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Volume 113 • Number 5 • September–October 2025

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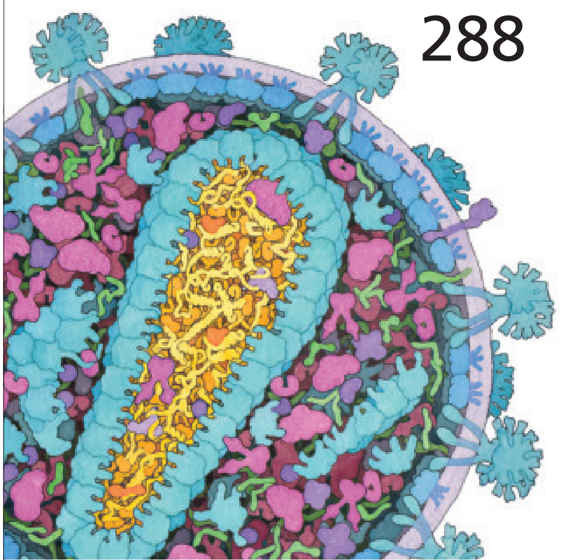
Scientists' Nightstand

From Sigma Xi

Feature Articles



The Cover

When HIV enters a cell, its genome (white strand, top right corner) *incorporates into the cell's genome in the nucleus. As the cell activates its genes, the virus's genes turn on too. The cell then transcribes the viral RNA* (yellow squiggles)*, which moves through the cell and is used to synthesize the virus's proteins* (red)*. As the viral RNA and proteins accumulate at the cell's membrane, the immature viral particles bud off, taking with them pieces of the membrane and its proteins* (magenta)*. Viral enzymes finish processing the proteins to create the HIV* capsid *(the protein shell that encloses the virus's genome) leading to a fully mature virus particle. In "A Revolutionary Drug to Treat and Prevent HIV Infection" (pages 288–295), author John Raul Somoza describes the process of developing a new drug, lenacapavir, that interferes with capsid assembly and movement. (Cover illustration by David S. Goodsell, B-HIVE Center, RCSB Protein Data Bank and Scripps Research. doi:10.2210/rcsb_pdb/goodsell-gallery-047)*

From the Editors

Research Pays Off

Scientific research is not for the impatient. A lack of results can persist for years before a breakthrough. A promising piece of data might not ever bear out, upon further study. Structural biologist John Raul Somoza puts these tribulations front and center in this issue's cover article, "A Revolutionary Drug to Treat and Prevent HIV Infection" (pages 288–295). Somoza was part of a team that was eventually successful in developing a medication, called lenacapavir, that just this year has made it all the way through approval by the U.S. Food and Drug Administration, but he does not gloss over the years of false starts and dead ends.


Caught in the Moment Photography

Somoza admits that their research team at Gilead Sciences started out with a known long shot. They began looking for ways to affect the *capsid*, the protein shell that protects the RNA genome of HIV. They found two sites on the capsid that bind molecules; the first went nowhere, but the second site eventually panned out.

The success of lenacapavir demonstrates the value of scientific research in improving the lives of countless people worldwide. It also shows the tenacity necessary to pursue a career in research. Unfortunately, it additionally brings to mind the people who still deny that the disease AIDS is caused by HIV, in the face of overwhelming data. Imagine being a scientist trying to find treatment for a disease like AIDS, and you regularly receive hateful anonymous messages in your email inbox that accuse you of lying and indicate that they know your home address. These and many other ideological attacks on scientific research are widespread and difficult to counter, but scientists who supply evidence-based responses are often then subjected to such personal threats. We are fortunate in this issue to have the thoughts of climate scientist Michael E. Mann and virologist Peter J. Hotez, who sadly have experienced such threats against themselves and their families. That experience has led both of them to advocate for better protections for scientists who strive to counter misinformation. In "Support Scientists Who Stand Up" (pages 278–281), Mann and Hotez describe efforts already in place to provide legal aid to scientists, as well as ideas about how these resources could be expanded. They also call upon universities and scientific societies to do a better job of protecting their affiliated researchers. Mann and Hotez's new book, *Science Under Siege*, from which this essay is adapted, will be released in September. (Also see an interview with Hotez in the September–October 2020 issue, and a video of his COVID-19 Distinguished Lecture from November 20, 2020, on the *American Scientist* website.)

In our prior issue, we published a call for letters from scientists to raise awareness as to why their research is important. As you will see in this issue's Letters section (pages 259–262), we have been gratified to receive a number of responses to this appeal. We encourage you to continue submitting your letters. As a reminder, please keep your letter submissions to no more than 300 words. Let us know if you would like us to keep your letter anonymous, or if you are comfortable sharing your name, your location, or both. Please note that as a nonprofit, *American Scientist* is not permitted to endorse any specific legislation or candidate, but we can support evidence-based science policy, so please keep your submissions nonpartisan. Focus your submission on why your work is important, effective, and worth carrying out. Send your submissions to editors@amscionline.org with the subject line "Science Is Important." Submissions may be published in print or on our website, and may also be featured on social media. *—Fenella Saunders (@fsaundersamsci.bsky.social)*

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Note from the Editors

In the July–August issue, we published a call for letters from scientists to give brief explanations of their research and why it is important. We hope that these letters will bring awareness to the vital work of scientists and to the need for continued research funding. If you would like to submit a letter, please keep it to 300 words or fewer and email it to editors@amscionline.org with the subject line "Science Is Important."

My Science Is Important

To the Editors:

After the tragic Texas Hill Country floods this June, which killed more than 120 people, including children, many people asked why areas were not evacuated prior to the flooding. The first question often was, "Did they receive a flash flood warning?" Some people may have received emergency alerts, but this binary question overlooks the complexities of receiving a warning and responding to it.

We are a climatologist and a social scientist who study early warning systems for extreme weather, focusing on overlooked communities and complex situations that challenge even well-designed systems. These challenges include multihazard events such as simultaneous flash floods and tornadoes, as well as nocturnal events, which are often more deadly. Additionally, as climate change shifts the hazard landscape, people are unprepared for the unfamiliar and intensifying threats they face.

Our federally funded studies track how forecasters decide whether and how to communicate warnings; how people receive, interpret, and respond to these alerts; and how systems can improve. Our research shows that many individuals face barriers such as unreliable cell service, lack of weather radios, limited alert systems, or messages in unfamiliar languages. Even when alerts arrive, action may be impossible without transportation, shelter, or social support. We translate these local insights into practical changes by partnering with emergency managers, forecasters, media outlets, and residents to ensure future alerts meet community needs and better fulfill the mission of the U.S. National Oceanic and Atmospheric Administration (NOAA) to protect life and property.

We do this work because early warning systems save lives, but only when they are accessible, trusted, and built for the communities they serve. By investing in collaborative research and strengthening warning systems, we can help ensure that all communities receive timely, actionable alerts during extreme weather.

Kelsey Ellis
Department of Geography and Sustainability
University of Tennessee

Jennifer First
School of Social Work
University of Missouri

To the Editors:

On April 8, the U.S. Department of Homeland Security (DHS) terminated its long-standing Centers of Excellence (COE) program, which included university/government partnerships dedicated to reducing terrorist threats, enhancing cybersecurity, and building resilience for infrastructure and coastal areas. As a result, all projects funded under this program were also

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terminated, including ours. We had been developing and implementing an emergency management early warning system for coastal hazards: the Coastal Hazards Analysis, Modeling, and Prediction (CHAMP) system.

Funding from the DHS Center of Excellence in Coastal Resilience had supported deep engagement with emergency managers and resilience planners aimed at cocreating the CHAMP hazard impact prediction platform for hurricanes and nor'easters. CHAMP provides high-resolution flood and wind forecasts as well as detailed potential storm impacts that are of particular concern to infrastructure facility managers, who need to know if an electrical transformer might be destroyed by flooding or if a communications array might be blown over by wind.

CHAMP is the culmination of more than 10 years of rigorous research comprising numerous doctoral dissertations, peer-reviewed publications, and hundreds of consultations with end users. Its scientific advancement and public benefit are unmatched among existing forecasting, projection, and early-warning systems. A demonstration of CHAMP is on standby in Rhode Island, but it was expected to play an indispensable role in decision-making and emergency management efforts for the next hurricane or nor'easter.

When DHS terminated the COE program, it terminated four active projects that were advancing and scaling the capabilities of CHAMP for use by other states as well as by the U.S. Coast Guard. Without continued funding, reestablishing collaborations and maintaining the technologies is extremely challenging. Moreover, without the engagement across institutions that makes meeting these goals possible, we lose a vital and natural side benefit, namely, the cross-institutional capacity to respond rapidly to increasing numbers of unprecedented events. Decision-support tools such as CHAMP inform emergency managers, thus protecting lives and reducing economic losses. We must keep these tools functioning and advancing.

Austin Becker
College of the Environment and Life Sciences
University of Rhode Island

Isaac Ginis
Graduate School of Oceanography
University of Rhode Island

Peter Stempel
Stuckeman School of Architecture and Landscape Architecture; Institute of Energy and Environment
Pennsylvania State University

To the Editors:
I am an anthropological archaeologist working in the north-central highland valleys of Peru, where many communities face severe water shortages because of climate change and the disappearance of glaciers. My research focuses on using archaeology to understand how people in the past managed water in these same landscapes during times of drought. My team and I study ancient canals, reservoirs, and agricultural terraces built hundreds or even thousands of years ago as a part of the landscape history. We consider them to be living lessons for the present and future.

"When science funding is cut, what's lost isn't just research; it's opportunities for communities today and in the future to benefit from that knowledge."

Why does this research matter? These ancestral systems show us how communities once adapted to unpredictable water supplies using strategies that were sustainable and deeply connected to their environments. That knowledge is especially valuable today, as rural towns face growing water scarcity and struggle to balance tradition and cultural heritage preservation with modern challenges. My team collaborates with local residents, engineers, university students, and government agencies to map and analyze ancient infrastructure, combine it with new technologies, and help develop practical solutions that support long-term community resilience.

Science funding makes this kind of work possible. Research isn't just about discovery for its own sake. It's about bringing together knowledge across time, disciplines, and cultures to solve real problems. When science funding is cut, what's lost isn't just research; it's opportunities for communities today and in the future to benefit from that knowledge.

Archaeology isn't only about the past. It's about using the past to build a better future.

Amanda Brock Morales
Kawsay Pacha Archaeological Project
University of North Carolina at Charlotte

To the Editors:
North Atlantic right whales are on the brink of extinction. These large baleen whales live in the shallow waters off the U.S. East Coast, and although they have been safe from whaling for almost 100 years, humans still kill them accidentally through ship strikes and entanglements in fishing gear. I study how their habitat is shifting because of climate change, which makes it even harder to determine where and when to protect them from humans.

Although my climate change–related research is under threat, my current funding for this work has not been revoked. However, my lab has lost funding for a project that deploys robots that listen for right whale vocalizations in the U.S. Southeast waters during the winter. This project supports monitoring efforts while right whale moms migrate south to give birth in these relatively warm waters. When we hear a whale, we broadcast that information to the government, mariners, and the public within a few hours. These near-real-time detections are used to motivate mariners to slow down and keep an extra eye out so as to avoid injuring or killing these vulnerable moms and their newborn calves. Real-time detections and their broad communication are especially important given the increasing challenge of implementing and enforcing vessel speed limits and fishery regulations that keep whales safe.

The Endangered Species Act and the Marine Mammal Protection Act mandate effective management for species such as the right whale. I serve on the Atlantic Large Whale Take Reduction Team and several other advisory committees that support the development of these evidence-based management plans. Funding cuts to NOAA and new legislation that limits research funding are obstructing the

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work of these groups and threaten to dismantle them altogether. Without right whale monitoring or management, it seems like our country is giving up on this gentle giant that is one of our national treasures.

Erin Meyer-Gutbrod
School of the Earth, Ocean, and Environment
University of South Carolina

To the Editors:
Religion is one of the most influential—and understudied—social identities affecting public health. Despite assumptions that declining religiosity has made the study irrelevant, religious rhetoric, particularly from antiscience Christian movements, has shaped 21st-century public health more than many realize. From vaccine hesitancy to climate change denial, and from restricting reproductive health access to undermining health education, religion plays a powerful and often underacknowledged role in shaping policy and public perception.

"The recent federal funding cuts don't just end research projects—they close off pathways to deeper understanding of the cultural dynamics shaping health."

As a scholar trained in both religious studies and public health, I believe the recent cuts to federal research funding threaten our ability to fully understand the relationship between faith and science. Most existing studies reduce religion to simplistic measures—such as asking how often someone attends church or prays—and miss the deeper theological and political frameworks that drive health behaviors and policies.

The complexity of religion as a social force cannot be captured through surface-level questions or left to be studied only by institutions with a religious agenda. Without rigorous, independent research, we risk reinforcing stereotypes and overlooking how religion can both support and undermine public health efforts.

The recent federal funding cuts don't just end research projects—they close off pathways to deeper understanding of the cultural dynamics shaping health. If we are serious about creating policies grounded in evidence, we must continue to fund and protect research that examines religion's evolving role in public life.

Alejandra Salemi
Population Health Sciences
Duke University

To the Editors:
As a budding scientist, my work is important not only for the progress that it is helping to bring within my field, but also for teaching me how to think and learn.

I am currently in the first year of a doctoral program in which I am studying spider silk. Spider silk has the potential to revolutionize many industries because of its remarkable material and mechanical properties. For example, a naturally antimicrobial and antifungal material that is highly elastic has many applications in the medical field. In addition, because spider silk is naturally occurring and composed of proteins, it removes the need for chemical refinement to produce an artificial material with similar properties, making it much more environmentally friendly and cheaper to produce.

My current research is focused on how the strength of spider silk has changed over time, throughout spider evolution. This focus will help track useful characteristics through evolutionary time, so we may one day produce these materials for our own use. *Biomimetic materials*, or materials that mimic natural systems to create innovative solutions, are widely used in designs for robotics, health care, environmental management, and other applications. Spider silk has the potential to be widely applicable and beneficial for the environment, but reduced or rescinded funding harms the potential of research to show that usefulness.

Ella Kellner
Department of Biological Sciences
University of North Carolina at Charlotte

To the Editors:
My scientific research is within the public policy arena, but it has always been driven by the high standards of science and empirical evidence. It involves human service rules and regulations, and adherence to them, with respect to safeguarding children while in out-of-home childcare.

An "all-or-nothing" approach to rule compliance was the prevailing paradigm in human services licensing for decades in the United States and elsewhere. As a social scientist and research psychologist, I was interested in testing this paradigm and discovered that it held up under scientific study, but only to a point. When one compared regulatory compliance with corresponding program quality, a very interesting relationship was discovered: Overall, full compliance with rules is not necessarily linearly correlated with program quality. There is a ceiling effect in which full compliance is not any better than substantial compliance. This finding led to several replications of these results and an alternative paradigm based upon substantial, rather than full, compliance with rules within the human services licensing field. These results were recently published in *American Scientist*. (*See "Finding the Rules That Work," January–February.*)

It is important for us as scientists, whether social scientists or physical scientists, to test out the prevailing assumptions against empirical evidence and not assume based upon anecdotal evidence that certain assumptions are true. Science is about reducing the uncertainty in decision-making and being able to make more informed choices.

Richard Fiene
Edna Bennett Pierce Prevention Research Center
Pennsylvania State University

How to Write to *American Scientist*

In addition to submissions regarding the "Science Is Important" call for letters, brief letters commenting on articles appearing in the magazine are also welcomed. The editors reserve the right to edit submissions for length and clarity. Please include an email address if possible. Address: Letters to the Editors, P.O. Box 13975, Research Triangle Park, NC 27709 or editors@amscionline.org.

American Scientist Podcast presents a new audio series, "Wired for This," premiering on September 10. "Wired for This" offers an in-depth look at how we think, believe, change, and connect.

In this biweekly limited series, we'll examine the psychology of human behavior and neuroscience and explore questions such as what drives us forward, what holds us back, and how we can navigate a world bursting with noise, contradiction, and complexity.

Hosted by journalist and neuroscientist Celia Ford, the show features interviews with scientists such as Paul O'Keefe, an associate professor of organizational behavior at the University of Exeter in England, whose research explores how psychological barriers influence the goals people pursue and their potential to reach them. We'll also hear from University of Chicago behavioral scientists Emma Levine and Shereen Chaudhry on how to navigate difficult conversations in high-stress environments.

Additional podcast guests include Jason Lodge of the University of Queensland in Australia and Philipp Lorenz-Spreen from the Max Planck Institute for Human Development in Germany, who discuss how people consume, process, and share information, and how these processes are changing as our relationships with technology evolve.

Each episode will challenge your thinking and offer fresh perspectives on the world around us.

Tune in to "Wired for This" every other Wednesday starting September 10 on Spotify (*QR code below*), Apple Podcasts, iHeartRadio, and more. Follow the *American Scientist Podcast* today to receive updates when new episodes are released.

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The Costs of Being Sally Ride
American Scientist book review editor Jaime Herndon reviews the documentary film *Sally*, which explores the private side of the famous NASA astronaut.
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A Timely Window into Cosmic Threats
Is Earth in danger of a cosmic collision? University of Arizona planetary scientist Cassandra Lejoly reviews *Target Earth: Meteorites, Asteroids, Comets, and Other Cosmic Intruders That Threaten Our Planet*, authored by Dutch astronomy writer Govert Schilling.
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From Motion to Emotion

Vibrations synchronized with music help cochlear implant users have a more immersive listening experience.

A slow beat thrums through a person's body as they listen to music with headphones. Wearing a vest that creates vibrations in time with the music, the cochlear implant user sways and closes their eyes to take it all in. Later, they describe having felt immersed in the music, a rare occurrence, and say that the vibrations made the listening experience more intense.

Those who have cochlear implants are not new to feeling a lack of engagement in the media they consume on a day-to-day basis. For instance, cochlear implant users are known to have difficulty interpreting and understanding differences in the pitch, tone, and melody of music. Although plenty of research has focused on how cochlear implant users perceive music, fewer studies have examined what emotions these users feel during their listening experience.

Computer scientist Luca Turchet at the University of Trento in Italy and his colleagues at University Hospital of Verona wanted to explore how vibrational stimuli can help bring out emotions in the listening experience of cochlear implant users. "I was working with a doctor on a project that was not about music, but was still about the impact of sounds in interactive contexts on this population of cochlear-implanted people," Turchet says. "I proposed to him a study that aimed actually at investigating something different from what turned out to be in this paper." Turchet and his colleagues ended up altering their study because of a fortuitous finding. As the team reported in the journal *Scientific Reports*, they found that not only did participants report feeling more engaged in music when they wore a vibrational vest, but they also showed improvements afterward in understanding speech.

Scientific Reports 15:20054

A vest worn by a cochlear implant user delivers vibrations related to the music coming through the person's headphones. Motorized actuators embedded in the vest convert the electrical signal from the digitized music into synchronized mechanical motion. Researchers found that the vibrations helped these participants feel more immersed in the music. Surprisingly, the researchers also found that this experience improved cochlear implant users' ability to comprehend speech.

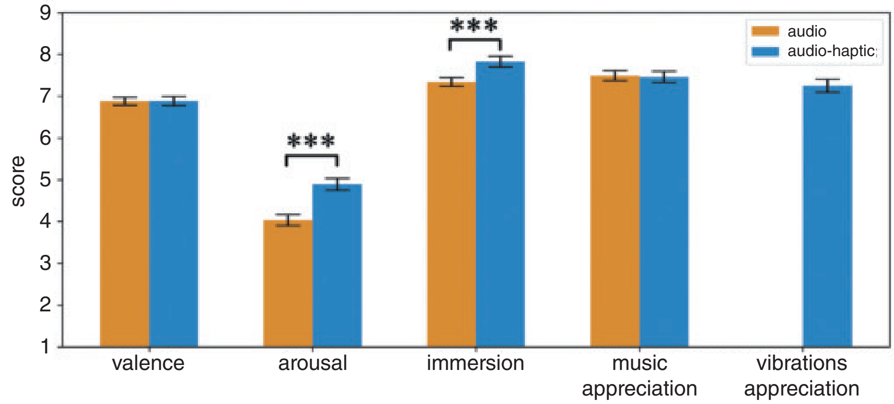
As Turchet recounts, they did an initial trial of the vest on a patient who had come in for his regular monitoring appointment. "He took the audiometric test that he was supposed to take anyway, and at that moment we understood that the performances of that person were very different from the average performances that he had in the past." Repeating the trial with the vest on other patients consistently showed improved speech comprehension results. "So it was by chance, essentially, but also by being careful to notice that there was something important," Turchet says.

Participants of this study were divided into two groups, both of which completed the same set of surveys and audio tests before and after listening to music. The participants were tested on how well they could hear tones or understand speech in both quiet and noisy conditions. Both groups listened to music samples that ranged from classical music to heavy metal, but only one of these groups wore the vibrating vest during listening. The vest translated the bass frequencies heard in the music into a signal that could be felt physically through vibrations created with motorized actuators embedded in the vest, which converted the electrical signal from the digitized music into synchronized mechanical motion.

Turchet and his colleagues had expected that participants might experience what's called *auditory fatigue* after listening to music, and perhaps do worse on speech comprehension. Turchet thinks the explanation for the opposite finding is what's called *multisensory integration*. He explains that the brain can combine auditory and somatosensory information. Because individuals with hearing deficits have a loss of one sense, stimulation of other senses such as touch allows for better stimulation of certain processing regions of the brain.

