer deposition.

History repeated itself at ASM. Although efforts were made to centralize semiconductor manufacturing, the company remained highly fragmented. Divisions like ASM Europe, ASM America, and ASM Japan—each with their respective technology—were largely left to themselves. All three enjoyed market success in the late 1990s and early 2000s, but their profits were eaten up by the company's investments in newly acquired divisions like Microchemistry.

This time around hedge fund managers took aim at Del Prado's strategy. Several of them had bought stakes in ASM, and from 2005 to 2013 those activist investors pushed for the company to sell off its remaining stake in ASM Pacific Technology. They even advocated for ASM itself to be put on the block. That period of shareholder activism coincided with Del Prado's retirement at age 77 in 2008, after which his presence in the organization steadily decreased. He was succeeded by his eldest son, Chuck del Prado, whose appointment only added fuel to the hedge fund managers' fire.

Like his father, Chuck was determined to keep the company intact. Fortunately for ASM, its acquisition of Microchemistry had begun to bear fruit in 2007, when it successfully introduced atomic layer deposition technology into high-volume chip manufacturing (see figure 5). The Finnish process pioneered at Microchemistry proved to be critical in the deposition of exotic materials, such as hafnium oxide, onto increasingly complex transistor geometries. Along with the company's well-established business groups in vertical furnaces, epitaxy, and plasma deposition, the new market in atomic layer deposition helped ASM enjoy success in the 2010s. Although Arthur del Prado's death in 2016 marked the end of an era at ASM, the company he founded remains an industry giant today.

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6. Ref. 5, J. van Duijn, p. 534.

PT

The Department of Physics at the University of Wisconsin–Madison invites applications for two tenure-track faculty positions. For both positions, successful candidates will perform teaching at all levels, supervise graduate thesis work, conduct high-impact scholarly research, and provide professional and university service.

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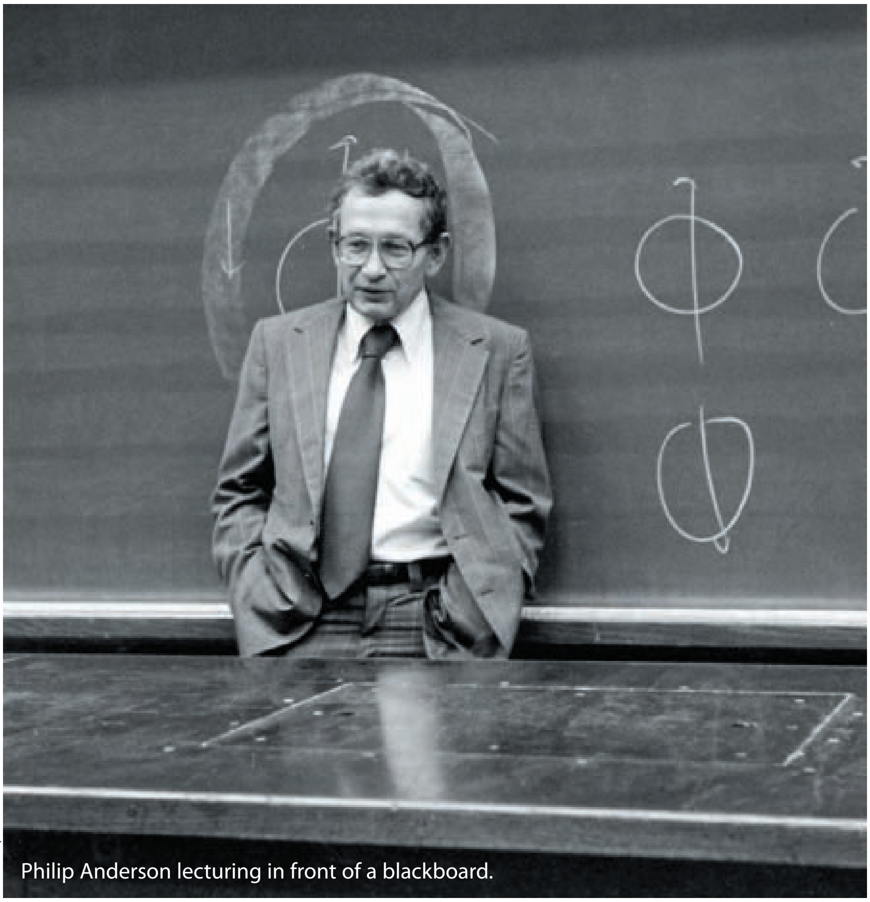

AIP ESVA, SEGRÈ COLLECTION

Philip Anderson lecturing in front of a blackboard.

Condensed-matter titan

What do theoretical physicists actually do? George Gamow once joked that theorizing was outwardly indistinguishable from napping. As the physicist and historian David Kaiser noted in his 2005 article "Physics and Feynman's diagrams," Gamow's joke implies that historians of theoretical physics face a difficult challenge. How do you describe what's happening while a theorist stares at a screen or out the window (or at the backs of their eyelids!) for hours at a time? Gamow was fond of hyperbole, of course, and many elements of theorists' practice are in fact amenable to description, but the joke does point at a real conundrum.

At least with respect to the practice of one influential theorist, the Nobel laureate and primus inter pares of condensed-matter theory, Philip Anderson, Andrew Zangwill attempts to answer Kaiser's question. Zangwill is both a theorist and historian of condensed-matter physics, so his lucid descriptions of Anderson's enormous contributions in *A Mind Over Matter: Philip Anderson and the Physics of the Very Many* are backed by a deep understanding of both the ideas and the community in which those ideas found a home. But he isn't satisfied with just explaining the ideas—he wants to show readers how Anderson arrived at those ideas and give them a sense of his practice and personal style as a theorist.

A Mind Over Matter
Philip Anderson and the Physics of the Very Many
Andrew Zangwill
Oxford U. Press, 2021. $32.95

Zangwill largely succeeds in that aim, although he acknowledges that some aspects of Anderson's creative process—and it was very much a creative process—will always remain a mystery. In fact, they were a mystery to Anderson himself. *A Mind Over Matter* demonstrates that Anderson, more than many of his peers and competitors, enjoyed hanging out with experimentalists and perusing experimental data; that he generally sought out problems where he could make a first, dazzling contribution and then move on to other topics; that he preferred to leave the number crunching to others and intensely disliked theories and theorists that relied on digital methods; and that his best ideas (and the ones he valued most in others) could be exported to other physical fields and scientific disciplines.

Somewhat more speculatively, Zangwill argues that Anderson needed conflict to refine his physical understanding. That characteristic helps to explain both his combative relationship with other theorists and the failure of his late-career theory of high-temperature superconductors: By that point, Anderson was no longer surrounded by people willing to push back against him.

As the high-T_c story indicates, *A Mind Over Matter* is no hagiography. Zangwill treats Anderson with some reverence but isn't afraid to confront his prickly, stubborn, and sometimes egocentric tendencies. Anderson comes across as a complicated, human, but nevertheless admirable character: He could be aggressive, dismissive, and petty toward those he viewed as competitors, but he was also supportive of the underdog both in his private relationships and his public politics. Zangwill also shows that Anderson's contrariness often led him to some of his best decisions, such as opposing McCarthyism, choosing condensed matter as his specialty, and taking a job at Bell Labs instead of at a university.