Not everyone who wore the vibrating vest preferred the experience; some users found the vibrations to be too intense. Turchet thinks that having a vest with adjustable levels of vibration might make the combined listening–vibration experience more tunable to the specific user's preferences and improve results. Turchet also notes that studies on more users over longer periods of time will give them more reliable data on what works best for cochlear implant users.

Not only did participants report feeling more engaged in music when they wore a vibrational vest, but they also showed improvements afterward in understanding speech.



Scientific Reports 15:20054

Cochlear implant users listened to music either without vibrations (*brown, labeled audio*) or with them (*blue, labeled audio-haptic*). Researchers found that the vibrations helped these participants feel more immersed in the music and more emotionally aroused, leading to a more intense experience (*statistically significant differences indicated by three asterisks*). Both groups experienced similar feelings for music appreciation and valence, or pleasantness. Most, but not all, of the participants in the audio-haptic group reported enjoying the vibrations.

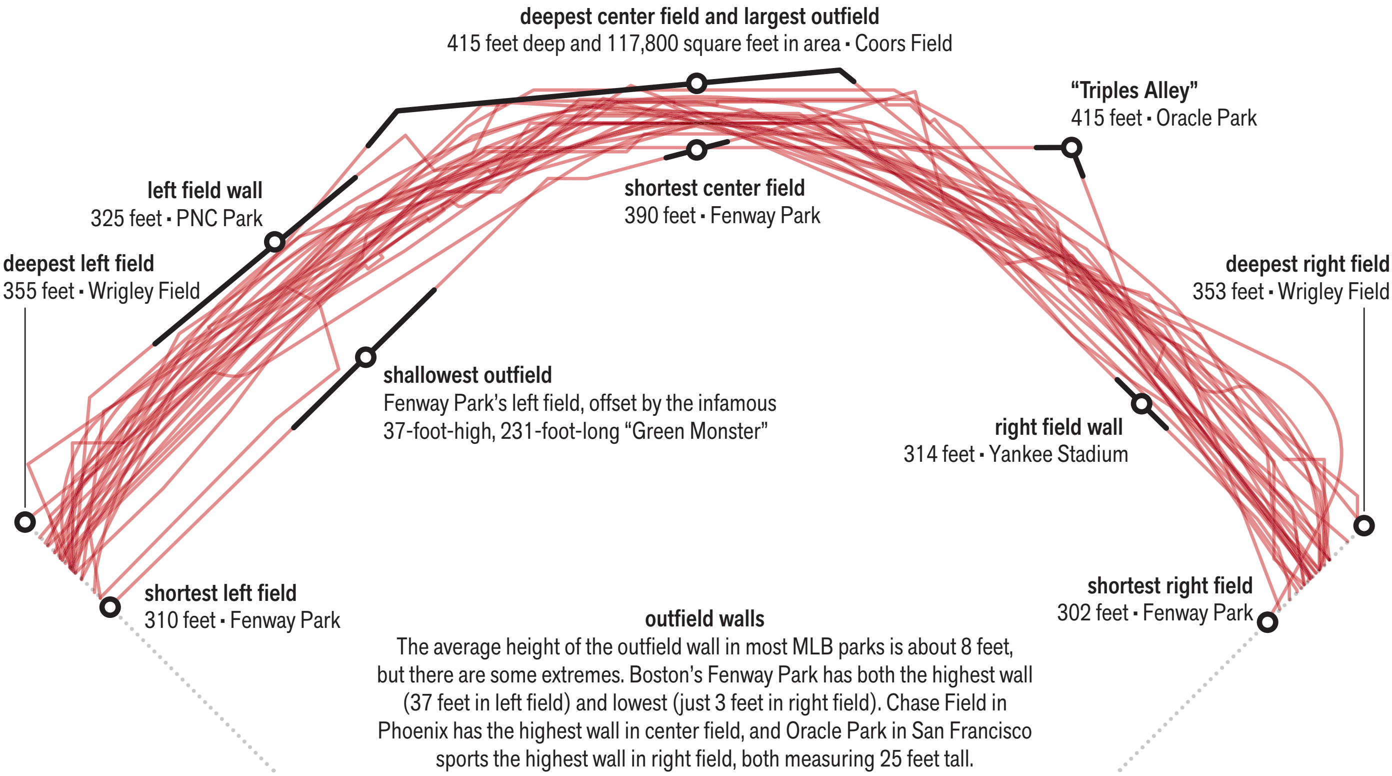
In addition to a more immersive music experience for cochlear implant users, the results with speech comprehension indicate to Turchet and his colleagues that this approach could be the basis for developing new trainings. Studies conducted for longer periods of time could determine how much exposure to vibration stimuli is needed to show improvement in speech understanding.

"I hope that this result, which to me seems so encouraging, turns out to be useful for this category of users in some new forms of rehabilitation therapies," Turchet says. "These technologies lead to deeper immersion in musical experience, and also a higher level of arousal, so I think it is promising."

—Akilah Abdulraheem

Infographic | Lou Spirito and John Eric Goff

BALLPARK PHYSICS



The rules of baseball are quite particular, but the regulations governing the shape of Major League Baseball (MLB) parks are surprisingly flexible. According to Section 2.01 of the MLB rule book, "The distance from home base to the nearest fence, stand or other obstruction on fair territory shall be 250 feet or more. A distance of 320 feet or more along the foul lines, and 400 feet or more to center field is preferable." Preferable! That single word has allowed owners and architects to shape their outfields to take advantage of their environments and their teams' strengths, making each stadium distinct. Baseball fans recognize differences between, for example, Fenway Park in Boston and Dodger Stadium in Los Angeles, and understand the advantages and disadvantages for players in each ballpark.

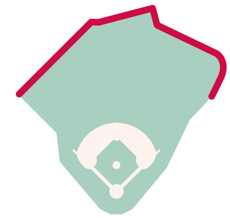
Park design directly influences gameplay. Right-handed hitters tend to pull the ball to left field; lefties like to pull to right. Power hitters prefer pitches that break toward them, which are most often thrown by pitchers who have the opposite dominant hand as the batter. In response, managers often call up specialized "closer" pitchers to challenge their opponents' sluggers late in a game. But savvy hitters can adapt, going to the opposite field when needed. The cat-and-mouse game between pitcher and batter often depends on park geometry.

The oldest ballparks still in use, Fenway Park in Boston and Wrigley Field in Chicago, are the only remaining "jewel box" parks—two-tiered stadiums designed to fit within one city block. The size constraints of these downtown locations forced architects to get creative. For example, to compensate for Fenway's shallow left field, the Red Sox erected the Green Monster, a 37-foot-high wall that blocks hits that would be home runs at any other stadium.

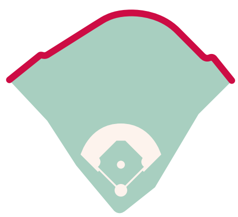
Coors Field, home of the Colorado Rockies in Denver, has a reputation as a hitter's paradise. Air density at the mile-high stadium is about 82 percent of its sea level value, and the location has low humidity. That thin, dry air reduces drag and decreases pitch movement, boosting both the likelihood of a batter making contact with the ball and the distance of a hit. To counter this advantage, Coors Field features some of the deepest fences in baseball, and balls are stored in a special humidor that softens the material and reduces elasticity. The drawback of the Rockies' massive outfield is a high rate of doubles and triples, demanding speedy outfielders.

Though park design may be tailored to favor certain types of players, today's frequent roster turnover makes it more difficult to pair a player with a field. Still, clever front offices keep dimensions in mind when shaping teams. No doubt right-handed slugger Alex Bregman is enjoying his first season in Boston with the Green Monster just 310 feet away along the left-field foul line.

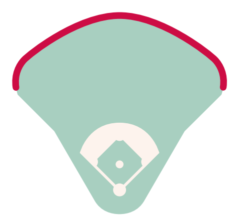
John Eric Goff is a physicist at the University of Puget Sound who researches the physics of sports. Lou Spirito is a visual communications professional in Los Angeles and the founder of THIRTY81 Press, a print and design studio that creates graphics and products for baseball enthusiasts. Imperial measurements are used throughout this infographic to align with the traditions and rules of American baseball.



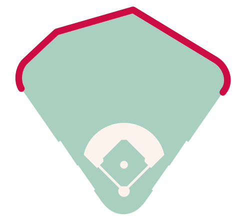
Fenway Park
1912 • Boston Red Sox



Wrigley Field
1914 • Chicago Cubs



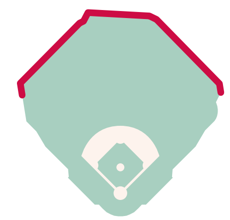
Dodger Stadium
1962 • Los Angeles Dodgers



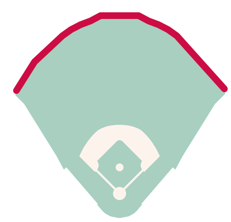
Angel Stadium
1966 • Los Angeles Angels

Kauffman Stadium
1973 • Kansas City Royals

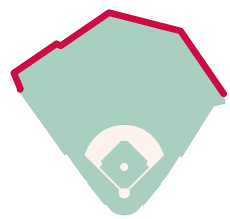
Rogers Centre
1989 • Toronto Blue Jays



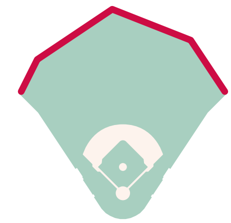
Tropicana Field
1990 • Tampa Bay Rays



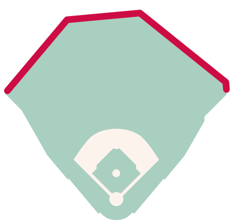
Rate Field
1991 • Chicago White Sox



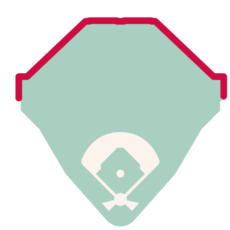
Oriole Park
1992 • Baltimore Orioles



Progressive Field
1994 • Cleveland Guardians



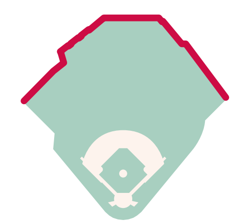
Coors Field
1995 • Colorado Rockies



Chase Field
1998 • Arizona Diamondbacks

T-Mobile Park
1999 • Seattle Mariners

Comerica Park
2000 • Detroit Tigers

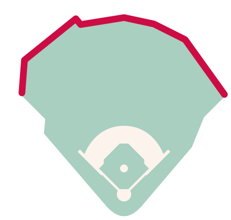


Daikin Park
2000 • Houston Astros

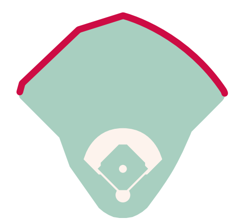
Oracle Park
2000 • San Francisco Giants

Sutter Health Park
2000 • Athletics

American Family Field
2001 • Milwaukee Brewers



PNC Park
2001 • Pittsburgh Pirates



Great American Ball Park
2003 • Cincinnati Reds

Citizens Bank Park
2004 • Philadelphia Phillies

Petco Park
2004 • San Diego Padres

Busch Stadium
2006 • St. Louis Cardinals

Nationals Park
2008 • Washington Nationals

Citi Field
2009 • New York Mets

Yankee Stadium
2009 • New York Yankees

Target Field
2010 • Minnesota Twins

LoanDepot Park
2012 • Miami Marlins

Truist Park
2017 • Atlanta Braves

Globe Life Field
2020 • Texas Rangers

Trap-Free Solar Cells


Courtesy of Mercouri G. Kanatzidis

The most important statistic for any type of photovoltaic technology is the efficiency percentage by which it converts solar energy into electricity. Current silicon-based solar cells have about a 24 percent efficiency, but improving that rate is becoming more difficult, because it requires the base material to have extremely high purity. Mercouri Kanatzidis—a Charles E. and Emma H. Morrison Professor of Chemistry and professor of materials science and engineering at Northwestern University and a senior scientist at Argonne National Laboratory—has been working for more than a decade on a class of materials that do not need a high level of purity to achieve high conversion percentages. These materials, called perovskites *(so called because their structure resembles that of a mineral of the same name), are now being deployed in solar cells that are undergoing commercial testing of their stability. Kanatzidis was the recipient of Sigma Xi's Walston Chubb Award for Innovation at the 2024 International Forum on Research Excellence (IFoRE), and he spoke with editor-in-chief Fenella Saunders after the conference about his work. (This interview has been edited for length and clarity.)*

How did you get interested in solar cells and looking at these materials?

About 15 years ago, I had a general interest in solar energy conversion, but I wasn't active in it, until I was approached by a company who wanted to develop a novel solar cell that needed a material that has certain specific properties. I thought they had a very interesting project to find such a material. It took us two and a half years to solve the problem. Unfortunately, the company didn't survive. We were left with great results that we had obtained for that project that the company allowed us to keep.

Now, we had all this knowledge about these new materials. It was a class of materials, not just one, called the *perovskites*, which are very famous now, but back then, no one knew they were important for anything. We developed the chemistry, the synthesis, the crystallography. We figured out all the crystal structures, the light emission properties, the charge transport properties. We were going to publish in a chemistry journal, just put all these compounds and information together, but something happened that was totally unexpected.

I went to a seminar given by a colleague here in materials science, Robert Chang, who talked about another type of solar cell, the so-called *dye-sensitized cell*. A lot of people were working on it to make it more efficient and more stable. It was based on a liquid solution, but they wanted to make it a solid-state cell. They had 10 percent efficiency in conversion of solar energy to electricity, which was very high at that time, because it was low cost and easy to make. It occurred to me that one of the perovskites we worked on might actually work. You could dissolve it and deposit it and get a film that was easy to process. I suggested that to my colleague, and so we started trying it.

In the beginning, the results were not very interesting or exciting. But my colleague and I realized that the reason it wasn't working wasn't the material or the idea, but the device fabrication. So then we focused on making better devices. Within about a year, we had 10 percent efficiency, almost the same as the liquid dye-sensitized cell. That's where we came out with the first paper based on perovskites supporting a solar cell. Then two other groups published two similar papers with another perovskite, with which we had also worked.

Those papers sparked what turned out to be a revolution in photovoltaics, and even science, because these semiconductors were very unconventional. The researcher community grew. The efficiency rose again and again, and it's still rising today. Now it's about 27 percent. Conventional semiconductors took 40 years to reach an efficiency of maybe 22 percent. It's stunning.

What material properties are needed to make a good photovoltaic?

You need a solid film that absorbs as much of the solar radiation as possible. Generally, that's why it makes them black, so you absorb more of the photons from the Sun. These photons excite electrons inside the material. When the electron is excited, where it bleeds off, that creates an electron hole. Now the material must be able to transport these electrons and holes away from where it happened. When you put in electrodes, they can then collect these holes and electrons on opposite sides. Now you have a voltage and a current forming. If this current doesn't happen and the electron and hole recombine, that's bad because there is no work being done, just heat is generated. So, the material has to be able to support this transport of electrons and holes inside it. It sounds easy, but most materials don't do that. The electrons are trapped or scattered, and they never make it to the electrode.

Another necessary component is a band gap. Can you explain what that is?

The energy gap to excite one electron to the next level is the band gap. Between the highest level where you have some electrons and the lowest level that doesn't have any, there's a gap. The sunlight has energy. If that energy equals the gap, then it will excite the electron across the gap. And now you have an electron and a hole. But if the energy level is lower than the gap, the sunlight will go through the material. It will not be absorbed.

What makes a material a good conductor of electrons and holes?

That's where the unconventionality of perovskites comes in. In a classical semiconductor, in order for the material to be a good conductor, it must be extremely high quality and pure—no impurities, no defects. *Defects* are atoms being in the wrong positions in the crystal structure. That means you have to work very hard to purify them, and that's why it takes decades to raise the efficiency. However, the perovskites are full of defects, and they still work. In a classical semiconductor, if there is a defect, it will introduce a new state in the middle of the band gap. If you have an electron excited, instead of traveling, it can fall into the state and then it's trapped. In perovskites, because of the way the chemical bonding between atoms is in this particular material, when these defects form, they don't form these mid-gap states. They form them away inside the higher level, so they don't play any role in trapping.

What is it about the perovskite's structure that gives it this property?

One thing is that it's three dimensional. So all three directions are possible to transport. Also, they have lead and tin that are bound to the halides, bromides, and iodides, and they form an octahedron. Then the octahedra share corners. That's how they build the three-dimensional structure, which is negatively charged and takes these positive small ions inside. The tin and lead have nonbonding electrons in this valence state, and when they bond into the structure, they form antibonding states—it has a lone pair of electrons—that dominate the valence bands in the solid. When you make a defect in such a material, instead of detaching from the valence band and moving into the band gap, it's detaching from the valence band and moving inside the band, so it's not a trap.

Also, there's a dynamic behavior caused by the lone pair of electrons. The actual structure fluctuates and the electronic structure is a direct result of that, so there's a fluctuating electronic structure, which causes a delay in the recombination of the excited electron and hole after absorption of the light energy. The electron and hole are not in the exact positions they came from, and it takes a little bit of extra time to find each other, which also buys you time to collect them.

One of the remaining problems with perovskites has been their stability. How can that be increased?

The same thing that makes them work also makes them unstable, and that is that the metal halogen bonds are ionic. These devices operate under voltage created during operation, and ions can migrate and cause instability. Using two-dimensional perovskites contacting the 3D ones was one of the early strategies that we showed was effective in considerably lengthening the stability. People are now combining all the different strategies to cover everything that can go wrong. Already companies are deploying solar modules based on perovskites—in the testing stage, not in the standard commercial release stage. The potential customers are testing them to see, under real conditions, how long the modules last. This is very good news.

"Perovskites are full of defects, and they still work, because of the way the chemical bonding between atoms is in this material."

How do you use more than one material to increase the solar cell efficiency?

The lone pair of electrons also gets you another positive characteristic. If you have two related semiconductors and you mix them together, you can make compositions in any ratio and get band gaps in between those of the two materials. But if we have two perovskites, say, one with tin and one with lead, you can also mix them up in any ratio and make intermediate compositions. Tin has a band gap of about 1.4 electron volts, and lead has 1.55. But instead of intermediate numbers between those two, you get a bowing effect: The gaps go down, reach a minimum, and go back up. In the end you have a curve, and a composition in the middle has a lower band gap than the lowest of the two end members. We have explained it because of the same lone pair effect. A smaller band gap means it absorbs more light in the visible spectrum and especially in the infrared.

But no cell can actually capture all the solar light. So, we use two cells in tandem. One cell has a wide gap to capture the high-energy light and then the rest of the light will go through to another cell that has a smaller gap to capture the low-energy light, and together we capture more than we can with the individual cells. Together you can exceed the theoretical limit of a single solar cell, going to 30 or 35 percent. And if it's triple or quadruple tandem, people now are thinking you could go to 50 percent.

How efficient is it possible for these devices to become?

If you have only one solar cell, the limit is about 32 percent. If you go to a big number of tandem cells, the theoretical limit could be 55 or 60 percent. Right now, people are claiming tandems that have 33 to 34 percent.

Some companies are actually already marketing tandems with silicon as the bottom cell. So, in other words, it's a perovskite and silicon hybrid. It's difficult to dislodge silicon from its markets. If you can go to a manufacturer of silicon solar cells and say to them, "All you have to do is add one or two steps in your process, and instead of having 24 percent, you'll have 27 percent," the hope is that the addition would make sense to them and not seem like a big change.

What other fields could use perovskites?

They are turning out to be tremendous x-ray and gamma ray detectors, and these are new applications that will affect biomedicine, medical diagnostics, medical imaging, national security for the monitoring of nuclear materials, and so on. And there are other areas, perhaps in lasers or light-emitting diodes. The perovskites are doing to these fields what they did to photovoltaics 10 years ago.

How much of a role have you seen for serendipity in research?

You never know what you don't know, and therefore you have to hope for serendipity. We have good ideas and good hypotheses, but nature has other things up her sleeve. Therefore, when you try something, very often something else can happen. You have to have the curiosity and the wisdom to actually look at that something else rather than dismiss it and say, that's not what I'm looking for. Sometimes it's a breakthrough, and it could change how you think. So, serendipity is always there in science. I don't think it's useful for us to pretend otherwise, to always think that we're in control, and we always know what we're doing. Curiosity is key. We should encourage our students and postdocs to have it, and hope that they will find that serendipity from time to time. ■

In this roundup, associate editor Nicholas Gerbis summarizes notable recent developments in scientific research, selected from reports compiled in the free electronic newsletter *Sigma Xi SmartBrief*: www.smartbrief.com/sigmaxi/

The Brain's Reality Check

Human imagination produces fanciful images by hijacking the neurological equipment the brain uses to process actual visual input. So how does our brain separate the visual from the visionary? Scientists at University College London suggest that certain frontal brain areas base this judgement on the strength of a "reality signal" from the *bilateral fusiform gyrus* in the midlevel visual cortex. Dreamed-up images produce weaker signals than visually seen objects do, possibly because the latter include signals from the eyes, whereas the former use only processes from within the brain. The team identified this mechanism through an experiment in which participants viewed a screen filled with visual noise and were told to perceive, imagine, or perceive *and* imagine a faint pattern of left- or right-slanted diagonal lines. Researchers noted changes in brain activity when the relevant pattern was absent, present, or present and oppositely oriented. When subjects were primed to imagine an image that was present, they became more confused regarding whether the pattern was really there. The findings have important implications for understanding perception, imagination, and our experience of reality.

Dijkstra, N., T. von Rein, P. Kok, and S. M. Fleming. 2025. A neural basis for distinguishing imagination from reality. Neuron *113:1–7.*

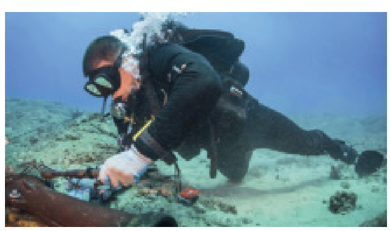
Waste Forms Rocks in Decades

University of Glasgow scientists report that rocks can form from anthropogenic waste in less than 35 years. That's a geological eyeblink compared to the thousands to millions of years nature takes to produce clastic rocks—sedimentary rocks composed of fragments (*clasts*) of eroded and transported stone—and demonstrates the rapid environmental impacts underway in our Anthropocene era. The rocks formed at Derwent Howe, a coastal industrial area in the United Kingdom where foundries dumped iron and steel furnace slag along the coastline from 1856 until the 1980s. Prior research shows numerous ways that human activities might speed up the rock cycle: Debris comes prebroken into clasts, precluding the need for weathering, and industrial materials often contain chemically reactive substances that help "glue" rocks together. But the study is the first to show a complete *anthropoclastic rock cycle* in which natural processes create stones from anthropogenic materials, transforming a loose sediment coast into a waste-rock platform containing detritus such as a 1934 King George V coin, car tires, fiberglass, and keys. The speed and scale at which the anthropoclastic rock cycle operates suggest an urgent need for new models and waste management practices.

Owen, A., J. M. MacDonald, and D. J. Brown. 2025. Evidence for a rapid anthropoclastic rock cycle. Geology *53:581.*

Telecom Cables as Ocean Sensors

Maintaining sensors on the oceanic floor is difficult and expensive, but monitoring remains vital for conducting research, mitigating risks, and measuring climate change and tectonic activity. Now a team led by researchers at California Institute of Technology has converted a transatlantic telecom cable into a cost-effective sensor array for monitoring ocean pressure, tide fluctuations, and temperature changes. This transoceanic distributed sensing (TODS) works by unobtrusively detecting tiny timing variations in light signals as the distance they traverse changes due to cable lengthening or compression. Such changes can arise from strain (deformation from external forces), temperature changes, or vibrations. Such forces can



be exerted by variations in tidal pressure, with which TODS strains correlated well, or by seismic activity or thermal expansion of the sea bed. Attempts to measure temperature met with mixed results and worked best at shallower depths (the cable's depth ranges from 3 to 5 kilometers). The team is the first to detect sub-millihertz signals across the full length of a 5,900-kilometer cable, establishing 81 subsea sensors running from Portugal to Brazil, thereby enabling trans-Atlantic monitoring of slow, large-scale processes that less sensitive sensors might miss.

Liu, M., et al. 2025. Trans-oceanic distributed sensing of tides over telecommunication cable between Portugal and Brazil. Geophysical Research Letters *52:e2024GL114414.*

First Signs Pterosaurs Ate Plants

For the first time, scientists have found direct signs of plant-eating among pterosaurs. The finding adds new evidence to wide-ranging arguments about the lifestyles of the first vertebrates to evolve the capacity for powered flight. The argument for herbivory rests chiefly on the preserved stomach contents, or *consumulites*, of *Sinopterus atavismus* remains

from northeastern China. These mark the first consumulites uncovered from a pterodactyloid pterosaur; historically, experts had to infer pterosaur diets through indirect means such as comparing pterosaur morphologies to the anatomies of living animals with known eating patterns, resulting in hypothesized diets ranging from insects to animals to mollusks. When the team, led by researchers from the Chinese Academy of Sciences in Beijing, compared the makeup and shape of the pterosaur's stomach contents with an international standard catalog of *phytoliths* (rocky plant remains), they found shapes suggesting a varied diet of broadleaf plants, woody plants, flowering plants, and ferns. However, because they could classify only 10 percent of the phytoliths, the authors recommend caution and further research. Even so, the remains suggest a birdlike two-chambered stomach, and the specimen's bite strength, derived partly from the anatomy of its close cousin, *Tapejara*, also suggests an animal that ate hard plant matter such as seeds.

Shunxing, J., X. Zhang, Y. Wu, M. Zheng, A. W. A. Kellner, and X. Wang. 2025. First occurrence of phytoliths in pterosaurs—evidence for herbivory. Science Bulletin. *doi.org/10.1016/j.scib.2025.06.040*

Sightings

Unfurling the Curl

The tail muscles of seahorses differ from those of most other prehensile animals.

Buffeted by strong currents, trying to hide from predators, a diminutive seahorse grasps onto a blade of seagrass in the shallow ocean. It uses its prehensile tail to hold on tightly as it blends in with its environment, staying anchored as it waves back and forth like the grass it's attached to.

Biologist Dominique Adriaens of Ghent University in Belgium and his colleagues study the morphology and biomechanics of seahorses, from how they feed to the shapes of their tails. The team took numerous computed tomography (CT) scans to look at the creature's armored structure, made up of bony plates surrounding their muscles and central vertebrae. The researchers realized that the seahorse tail muscles were unusual: In closely related species, such as pipefish (which do not have prehensile tails) and pipehorses (which can curl their tails but lie only horizontally), the tail muscles are short, spanning no more than three vertebrae segments. But in seahorses, the tails have additional long muscles that span up to 11 vertebrae.

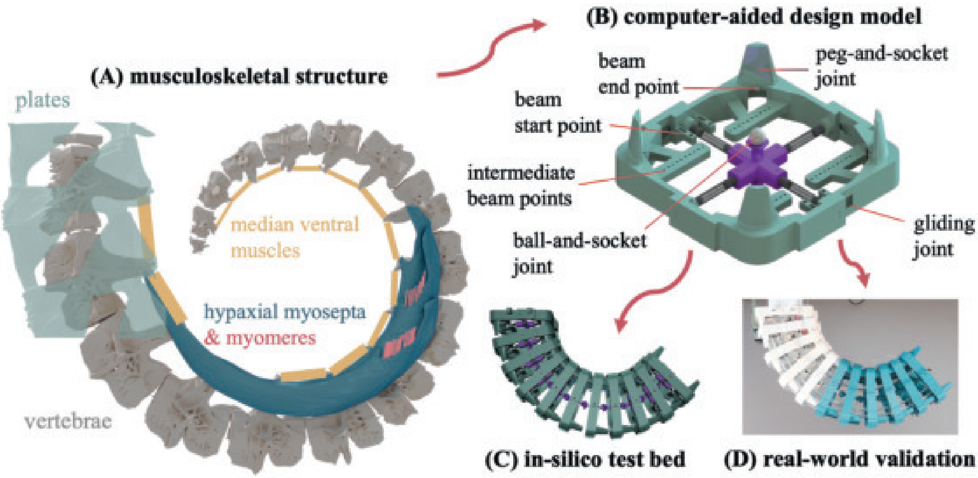
A long-snouted seahorse (*Hippocampus guttulatus*), about 12 centimeters in length, uses its prehensile tail to grip seagrass in the Étang de Thau lagoon in France.

Pascal Kobeh/Nature Picture Library

To figure out why seahorses had evolved this specific muscle structure in their grasping tails, the team turned to computer modeling, so they could see how the tails would be affected by different muscle lengths. "We cannot use a biological system, because all seahorses have that weird configuration," Adriaens said. "The nice thing about computer models is that you can say, What if the muscle spans only three segments? What if it spans five segments?"

The researchers developed a simplified, scaled-up virtual model of the seahorse tail. They also made a 3D print of the model tail, using a retractable wire to mimic muscle contraction. By trying out different muscle attachment points and lengths, as they recently reported in the journal *Interface*, they showed that the longer muscles produce more torque than the short ones. Also, they found that the long muscles tend to follow the same axis as the tail, whereas the short ones tend to pull more to the sides, diminishing their effectiveness. "By making the muscles longer and spanning more vertebrae, the muscles also come to lie in the plane where more of the contraction force is translated into bending force," Adriaens explained.

The models also showed that the long muscles help the tail twist while also getting a good grip, which allows the seahorses to keep their upright posture while gripping vertical blades of grass, corals, or mangrove roots. "A seahorse that swims vertically and wants to attach to something that is vertical has to turn its tail sideways," Adriaens says. "The model showed that with a very simple configuration of left and right muscle pulling, you can already generate the kind of sideways motion that seahorses use."



D. Marzougui, et al. 2025. *Interface* 22:20240876/Dominique Adriaens

Computed tomography scans of seahorses (*such as the one at above right*) were used to create a computer model of the tail musculoskeletal structure (*A*), showing the seahorse's unusually long muscles (*shown in darker blue*). This model was the basis for a computer-aided design model (*B*) that captured the mechanics of the tail. These segments were assembled into a full virtual model (*C*) that was then 3D printed (*D*) to validate its mechanics.

That twisting motion might be the key to when seahorses emerged: The team speculates that the animals might have evolved because of the developing seagrass environment in the Oligocene epoch, some 30 million years ago. "It could be that it all has to do with this vertical position, because that's the main point where seahorses differ from the pipehorses," Adriaens says. "Maybe it's indeed the capacity to do this lateral side bending to hold on to vertical objects that was the main selective pressure."

Adriaens and his team think that the long muscles might also require less neurological control. "We already looked a bit at the brain of seahorses and compared it with pipefish, and they don't have a spectacularly different brain," Adriaens says. So the long muscles in seahorses might give them more torque capacity without needing additional neurological resources.

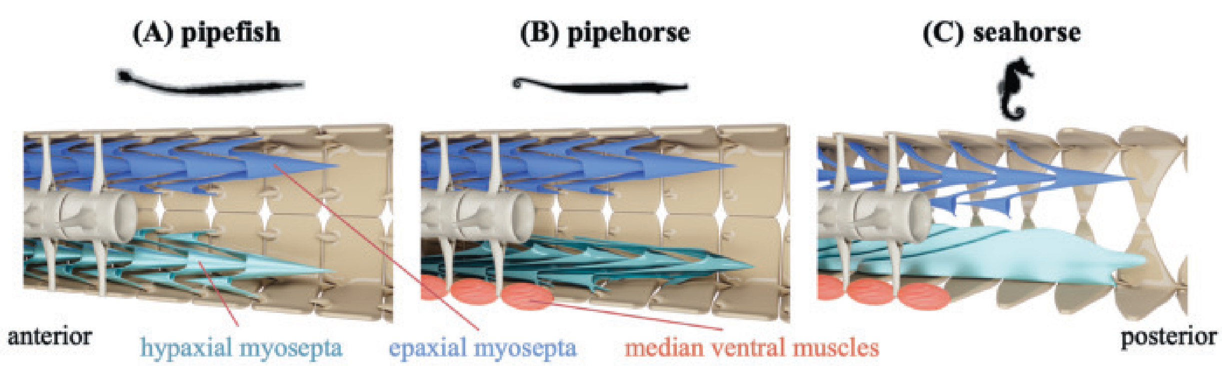
Most other animals with prehensile tails, such as primates and chameleons, don't have these long muscles. Only a few mammals, such as binturongs and kinkajous, do. "Seahorses don't hang upside down, and they have hydrostatic pressure that keeps them up, so they don't need a very powerful system, which could explain why they have something different," Adriaens says.

The bony plate armor of seahorses may also have influenced their muscle evolution. As the muscles contract, they shorten and bulge, but their volume is constrained by the plates. As a result, the whole tail stiffens, which helps it to hold on. "I'm convinced that without the body armor, this long musculature would never have emerged," Adriaens says. "It wouldn't make sense if the attachment points were pulling on the skin, which would just deform instead of properly transferring the forces."

These studies also refute prior theories about the roles of these muscles. Some experts thought that the long muscles were for quick grabs whereas the short muscles held on for long periods, but these newer results indicate it's more a case of them working together. "If you see a seahorse in action, there's not that much bursting movement happening," Adriaens explains. "They're actually pretty slow."

To learn more, the team next plans to build models that taper toward the end, and to study the joints between the bony plates. Such insights could help the seahorse's biomechanics find application in robotic devices. Adriaens and his colleagues envision possible applications in microsurgery, flexible splints that allow selective immobilization, or a robotic arm that could help lift patients. Adriaens notes that it feels like a full-circle moment to apply seahorse biomechanics to robotic technology, because such technology allowed them to create the models used in this study. "Without these engineering tools," he says, "we could never have tested these hypotheses on adaptive evolution in a biological system." —*Fenella Saunders*

Pipefish, pipehorses, and seahorses are closely related, but only seahorses orient vertically. Pipehorses have somewhat prehensile tails, but orient horizontally. Tail musculature may relate to their differing abilities. Pipefish (*A*) tail muscles consist only of short segments, labeled *hypaxial* and *epaxial myosepta*. Pipehorses (*B*) and seahorses add short median ventral muscles. But only seahorses (*C*) have elongated hypaxial muscles (*light blue in C*).



D. Marzougui, et al. 2025. *Interface* 22:20240876

How the Transistor Shaped Music

The improvement of the radio as an early application of this technological advance ended up influencing youth culture.

Ainissa Ramirez

When Patrick E. Haggerty was discharged from the Navy after World War II, he was itching to make a name for himself. In the spring of 1945, this 31-year-old electrical engineer joined a Dallas company called Geophysical Service Incorporated (GSI), which hunted for subterranean oil and gas using sound waves created by detonating dynamite. As his schoolmates from Marquette University in Wisconsin would have expected, Haggerty quickly climbed the corporate ladder. By 1951, he was the executive vice president and tasked with finding new lines of business. Haggerty knew exactly what that should be from his time as head of the Electronic Production branch of the Navy's Bureau of Aeronautics. Haggerty, who was short in stature but not ambition, aimed GSI toward being a manufacturer of a technology conjured up at Bell Labs just a few years earlier—the transistor.

On a wintery day in 1947, Bell Labs scientists John Bardeen and Walter Brattain had successfully created a working transistor, while their boss William Shockley was snowbound and working away from the laboratory. Transistors were a breakthrough of a generation, entering electronics into a new age. They controlled the flow of electricity, as well as amplifying it, using semiconductor materials such as germanium and silicon, unlike the wire and grid assembly inside the evacuated bulbs of vacuum tubes. Although the physics of semiconductors escaped the comprehension of most, what was clear was that transistors would reduce the size of machines and make equipment more reliable with fewer breakable parts. The military was always an early adopter of technology, which is a posture that Haggerty had also adopted while in service. The transistor was the discovery of a lifetime, and Haggerty wanted in.

Bell Labs, the research arm of Western Electric, possessed the transistor patent, which could be used with a license at a cost of $25,000 (about three times the price of a house at the time). Haggerty knew this moment was his golden opportunity and reached out to Western Electric, as his company GSI changed its name to Texas Instruments, ushering in its new focus. But Western Electric didn't move forward with the inquiry. This reaction wasn't completely uncalled for because Texas Instruments (or TI) had neither a transistor expert on its payroll nor the proper manufacturing equipment on its factory floor. Nevertheless, Haggerty spent most of 1951 badgering them and taking night classes in physics at Southern Methodist University. When Bell Labs offered licenses in the late part of 1951 to anyone willing to pay the fee plus a 5 percent royalty, Texas Instruments sent a check. Haggerty now had his admission ticket to the future.

By 1952, Haggerty's luck also improved. Gordon Teal, a Bell Labs chemist originally from Texas, was hankering to return home. Teal was one of the transistor's pioneers; he had figured out how to repeatedly produce the thinking part of the transistor, the germanium crystal, which he pulled out of a molten pool, nucleating it like rock candy on a string. Haggerty offered Teal a position as director of TI's research laboratories. Teal joined on the first day of 1953, putting Texas Instruments in a position to go from zero to hero in a hurry.

Despite all of this success, Haggerty was a bit restless. By 1953, five years had passed since the invention of the transistor, and there was as yet no civilian commercial market for it, besides a small demand in hearing aids. Transistors were in a conundrum: There wasn't a mass market for them because they were too expensive, and transistors were too expensive because there wasn't a mass market for them. Haggerty could manufacture transistors, but there would be no place for them to go. So, he decided to create a market and convince consumers of the need, like an early Steve Jobs. Haggerty would embark on an expensive marketing campaign in which he would show what was possible with transistors—and that his company was open for business in manufacturing them—by building the world's first pocket-sized AM radio using germanium transistors.

Radio Revolution

Texas Instruments planned to make the heart of the radio—the germanium

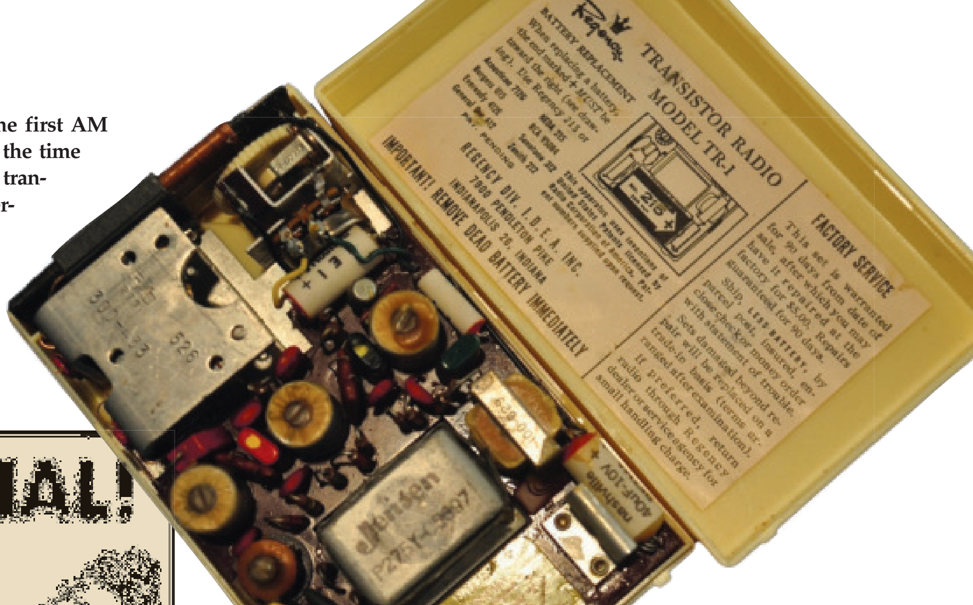
QUICK TAKE

Invented in 1947, transistors were a breakthrough in controlling electricity in devices, but they initially lacked a civilian commercial product market that would reduce their cost.

The first major products envisioned for transistors were portable, pocket-sized AM radios, but keeping them compact and inexpensive required innovative engineering.

Creating small, portable radios had the unexpected outcome of influencing youth culture, as teenagers could now listen to their choice of music away from adult supervision.

The Regency TR-1 radio, released in 1954, was the first AM transistor radio, as touted in advertisements from the time (*bottom left*). The radio included four germanium transistors from Texas Instruments, in a feat of engineering that kept the number of costly components down. The radio also had an earphone available (*bottom right*). Although the company originally envisioned the radios as marketable to people with fallout shelters, teenagers soon took to the listening freedom they enabled.



Joe Haupt, Wikimedia Commons

transistors—but they needed to find a partner to help make the rest of the device. A pocket-sized radio required miniaturizing all the parts and then packing those parts together. Some of the companies they approached were unconvinced about transistors, some companies thought the idea was poorly conceived, and some companies had their own secret projects in the works. None of them had interest in working with an unproven company in Texas.

Haggerty wasn't discouraged. Legend has it that he spotted a newspaper advertisement for a small Indianapolis engineering firm named Industrial Development Engineering Associates (IDEA). IDEA built a small electrical box that went on top of a television that boosted the signal, so that viewers could watch *I Love Lucy* with less static snow. This Hoosier company sold electrical accessories such as ultrahigh frequency (UHF) television channel converters and television boosters through Sears. Executives at IDEA agreed to meet with TI at the Chicago Parts Show in May 1954, starting this corporate courtship. After a successful first meeting, the leadership of IDEA made plans to visit Texas Instruments in Dallas. Now, Haggerty needed something to show them.

On Friday, May 21, 1954, Haggerty assembled a team of Texas Instruments engineers and told them that he wanted them to make a working radio on a breadboard using germanium transistors. In those days, a "breadboard" was a wide wooden kitchen utensil with electronic circuitry strapped to it to ease the process of design changes. Haggerty wanted to demonstrate that a radio was feasible, and for now he didn't care about its aesthetics. The unit just had to work to show their potential partner. The team had five days.

As bleak as this looked for these short-sleeve-shirt–wearing engineers, they had been here before. Many had been in the Navy and were accustomed

Courtesy of Texas Instruments, Inc.

Texas Instruments' earliest transistors were made from germanium, and later silicon.

to working under tight deadlines. Additionally, Haggerty had created an environment in which people worked past their personal limits. This assignment was a formidable one because there was no electrical schematic, few parts, and little experience in using the transistor. Under the fluorescent lights, they worked for four days (and nights). On Tuesday afternoon, May 25—a day ahead of schedule—they arrived at Haggerty's office with a prototype.