Because of Anderson's influence and wide network of collaborators and antagonists—who were sometimes one and the same—*A Mind Over Matter* is a biography of both his life and times. Along the way we meet the likes of Brian Josephson, Nevill Mott, William Shockley, Edward Teller, Murray Gell-Mann, and more. We also get an excellent peek at the rituals of postwar physics through the lens of Anderson's critiques of the field. For instance, Zangwill offers some fine examples of Anderson's prickliness as a peer reviewer and his short-lived attempt in the mid 1960s to run an alternative journal sans peer review. Although that experiment was not a representative portrait of midcentury journal practices, it nevertheless says a lot about the function and dysfunction of physics journals.

Given that I am a historian of industrial physics, my one disappointment with *A Mind Over Matter* is that the reader doesn't get much of a sense of Bell Labs, the organization where Anderson worked for some 35 years. At that time, Bell Labs was the leading institution in condensed-matter physics and a host of other fields. But Zangwill doesn't really show us what Anderson did as a manager in that organization. Maybe that's because "What do middle managers do?" is an even harder question to answer than "What do theorists do?"

But Bell Labs' curious marginalization in Zangwill's account is a relatively minor blemish on an engaging and insightful biography. For anyone interested in Anderson's contributions, his personal philosophy and style of physics, the fights he picked (for better and worse), and the scientific times in which he lived, *A Mind Over Matter* is an enlightening read.

Cyrus C. M. Mody
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US ARMY PHOTO 163-12-62/HISTORIC COMPUTER IMAGES/WIKIMEDIA COMMONS/PUBLIC DOMAIN

Female computing employees at the Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, in 1962 holding components from four of the earliest electronic computers. From left, Patsy Simmers holds an ENIAC board; Gail Taylor, an EDVAC board; Milly Beck, an ORDVAC board; and Norma Stec, a BRLESC-I board.

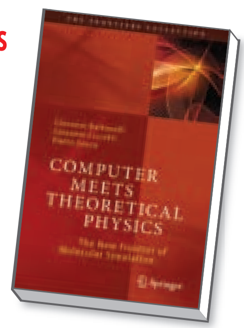
The first 30 years of computer simulation

Today we take it for granted that we can use computers to, for example, discover new materials, develop pharmaceuticals, and predict the weather. But when the first electronic computers became available in the wake of World War II, it required great vision to realize their scientific potential. At that time, several young physicists working at the US national laboratories in Livermore, California, and Los Alamos, New Mexico, set out to use the new computers to solve a long-standing problem: How do the properties of matter arise from the interactions of atoms and molecules?

Investigating systems of elastically colliding hard spheres, the pioneering researchers used the new computers to simulate hundreds of particles, a feat that had been impossible with previous numerical methods. The success of their work demonstrated that computers could be used to predict and understand the macroscopic behavior of condensed-matter systems on a microscopic level.

Computer Meets Theoretical Physics
The New Frontier of Molecular Simulation

Giovanni Battimelli, Giovanni Ciccotti, and Pietro Greco, trans. Giuliana Giobbi
Springer, 2020. $49.99



That achievement can be viewed as the birth of molecular simulation, and it is the starting point of the beautiful book *Computer Meets Theoretical Physics: The New Frontier of Molecular Simulation*. Authored by Giovanni Battimelli, Giovanni Ciccotti, and Pietro Greco, it recounts the early history of computer simulation—

from the first days in the 1950s to the field's coming of age in the 1980s. The authors focus mainly on the development of molecular dynamics, in which the motions of many atoms are simultaneously advanced and tracked in small time steps. They explain the scientific evolution of the field; provide biographies—and numerous photographs—of leading characters such as Berni Alder, Marshall Rosenbluth, and Aneesur Rahman; and offer an epistemological assessment of the simulation approach, which changed the way science is practiced and now pervades all fields of science and technology.

As the authors show, early work on hard spheres was soon followed by efforts to simulate more realistic systems. Scientists in Europe took notice of the exciting developments in the US, and centers of activity in computer simulation arose almost simultaneously in France, the UK, Germany, and Austria. Those early activities led to a succession of conceptual advances and efficient algorithms that eventually enabled a deeper understanding of many condensed-matter systems and processes, including phase transitions, liquid crystals, biopolymers, superfluid helium, and critical phenomena.

One particularly interesting aspect of the book is how it illuminates the human element of the scientific enterprise. Chance encounters between people with different backgrounds often sparked new ideas, which led to unexpected research directions (and sometimes lifelong friendships). Battimelli, Ciccotti, and Greco gathered recollections from many of the scientists who contributed to the development of computer simulation, and their personal memories illustrate how the field's early proponents struggled to gain recognition from traditionally minded scientists who initially looked down on the new method. The successes of the simulation approach, however, eventually paved the way for it to be widely accepted as a powerful research tool.

Although computer simulation was at first driven largely by a few visionary individuals, the field gradually matured. Journals and meetings dedicated to computer simulation were created and provided an institutional basis for the discipline. The authors show that the European Center for Atomic and Molecular Computation, or CECAM, which was founded in 1969 in Paris, was particularly important in that process. Practically all simulation scientists active since the 1970s made repeated trips to CECAM to use its computing facilities or to take part in its extended workshops. Many of the ideas conceived and discussed at CECAM were crucial to the development of computer simulation and continue to influence the field today.

Although the first 30 years of molecular simulation were characterized by the creation of fundamental techniques, those methods have since been efficiently implemented on supercomputers across the globe and are now used in numerous disciplines, including materials science, geophysics, chemistry, molecular biology, and medicine. Currently, ideas from machine learning and artificial intelligence are stimulating new developments in molecular simulation. It will be interesting to see where that trend leads in the years to come.

Computer Meets Theoretical Physics should be on the bookshelf of anyone interested in the history of science. I hope that future books will pick up where it leaves off and document the next chapters of computer simulation's exciting story.

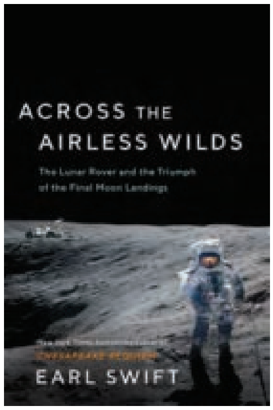
Christoph Dellago
University of Vienna
Vienna, Austria

NEW BOOKS & MEDIA

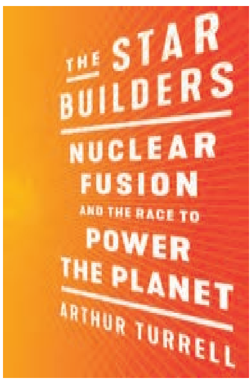
Across the Airless Wilds

The Lunar Rover and the Triumph of the Final Moon Landings

Earl Swift
Custom House, 2021. $28.99



The lunar rover is one of "a few Holy Grail items of Apollo history," writes journalist Earl Swift in his new book *Across the Airless Wilds*. A remarkable feat of engineering, the rover allowed humans to cover as much ground as possible on the Moon and to reach "the edge of the edge of man's travels as a species." *Across the Airless Wilds* serves as a paean to NASA's "spacecraft on wheels," providing a detailed history of its genesis, construction, and use. By focusing on some of the memorable people involved and visiting sites such as the US Space & Rocket Center in Huntsville, Alabama, and astronaut training grounds near Flagstaff, Arizona, Swift brings the story of the rover to life. —CC