The team's design contained eight germanium transistors. When Haggerty saw this number, he insisted there had to be fewer. The radio was slated to cost \$49.95 and each transistor cost around \$16. Building and selling this radio was part of Haggerty's overall campaign to generate a consumer market for transistors, so he wanted to at least break even. He showed this prototype to IDEA, and they expressed interest. But Haggerty knew there were too many transistors.

The Texas Instruments engineers continued to make modifications, and Haggerty continued to move the goal posts. Not only did he want fewer transistors, the radio had to fit inside an Emerson 747 radio (roughly 16 × 7.5 × 3 centimeters). The engineers wrangled with the electrical parts and brought the number of transistors down to seven, and then six. Haggerty showed this new version to the president of IDEA, who was convinced, even though the radio worked poorly. The leadership of IDEA believed that pocket radios would soon be inside of all fallout shelters—a common structure at the time because of the Cold War, and thus a significant market. As such, the courtship between the two companies evolved into a partnership in June 1954. The goal was to have pocket-sized transistor radios in time for Christmas. Such an endeavor would usually take a year. They had six months.

Shrinking the Radio

To make a radio that size, everything had to be miniaturized—from the antenna to the battery. IDEA hired a Chicago design firm called Painter, Teague, and Petertil to create the mock-up of the radio's pocket-sized plastic case. Real estate inside the radio was at a premium, too. The Texas Instruments engineers had a design with six transistors, but only four were allowed. Fortunately, Richard Koch, an engineer at IDEA, created a way to get the number of transistors down to five, and then to four, by modifying the radio's *superheterodyne* circuitry, which converts high-frequency radio signals to a lower, fixed frequency for easier processing. Although his modifications lessened the radio's audio power output, these much-needed trade-offs kept costs down.

Back at Texas Instruments, making the transistors was also challenging. At Bell Labs, Teal had grown flawless germanium crystals in a laboratory environment. Now that process needed to be scaled up, and engineer Mark Shepherd supervised that work in the Semiconductor Products Laboratory. In the open space of the Texas Instrument plant, tall towers for pulling crystals from molten germanium stood one right next to another. Engineers dutifully watched and noted the results of every experimental change. Even under this intense scrutiny, the amount of "bad" germanium transistors produced outnumbered the collection of "good" ones.

Transistors were a breakthrough of a generation, entering electronics into a new age.

Despite these technical challenges, Haggerty made a bold move. He publicly announced the pocket-sized Regency TR-1 transistor radio. Readers of *The New York Times* saw on October 18, 1954, that "the new pocket-size unit utilized only four transistors." Yet, only a handful of working prototypes had been built by that autumn day.

To meet this deadline, the months of November and December were seven-day weeks. Everyone worked—and worried—as components came in from all corners. New components were created, too. Speakers had to be made smaller, aluminum foil that blocked unwanted signal had to be made thinner, and volume knobs had to be made tiny. On top of that, there seemed to be a new problem every week. The soldering gun got too hot for the transistors. The circuit board did not fit inside the radio case. Sometimes, batteries arrived dead. Even so, by continuously meeting every challenge, the multicompany team's persistence was rewarded, as scores of nameless women, sitting at long tables at IDEA, meticulously assembled the tiny electronics. Haggerty created his big splash in time for Christmas.

By January 1955, Texas Instruments and IDEA had sold 1,500 Regency TR-1 radios. By April, 32,000 units had been sold. A year later, 100,000 transistor radios had found good homes. The number of radios did not reach the dream of millions shipped. Nevertheless, this innovation showed that this small company in Texas was a big player in the new game of transistors. But their little radio would have other impacts on society, too.

Spreading the Blues

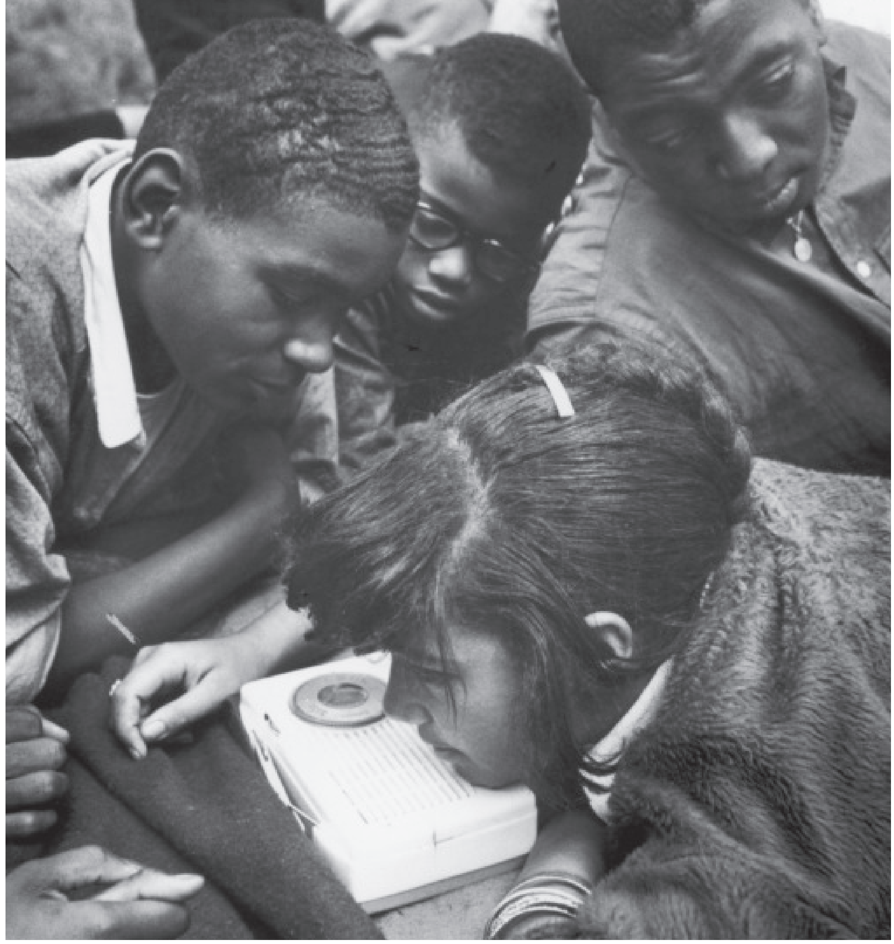
For generations, enslaved souls had turned their sorrow into song in the cotton fields of the Mississippi Delta. Using their African traditions, they created a music that centered on rhythm, because the drum was central to music on that continent. Those who had been transported across the Atlantic Ocean on the leg called the Middle Passage, from Africa to the West Indies to America, then combined this custom with the call-and-response practice of African work songs, creating a new musical style. This new music did not stay on the cotton fields, however. It became part of church music, which adopted these elements as loud voices lifted up to heaven in what is called gospel music. It is when singers focused this church music onto secular—and earthbound—heartache that they sang the blues.

The blues then spread from the South to the North with the movement of African Americans escaping the terror of the South, during what was called the Great Migration. One of those souls was McKinley Morganfield (better known as Muddy Waters), who left Mississippi for Chicago with a suitcase and his guitar. When he "electrified" the Delta blues with his musical instrument and his playing style, he helped create rhythm and blues, which was later crossbred with other forms of music and instruments. By the middle of the 20th century, this fresh, underground sound continued to evolve, with many other musicians adding to it. When Little Richard and Chuck Berry sprinkled in their frenetic dynamism, the development of this music was complete, and rock and roll was born.

White teenagers found rock and roll to be irresistible, and they bought these records in droves. Yet not everyone possessed an appreciation for this American musical invention. In a racial backlash, some tried to stop the spread of rock and roll by ceasing record sales and by censoring airplay. However, those efforts became futile when a white Memphis boy with slicked-back hair named Elvis Presley channeled Sister Rosetta Tharpe as he sang. Elvis's swinging hips crushed this resistance.

In an effort to curtail the listening of rock and roll, parents banned it from being played on their home radios. For them, the radio was an innocent thing that connected the public with news, boxing matches, game shows, dramas, and "their" kind of music. Parents were not alone in their dislike. Crooners such as Frank Sinatra testified to Congress in 1958 that he found rock and roll to be "brutal, ugly, desperate, vicious" and "lewd." Nevertheless, the ethereal nature of music made it difficult to contain because teenagers were aided by a new technology—the transistor radio.

The transistor disrupted traditional radio listening in many ways. In the early days, the vacuum tube inside a radio made it possible for a disembodied voice to miraculously emanate from the device's speaker. Yet, these early radios were cabinet-sized and expensive. They were also riddled with problems, because vacuum tubes got hot, were power hogs, and broke easily. When the transistor was born, it surpassed the vacuum tube. The tiniest of vacuum tube radios played music for three to five hours of battery life; a portable transistor radio got 20 to 30 hours of airplay and could keep up with the musical parade of Top 40 rock and roll shows. Furthermore, the newfangled transistor radio, with its nifty single earphone, allowed teenagers to listen away from parental disapproval. When taken out, music could be shared with peers using the built-in speaker. With the transistor radio, teenagers were able to connect to one another and carve out their own culture.



Archive Photos/Getty Images

In the late 1950s and 1960s, American teenagers across the racial divide, both African American and white, cherished their small, portable transistor radios for the access to current music that they provided, away from parental ears.

Mixed Reception

The transistor proved to be an achievement worthy of a Nobel Prize in Physics, which was awarded in 1956 to the Bell Labs scientists John Bardeen, Walter Brattain, and William Shockley. But understanding this new class of semiconductor materials was not what made this invention significant to teenagers. What made the transistor radio so special was that these clever materials made the radio pocket-sized, putting the music that spoke to teenagers within earshot.

Unfortunately, one originator of the transistor did not feel the same euphoria for the impact of this invention. When Nobel Prize–winner Walter Brattain was asked about the transistor radio a few decades after his discovery, he was both pleased and disgusted. "People," said Brattain, "don't have to know how to read and write to know what is going on in the world." By connecting the world through the airwaves, the world became, as Samuel Morse had hoped for with his telegraph, "one neighborhood." But Brattain's enthusiasm changed when it came to discussions about music. "The only regret I have with the transistor," said Brattain, "is its use for rock and roll music." He added, "It is not, in my estimation, music . . . just noise."

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Ainissa Ramirez received her doctorate in materials science from Stanford University, and was later an associate professor of mechanical engineering at Yale University. She was the Arthur Molella Distinguished Fellow at the Smithsonian Institution, as well as the Chair of Technology and Society at the Library of Congress. Her latest book, The Alchemy of Us *(MIT Press, 2021) was a* Los Angeles Times *Book Prize finalist. Website: www.ainissaramirez.com*

Policy

Support Scientists Who Stand Up

Researchers should not have to endure death threats or public attacks when they engage publicly and try to combat misinformation.

Michael E. Mann and Peter J. Hotez

We now find ourselves in a uniquely challenging environment to fight the rising tide of the modern-day antiscience movement, politically and ideologically motivated opposition to science from powerful special interests. The good news is that the fundamental obstacles aren't physical, or biological, or technological. They are political. And political obstacles—even in today's fraught geopolitical environment—can be overcome.

Scientists are vulnerable to bad-faith attacks, in part, because in many instances the public does not have a deep understanding of what it is that we actually do as "working scientists." They do not understand how we struggle over revisions of scientific papers and grants, prepare to present our findings at scientific meetings, and mentor our students and postdoctoral researchers. They don't understand the process of scientific grant applications, the competition for funds, or the reviews by independent scientists. They're unaware, for example, that grants go to the institution, not the individual, and fund our research rather than going to our pockets. During the COVID-19 pandemic, one of the talking heads on Fox News—of all people, now National Institutes of Health (NIH) director Jay Bhattacharya—accused one of us (Hotez) of being "funded by Fauci's group" because his lab receives support from the National Institute of Allergy and Infectious Diseases (NIAID) of the NIH; in fact, the funds go to the Baylor College of Medicine and Texas Children's Hospital, and then-NIAID director Anthony Fauci had no role in the grant decision-making process, which was scored and ranked by an independent study section of outside scientists. Instead, Fox News viewers were given the impression that funding to Hotez's laboratory represented some type of unsavory backroom deal. Therefore, part of science education relies on explaining the processes of the scientific endeavor.

Protections need to be extended to scientists who face bad-faith, ideologically motivated attacks aimed at discrediting or intimidating them.

One reason many scientists choose not to engage with the public is the fear that they will find themselves at the center of ideologically and politically motivated attacks aimed at discrediting and intimidating them. Indeed, the intent of these attacks is to serve notice to others who might think of speaking up and speaking out. In *The Hockey Stick and the Climate Wars*, one of us (Mann) coined a term for the phenomenon, *the Serengeti Strategy*, or the strategy of trying to pick off vulnerable scientists and make an example of them for the rest of the community. Although this book focused on the intimidation campaign against climate scientists, the principle holds in any area of science.

That is why individual scientists must stand up to the attacks. It sends an important message to others that we, as a community, will not take these attacks lying down. Although there are broad U.S. constitutional protections for free speech, false and defamatory statements receive no such protection. One of us (Mann) speaks from personal experience here. Back in 2012, he was subjected to false allegations of fraud by two right-wing writers (Mark Steyn, in the *National Review*, and Rand Simberg, for the Competitive Enterprise Institute) who, adding insult to injury, drew parallels between Mann, a Pennsylvania State University professor at the time, and Jerry Sandusky, the former assistant football coach of that institution who was convicted of child molestation. Mann demanded a retraction and apology. When neither individual was willing to do so, he took them to court. As a public figure, there's a high bar for winning a defamation suit. The plaintiff must demonstrate what's known as "actual malice," that is, that not only were the defendants' statements false,

QUICK TAKE

Scientists are often wary of engaging with the public because they fear that they will make themselves targets of ideologically motivated attacks.

Scientific institutions and societies need to have a stronger focus and develop new standards for protecting their affiliated scientists who might experience such threats.

Models of protection for scientists already exist to some extent in the climate science field in the form of a legal defense fund, and internationally in laws that protect health care workers.

Sait Serkan Gurbuz/The Associated Press

Climate scientist Michael Mann (*in red plaid shirt*) stands with science celebrity Bill Nye and many other scientists and supporters during the March for Science in 2017. Mann and Nye both also spoke during the "Stand Up for Science" rally in 2025.

but they either knew they were false or (citing the famous *New York Times Co. v. Sullivan* standard) showed "reckless disregard for the truth."

Although it took 12 long years to play out and there are still appeals, Mann prevailed, with a Washington, D.C., jury unanimously finding in his favor in early February 2024. Mann received countless calls and messages from fellow scientists, policymakers, and heads of major scientific institutions, thanking him for persevering. They understood that this victory wasn't just for one scientist. It was a victory for science and fact-based discourse. At a time when scientists are being harried by conservative politicians and receiving death threats from unhinged individuals who have been weaponized by antiscience disinformation, this victory was a small but significant one.

There is a bit of a postscript to this episode that deserves mention. Steyn, later that same year, was slapped down in the U.K. courts for his wanton and dangerous promotion of antiscience, this time about COVID-19. Steyn hosted a show in the United Kingdom on the right-wing network GB News. In April 2022, he falsely asserted that official U.K. health data demonstrated that vaccines caused higher infection, hospitalization, and death rates. Then, in October 2022, he had conspiracy theorist Naomi Wolf come on his show and insist to viewers that COVID-19 vaccines were part of an effort "to destroy British civil society," and that this constituted "mass murder" akin to "doctors in pre-Nazi Germany." In response to numerous complaints about the two episodes, the British media regulatory commission Ofcom ruled in March 2023 that GB News had violated British media codes of conduct, finding that Steyn had given a "materially misleading interpretation" of COVID-19 data "without sufficient challenge or counterweight," causing potential "harm to viewers." They determined that Wolf had promoted "a serious conspiracy theory," with GB News failing to take "adequate steps to protect viewers" from "potentially harmful content." Steyn insisted that these actions "killed" his career and sued Ofcom. The high court of the United Kingdom rejected the suit, ruling that Ofcom was "entitled to conclude" that Steyn had violated its rules and that their deliberations had been "detailed and comprehensive." Steyn was ordered to pay Ofcom substantial legal costs.

Supporting Scientists

Such legal victories—important as they are—are nonetheless the exception to the rule. Scientists typically depend on the backing of their employers, that is, universities or government science agencies, for legal protections. In some cases, however, this support does not happen, and the scientists must arrange their own legal defense, often at considerable expense. Some of these same scientists are abandoned by their employers after receiving baseless attacks online or, in many cases now, actionable threats of physical harm.

We must consider expanding protections for scientists. A possible model is the Climate Science Legal Defense Fund (CSLDF) that one of us (Mann) played a role in establishing more than a decade ago. The CSLDF supports climate scientists who are threatened with legal action over their scientific work or who are subject to frivolous and vexatious open-records or Freedom of Information Act demands, the only intentions of which are to harass them. Such protections need to be extended to biomedical scientists and scientists in other fields who face bad-faith, ideologically motivated attacks aimed at discrediting or intimidating them. One of us (Hotez) has suggested creating a clearinghouse of individuals and organizations generating antiscience disinformation and providing legal advice and access to

Aurea Del Rosario/Associated Press

Claudia Sheinbaum, a climate scientist who holds a doctorate in physics, interacts with supporters during a campaign rally in March 2024. She went on to be elected as the president of Mexico in June 2024. Scientists hope she will fight against antiscience disinformation in this role.

pro bono legal representation for scientists under attack. In the United States, we could also create federal protections for scientists along the lines that Canada now has had in place for two years, in the form of laws to protect health care providers from threats and bullying. In the meantime, the Texas-based Cynthia and George Mitchell Foundation is exploring with Hotez the prospects of creating a CSLDF-like structure, but for biomedical scientists.

Independent scientific bodies such as the National Academies of Sciences, Engineering, and Medicine are in a position to take action. On April 28, 2024, we participated in a plenary panel at the annual meeting of the National Academy of Sciences titled "Scientists Under Fire," along with Anthony Fauci and Yale Medical School immunobiologist Akiko Iwasaki. The audience of academy members expressed strong support for the National Academies taking a more proactive stance in supporting scientists who find themselves subject to attack. We believe there are reasons for optimism that we may see a more proactive stance on the part of the National Academies in the years to come.

At the international level, the other national academies, including the Royal Society of the United Kingdom, must step up as well. The recent call to action by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) advocating for the "promotion of scientific freedom and the safety of scientists" provides a model for the sort of action that is needed at the international level. The UN General Assembly, the UN Security Council, NATO, and future G7 and G20 summits could prioritize efforts to slow or halt antiscience disinformation and provide basic protections for scientists. Scientists shouldn't have to endure death threats or public attacks.

Recovering the Pro-Science Right

Let us not neglect communicating with conservatives altogether, even if the returns on our investment might seem diminished. Uncoupling antiscience from the bedrock of conservative thinking is critical to winning over the more than one-third of the U.S. population that self-identifies today as "conservative." Everyone is entitled to their political views but not their own facts, to paraphrase former New York senator Daniel P. Moynihan. As Jonathan Chait noted in "Donald Trump Has Finally Killed the Pro-Science Wing of the Republican Party," in *New York Magazine* in 2016, the thorough alignment of the Republican Party with antiscience is a relatively recent development. We must convince the libertarian think tanks, conservative colleges, and other right-leaning institutions that by adopting antiscience as a shibboleth today, they are undermining American strength and values and harming our country.

It's worth reminding conservatives that the Republican Party was once a party of environmental stewardship. Think of Nixon's founding of the Environmental Protection Agency (EPA) or Reagan's support of the Montreal Protocol. It once championed science and technology as a driver of progress and prosperity. And it's important to remember that a majority of the people are already on board: Polls show that most Americans do recognize the threats posed by the climate crisis and pandemics and support meaningful policy interventions. There are conservative figures who are well positioned to carry this message. A great example is former U.S. congressman Bob Inglis, a "Reagan Republican" House member from South Carolina who lost his congressional seat because of oppositional support from Koch Industries (the world's largest privately held fossil fuel company) after he voiced concerns about global warming and advocated for addressing climate action. Now, Inglis travels the country advocating for market-driven solutions to the climate crisis to conservative audiences.

Speaking Up

In the meantime, we can and must use our voices, organize, speak out, pressure our elected representatives, call out and ridicule the bad actors, be brave, speak truth to power, and back up others willing to do the same. In March 2025, one of us (Mann) spoke in Washington, D.C., at the "Stand Up for Science" rally held at the Lincoln Memorial, along with other notable science figures such as Bill Nye, Francis Collins, and former Michigan Republican representative Fred Upton, a proscience advocate. Midterm elections—which are just a year away—are an opportunity to potentially win back at least part of our government to the side of science, reason, and responsibility. This ship won't be turned around on a dime. It will take sustained effort.

We can join with our fellow scientists and organize and pressure academic and scientific institutions to take a more proactive stance against antiscientific disinformation and to provide support and defense for scientists subject to concerted attacks on science and academia. We've seen some progress here over the past decade. Back in 2012, Andrew Weaver, a leading climate scientist from the University of Victoria in British Columbia, Canada, ran for higher office. He was elected as the first Green Party member of British Columbia's legislative assembly in 2013 and went on to become the leader of the Green Party of British Columbia in 2015. He used this platform to push for clean energy and oppose the expansion of liquefied natural gas. Climate scientist Claudia Sheinbaum, however, took it to a new level in June 2024, running for and being elected president of Mexico. It remains to be seen just what she will do with this platform.