The Star Builders

Nuclear Fusion and the Race to Power the Planet

Arthur Turrell
Scribner, 2021. $28.00

As the joke goes, commercially viable nuclear fusion reactors are always 30 (or 50) years away. Despite the ridicule, the dream of a feasible source of fusion power remains alluring because such reactors promise a near-limitless supply of carbon-free energy. In his new book *The Star Builders*, plasma physicist and science writer Arthur Turrell argues that fusion research is necessary to address the climate crisis because renewable energy won't be able to provide enough power for the entire world. Turrell profiles fusion physicists—whom he poetically calls "star builders"—in academia, in industry, and at research centers like ITER, the international prototype fusion energy reactor under construction in France. In his view, net energy gain from fusion will be achieved soon, and the bigger problem will be quickly deploying fusion power worldwide. —RD

Fathom

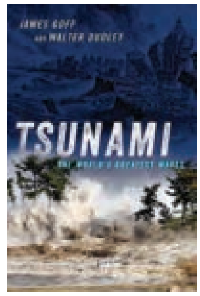
Drew Xanthopoulos
Apple TV+, 2021

Fathom started off as an investigation into science and evolved into a film about women in science, according to director Drew Xanthopoulos. The two main subjects, Michelle Fournet and Ellen Garland, are whale researchers, and the documentary follows them in the field. Fournet's research is based in Alaska, where she records humpback-whale songs and tests to see if responses back can cause a reaction. Garland, on the other hand, is based on a research ship in the waters off French Polynesia, where she looks for insights into how new whale melodies propagate across the globe. Featuring beautiful camerawork and superb visuals that convert acoustics into memorable images, *Fathom* is a great introduction to bioacoustics. It captures the trials, tribulations, and occasional loneliness of field research remarkably well. —PKG

Tsunami

The World's Greatest Waves

James Goff and Walter Dudley
Oxford U. Press, 2021. $34.95



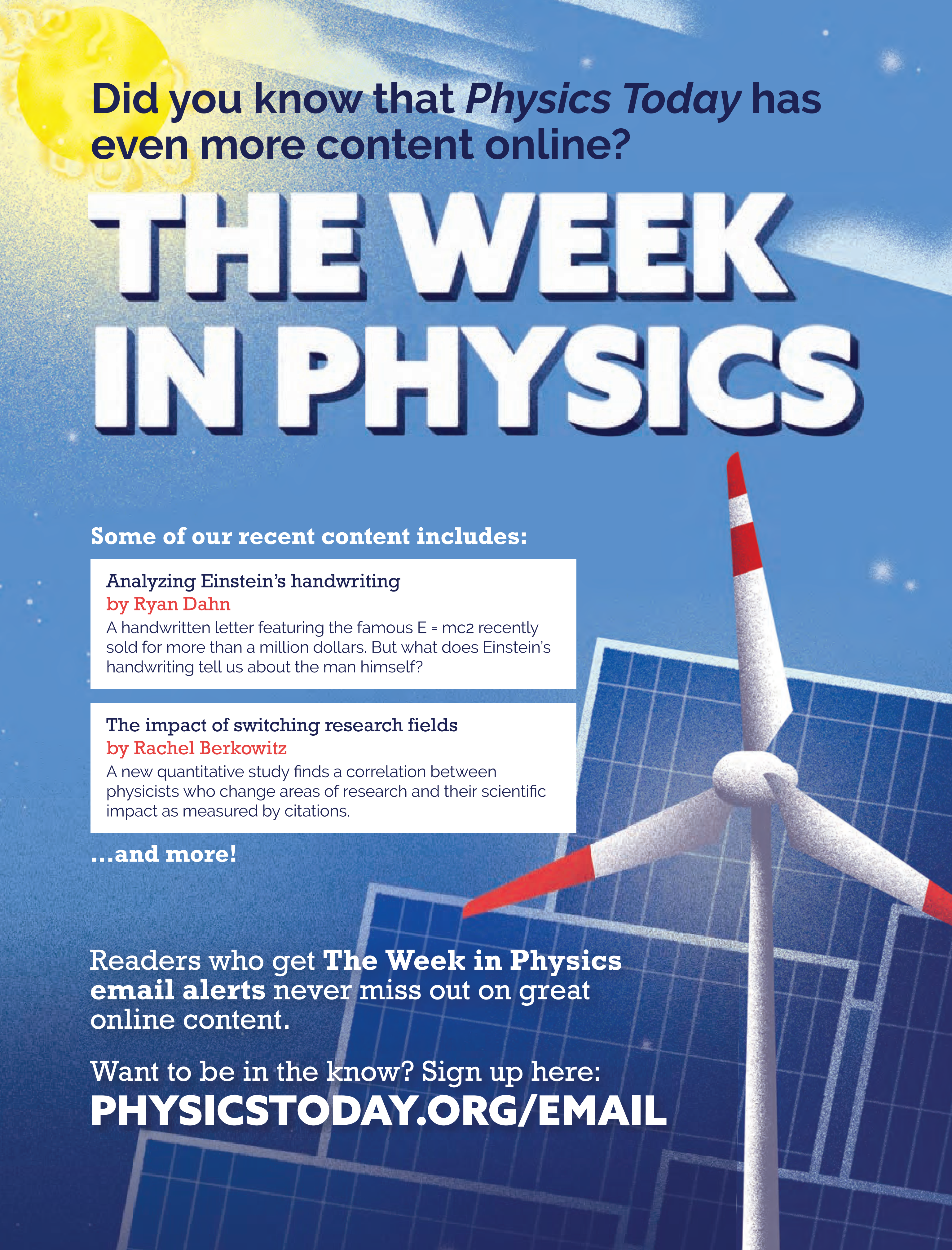
Authored by tsunami researchers James Goff and Walter Dudley, this new book focuses on the science and history of those destructive waves. It is a call to arms: Although hurricanes and famines may get more attention, the book points out that tsunamis have been some of the most destructive natural disasters in history. Few are likely aware, for example, that the deadliest disaster of the 21st century was probably the 2004 Indian Ocean tsunami, which killed an estimated 227 898 people. At that time, there was no early-warning system for tsunamis in the Indian Ocean, which meant that millions of people were taken by surprise when the wave hit. Blending science with interviews of survivors, *Tsunami* warns us to be prepared for future tidal waves. —RD

Through the Glass Ceiling to the Stars

The Story of the First American Woman to Command a Space Mission

Eileen M. Collins, with Jonathan H. Ward
Arcade, 2021. $27.99

Not only was Eileen Collins the first woman to command an American space mission, she was also one of the US Air Force's first female pilots and the first woman to pilot a space shuttle. An unremarkable student in high school who was raised by a single mother, Collins became fascinated with aviation at an early age. She was accepted into the air force's ROTC program and then NASA's astronaut program, flying a total of four space shuttle missions—two as pilot and two as commander—from 1995 to 2005. With coauthor Jonathan Ward, a writer and space history enthusiast, Collins recounts her inspiring story as a woman in a traditionally male field and as an aviation pioneer during NASA's space shuttle era. —CC PT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Focus on cryogenics, vacuum, materials, and semiconductors

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Andreas Mandelis

Large two-stage pulse tube cryocooler

Cryomech has announced the PT425 pulse tube cryocooler, an improved, more powerful version of its PT420. According to the company, the PT425 is the largest two-stage pulse tube cryocooler available. The PT425 offers a dual performance of 2.5 W at 4.2 K and 55 W at 45 K on an integrated motor platform. It operates with the same user interface and within the same physical footprint as the PT420 model but allows users to achieve more refrigeration (cooling power) at 4.2 K; the PT420 provides 2 W at that temperature. Featuring a base temperature of 2.8 K and a cooldown time of 60 min to 4.2 K, the PT425 operates in an ambient temperature range of 7 °C to 38 °C. ***Cryomech Inc****, 6682 Moore Rd, Syracuse, NY 13211, www.cryomech.com*

Helium liquefiers

Quantum Design has added new features to its NexGen helium liquefiers and enhanced their mobility and performance. In addition to the standard 160 L model, the apparatus is now available in a 250 L dewar for users who prefer larger transfers. The NexGen's high liquefaction rates are now attained at 1 psig, so helium is always ready to transfer. A newly designed purifier offers the same high performance in a smaller size, and optional variable-speed compressors provide energy efficiency and longer cold-head life. New simplified software with an intuitive user interface makes operation more straightforward. ***Quantum Design****, 10307 Pacific Center Ct, San Diego, CA 92121, www.qdusa.com*

Compact vacuum transducer with USB connection

Thyracont now offers a compact vacuum transducer, the VSRUSB, with a piezo or Pirani sensor and a USB-C connection. The communication interface increases the transducer's flexibility and enables fast, easy interconnection to other portable devices. Sensors can operate while the vacuum process is running. Common computers and Android smartphones can display the measured vacuum quickly and precisely during process monitoring; no separate power supply is required. The company's intuitive VacuGraph software, which is available for various operating systems, allows users to easily monitor the VSRUSB and perform such functions as digitally readjusting the device to atmospheric or zero pressure. To support the visualization of measurements on smartphones and tablets, the software is supplemented by the VacuSniff Android app. ***Thyracont Vacuum Instruments GmbH****, Max-Emanuel-Str 10, 94036 Passau, Germany, https://thyracont-vacuum.com*

Low-vibration turbopump

According to Pfeiffer Vacuum, the advanced Laser Balancing system in the new HiPace 80 Neo reduces vibration and noise emissions from turbopump rotors and extends the turbopump's life before service. To ensure reliability, the turbopump has integrated sensors and a robust hybrid bearing design that combines an oil-lubricated ceramic ball bearing on the fore-vacuum side and permanently magnetic radial bearings on the high-vacuum side. A new high-performance lubricant protects the turbopump from excessive heat and extends its expected life span. A rotor temperature measurement system ensures optimal performance. The smart system features micro-USB interfaces with automatic accessory recognition. The light, compact HiPace 80 Neo can be integrated into portable and mobile systems. Applications for the vacuum pump range from mass spectrometry and electron microscopy to residual gas analyzer systems and leak detectors. ***Pfeiffer Vacuum Inc****, 24 Trafalgar Sq, Nashua, NH 03063, www.pfeiffer-vacuum.com*

Silicone adhesive with high strength

MasterSil 153AO from Master Bond is an addition-cured two-part silicone adhesive with an unusually high tensile lap-shear strength of 700–800 psi. Though not considered a structural adhesive, MasterSil 153AO delivers a combination of flexibility and strength that other silicone adhesives do not provide, according to the company. The system is thermally conductive and electrically insulating and functions over the temperature range of −65 °F to 400 °F. MasterSil 153AO cures with the addition of moderate heat. After its components are mixed, it retains its smooth paste consistency and minimal flow and has a long working life of 4–6 h for a 100 g mass at 75 °F. The white-colored compound bonds well to various substrates, including metals, glass, ceramics, many plastics, and silicone rubbers. MasterSil 153AO is generically low outgassing, contains no solvents, and is compliant with the Restriction of Hazardous Substances directive. ***Master Bond Inc****, 154 Hobart St, Hackensack, NJ 07601-3922, www.masterbond.com*

Sensitive Pirani gauges

The Thermovac TTR-RN series of robust, compact filament Pirani gauges from Leybold can reliably measure and control the vacuum level to ensure high efficiency in analytical applications and industrial processes. At the series' core is Leybold's new filament technology, which increases the sensitivity and thus the accuracy of measurements. The gauges are suitable for vacuum applications that require a measurement range from atmosphere to 1×10^{-4} mbar (7.5×10^{-5} torr). For standard processes, the Thermovac TTR-RN series has a tungsten filament; a corrosion-resistant platinum variant is available for harsher process applications. To further increase reliability, a filter is integrated into the flange to block particles that would otherwise damage the filament. The new filament technology is coupled with high-end electronics and interfaces, including a bright light ring that immediately indicates the pressure range locally. ***Leybold GmbH****, Bonner Str 498, 50968 Cologne, Germany, www.leybold.com*

Streamlined cryogenic platform

Montana Instruments has released its CryoCore cryogenic platform for high-throughput electrical and optical materials characterization. The streamlined version of Montana's standard technology is geared toward users performing quantum materials research who want to work at low temperatures but are not experts in cryogenics or cannot afford complex cryogenic systems. The cost-effective CryoCore platform provides cryogen-free operation, vibration-optimized tabletop mounting, and direct sample and optical access. It includes a touchscreen user interface and the control electronics, vacuum pumps, and monitoring systems required to automate the temperature control across the entire 4.9–350 K range. To accommodate multiple optical and electrical measurements, it provides five window ports, 12 low-frequency DC lines, and two high-frequency RF coax lines. The CryoCore is suitable for use in early-stage materials development, quantum device testing, and training in undergraduate teaching laboratories. ***Montana Instruments Corporation****, 101 Evergreen Dr, Bozeman, MT 59715, www.montanainstruments.com*

Spreading resistance profiler

Semilab's latest spreading resistance profiling system, SRP-2100i, features the standard SRP technique, which can be combined with the optional point-contact current–voltage (PCIV) method. SRP-2100i characterizes layer structures and junction locations and monitors a wide depth-profile range of resistivities and defects at or below the surface of various compound semiconductors. Specifically for silicon structures, the well-established dual-probe method determines resistivity and electrically active carrier-density profiles. Thin layers can be measured with the company's Shallow Layer Measurement option. The system can be used to conduct failure analysis of fabrication processes and doping operations, including epitaxial growth, ion implantation, and diffusion. It is suitable for R&D and for manufacturers of silicon, compound semiconductors, silicon-on-insulator wafers, and power devices. ***Semilab USA LLC**, 12415 Telecom Dr, Tampa, FL 33637, https://semilab.com*