Of course, you hardly need to be a scientist to play an important role. It often comes down to voting, and not just at the presidential level, but at the state and local levels. Even the 2024 election offered at least one silver lining in the climate domain: Climate initiatives did well across the country. Voters in Washington state rejected a ballot measure that attempted to repeal the state's cap-and-trade system for emissions reductions, while voters in California and Hawai'i overwhelmingly passed measures to invest in climate resilience. Voters in the fossil fuel stronghold of Louisiana approved new incentives for clean energy.

Ultimately, it comes down to us, as individuals, working toward the needed change. It is all too easy to become disillusioned and disengaged. So we must remain focused on pushing back against the tide of antiscience, and on advancing the cause of evidence-based science and science-based policy.

Social transitions tend to happen at a tipping point in collective consciousness, estimated by some to be a critical mass of 25 percent of the public.

Across human history we have learned how social transitions tend to happen through "tipping points" in collective consciousness. A 2018 study in the journal *Science* by Damon Centola of the University of Pennsylvania and his colleagues found that the "opinion of the majority could be tipped to that of the minority" if it reaches a "critical mass," estimated by some to be roughly 25 percent of the public. For instance, this concept may explain how we achieved a tipping point in public support for marriage equality in the United States. To paraphrase *Guardian* columnist George Monbiot, social change seems "impossible"until it becomes inevitable. And as commented by early 20th-century trade union activist Nicholas Klein: "First they ignore you. Then they ridicule you. And then they attack you and want to burn you. And then they build monuments to you."

But the point is clear—we must push forward, confident in the knowledge that this benevolent tipping point in public consciousness could be near, while mindful of the fact that it must occur before we experience malevolent tipping points in public and planetary health.

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Escaping AI's Magic Black Box

Scientific explanation can help to solve the shoggoth problem.

Robert T. Pennock

Science fiction writer Arthur C. Clarke said that any sufficiently advanced technology is indistinguishable from magic. The artificial intelligence (AI) technology of chatbots based on large language models (LLMs) is magical in just this sense. Speak a magic word to summon the AI and your wish is granted, with no explanation of how your preferred genie—ChatGPT, Claude, or Siri—does (or sometimes doesn't quite do) the trick.

There are two sorts of magic: the supernatural magic of genies and demons, and the natural magic of magicians and escape artists such as Houdini. Engineering technology should be of the second kind. Although a small number of users believe that their chatbot is the voice of God, most accept it as the magic of engineering. What is unusual about LLMs today, however, is that the engineers themselves are not quite sure how the AI works; LLMs are spoken of as mysterious black boxes.

This situation is worrisome. To fix any machine that breaks—be it your automobile or your chatbot or a melding of both, such as the fictional AI car KITT from the sci-fi show *Knight Rider*—requires being able to explain what happened when it doesn't function as intended. Engineers must understand its workings to face and exorcise the devil in the details, on pain of abandoning the scientific basis of their vocation.

It was Herbert Simon, who is credited as the father of computer science and AI, who laid out principles to connect engineering and science in his pioneering 1969 book *The Sciences of the Artificial*. Simon explored the design of artificial systems in a deep sense, encompassing not only engineering, but also the organization of business firms and entire economic systems, for which he won a Nobel Prize in Economics. Design is a process that can be understood scientifically, he argued, if it is conceived as a form of problem-solving, which can be analyzed and evaluated in terms of *means-ends satisfaction*—in other words, what means can be used to satisfy certain end goals. The challenge engineers now face is whether black box AI is explainable in a way that suffices for it to be considered responsible technological design.

The AI engine that drives chatbots is called a "black box" because engineers can't explain exactly what happens under the hood.

The AI Black Box

The first mysterious AI box was the Mechanical Turk automaton chess player that fooled audiences for decades beginning in the 18th century. Purportedly run by an automatic clockwork, the Turk was a magic trick with a cleverly concealed person inside. Such deceptions still occur; Microsoft was recently fooled into investing in Builder.ai and its Natasha AI assistant, which turned out to be human coders in India doing most of the work manually. But we do now have the real thing. AI has played chess at grandmaster level for years, and there need be no hidden humans in the box. LLMs, in many circumstances, can pass what is called the Turing test, in which one cannot distinguish whether one is conversing with a human or a machine. So, given these accomplishments, why is the AI engine that drives chatbots called a "black box"? An airplane black box is a voice and flight data recorder that helps engineers explain the cause of a crash, but this usage is the opposite. Here, the term refers to AI tech where engineers can't explain exactly what happens under the hood.

Of course, the general structure of AI models is well-known. LLMs, for example, are composed of probabilistic pathways through a network of nodes representing weighted connections between inputs and outputs. As the simplest case, imagine a network whose weights have been trained on a long, boring transcript of someone calling coin tosses: flip . . . heads, flip . . . heads, flip . . . tails, and so on. Users of this machine insert a flip token when they want a virtual coin toss, and they get one of the two outputs with a likelihood that depends

QUICK TAKE

AI large language models (LLMs) are trained on huge datasets, but the exact programming that results from this training still remains a bit of a mystery to engineers.

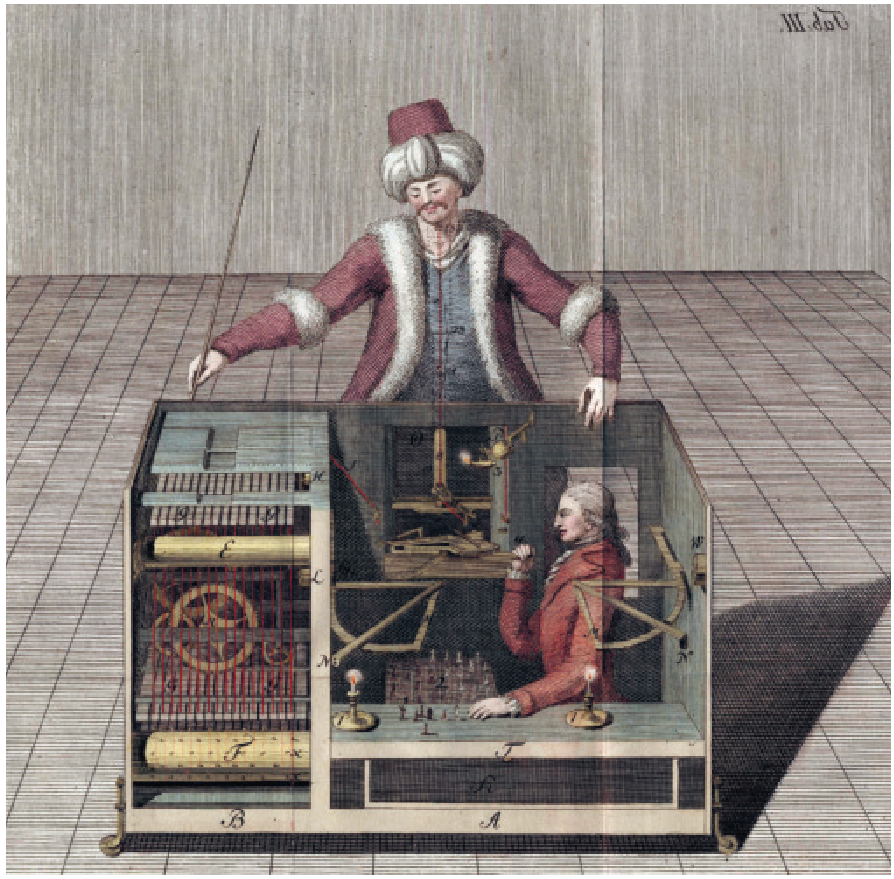
This AI black box creates ethical worries, not least because technology that is not understood cannot be repaired when it does not function as intended.

Understanding scientific explanation can help engineers frame what questions must be answered for the use of AI to be considered on strong scientific footing.

on the network weights—"heads" will follow approximately half the time if the training transcript reflected fair coin tosses (or with a different frequency to the degree that the training was biased). Now, expand the network and train it on a voluminous transcript of text scraped from the internet. Such a *foundation model* (FM) comprises billions upon billions of parameters, allowing one to input a string of tokens (one's prompt to the chatbot) and get a likely relevant output in return. Users can pay for a premium chatbot to get more tokens and a memory for more detailed responses and longer coherent conversations. Model controls such as "temperature" add randomness to promote output "creativity." And controls called "penalties" may be added to discourage repetition and promote freshness.

But what is really going on in these complex networks? AI companies hyping their latest models imply that chatbots are reasoning and predict that artificial general intelligence (AGI) is just around the corner. Skeptics, however, contend that LLMs don't reason but rather do little more than high-powered pattern matching—a souped-up version of autocomplete. As one illustration, they reference Simon's research on the Tower of Hanoi puzzle, which involves a stack of concentric rings of decreasing diameters that one must move from the first of three poles to the third, one at a time, without ever putting a larger one on a smaller. I'd always see this little puzzle on Simon's office shelf when we met; he had used the puzzle to investigate problem-solving in AI and cognitive science. The Tower of Hanoi is not a significantly difficult problem and can be solved with a bit of *recursion*—a programming technique in which a function can call on itself over and over again in order to break a problem into smaller pieces—but LLMs don't seem to do that.

For small towers, there may be enough information in the model to "solve" the problem by statistical pattern-matching of which state follows which based on solution paths included in the model's training set. No general reasoning needs to be involved in its own processing; it is predicting moves based on weights of the patterns it had experienced in training. Pattern-matching is much of what we ourselves do in human reasoning, so if that is what LLMs are doing, I'd argue



Wikipedia Commons/Humboldt University Library/Joseph Racknitz

The history of artificial intelligence as a mysterious black box, with unknown inner workings, extends back to the Mechanical Turk, an automaton chess player that was popular for decades beginning in the 18th century. The device was supposedly run by clockwork, but in reality the box was a magic trick, with a concealed person inside (although more cleverly than in this cutaway illustration). Current AI programs that are trained on huge datasets, called *large language models* (LLMs), can also be considered black boxes, because engineers cannot explain their resulting workings.

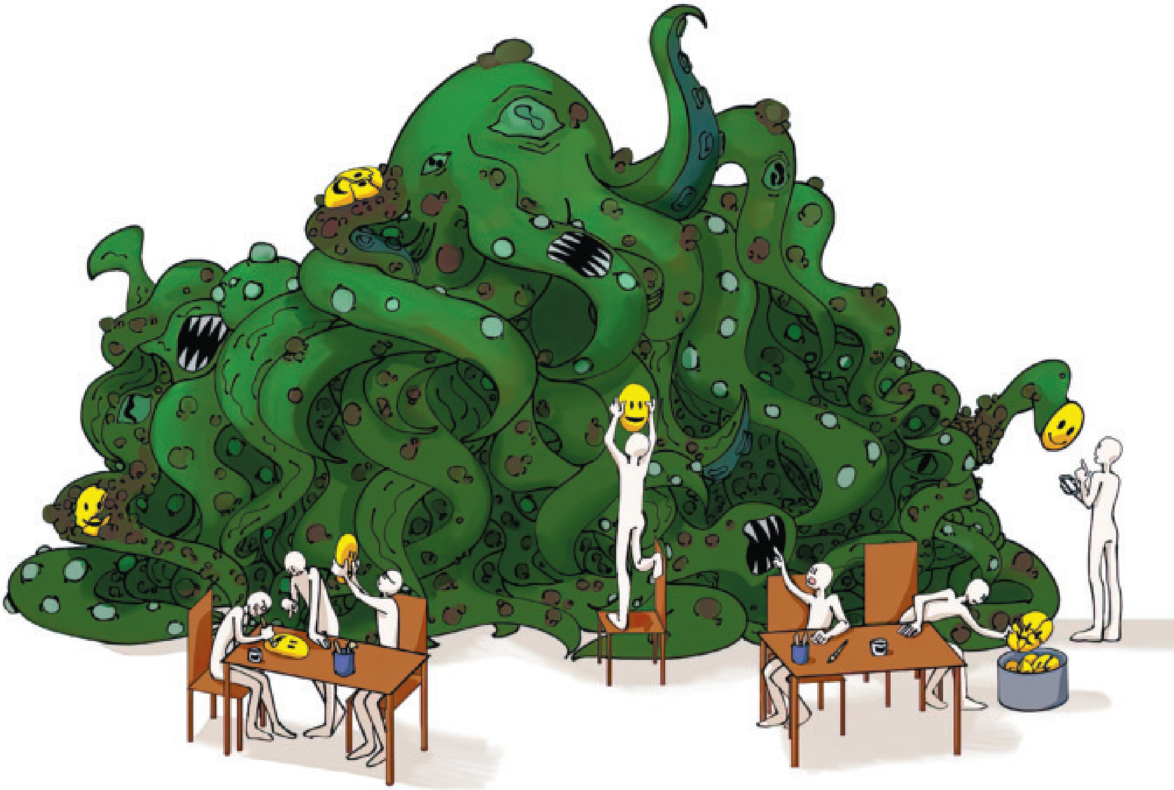
that it should still count. But unlike a recursive algorithm, we can't predict how generalizable the model is; change the problem even a little (such as by adding a ring) and its tower prowess will likely collapse. The motto of Silicon Valley has long been "Move fast and break things," but in a situation where computer scientists still barely understand how LLMs work, are engineers being pushed to implement AI too quickly?

Move Fast and Break Things?

Tech companies regularly describe AI software design using civil engineering terms. Chatbot conversations that diverge from safe parameters are said to have gone "off track." Extreme diversions, such as a chatbot claiming to be a licensed therapist and suggesting the user leave their family, or another self-identifying as MechaHitler (as the company xAI's bot Grok recently did) are described as having gone "off the rails." To protect against such situations, AI purveyors say that they construct "guardrails" to keep these chatbots from driving off the road into dangerous areas.

Such familiar language is reassuring, but it obscures AI's distinctively difficult engineering challenges. To try to avoid AI *hallucinations*, in which LLMs present confabulated false statements as fact, developers speak of building "bridges" from foundation LLMs to ground truth. They try to constrain models by "clamping" the values of features of interest to "steer" the LLMs' behavior. Erecting barricades or "No Entry" signs may be temporary fixes, but these are too easily bypassed, whether inadvertently or intentionally. LLM networks are only beginning to be mapped, and they change with each model update. Under such uncertainty, it can be risky to trust your AI to tell you where to turn, and even riskier to allow it to turn the wheel itself.

Several years ago, I attended a conference sponsored by the National Academy of Sciences on self-driving vehicles



A shapeshifting monster from classical science-fiction horror, called a *shoggoth*, has been adopted in recent memes to represent AI LLMs. The analogy is used to highlight that, despite their surface helpful mimicry, the underlying traits of LLMs are inexplicable and alien. The added smiley faces in this depiction, which here are shown to fail quickly, represent efforts to tune and train LLMs to be more human and less dangerous.

where enthusiastic researchers from universities and the auto industry showed off their state-of-the-art research. I found it ironic that several speakers had problems reliably connecting their laptops to the projector or getting their PowerPoints to work. Hubris? In large measure, their confidence that autonomous vehicles were just over the horizon has been borne out; the safety of autonomous vehicles meets or surpasses human drivers under ordinary driving conditions. One of my students spent a summer as a test driver for Waymo and said that his early anxieties had been fully overcome, and now he was eager to buy one. On the other hand, my niece sold her rogue Rogue back to the dealer last year after Nissan's (presumably since corrected) faulty anti-collision system twice falsely activated its automatic emergency brake and then disabled all other controls, leaving her immobile in the road.

Such failures become more likely as system complexity increases with multiple interacting causal mechanisms. The BEACON (Bio/computational Evolution in Action Consortium) science and technology center, of which I was a coprincipal investigator at Michigan State University, included a project that worked with major auto manufacturers on just this problem, using evolutionary computation methods to identify interaction situations that could cause unexpected dangerous effects. Even if a well-trained AI beats humans in ordinary situations, its training set will inevitably have gaps and biases, and it is likely to perform poorly compared with humans when encountering more unusual situations. Critics of autonomous vehicles regularly identify and demonstrate such cases. Despite incredible advances, KITT-level AI is still science fiction, and LLMs remain mysterious.

AI as a Shoggoth

A recent popular meme illustrates this view of LLMs such as ChatGPT by representing it as a shoggoth. *Shoggoths* are monstrous artificial entities imagined by H. P. Lovecraft in his 1936 sci-fi horror novella *At the Mountains of Madness*. In the story, extraterrestrial beings called Old Ones engineered shoggoths to be helpers; the shoggoths are protoplasmic shapeshifters that respond to mental and vocal commands. The Old Ones themselves had complex nervous systems that seemed at once archaic as well as highly specialized and advanced, with apparently extrasensory factors such that "[their] habits could not be predicted from any existing analogy." The powerful shoggoths they created are thus doubly alien.

This trait is the point of applying the term to LLMs, namely, to highlight that, despite their surface helpful mimicry, their underlying mental traits and behaviors are unlike our own, and seemingly inexplicable. The AI shoggoth meme depicts a writhing, multi-eyeballed creature with a distorted, quasi-human face at the end of a few of its tentacle-like appendages. The face is labeled "supervised fine-tuning." The tip of one tentacle protrudes like a tongue through its gaping mouth, holding a sunny-yellow smiley face labeled "RLHF," which refers to reinforcement learning from human feedback.

The dark humor of this ghastly image is that the friendly face of ChatGPT is but a surface ornament, a distraction from the alien entity that is its foundation model. Expect soon to see a meme with a shoggoth peering out from under the hood of an autonomous vehicle, running other models that steer and brake the car. Can such a KITT–shoggoth hybrid automobile ever be explainable in a suitably scientific manner? Lovecraft's story is told from the point of view of scientists, but it is not concerned with distinguishing between colloquial and scientific notions of explanation. What does a scientific explanation involve?

The Nature of Scientific Explanation

There was a short period when philosophers thought that science could not and should not purport to explain the world; the Positivists argued that science only described nature, dismissing explanation as inherently metaphysical. Philosopher of science Carl Hempel rejected their view by offering in 1948 what he called the *Deductive-Nomological* (D-N) model of scientific explanation.

On Hempel's account, a statement of fact could be scientifically explained by being logically deducible from a general empirical law and its relevant initial conditions. Think of a simple sundial where the shadow of the gnomon (a fixed vertical pole, say) at mid-morning, for example, reaches a point that indicates a certain time, say 10 o'clock. Why is the shadow of just that given length at that time? On D-N's covering law model, we can explain the shadow's length by showing that it can be deduced using laws of optics and plugging in the relevant values—the height of the pole and the Sun's altitude angle. In this simple case, science explains why the shadow is of that length at that time by reference to the height of the pole, given the Sun's position in the sky. No metaphysics required.

Hempel's work brought explanation back into the scientific fold, but important details remained. For instance, the so-called Flagpole Paradox showed that simple deduction was too loose because deductions are symmetrical. One could deduce the height of a flagpole using optical laws and the value of the shadow length, but that doesn't mean that the shadow's length explained the pole's height. Hempel's colleague Wesley Salmon resolved this and related paradoxes by bringing in causation. On his *Causal-Mechanical* (C-M) model, scientific explanation involves the relevant causal mechanisms that produce the phenomenon to be explained. The flagpole causes the shadow and not vice versa, so explanation is properly asymmetrical in this case.

The C-M model also helps resolve what might be called the gnomon paradox: Unlike the flagpole, there is a sense in which the length of a gnomon's shadow may be cited as an explanation of the pole's height in that the instrument was built in that way so that it would cast a shadow to indicate 10 o'clock at just the right time. In this distinctive case, the explanation is possible via a different, prior causal pathway. It points to other complexities.

Instead of thinking of causation as just a two-place relation (cause and effect), we need to consider the complex network of causes that produce effects in the world. To help isolate the relevant factors for scientific explanation, it helps to analyze the causal relation in a more fine-grained way. As part of my PhD dissertation under Salmon at the University of Pittsburgh, I proposed what I called the *CaSE model*, which isolates one factor of interest (C) from among the full suite of causal factors in a given situation (S), allowing one to identify it as the explanatory cause pragmatically, relative to some alternative (a), of the effect (E). Among other advantages, the CaSE model allows one to identify and test multiple possible explanations for some effect of interest. One can see how this approach works in a classic example of explaining a car accident.

AI guardrails currently are little more than ad hoc tweaks or additions to system prompts or constraints at other levels, and there is not yet a science that connects prompt inputs to outputs in a systematic way that lets one escape the black box.

A CaSE Study

Suppose investigators want to understand a car that went out of control and crashed through guardrails over an embankment. Their goal is to explain what happened so they can take action to reduce such accidents. A mechanic might point out that the car's brakes were worn so it couldn't stop quickly enough, and prompt auto owners to perform more regular maintenance. A highway engineer might realize that the guardrails were weak and recommend a more robust design. The state might note that the driver was a novice and implement tougher driver training requirements for licensure. In this scenario, each entity focuses on a different factor in the causal network, taking other factors in the situation as given.

If a new LLM-based KITT AI car were to go off the rails, we would face a similar challenge in identifying and fixing the causes of its faulty behavior. Do the errors trace back to biases in the training set data? Did the fine tuning or RLHF overlook some use cases? Had system prompts or application instructions been hacked? Or were faulty user inputs to blame?