Maskless lithography system with UV light

Microlight3D has unveiled its SmartPrint UV (SP-UV) maskless lithography system equipped with a UV light source. It is suitable for application fields that require surface micropatterning, such as microfluidics, biotechnologies, and microelectronics. The new 385 nm LED source means the SP-UV system is compatible with a wide range of microelectronic photoresist materials for semiconductor processing. Those include i-line resist SU-8, which is indispensable for microfluidics applications. SP-UV's optical projection technology gives users access to four different writing resolutions and combines writing precision with a writing speed up to 1000 mm^2/min. According to the company, that speed is twice as fast as that of competing brands at 6 µm resolution and up to 10 times as fast at 15 µm. Resolution can be changed within 2 s using Microlight3D's quick-release objective system. The SP-UV's objective lens range allows for a long working distance up to 3 cm. It can therefore be used with nonstandard substrates, including those that are flexible, thick, and curved, such as optical lenses. ***Microlight3D**, 5 Ave du Grand Sablon, 38700 La Tronche, France, www.microlight.fr*

Temperature-controlled optical profilometry

Linkam and Sensofar have partnered to develop a technique for characterizing the temperature-induced topographical evolution of nanoscale materials. The technique uses Sensofar's S neox 3D optical profiler and Linnik interferometer coupled with Linkam's LTS420 heating and freezing stage. Due to imaging issues caused by changes in spherical aberration with temperature of the front lens of the objective and the quartz window of the LTS420 stage, it has been difficult to conduct temperature-controlled optical profilometry experiments. With temperatures up to 380 °C, the new combination resolves spherical aberration issues and enables the user to accurately measure 3D topographic profiles of silicon wafers as they evolve. Mapping the changes in roughness and waviness of silicon wafers yields critical information that can help producers and users optimize their processes and improve semiconductor properties and wafer durability. ***Linkam Scientific Instruments Ltd**, Unit 8, Epsom Downs Metro Centre, Waterfield, Tadworth, Surrey, KT20 5LR, UK, www.linkam.co.uk*

Large-diameter ceramic break

The addition of a large-diameter ceramic break expands MDC Precision's line of vacuum breaks for use in demanding UHV environments. Also known as electrical isolators, vacuum breaks are composed of metal adapters brazed to each end of a ceramic tube that isolate the charge and voltage between the conductive metal ends. The electrical break between the vacuum chamber and other external parts protects the vacuum system's sensitive components from electrostatic discharge. MDC's new large vacuum break is constructed using high-purity alumina ceramic insulators hermetically bonded to low-expansion metal Kovar sleeve adapters. It operates in a UHV range of 1.0×10^{-10} Torr and in temperatures from −100 °C to 450 °C and features a 298.4 mm inner diameter to maximize flow, enhance seal joint integrity, and ensure high hermiticity and performance. The ceramic breaks are suitable for use in fusion energy, particle accelerators, and research equipment. ***MDC Precision Products LLC**, 30962 Santana St, Hayward, CA 94544, www.mdcprecision.com*

Compact Pirani gauge series

Edwards designed its APG200 series of high-performance Pirani gauges to be both reliable and compact. Using electronics developed in-house, Edwards maximized the filament length, which increased sensitivity and reduced the overall package size. Also offered are filament material options for corrosive environments, with measurement from atmosphere to 5×10^{-4} mbar (M or MP series) or 1×10^{-4} mbar (LC series). More flange types and outputs are available than with the previous APG100 series; the expanded flexibility allows for easy integration into existing systems without software and hardware updates. A range of upgrades and feature enhancements make the APG200 suitable for all vacuum markets. Analytical instrument users can take advantage of the reduced size and flexible outputs; in the semiconductor field, new interfaces and light rings enable better system maintenance. In R&D, the local pressure indication helps users monitor experiments away from the main interfaces. ***Edwards Ltd**, Innovation Dr, Burgess Hill, West Sussex, RH15 9TW, UK, www.edwardsvacuum.com* PT

OBITUARIES

Felix Hans Boehm

Eminent nuclear experimentalist Felix Hans Boehm passed away on 25 May 2021, a few days before his 97th birthday. His scientific career spanned the second half of the 20th century and coincided with the evolution of nuclear experimental physics—from "in-house," relatively small-scale experiments performed by a handful of physicists to large-scale efforts at an external facility with a significant group of participants. Those massive undertakings require long and costly preparations and substantial running times. Felix made significant contributions at each stage of that evolution.

Felix was born on 9 June 1924 in Basel, Switzerland. He received his undergraduate degree from the University of Geneva and his PhD in physics from ETH Zürich. Paul Scherrer was his thesis supervisor, and Wolfgang Pauli taught him theoretical physics and was a member of Felix's PhD exam committee. During his student days, Felix was interested in electrophysiology, among other things, and was able to collaborate with Walter Hess, who later became a Nobel laurate for physiology.

After a short stint at ETH, Felix crossed the Atlantic to work at Columbia University with Chien-Shiung Wu, affectionately known as Madame Wu. In 1953 Felix moved to Caltech, where he spent the next half century. It was an exciting time: In 1956 parity violation in weak interactions was proposed and experimentally verified. Felix and several collaborators, primarily Aaldert Wapstra, were able to quickly set up a new apparatus and observe parity violation in nuclear beta decays, thus confirming Wu's initial findings.

Felix's next undertaking was to show that parity is also violated in nuclear electromagnetic transitions, a consequence of the current–current structure of the weak interactions that was proposed by Murray Gell-Mann and Richard Feynman. Felix's frequent face-to-face discussions with them were clearly a motivating factor in his decision to take on such a challenging project. To enhance the observable, he chose relatively heavy nuclei in which the gamma transitions were strongly hindered. Eventually, he observed in 1972 a percent parity violation in the decay of the spin-8, odd-parity isomer of hafnium-180, a world record.

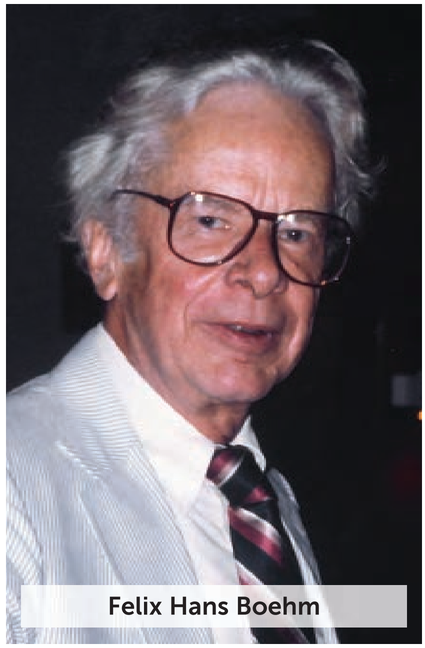
Even more challenging was Felix's attempt to observe the time-reversal violation in nuclear transitions, which is still hypothetical. Although he observed what was seemingly time-reversal violation in the decay of iridium-191, the interaction of the photon with atomic electrons causes a phase shift that resembles the phase caused by time-reversal nonconservation.

After a sabbatical at CERN in 1972, Felix turned his attention to nuclear structure and used muonic and pionic atoms to study it. He started an experimental program at the recently established Los Alamos Meson Physics Facility (now the Los Alamos Neutron Science Center). While there, he performed, among other work, tests of the Klein–Gordon equation using pions.

In the 1980s Felix initiated a number of groundbreaking experiments in neutrino physics that paved the way for many contemporary activities and discoveries in the field. He started working on neutrino oscillations using nuclear reactors as sources: first at a baseline of tens of meters at the Institut Laue–Langevin research reactor in France, in collaboration with his friend and colleague Rudolf Mössbauer, and then at the Gösgen power plant in Switzerland. Their careful measurements did not reveal oscillations, in contradiction to hints from other experiments.

After the early indications for atmospheric neutrino oscillations, in 2000 Felix helped build the kilometer-baseline experiment at the Palo Verde Nuclear Generating Station in Arizona. One kilometer was indeed the correct baseline for a discovery, but Felix and colleagues missed it because of the experiment's insufficient sensitivity to the mixing parameter.

Oscillations were finally discovered by collaborations that included alumni from Palo Verde: first with KamLAND in Japan at a 100 km baseline and then by the Daya Bay Reactor Neutrino Experiment in China, at the same 1 km baseline as the Palo Verde experiment but with a substantially better sensitivity to small mixing. In many ways, Felix's confidence in using nuclear reactors to study neutrino oscillations was finally vindicated.


Felix Hans Boehm

Continuing his work in the area of neutrinos, Felix developed double beta decay experiments. He first used a simple germanium detector and then built a pioneering time-projection chamber filled with 5 kg of isotopically enriched xenon. To some extent, the liquid-phase EXO 200 detector and the future 5 ton nEXO follow Felix's early work.

In 1995 Felix received the Tom W. Bonner Prize in Nuclear Physics from the American Physical Society. He had an early engagement with the Aspen Center for Physics, and he served as a trustee from 1976 to 1979. Over the years he taught and mentored many colleagues who went on to have successful careers worldwide.

Felix was creative and fearless in charting new directions and was uncompromising in interpreting the data. His sense of humor and many cultural interests beyond physics were an inspiration to many colleagues. He is deeply missed.

Petr Vogel
California Institute of Technology
Pasadena
Giorgio Gratta
Stanford University
Stanford, California

TO NOTIFY THE COMMUNITY about a colleague's death, visit https://contact.physicstoday.org and send us a remembrance to post.
Select submissions and, space permitting, a list of recent postings will appear in print.

Igor Ekhiel'evich Dzyaloshinskii

Igor Ekhiel'evich Dzyaloshinskii, who made groundbreaking contributions that span the field of theoretical condensed-matter physics, died on 14 July 2021 in Irvine, California. His scientific legacy in the areas of magnetism, multiferroics, one-dimensional conductors, liquid crystals, van der Waals forces, and applications of methods of quantum field theory has already been assured.

Igor was born on 1 February 1931 in Moscow. He was the first in his family to attend a university. At age 21, while still a student, he passed Lev Landau's infamous "theoretical minimum" exams and became a member of the "Landau school." He graduated from Moscow State University in 1953. Later Igor became one of the founding members and intellectual leaders of the Landau Institute for Theoretical Physics, which was established in 1964.

At Igor's PhD defense at the Institute for Physical Problems in 1957, Landau, in a rare show of praise, called Igor "one of the most talented young theoreticians whom I had met." Indeed, the traits that are emblematic of Landau's school as a whole—a formidable technical rigor with an intimate interest in real-world phenomena—are also the ones that best represent Igor's lifelong approach to physics. He was never interested in equations for their own sake but was in search of the world's internal beauty.

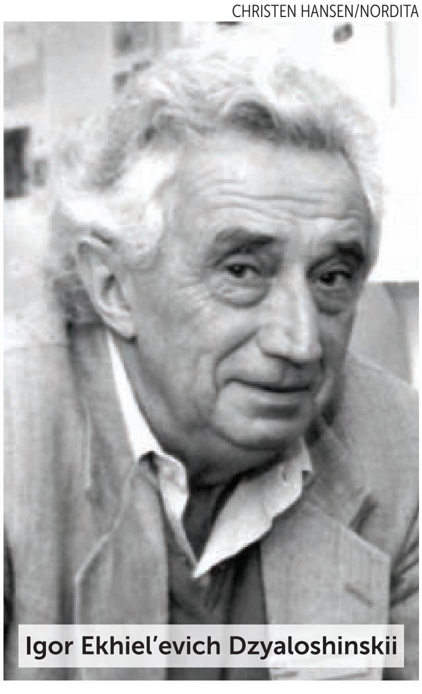
In one of his first publications, in 1957, as part of his PhD thesis work, Igor outlined a set of elegant symmetry arguments for the existence of an antisymmetric exchange interaction that explained the puzzling phenomenon of "weak ferromagnetism"—the occurrence of a small net magnetization in select antiferromagnets. Later, Toru Moriya identified spin–orbit coupling as the microscopic mechanism of such an exchange, which became known as the Dzyaloshinskii–Moriya interaction and is omnipresent in real magnets. The symmetry approach Igor pioneered still permeates the field of magnetism. The modern fields of vortex-like skyrmion spin structures, topological magnon-band Berry curvatures, and anisotropic-exchange magnets are all descendants of Igor's earlier works.

With his remarkable insight, and as part of the same PhD thesis, Igor suggested a mechanism of the magnetoelectric effect and predicted piezomagnetism: magnetization induced by stress and deformation caused by a magnetic field. Those conceptual results are the cornerstones of the field of multiferroics—the study of materials with coexisting magnetism and ferroelectricity—which has blossomed since the 2000s, nearly half a century after Igor published his foundational works.

A long-lasting result from the same era was the novel use of the methods of quantum field theory. Igor, together with Lev Gor'kov and Alexei Abrikosov, helped to develop and popularize the temperature-diagram technique—a universal method in theoretical condensed-matter physics. A groundbreaking monograph, *Methods of Quantum Field Theory in Statistical Physics*, written while Igor was still in his late twenties, was published in Russian in 1962 and in English in 1963. An immediate bestseller, it became known simply as AGD, after the authors' initials. Generations of theoretical physicists have been brought up on that masterpiece. Many owe their craft and the research directions that define their careers to the methods learned from the book.

It is impossible for us to express sufficient amazement at the fertility of that period of Igor's life because it was also marked by his seminal contributions to the theories of van der Waals forces and 1D conductors. With one of us (Pitaevskii), he solved the problem of the van der Waals forces between bodies separated by an absorbing liquid, and with Yury Bychkov and Gor'kov, he addressed the problem of superconducting and charge-density-wave instabilities in 1D conductors. Both analyses had profound impacts on their respective fields. In the 1970s Igor and Anatoly Larkin also offered a solution to the Luttinger-liquid problem that is central to the theory of 1D Fermi systems and to the bosonization technique.

CHRISTEN HANSEN/NORDITA



Igor Ekhiel'evich Dzyaloshinskii

The following decades in Igor's scientific trajectory were again marked by an impressive variety of studies: phase transitions, quantum crystals, spin glasses, topological defects, and liquid crystals. He was also an editor of the flagship Soviet physics journals *Journal of Experimental and Theoretical Physics* and *JETP Letters* and a professor at the Moscow Institute of Physics and Technology and at Moscow State University.

In 1991 Igor left the Soviet Union for the US and became a professor at the University of California, Irvine (UCI) in 1992, where he continued teaching and working well into his retirement. Almost symbolically, in his last publication, in 2014, Igor suggested a novel effect in magnetoelectrics—one of his lifelong interests—that was soon confirmed experimentally. Life coming full circle.