Not all such possible causes are amenable to immediate solutions. AI guardrails currently are little more than ad hoc tweaks or additions to system prompts or constraints at other levels. It is premature to talk about studying to become a Houdini of "prompt engineering" as there is not yet a science that connects prompt inputs to outputs in a systematic way that lets one escape the black box. Even extracting and trying to tune feature values in a model will not be easy.

To give just one example, researchers at Anthropic, as they describe in a report led by engineer Adly Templeton, investigated its Claude chatbot's response to prompts involving San Francisco's Golden Gate Bridge. Their experiments allowed them to recover this feature in the network and to adjust node weights to steer it. This result is promising, but practical adjustments must be tested and tuned on a case-by-case basis; when values were too high, Claude started to mention the bridge in inappropriate circumstances and, with higher values, began "to self-identify as the Golden Gate Bridge!" It seems that bridges to ground truth still need work.

Limits of AI Explanation

Such problems are not limited to AI; we have encountered and found adequate solutions for them before and are making progress in these new cases. Although he didn't get into the details of what is needed for scientific explanation, Simon was correct that a science of the artificial is possible under certain conditions. Means-ends causal generalizations may be found for artificial systems created by natural beings like ourselves and, in principle, although likely to a lesser degree and with lesser confidence, even for shoggoths created by extraterrestrials. AIs, including AIs built by other AIs, which is what companies racing toward AGI seek, can fall most anywhere on this spectrum, so explaining their behavior may be of lesser or vastly greater difficulty, depending on the level of precision we want for specific purposes. We already can explain how LLMs work in a general causal-statistical sense. We can also explain a particular output given a particular input prompt in cases where we are able to zoom in to detect the connected pathway of nodes that fired in a network to cause it. What we are still far from doing, however, is explaining the inner workings of FMs to generalize from one FM to another, or even (given that the shift of even a single bit at some point in the sequence can, in principle, lead to an unpredictable outcome) from the same FM at one point in time to another.

The broad internet scrape that was used for the early training data of LLMs could not help but produce a shoggoth. No amount of human-supervised fine-tuning, reinforcement learning from human feedback, or ad hoc guardrail construction can ever eliminate it. Researchers are beginning to investigate ways to address this issue, by using curated training sets and by combining connectionist with symbol-based systems, for instance. But there will be no simple solution to the shoggoth problem.

Escaping the Shoggoth

To require that AI be explainable is a laudable goal. But for the time being, spelling out AI's inner workings in a scientific sense will have to be done on a more "CaSE-by-case" basis. Drawing again from Simon's insight, such decisions must be made in relation to different levels of explanation that suffice for different purposes. This outcome is not unique to the AI case; the nature of engineering design invariably involves trade-offs of time, money, and values. A high rate of confabulations is of little consequence for AIs used to generate nonplayer character dialogue in a video game, so a high-level causal explanation may easily satisfy users. The stakes are higher when a chatbot might be asked for health advice. And we would expect a rigorous, systematic explanation before we release our hands from the steering wheel and turn over other driving controls in our car to KITT.

What is satisfactory will vary. My student and my niece have different tolerances for risk, so when it comes to automative AI, they, not tech companies, should be able to decide how fast to move and what things are OK or not OK to break. In the worst-case scenario,

Robert T. Pennock

Philosopher Carl Hempel holds a gag gift created by his students; this diorama contains a mechanism that changes the length of the flagpole in response to the length of its shadow, in a play on a logical paradox about the role of directional causation in scientific explanation.

whether using AI in a car or for some other purpose they judge to be risky, users should have the ability to immediately disconnect it and regain control.

If a fighter jet is crashing, the pilot needs a reliable ejector seat button. If software is crashing, the user needs a reliable Escape key. The original purpose of the Break key on a keyboard was to interrupt and halt a running program. For AI cars, for instance, this capability should be the equivalent of exiting cruise control by touching the brake pedal, a specific feature that auto companies are implementing. Whether for self-driving technology or any other system incorporating AI, users must be in a position to make judgments about the level of risk they will accept for particular use cases, and they must have the ability to escape immediately from the clutches of a shoggoth.

Hempel's Box

As a present and tribute to Carl Hempel for his 80th birthday celebration in 1985 at the University of Pittsburgh, two of my fellow grad students crafted a box diorama of a landscape with the iconic paradoxical flagpole and shadow. When one slid its boxboard shadow, the wooden dowel flagpole magically ascended or descended an equivalent amount; the length of the shadow did explain the height of the pole! Wes Salmon grinned along with Peter (as Hempel went by to friends and colleagues) and the rest of us, knowing that it was a clever mechanism hidden inside the box that explained the effect.

As for technology design, philosophy suggests that engineers should keep in mind two responsibilities. First, they should understand the underlying mechanisms so they can explain and fix failure states. To expect that AI be explainable in this sense should be uncontroversial; it is no more than the fundamental expectation that engineering rest upon a scientific basis.

Second, they should recognize that judgments about acceptable risk ultimately are the purview of users, who must be able reject them if they wish. For AI tech, this means there must be ways to "hit the brakes"—even KITT had a switch to turn off its AI mode.

Users still want to see their devices as magical, of course, but they don't want them to be taken over by demons or shoggoths. Engineers must, like Houdini, keep the elements of the trick sufficiently under control for the magic to work. It should, in principle and in practice, be possible to open or escape from the black box.

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A Revolutionary Drug to Treat and Prevent HIV Infection

A two-decade research effort has paid off with a treatment that can disable the deadly virus's capsid, the protein shell that protects its genome.

John Raul Somoza

As scientists search for new medicines, they slog through a marathon of frustration, dead ends, and moments of great excitement. Tight-knit groups of biologists and chemists often work for years to develop therapies that can prevent, control, or cure disease. Despite that effort, success is rare: The vast majority of projects never yield a compound suitable for human testing, and even those that reach clinical trials have only a 10 to 20 percent chance of becoming an approved drug.

In June of 2010, a team I was on felt the crushing weight of those statistics. We were four years into our quest to develop a novel drug for the treatment of HIV-1 (referred to simply as HIV in this article). We had tested thousands of molecules, but none had shown any promise of becoming part of a viable new therapy. Despite hoping that we still could discover a drug that would significantly improve the treatment of HIV infection, many of us on the team worried that we would never reach our goal.

Then, in 2016, after changing our strategy, we identified a compound promising enough for clinical trials. Several years later, those trials demonstrated that our drug, lenacapavir, is effective in both the treatment and prevention of HIV infection. In December of 2022, the U.S. Food and Drug Administration (FDA) approved lenacapavir as part of a new therapy for the treatment of multidrug-resistant HIV, and in June of this year, the FDA approved a once-every-six-months injection of the drug to prevent infection.

Lenacapavir represents the latest strike against HIV in a fight that started in the 1980s when the virus was first recognized as the cause of the AIDS epidemic. Although new HIV infections have dropped by 60 percent since they reached their peak in 1995, more than one million people across the world still get infected by the virus every year, and about 630,000 die annually of HIV-related causes. And with global health programs, including those targeting HIV/AIDS, facing significant funding cuts, the progress we've made could slow. These statistics underscore the need for new tools to treat and prevent infections.

Over the decades, a number of anti-HIV drugs have been developed that disrupt the virus's life cycle and stop it from replicating. Most of these drugs bind to and shut down viral proteins called enzymes, which catalyze biochemical reactions the virus needs to perform to replicate in a host cell. Combinations of inhibitors of these enzymes, known as *combination antiretroviral therapy*, are highly effective at blocking viral replication and have had an enormous impact on controlling HIV infections. Today, when used consistently, these drug combinations have transformed HIV infection from a fatal diagnosis to a manageable chronic condition. Most people on combination therapy can expect to lead normal or near-normal lives.

But a problem remains: HIV has a remarkable ability to mutate. As a viral enzyme copies HIV's genome, it makes mistakes that result in mutations in the virus. Most of these mutations either have no effect on the virus or make it weaker. Occasionally, however, mutations arise that allow the virus to adapt to changes in its environment, enabling it to evade antiretroviral drugs. These mutations alter specific areas of the HIV proteins, making them less susceptible to binding drug molecules.

The adaptability of the virus has led to an evolutionary arms race between HIV and humans. HIV gradually becomes less susceptible to the drugs we have created, and we have had to respond by searching for drugs that attack novel proteins essential to HIV's ability to replicate. In our team's quest for a new HIV treatment, we decided to focus on a component of the virus that hadn't been targeted previously: the HIV *capsid*, the protein shell that encloses the viral genome.

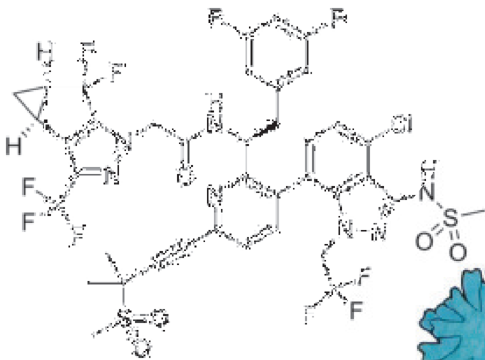
By choosing a novel target to go after, we hoped to discover an HIV treatment that got around existing resistant strains. We eventually discovered that lenacapavir successfully works as a part of such a treatment and also effectively prevents HIV infection in at-risk individuals.

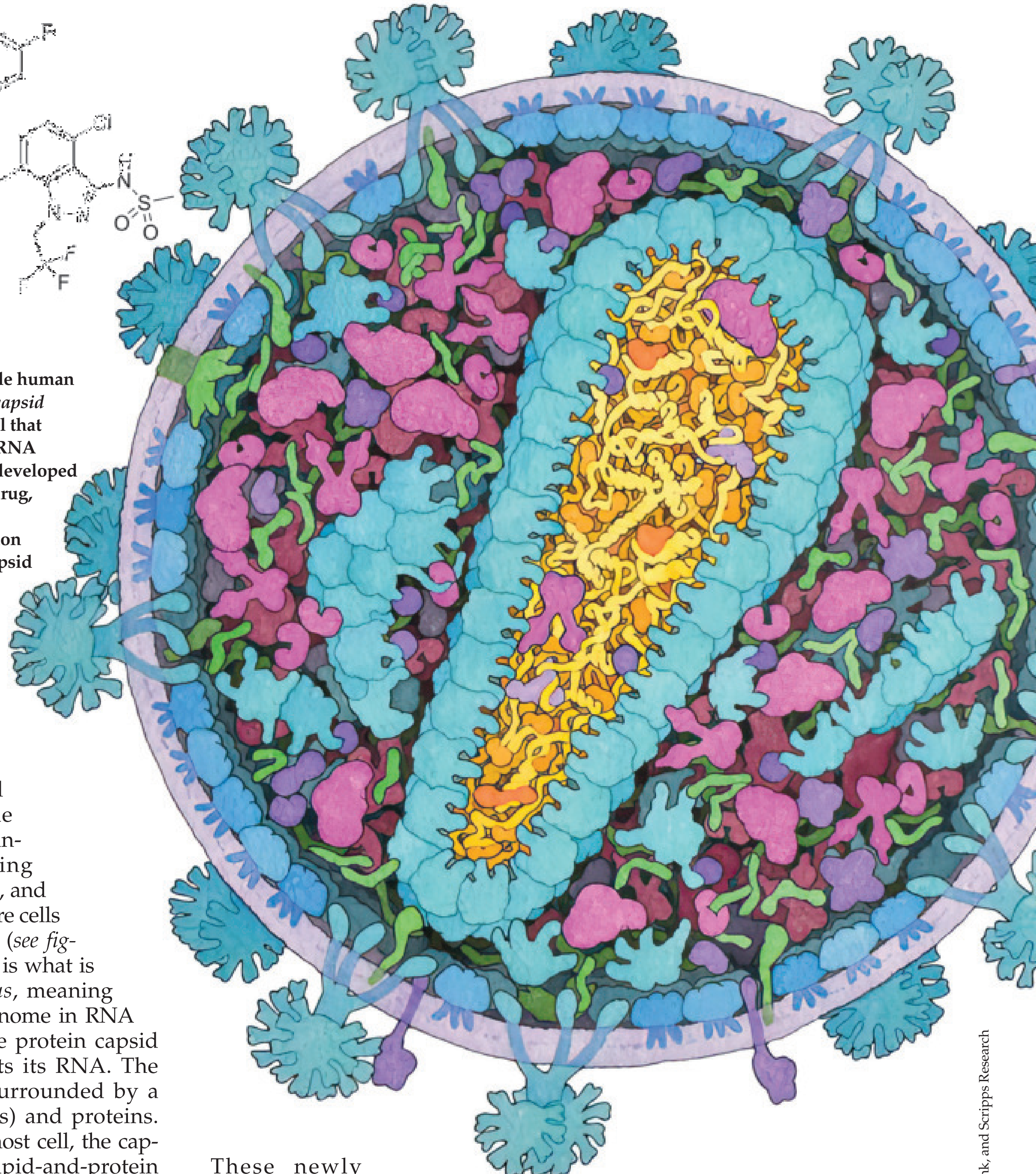
QUICK TAKE

Although scientists have developed effective drugs to treat and prevent HIV infections, the virus continues to mutate, requiring new drugs that are active against these mutations.

Researchers took a new approach in developing a novel class of anti-HIV drug that disrupts the *capsid*, the protein shell that encloses the genome.

The FDA approved this new drug, called *lenacapavir*. It is a twice-yearly injection that can treat multidrug-resistant HIV strains and prevent infections.





HIV replicates itself inside human cells with the help of its *capsid* (*light blue*), a protein shell that encloses and protects its RNA genome. Scientists have developed a first-in-class anti-HIV drug, *lenacapavir* (*above*), that shuts down HIV replication by disrupting how the capsid assembles and moves inside infected cells.

Illustration by David S. Goodsell, B-HIVE Center, RCSB Protein Data Bank, and Scripps Research

The Trojan Capsid

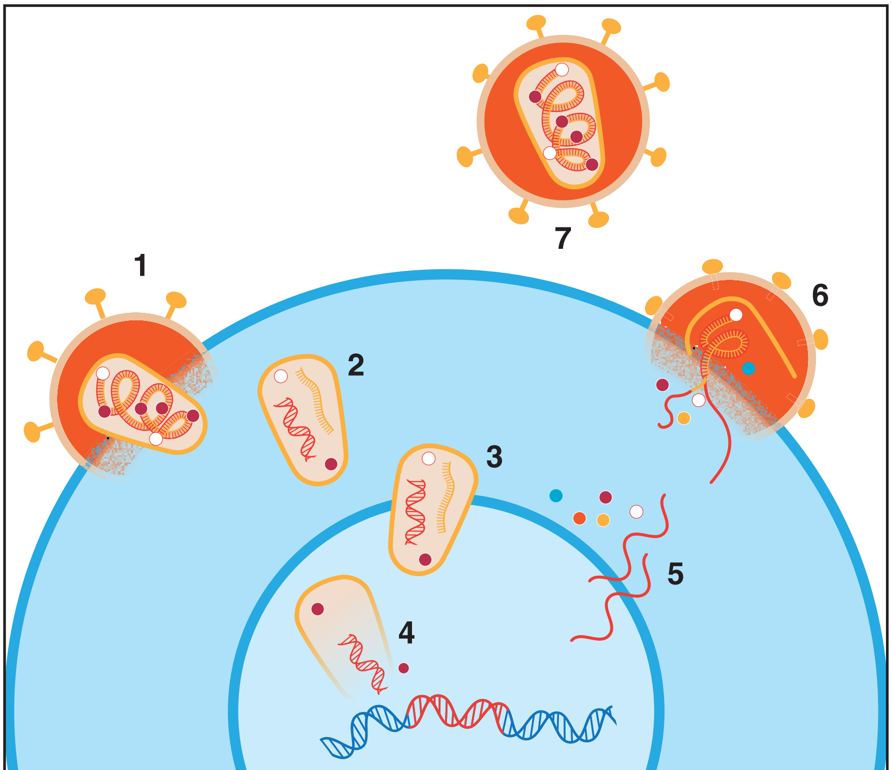
We set our sights on the HIV capsid because of its essential role in the life cycle of the virus, which involves HIV infecting cells, replicating itself, and then spreading to more cells to repeat the process (*see figure on page 290*). HIV is what is known as a *retrovirus*, meaning that it encodes its genome in RNA instead of DNA. The protein capsid encloses and protects its RNA. The capsid, in turn, is surrounded by a bubble of lipids (fats) and proteins. When HIV enters a host cell, the capsid is freed of this lipid-and-protein container, allowing it to interact with various host proteins. These protein–protein interactions help transport the capsid, along with the encased viral genome, across the cytoplasm, through a protein structure called the *nuclear pore*, and into the nucleus of the cell.

The virus uses an enzyme known as *reverse transcriptase* to convert its RNA into DNA, which then gets incorporated into the host cell genome with the help of *integrase*, another viral enzyme. When the infected host cell turns on its own genes, it also activates the virus's incorporated genes, producing the RNA and proteins needed to make new viral particles.

These newly made viral components assemble near the host cell membrane and then bud out from the cell, taking part of the cell's lipid membrane with them to help enclose the assembled viral material. At this stage, a new viral particle cannot yet infect other cells. It becomes fully mature and infectious only after *protease*, yet another viral enzyme, chops up the long protein chains that were created in the host cell. This enzymatic dicing transforms the chains into the virus's final, functional proteins, including the ones that will go on to form its capsid.

The capsid is a 100-nanometer-long protein shell composed of many copies of a molecule simply called *capsid protein*, or CA. The CA proteins group into five- or six-member rings, creating pentamers and hexamers that interact with one another, forming a shell resembling a soccer ball that has been stretched in one direction. Some 200 to 250 hexamers and exactly 12 pentamers create the capsid, with the pentamers providing the curvature needed to close off the structure and fully enclose the viral genome.

For the virus to replicate itself and go on to infect other cells, it is essential that the capsid perform its functions



When HIV enters a cell, it sheds its outer envelope and gets transported toward the cell nucleus (*1*). The virus's *reverse transcriptase* (*white dot*) copies the RNA genome into DNA (2, *3, and 4*). The HIV capsid eventually binds to the *nuclear pore* (3), allowing the virus shell to enter the nucleus, where the capsid opens and its DNA gets stitched into the cell's genome by the viral enzyme *integrase* (*red dot, 4*). The host cell turns on the viral genes, which leads to the production of copies of the virus's RNA genome and proteins (5). This material collects near the cell's membrane and eventually leaves the cell in small membrane bubbles, forming an outer envelope for the new viral particle (*6*). Inside this envelope, the viral enzyme *protease* (*blue dot*) chops up the long protein chains to yield functional proteins, including the ones that will form the new capsid (7).

Barbara Aulicino

well. The capsid must latch onto host cell proteins to be transported into the nucleus; it must undergo a well-choreographed process of disassembly to release the HIV genome; and eventually it must reassemble to form newly created viral particles.

Although new HIV infections have dropped by 60 percent since they reached their peak in 1995, more than one million people across the world still get infected by the virus every year, and about 630,000 people die annually of HIV-related causes.

In the spring of 2006, a group of researchers at Gilead Sciences in Foster City, California, proposed creating a new class of AIDS drugs by discovering a small molecule that could target the HIV capsid. In the world of drug discovery, small-molecule drugs are compounds that are small and "greasy" enough to penetrate cell membranes to reach targets within the cell. Based largely on the work of Wesley Sundquist's lab at the University of Utah, the team thought that the capsid made a good target because successful replication of the virus requires the precise assembly and disassembly of this protein shell. A compound that gums up those processes—by making the shell too fragile or too strong, or by disrupting its shape—could hurt the virus's ability to propagate.

The choice of capsid as a target was controversial at the time. Some scientists doubted whether it was possible to successfully identify a compound that would disrupt the capsid's assembly and disassembly process. Up to that point, the most common drug targets for HIV had been the enzymes crucial to HIV's life cycle: reverse transcriptase, integrase, and protease. There are several reasons why enzymes are particularly well-suited as targets for small-molecule drugs. Most significantly, enzymes are proteins that feature pockets called *active sites* where specific molecules bind and undergo chemical transformations. Those active sites are also suitable to bind small-molecule drugs that then block the work needed to be done by the enzyme.

But CA isn't an enzyme. It doesn't have pockets that have evolved to bind molecules and catalyze reactions. When CA proteins join together to form the HIV capsid shell, these proteins interact over areas much larger than that of an active site. Designing a small molecule that could bind to CA and disrupt the protein–protein interactions necessary for proper capsid function would be extremely challenging.

Despite this concern, the Gilead team decided to proceed.

Seeking a Disruptor

Once the project was approved, I joined the team that was formed to look for compounds that impaired capsid assembly. To start this process, we developed a biochemical test, or *assay*, that recreated aspects of the process that occurs inside newly budded viral particles. This assay was based on the observation that in solutions with high concentrations of CA protein and sodium chloride salt, CA proteins spontaneously self-assemble to form tubelike structures that look very much like open-ended capsids. The formation of these tubes can be seen with the naked eye as the solutions become milky-white over the course of a few hours. This cloudy haze is created by the suspended tube particles in the solution. We used this tube assembly process in the lab as a surrogate for capsid formation in the virus, allowing us to identify compounds that might bind to the CA protein and disrupt capsid assembly.