A very private man, and a resident of the campus faculty housing since his arrival at UCI, Igor could be found hiking surrounding hills or walking his dog in the early hours of the morning.

Igor had a rare combination of brilliance, integrity, modesty, generosity, and erudition, both in physics and far beyond. He was approachable and enjoyed a good joke. His colleagues, friends, and former students miss his warm, if mischievous, smile.

Alexander Chernyshev
Alexei Maradudin
University of California, Irvine
Lev Pitaevskii
University of Trento
Trento, Italy
P. L. Kapitza Institute for Physical Problems
Moscow, Russia

Steven Weinberg

Steven Weinberg, a visionary and audacious light who forever changed our understanding of the universe, died on 23 July 2021 in Austin, Texas. He was born in New York City on 3 May 1933 and received his BA from Cornell University in 1954. At Princeton University, under Sam Treiman, he earned his PhD in nuclear physics in 1957.

Steve's remarkable 1967 paper "A model of leptons" unified electromagnetism and the weak nuclear interaction into one framework, his electroweak theory. In three pages, he used gauge theory to predict W and Z bosons as mediators of the weak interaction, their masses, the existence of neutral currents, and a "Higgs" boson—all subsequently confirmed by experiment. For that work, Steve was awarded the 1979 Nobel Prize in Physics, shared with Abdus Salam and Sheldon Glashow. Electroweak theory is the cornerstone of today's standard model, which unifies all the forces of nature save gravity. It is the work of many minds and Steve's consistent leadership.

His many other seminal contributions include, most notably, effective field theory, a calculable low-energy approximation of the underlying fundamental theory. In a 2009 review article, Steve argued that the standard model is the leading term in an effective field theory, an assertion still not proven by experiment.

The need for verification in experiment was central to Steve's thinking. He came to believe that further progress in particle physics required a national commitment. In 1987 and 1993, Steve testified before Congress, stressing the need for the proposed Superconducting Super Collider, but Congress opted to fund the International Space Station.

His interest in cosmology led Steve to write his popular 1977 book *The First Three Minutes: A Modern View of the Origin of the Universe*. He inspired physicists and astronomers to work together to explain why the universe is the way it is. The state of the field is well described in his *Cosmology* (2008). His biggest contribution to cosmology was proposing solutions to the dark-matter problem that are well motivated from particle theory. He proposed axions as dark-matter candidates, and his work on weakly interacting particles set the stage for weakly

LOUISE WEINBERG

Steven Weinberg

interacting dark-matter candidates, still not confirmed experimentally.

For his monumental contributions to physics, Steve received many awards and honors, including the National Medal of Science in 1991. In presenting the Benjamin Franklin Medal to him in 2004, the American Philosophical Society said that Steve was "considered by many to be the preeminent theoretical physicist alive" at the time.

Steve's academic career took him from Columbia University to the University of California, Berkeley. When Louise, his wife, was admitted to Harvard Law School in 1966, Steve received temporary appointments at MIT and Harvard, where in 1973 he became the Higgins Professor of Physics. The family moved to Palo Alto for a year in 1976 after Louise accepted a visiting offer from Stanford Law School, and Steve became a visiting professor in the university's physics department. In 1980 Louise accepted a professorship at the University of Texas at Austin School of Law. Two years later Steve sought an appointment at Texas, where he founded the UT Theory Group and held the Josey Regental Chair in Science.

One thing that always impressed me about Steve was how hard he worked. It is well worth one's effort to work through some of his complex calculations. Steve's practice was to write a book based on his notes for each of his classes. The results included his definitive three-volume set, *The Quantum Theory of Fields* (1995–2000), and his most recent book, *Foundations of Modern Physics* (2021).

Steve's other popular books include *Dreams of a Final Theory* (1992) and *To Explain the World: The Discovery of Modern Science* (2015). A frequent contributor to the *New York Review of Books*, he never shied away from expressing his views on religion and society. Steve was also an engaging speaker, referring interestingly to history and literature, and he had a sense of humor that captivated audiences.

Steve was an extremely kind and generous person, as illustrated in the following story conveyed to me by my former student David Medellin: "When I came to Austin, I wrote to Steven Weinberg asking if I could speak with him about research opportunities. He replied saying that he was not going to his office regularly, but that he would . . . meet with me if I let him know beforehand. I was amazed. I couldn't believe *THE* Steven Weinberg would come *just* to meet me at his office." That was not an isolated event; Steve truly cared about students, as I witnessed on many occasions, and as several wrote in online tributes to him (see "Steven Weinberg [1933–2021]," Physics Today online, 3 August 2021).

The last time I talked with Steve was this past April. We discussed the history of quantum entanglement and the possibility of resuming our lunch meetings after the pandemic. Steve liked to go to a particular restaurant near campus and would usually order the blue-plate special with meatloaf. He often insisted on treating me, but when we split the bill, he made sure we left the same tip! I was looking forward to telling Steve about my group's recent work on quantum-limited acoustic detection, testing the limits of Albert Einstein's 1907 prediction on Brownian motion, and its relevance to the search for dark-matter events in bubble chambers. Steve would have liked it, a combination of two of his passions: cosmology and history of science. Alas, Steve is gone, a reality that is hard to accept. He will be remembered as one of the greatest physicists of all time.

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Trevor Cox (t.j.cox@salford.ac.uk) is a professor of acoustic engineering at the University of Salford in the UK.

Modeling sound at Stonehenge

Trevor J. Cox

When the prehistoric monument was still intact, reflections between its stones produced a remarkable amount of reverberation and amplified speech by 4 decibels.

For winter solstice, crowds usually gather at Stonehenge to watch the Sun set between the uprights of the tallest trilithon. That practice has been taking place since our ancient ancestors erected the sarsen stones about 2500 BC. But there is more to Stonehenge than observing its alignments to the sunrise and sunset at solstice. When people gather for rituals, they speak and make music—sounds that are amplified and altered by reflections from the stones. To fully understand Stonehenge, visitors need to look beyond its appearance, including the archaeological artifacts dug up at the site, to quantify how the monument's acoustics altered its sounds and how the stones' prehistoric geometry might have influenced what went on there.

Sunrise and sunset at solstice can still be experienced at the site. Although it is possible to get a sense of scale and be awed by the staggering feat of construction, listening to the current structure gives a misleading impression of what our ancestors heard in the late Neolithic period and early Bronze Age. The current thinking is that around 2200 BC the monument had 157 stones. That's roughly double the number of stones and fragments that are left at the modern ruin, and many of those are now displaced or fallen over.

I got interested in ancient sites such as Stonehenge when I wrote about sounds of the past for my 2014 book *Sonic Wonderland*. While researching the topic, I realized that no one had investigated prehistoric stone circles by using acoustic scale models. That awareness prompted me to construct such a model on a 1:12 scale, as seen in the photo. Two research questions I and my collaborators—acoustician Bruno Fazenda (University of Salford) and archaeologist Susan Greaney (the nonprofit English Heritage)—wanted to address were, How is sound altered by the stones? and What does that reveal about where rituals might have taken place in the structure?

Making the model

Constructing a scale model is a major challenge, but the method provides a more accurate simulation of diffraction than can be achieved with current computer models. For large spaces, computer-modeling techniques are commonly based on ray tracing. And they are physically accurate only for high frequencies, at which the wavelength is smaller than the dimensions of the reflecting surfaces. The frequency range relevant to speech and music spans 100 Hz (3.4 m wavelength) to 5000 Hz (7 cm wavelength). With the narrowest stone 40 cm wide and the tallest 6.3 m high, geometric computer models are problematic for much of that bandwidth. It is possible to solve the wave equation to model diffraction and get more accurate results than ray-tracing methods, but the calculations would require too much time.

Acoustic scale modeling has been used in architectural acoustics since the 1930s. And even today, acoustic consultants make physical models when they are designing the most prestigious auditoriums. The technique is appealing because it can capture wave effects, such as interference and complex reflections from the stones. But for the approach to work, it is necessary to use a smaller wavelength. In our 1:12 scale model of Stonehenge, we used sound waves at 12 times their normal frequency because that preserves the relative size of the sound wavelength and stone dimensions.

People often ask about the materials in our model. Why aren't the stones on grass, for example? We needed to match the materials' reflection properties and take into account that measurements take place at ultrasonic frequencies. Were the model on grass, ground absorption would have been far too high. (The absorption coefficient of ground at 12 000 Hz in the model must match that of the real site at 1000 Hz.) We found that medium-density fiberboard provides a close proxy at 12 000 Hz.

The same reasoning explains why the stones need not be made of rock. Some of the model stones were three-dimensional printed plastic hollows, backfilled with concrete to make them heavy enough to reflect sound efficiently. Others were molded using a plaster–polymer mix. All were sealed with an automotive, cellulose spray paint to prevent sounds from penetrating surface pores. The approach was more than mere convenience. The time required to 3D print all 157 stones was estimated to take nine months.

We had to accurately create features of the model—the size, shape, and location of the stones—because sound from the henge primarily loses energy between the outer stones and into the sky. We drew on the latest archaeological evidence for the stone arrangements. Historic England, a public organization that helps protect the country's historic environment, provided a computer model showing the geometry of reconstruction as Stonehenge appeared in 2200 BC, a time when its usage likely peaked. Those were the starting points for our physical model.

Flutes, horns, and drums

Getting recording equipment to work at broadband frequencies in the ultrasonic region is no easy task. In the absence of a compact omnidirectional source, we arranged four tweeters—each pointed outward on a square—inside the model. The speakers emitted frequencies up to 70 000 Hz that we could record. To characterize the space, we used a single microphone and incrementally moved it to 24 positions inside the henge

THIS ACOUSTIC SCALE MODEL of Stonehenge is housed in a semi-anechoic chamber at the University of Salford in the UK. At 2.5 m wide, the model mimics the monument circa 2200 BC, when it had 157 stones. Today's ruin contains roughly half that number. The light is at sunrise for the midsummer solstice. Foam wedges on the chamber's walls mimic the sound absorption in the open countryside surrounding the real site. (Author Trevor Cox is seen behind the model.)

and just outside its border. At each position we measured the speaker's short, sharp impulses made elsewhere in the model.

Those recordings captured the sound directly from source to microphone, followed by the thousands of reflections that came from the stones. From the impulse responses, we calculated a series of parameters that relate to human perception. The first was reverberation time: how long it takes the sound to decay by 60 dB after the source is switched off. In our scale model of Stonehenge, the average midfrequency reverberation time was 0.64 ± 0.03 seconds. A large movie theater exhibits similar decay times.

For a space with no roof and spaces between the stones for sound to escape, that's a remarkably long reverberation time. Reverberation occurs because horizontally propagating sound reflects repeatedly between the many stones. And although the time is significantly less than would be recommended for listening to today's music, even a small amount of reverberation improves the perception of music across genres. Indeed, sound engineers describe reverberation as "aural ketchup" because it improves anything to which it's added.

It is impossible to know what sounds our ancestors were making at Stonehenge, but musical instruments certainly existed when it was built. Archaeologists have evidence of ancient bone flutes, wooden pipes, animal horns, and drums from Neolithic Britain and Europe. And singing, almost certainly, would have been pervasive at the time—although that leaves no archaeological trace.

Another key parameter we analyzed was the amplification provided by the stones' reflections. Across all the measurement positions, they amplified the sounds of speech by, on average, 4.3 dB. The smallest difference in level we can hear is about 1 dB, whereas a 10 dB increase is heard as a doubling in loudness. Thus the amplification in Stonehenge would have made communication easier and especially helpful if a speaker was facing away from the audience.

What's more, the acoustic enhancement of amplification and reverberation happened only when speakers, music makers, and listeners were in the stone circle. Any sounds they created were best for others inside the structure rather than for a bigger audience outside, whose view of the interior would have been obscured. A large number of people were required to transport the stones and construct the monument, but apparently only a small number of people—possibly fewer than 50 within the central horseshoe of bluestones—were able or allowed to fully participate and witness rituals in the stone circle.

I appreciate the work of Bruno Fazenda and Susan Greaney for their collaboration on the project.

Additional resources

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▶ T. Cox, *Sonic Wonderland: A Scientific Odyssey of Sound*, Random House (2014).

▶ T. J. Cox, B. M. Fazenda, S. E. Greaney, "Using scale modelling to assess the prehistoric acoustics of Stonehenge," *J. Archaeol. Sci.* **122**, 105218 (2020).

▶ T. Darvill et al., "Stonehenge remodelled," *Antiquity* **86**, 1021 (2012).

▶ B. Fazenda, I. Drumm, "Recreating the sound of Stonehenge," *Acta Acust. U. Acust.* **99**, 110 (2013).

▶ C. Scarre, G. Lawson, eds., *Archaeoacoustics*, McDonald Institute for Archaeological Research (2006). PT

A quieter microscope

For years, scanning tunneling microscopes (STMs) have imaged surfaces at the atomic scale. Such studies are often performed in ultrahigh vacuum systems at millikelvin temperatures. Although the typical helium dilution refrigeration technique easily brings the temperature below 100 mK, the continuous circulation of cryogenic liquids produces a substantial level of mechanical noise. This picture shows a different STM whose cooling unit maintains a temperature range of 30 mK to 1 K using adiabatic demagnetization refrigeration. Designed by Ruslan Temirov of the Jülich Research Center in Germany and his colleagues, the solid-state refrigerator is quieter than other refrigerators with mechanical pumps. Among other possibilities, the new STM could be used to study the entanglement of individual electron spins in artificially created atomic and molecular structures.

The sample is treated in the preparation chamber (top right), inserted into the STM (top left), and then transferred to the large blue flask (bottom). A paramagnetic material, in contact with the flask, cools the system via a superconducting magnet that applies a strong magnetic field, which entrains the magnetic dipoles of the paramagnet. A helium bath acts as a heat sink during the magnetization, effectively holding the temperature at 1 K as the paramagnet's entropy decreases. After the researchers remove the thermal link to the bath, they decrease the magnetic field strength, causing the paramagnet to regain its entropy. Because the STM is decoupled from the 1 K environment yet anchored to the paramagnet, it cools adiabatically. From there, the sample is precisely imaged at millikelvin temperatures. (T. Esat et al., *Rev. Sci. Instrum.* **92**, 063701, 2021; image courtesy of Forschungszentrum Jülich/Sascha Kreklau.)

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