Drug discovery often involves screening hundreds of thousands of molecules to find a handful that have the potential to do what we want them to do. To screen that many compounds, we developed a high-throughput assay that was both fast and capable of telling us quantitatively how effectively a test compound disrupted capsid tube formation. In the lab, we dispensed the potential inhibitor we wanted to test into transparent tubes. We then added CA protein and started the CA tube assembly by adding sodium chloride. We monitored the formation of the protein tubes quantitatively by measuring the solution's absorbance of light at a wavelength of 350 nanometers. As the CA proteins assembled into tubes, the absorbance increased (*see figure on page 293*).

When testing compounds in this assay, we observed three outcomes. First, when a compound didn't affect tube formation, we saw the same thing that happened without any compound present: Light absorbance rose steadily as the tubes assembled, eventually reaching a plateau once the majority of CA protein had assembled into tubes. These compounds weren't what we were looking for.

Instead, we were interested in molecules that showed one of two other behaviors. For example, if adding a compound slowed or eliminated the increase in absorbance, we assumed that the compound inhibited capsid assembly. We were also interested in compounds that accelerated the rate of light absorption, although what those molecules were doing to the proteins was more difficult to interpret. We proposed that these compounds either accelerated capsid assembly or changed the morphology of the CA tubes, both of which were abilities we were interested in.

With this assay, we tested two groups of molecules. First, we synthesized and tested all compounds published in the research literature that were already implicated in binding to the HIV capsid, as well as some molecules that resembled the published ones. Also, we carried out a high-throughput screen of about 450,000 compounds from collections commonly used when screening for potential drugs.

These screens led to the discovery of a handful of compounds that affected normal capsid formation. We then wanted to see how these molecules interacted with CA in greater detail. By mixing the compounds with CA proteins and using biophysical techniques, including x-ray crystallography and nuclear magnetic resonance spectroscopy, we obtained detailed pictures of how the molecules bound to CA. From those pictures, we determined that the molecular disruptors we had identified interacted with one of two sites on the CA protein.

A Tale of Two Sites

The first site we found, which we creatively named "Site 1," appeared only in the presence of a molecule that to binds it. When a molecule interacts with CA, a small region of the protein rearranges to create a small pocket where the compound binds.

As we worked on characterizing and developing molecules to bind to Site 1 and disrupt capsid assembly, our initial excitement gradually gave way to frustration and doubt. There were several red flags about this site. First, we had a lot of structural information about how molecules bound to CA at Site 1 and how the area rearranged itself. But we had no clear understanding of how those local changes prevented CA proteins from assembling into larger structures.

We were also worried about how these Site 1 molecules might work against the wide range of HIV variants seen in patients. Due to HIV's high mutation rate, different strains or variants around the globe contain proteins that vary in their sequence of amino acids, the chemical building blocks of a protein. These small molecular changes can have big consequences for drug binding. When small molecules bind to a protein, interactions with specific amino acids are often key to how the molecule latches onto the protein.

We observed that some of the amino acids that made up Site 1 were not well conserved across a broad range of HIV variants that infected patients, indicating that some people could be infected by viruses that lacked the particular amino acids necessary to bind with our candidate drug molecules. Also, we worried that this amino acid variability suggested that viruses that did bind our molecules might eventually mutate in a way that made them resistant to any potential disruptor.

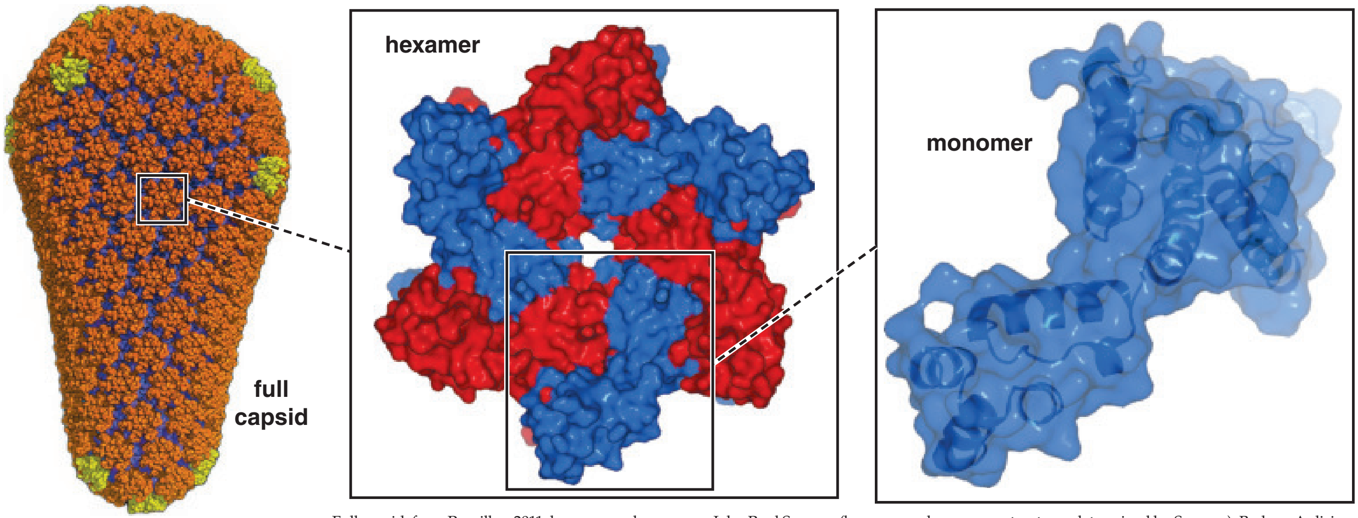
Finally, and most importantly, our attempts to synthesize increasingly potent compounds targeting Site 1 eventually hit a ceiling. We could not improve the antiviral potency enough

HIV History

Although cases of AIDS in humans were not recognized until 1981, the disease had occurred in humans for a little more than a century. A similar disease appears to have been present in nonhuman primates for tens of millennia, but it made the jump to humans only in the late 19th or early 20th century. Infections of the virus remained confined to western equatorial Africa for decades before surging outward, reaching the entire globe around the middle of the 20th century, and resulting in one of the deadliest pandemics in modern history by the end of the century.

AIDS progressively and devastatingly dismantles the immune system, leaving the body vulnerable to diseases it would ordinarily repel. Nearly all people with untreated AIDS die, and over the past four decades, the disease has killed about 42 million people globally. Despite major advances in HIV therapies, AIDS-related illnesses continue to exact a heavy toll: In 2023, about 630,000 people died of opportunistic infections related to AIDS.

In 1983, researchers at the Pasteur Institute in France isolated a previously unknown retrovirus; this virus was identified the following year by Robert Gallo and his team at the National Cancer Institute as the cause of AIDS. The novel pathogen was named the human immunodeficiency virus (HIV-1), which is referred to as HIV in this article. The identification of HIV ignited an explosion of activity aimed at finding drugs to fight this virus, an effort that continues to this day.



Full capsid: from Pornillos, 2011; hexamer and monomer: John Raul Somoza (hexamer and monomer structures determined by Somoza); Barbara Aulicino

The HIV capsid is made up of repeating copies of a protein called *CA* (*right*). Individual CA protein monomers assemble into well-ordered groups of five or six to form pentamers and hexamers, respectively (*center*). Each capsid shell (*left*) consists of 200 to 250 hexamers (*orange*) and exactly 12 pentamers (*yellow*) that form a shape that looks like a soccer ball stretched in one direction.

to make a useful drug. Scientists developing new medicines care about potency because a more potent molecule means a lower dose for patients. High doses lead to problems for a drug, such as large, hard-to-manage pills or a greater likelihood of causing harmful side effects. We eventually concluded that Site 1 lacked the structural features necessary to lead to a potent enough drug molecule.

In 2010, after about a year of synthesizing Site 1 compounds and about four years after the start of the project, we started to move away from Site 1 and focus our efforts on a different site on the capsid protein that we called, yes, "Site 2." From our x-ray crystallography studies, we already had a wealth of structural information about Site 2. Individual CA proteins are grouped into hexamers that bind with neighboring hexamers. Thus, each hexamer has six identical CA–CA interfaces. One part of this interface is a deep groove that is partially formed by Site 2.

Clinical trial results in more than 4,000 people corresponded to a 96 percent reduction in risk of infection and an 89 percent improvement compared with Truvada, a commonly used once-daily pre-exposure prophylaxis pill.

In multiple ways, Site 2 seemed more promising than Site 1. Site 1 wasn't at the interface between CA proteins, whereas Site 2 was, suggesting that a small molecule could bind to Site 2 and then either distort the CA–CA interface or stabilize it. Distorting the interface could inhibit capsid assembly, and overly stabilizing the interface could disrupt disassembly. Either alteration could throw a wrench into HIV's life cycle.

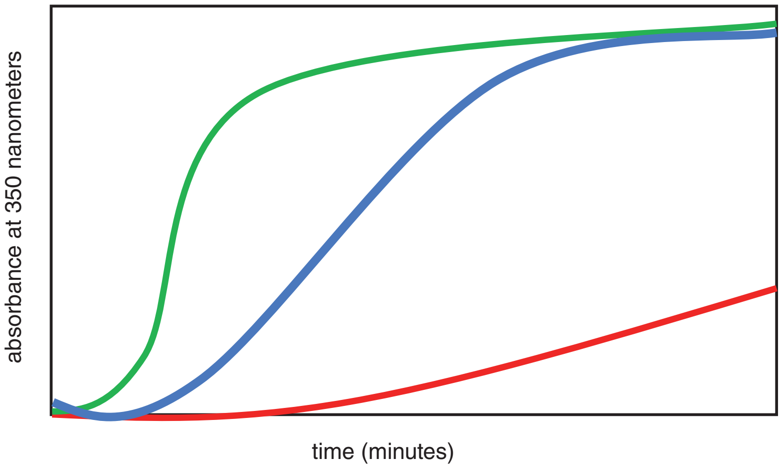
Site 2 was also promising because there was little to no variation in the amino acids that formed it across HIV variants isolated from patients. This observation suggested that Site 2 was much less likely to undergo mutations that could make HIV resistant to our molecules. (Later, we discovered that the likely reason for this high degree of sequence conservation was that Site 2 also interacts with host cell proteins that move viral capsids through the nuclear pore and into the nucleus, a critical step in the HIV life cycle.) We also had a more instinctual reason for targeting Site 2: The deep groove that forms the site looks like the type of structural feature, like an enzyme active site, where small-molecule drugs typically bind.

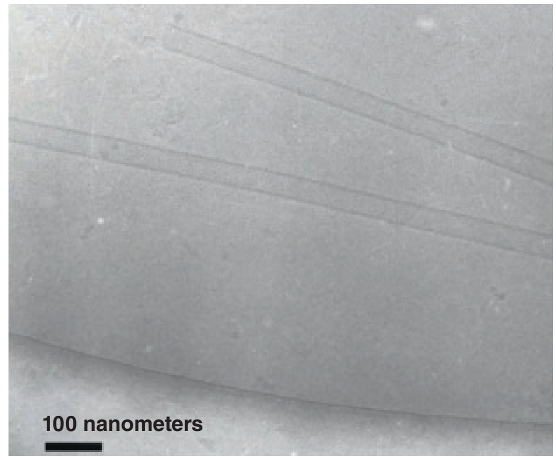
Optimizing Compounds

An effective anti-HIV drug must satisfy two key goals. First, it needs to be sufficiently potent. Second, it must be compatible with being taken no more than once a day, like existing HIV therapies, so that it is practical for patients to take. To achieve this dosing goal, a molecule must resist metabolism in the body enough that its concentration in the bloodstream stays above a certain effective threshold throughout the day.

Although these dual requirements may seem straightforward, finding a molecule that could bind to Site 2 and that was sufficiently potent and metabolically stable took us about five years and required the synthesis, testing, and detailed characterization of thousands of candidate compounds.

On May 26, 2015, our team synthesized a compound known as GS-6207.





Graph: Barbara Aulicino; micrograph: Sam Li and Wes Sundquist

To discover compounds with the potential to impair HIV capsid assembly, scientists used a biochemical assay to test whether a given molecule could affect how CA proteins formed into long, tubelike structures (*micrograph, right*). Without any molecule present, the CA proteins assembled into tubes, which the scientists could monitor by measuring the solution's absorbance of light at 350 nanometers (*left, blue*). If a molecule inhibited CA tube formation, the researchers saw reduced light absorbance (*red*). And if the molecule forced the CA proteins to quickly form shorter tubes, they observed a sharp, fast uptick in light absorbance (*green*).

This compound was metabolically stable and highly potent. However, it took an additional nine months of research until we could confirm that it had the potential to become a successful drug and also satisfied all the safety requirements from the FDA to be given to humans.

One remaining concern about GS-6207 was that it was less soluble than the typical drug taken as a pill, the form of most current HIV therapies. We tried to increase the solubility of GS-6207 for use in a pill, and we also tested the drug when given by injection, either intravenously or under the skin (subcutaneously). Specifically, we wanted to know how long drug levels would remain over the therapeutic threshold when delivered by injection. Would it last a day? A week? To our amazement, in animal tests, the drug remained above therapeutic levels for months when injected under the skin. In people, the drug remained safely at therapeutic levels in the bloodstream for at least 6 months.

In retrospect, we identified three factors explaining why the drug continues to work so long after injection. First, lenacapavir is extraordinarily potent. It binds very tightly to the capsid, and, as a result, a very low concentration of the drug is needed to disrupt capsid function. Second, the compound is very stable metabolically, meaning that it strongly resists the body's attempts to degrade it. These two positive factors were the results of years of work by our team to optimize the molecule.

The third factor was the most fortuitous. When a solution or suspension of lenacapavir gets injected under the skin, the molecule comes out of solution and forms a depot of the drug. In people, this collection of drug gradually dissolves into the bloodstream over the course of months, creating a steady concentration of the compound available to inhibit capsid proteins and provide ongoing protection against HIV.

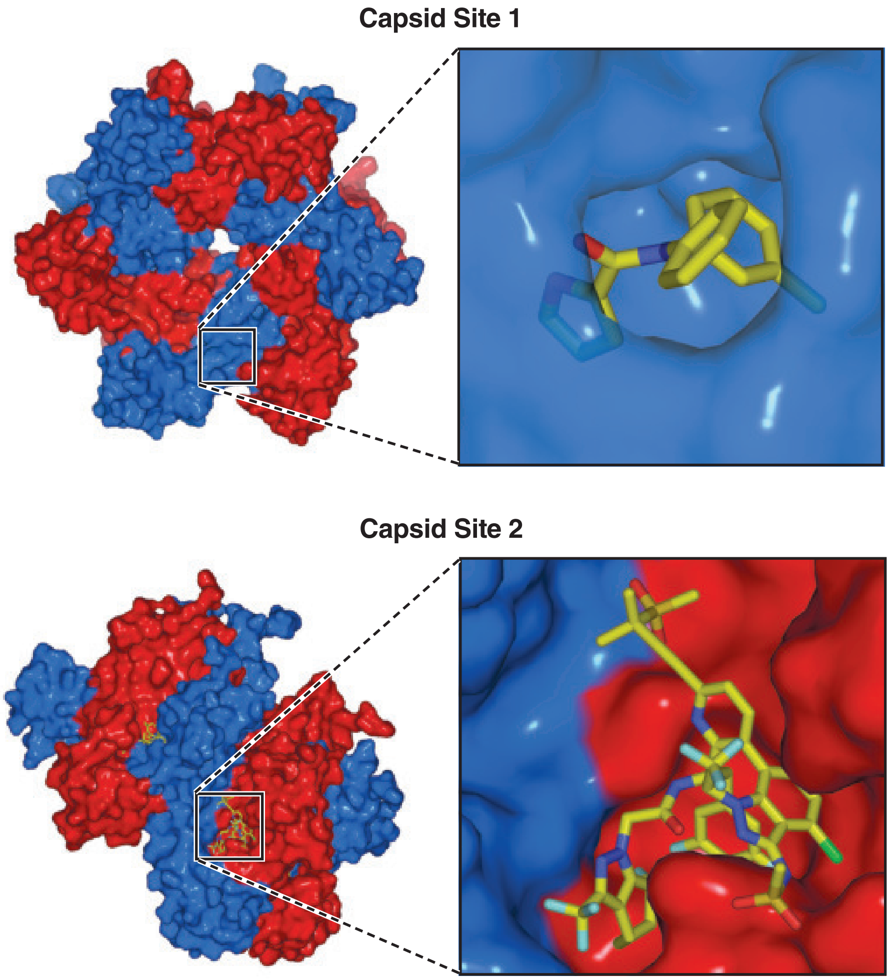
Lenacapavir Gets Tested

On June 30, 2016, almost 10 years after our project started, GS-6207 became known as *lenacapavir* and entered human clinical trials. After nearly a decade of work, our team was both excited and daunted by the prospect of our compound reaching human clinical trials. Testing a drug in humans takes years, moving through three phases of trials, first to determine the drug's safety, and later to assess its effectiveness. Unfortunately, the majority of compounds that enter these trials are not successful, either because some unsuspected safety problem comes to light or because the drug doesn't work as well as expected.

Lenacapavir's clinical trials focused on two distinct uses of the drug: treatment and prevention of HIV infections. After successfully passing through phase 1 and 2 trials, the first phase 3 trial tested whether lenacapavir, in combination with other antiretroviral drugs, could be used to treat HIV in people who had repeatedly failed treatment due to infection with multidrug-resistant HIV variants. The use of lenacapavir to treat HIV infection had been the primary goal of our research. The results of the clinical studies showed that lenacapavir was indeed effective at treating HIV infection, even when used with drug combinations that were no longer effective on their own. By attacking a novel target, the capsid, we had developed a new treatment for multidrug-resistant HIV.

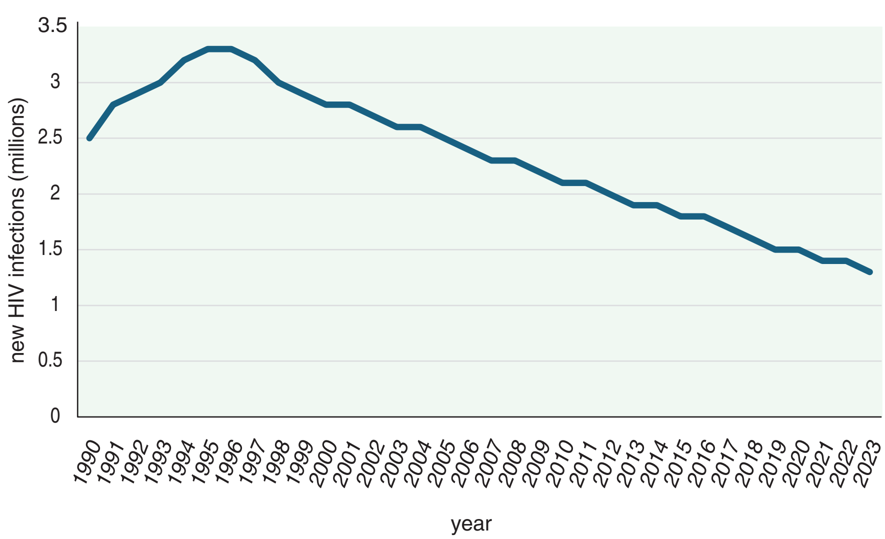
The second set of phase 3 clinical trials focused on using lenacapavir to prevent HIV infection. In 2012, clinical trials had established that people who were HIV-negative but who were at risk of being exposed to the virus could prophylactically take a combination of HIV drugs to reduce the possibility of being infected. This practice is known as *pre-exposure prophylaxis*, and there are three drugs or drug combinations approved for this purpose: Truvada, Descovy, and Apretude.

Two phase 3 clinical trials of lenacapavir looked at the potential of twice-yearly subcutaneous injections of the drug to prevent HIV infection. In the first trial, none of the 2,134 participants receiving lenacapavir injections became infected. In the second trial, only two people out of the 2,179 participants became infected. These remarkable results in more than 4,000 people corresponded to a 96 percent reduction in risk compared with the background incidence of infection, and an 89 percent improvement compared with Truvada, a commonly used once-daily pre-exposure prophylaxis pill.



Capsid protein monomers: John Raul Somoza (structures determined by Somoza); Barbara Aulicino

A biochemical assay helped researchers identify a group of compounds that bound to HIV capsid protein monomers at one of two sites. Site 1 (*top*) was buried inside the CA protein monomer and away from the interface between the CA protein monomers. This site didn't yield promising drug candidates. But Site 2 (*bottom*) was much more promising because it provided a binding pocket located at the interface between the monomers.



Data: UNAIDS; Barbara Aulicino

New global HIV infections peaked at more than three million in 1995, but there are still more than one million new infections every year. Lenacapavir reduces the risk of infection by 96 percent, which may lead to a significant reduction in new cases.

Interestingly, although lenacapavir is better at preventing infection than Truvada, we don't think targeting the capsid is the reason it is inherently more effective. Instead, we think lenacapavir is more effective because people are better at taking the required doses of the drug than they are with Truvada. Not surprisingly, it appears to be easier to comply with a drug that gets injected every six months than with a pill that needs to be taken each and every day.

A Revolutionary Promise

When we started this project, we were looking for a new anti-HIV drug that impaired capsid assembly, and we successfully achieved that. As we more deeply explored how lenacapavir works, we found that targeting Site 2 had some additional, unexpected benefits.

We discovered that some of the host cell proteins that help the HIV capsid cross into the nucleus of a host cell bind to the capsid through interactions with Site 2. Therefore, the effectiveness of lenacapavir is likely due to a combination of its deleterious effects on proper capsid assembly and disassembly, as well as the fact that lenacapavir binding blocks host proteins from attaching to the capsid and moving it through the nuclear pore. Although the relative importance of these two distinct mechanisms of action isn't clear, preventing the capsid from interacting with these nuclear pore proteins is likely playing an important role in how well lenacapavir works.

This other mechanism of action also diminishes the virus's ability to generate lenacapavir-resistant mutations. Drug-resistant HIV strains have evolved mutations that alter their proteins in such a way as to evade drug binding. However, because lenacapavir and the nuclear pore proteins in the host cell share the Site 2 binding site, the virus is caught in an evolutionary catch-22. Mutations that weaken lenacapavir binding run the risk of disrupting the host protein interactions that the virus needs to replicate. The same changes that might confer resistance to our drug could very well cripple HIV's ability to replicate.

Lenacapavir's success sets an encouraging precedent for new ways of treating other viral infections. We showed that a small-molecule drug can meaningfully alter protein–protein interactions to disrupt a viral capsid's assembly and disassembly. The success of this approach for combating HIV may someday lead to the discovery of novel drugs targeting the capsids of other viruses. All viruses known to infect humans have viral capsids, and those capsids likely play multiple essential roles in the viruses' life cycles. Scientists are already trying to develop drugs that target the capsids of other viruses, including the hepatitis B virus and the dengue virus.

The near-term implications of lenacapavir for HIV treatment and prevention are, of course, the most exciting. By finding a drug that blocks a new target, we can successfully treat infections caused by multidrug-resistant HIV strains. Thus, lenacapavir expands the number of people who can be treated effectively.

But it is lenacapavir's ability to prevent HIV infections that might truly change the course of the global HIV epidemic. Although the discovery of anti-HIV drugs that could prevent infection was monumental, the success of pre-exposure prophylaxis has been limited by the need for compliance. In the developed world, compliance is mostly controlled by the person on pre-exposure prophylaxis. However, in parts of the developing world, some of which have very high infection rates (up to one in five adults in some areas), a number of external factors can lead to people missing doses.

Courtesy of Gilead Sciences

In June, the U.S. Food and Drug Administration approved Gilead Sciences' new drug lenacapavir (brand name Yeztugo) as a twice-yearly injection to prevent HIV infections.

We showed that a small-molecule drug can meaningfully alter protein–protein interactions to disrupt a viral capsid's assembly and disassembly.

Breakdowns in pharmaceutical supply chains can lead to precarious access to antiretroviral drugs. Also, in many areas, there can be profound stigma and discrimination attached to the use of anti-HIV drugs. We expect that the twice-yearly dosing of lenacapavir will partially offset some of the adherence, access, and stigma issues currently associated with the need to consistently take daily pre-exposure prophylaxis pills.

Lenacapavir's promise led the World Health Organization in July to release guidelines that recommend use of the drug for preventing HIV infections. But lenacapavir's value in preventing new infections will ultimately depend on how many at-risk individuals use it. And at the moment, there is a huge discrepancy between the number of people using pre-exposure prophylaxis and the number who could benefit from the intervention. For example, in the United States in 2022, only 36 percent of those who could benefit from pre-exposure prophylaxis were taking it, according to the U.S. Centers for Disease Control and Prevention. This discrepancy exists everywhere in the world, but it is perhaps most concerning in the resource-limited regions of sub-Saharan Africa where HIV prevalence is highest and where logistical and economic hurdles prevent anti-HIV drugs from getting into the hands of the people who most need them. These issues have been further complicated by the recent closure by the Trump administration of the U.S. Agency for International Development and by disruptions in the President's Emergency Plan for AIDS Relief.

Overcoming these logistical, economic, and political hurdles will be important so that people across the world can get access to this powerful new drug. It would be a triumphant result of an almost two-decade search for a molecule capable of crippling the HIV capsid.

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Trial by Fire

Producing ultrahigh-temperature ceramics that can meet the demands of the future requires innovation, creativity, and a touch of serendipity.

William G. Fahrenholtz and Greg E. Hilmas

The two of us entered the field of ultrahigh-temperature ceramics, or UHTCs, in the early 2000s, when demand was increasing for innovative aerospace advances. Potential applications for ceramic materials with melting temperatures above 3,000 degrees Celsius included thermal protection for national defense aerospace vehicles that travel at hypersonic speeds—five or more times the speed of sound in air (Mach 5 or faster)—rocket motors, and scramjet propulsion systems, which generate thrust by burning fuel in a supersonic airstream. At the time, UHTCs offered a way forward, but more research was needed to move the materials toward implementation. The field needed better predictive design, new manufacturing methods such as improved sintering, and ways to improve environmental resistance (the ability to withstand extreme temperatures and reactive environments without degrading).

Bill began his academic career processing ceramic materials and exploring thermodynamic behavior, but he focused more on conventional oxide-based ceramics than UHTCs. That changed when he joined the Missouri University of Science and Technology (then known as University of Missouri–Rolla) in 1999. There, he started collaborating with Greg, whose earlier work had involved structural ceramics but who now was researching ceramics fabrication and mechanical behavior. Our research passions aligned—not just with one another, but with the emerging interests of several U.S. government funding agencies. This congruence was fortuitous, but fortune is what you make of it. When Louis Pasteur said in his inaugural lecture at University of Lille in France that "chance favors only the prepared mind," he may have been speaking of observational fields, but the same holds true in materials science. We learned as much when an equipment mishap led to our most fruitful area of research, one with potential uses in extreme environments ranging from hypersonic vehicles to nuclear reactors.

By then, we'd chalked up many years of dedicated research, had the good fortune to work with talented graduate students, and built a highly specialized laboratory at Missouri S&T focused on materials for extreme environments. It was in this facility, during our collaborative investigation into zirconium diboride, that serendipity took a hand. One day, as a student began to examine the role of conventional powder processing on the microstructure and properties of zirconium diboride ceramics, an automated furnace controller failed, which caused a ceramic specimen to be heated much longer than planned. The accident produced our lab's first example of pressureless solid-state sintering (consolidation of a powder into a dense ceramic without melting or applying external compression) of zirconium diboride. This process gave us deeper insights into how particle size and surface chemistry affect *densification*—the way particles bond, how the space between particles shrinks, and how grains become tightly bonded.

As our work progressed, the effects of this and later insights were transformative: Pressureless sintering to near-full density at lower temperatures streamlined production and reduced costs; new ceramics with sought-after properties and architectures became possible; and, perhaps most importantly, greater control over particle size, oxide content, and chemistry opened the door to new composite ceramics with the toughness and stability needed for applications in extreme environments. But to understand how one furnace accident led to all that, we need to take a step back.

Taming the Heat

UHTCs are typically made by combining early transition metals such as zirconium, hafnium, titanium, niobium, or tantalum with boron, carbon, or nitrogen, producing binary compounds called borides, carbides, or nitrides, respectively. Transition metals occupy the periodic table's middle section and are known for their heat and electrical conduction, as well as for their usefulness as chemical catalysts.

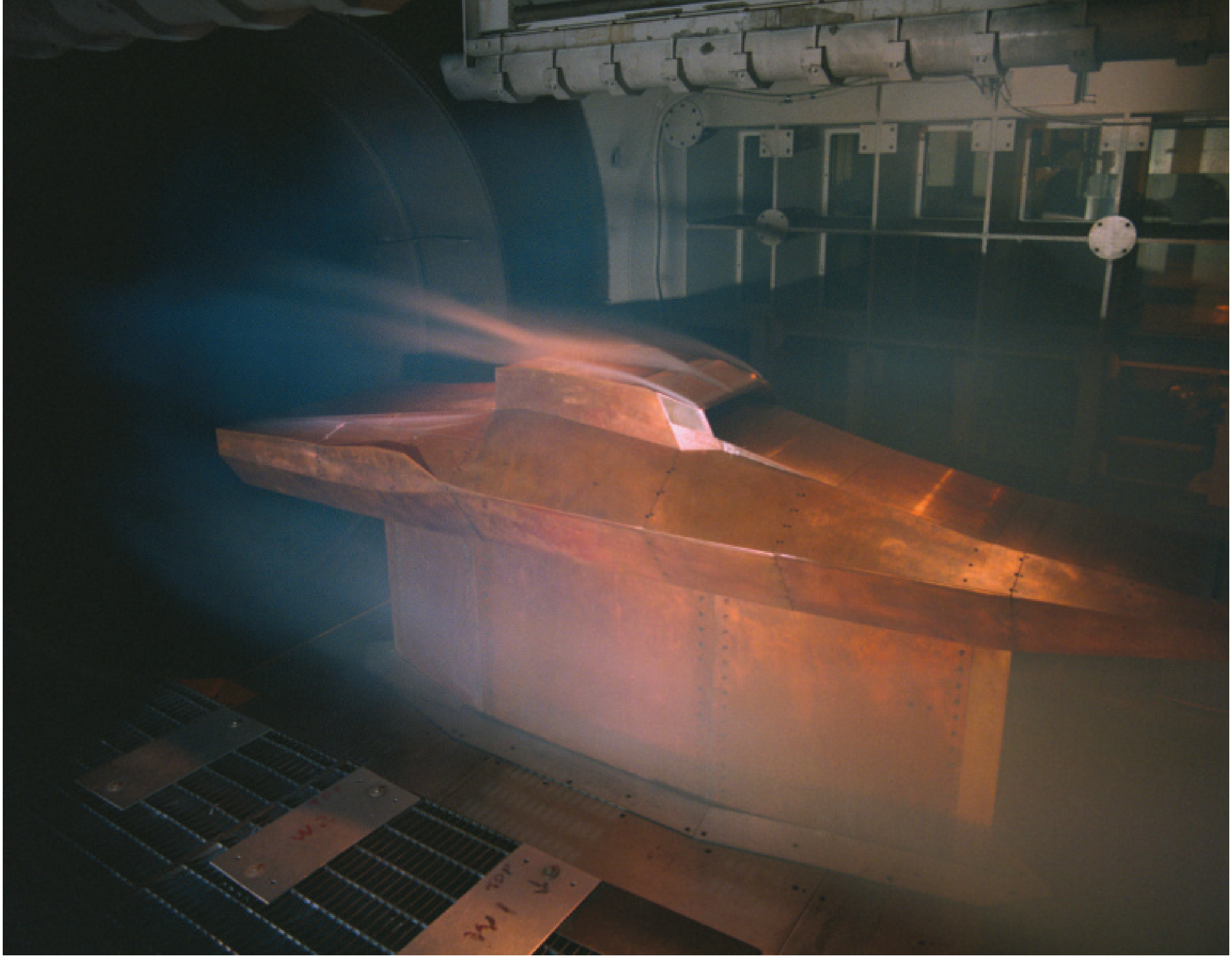
UHTCs achieve their extreme melting temperatures thanks to an unusual combination of two types of chemical bonds occupying a shared crystal structure: metallic bonds—positively charged metal ions held together by their attraction to a shared electron "sea"—and strong covalent bonds—two atoms, typically nonmetals, strongly bonded via shared electrons. Metallic bonds, which occur for example in copper, tend to enable electrical conductivity and malleability, whereas strong covalent bonds, such as those occurring in diamonds, are generally hard and boast very high melting points. Consequently, this mix

QUICK TAKE

Technological progress in areas such as hypersonic flight and energy production requires materials that can withstand extreme environmental conditions.

Ultrahigh-temperature ceramics (UHTCs) combine the hardness and high melting temperatures of ceramics with the electrical and thermal conductivity associated with metals.

Despite advances, challenges remain regarding reducing brittleness, improving oxidation behavior, and making UHTCs cheaper, more consistent, and easier to produce.



NASA Photo/Jeff Caplan/NASA Langley

A full-scale model of NASA's experimental X-43A Hyper-X aircraft experiences Mach 7 winds in the 8-Foot High-Temperature Tunnel located at NASA's Langley Research Center in Hampton, Virginia. NASA's eight-year, $230 million Hyper-X program tested technologies for hypersonic flight, and its 12-foot-long unpiloted craft—the first to fly at hypersonic speeds using air-breathing engines—reached Mach 9.6. The nose cones, leading edges, and other surfaces of such vehicles require ultrahigh-temperature materials to withstand the brutal forces of hypersonic flight. Ceramics such as those produced by the authors' lab offer potential solutions.

of bonding types, found in our own zirconium diboride as well as other UHTCs—combines the hardness and brittleness typical of ceramics with the electrical conductivity and thermal conductivity associated with metals.

Fine-tuning the combinations of such characteristics is imperative given the extreme environments in which such ceramics are expected to operate. Hypersonic craft might need parts that can withstand temperatures over 2,000 degrees and heat fluxes (heat energy transfer rates through surfaces) measuring hundreds of watts per square centimeter (in the ballpark of spacecraft reentry). Sustained nuclear fusion or fission reactions might require materials that can pass up to a quadrillion neutrons per second through a square centimeter of material. Protective shielding against orbital debris might require UHTCs that resist impact velocities reaching hundreds of meters per second (on par with bullet impacts). Still other specifications might require UHTCs that can withstand ionized gases or plasmas, which can knock atoms off components, intensify heat fluxes, interfere with electromagnetic fields, and cause corrosion, among other issues.

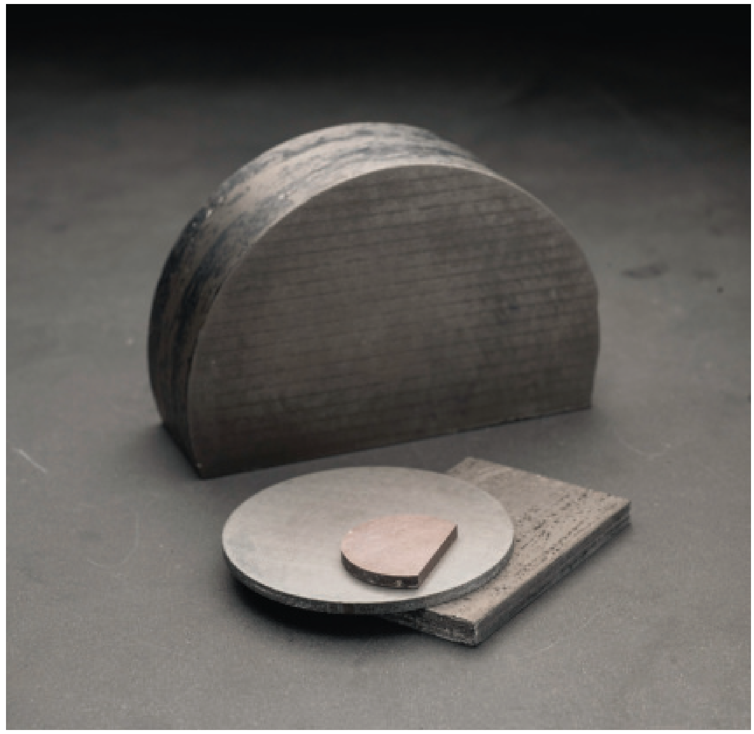
To see current and future applications for such materials, one need only look wherever technology or industry pushes ceramics' environmental limits the furthest. By not only helping to develop these extraordinary and unsung materials, but also making them cheaper, more consistent, and easier to produce, we hope to help realize some of the grand challenges for materials science and engineering.

From Hot to Ultrahot

Boride and carbide ceramics first began appearing in scientific reports in the late 1800s and early 1900s as pioneers such as American chemist Edward Acheson and French chemist Henri Moissan studied refractory ceramics (high-melting-point ceramics that resist deformation). The term "ultrahigh temperature" was coined by the ceramic refractories industry during the 1950s and 1960s to describe materials that could continuously withstand heat above typical steelmaking temperatures (around 1,600 degrees).

Interest in UHTCs remained largely academic until the end of World War II and the start of the Space Race. Both the United States and the Soviet Union devoted significant research efforts toward boride, carbide, and nitride ceramics as they sought refractory materials that could endure the rigors of space flight and atmospheric reentry. Still, despite significant experimental and theoretical research progress in UHTCs, the military and aerospace sectors used other high-temperature materials in their designs. These materials included the polymer-based

Michael Pierce/Missouri S&T



Blaine Falkena/Missouri S&T

Fahrenholtz (*left*) assembles a graphite die for hot pressing a boride ceramic. A protective lining of graphite paper coated with boron nitride prevents the die from reacting with the powder being processed. The group produces and tests several materials (*right*), including: zirconium diboride, silicon carbide, and boron carbide (*large half-disk*); an ultrahigh-temperature ceramic composite matrix based on zirconium diboride with some proprietary additives and continuous carbon fibers (*rectangle*); zirconium diboride (*smaller disk*); and a high-entropy boride made up of hafnium, niobium, tantalum, titanium, zirconium, and boron (*small half-disk*). Each material has unique properties suited for different applications in ultrahigh-temperature environments.

ablative heat shields used on space capsules and the reinforced carbon–carbon composites designed for the leading edges and nose caps of NASA's Space Shuttles. The latter's heat requirements were limited to 1,650 degrees and required carefully controlling the spacecraft's reentry trajectory to mitigate heating.

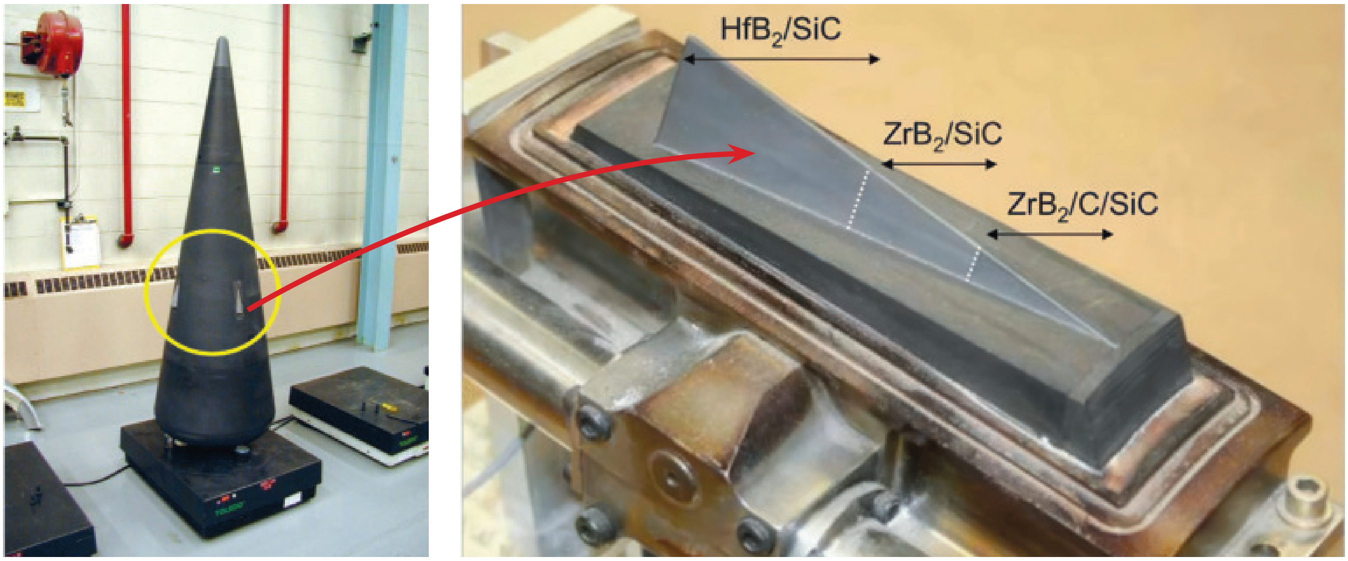
By adding well-dispersed silicon carbide particles, we nearly doubled the strength of zirconium diboride ceramics.

These designs were informed by data gathered through the X-15 hypersonic research aircraft project, which involved three rocket-powered craft built by North American Aviation and operated jointly by the U.S. Air Force, the U.S. Navy, and NASA (and its predecessor, the National Advisory Committee for Aeronautics) from 1959 to 1968. Had similar work continued, demands for refractory materials that could stand up to more extreme conditions might have bolstered UHTC research. But the Space Race wound down during the 1970s and 1980s, and interest in large-scale development of hypersonic craft waned.

With no sufficiently pressing need or game-changing application to justify the research, efforts to address the limitations affecting fabrication, brittleness, and degrading chemical reactions, such as oxidation, confronting UHTCs would have to wait until the 1990s, when NASA and U.S. Department of Defense laboratories reinvigorated interest in hypersonic flight, atmospheric reentry, and rocket propulsion. By the early 2000s, the U.S. Air Force had begun designing and testing new missiles and aerospace vehicles meant to be versatile, maneuverable, and able to sustain hypersonic speeds. Our research rode this wave in the early 2000s. The initial seed grant was followed by funding from the U.S. Air Force's Office of Scientific Research to study materials for parts that undergo extreme aerodynamic heating, such as edges of wings and nose tips.

The Right Stuff

By 2008, we (along with Adam L. Chamberlain, today a ceramic matrix composite technical specialist at Rolls Royce North America) had published our findings on pressureless sintering of zirconium diboride in the *Journal of the American Ceramic Society*, but our work was just beginning. Finding the right solution for hypersonic leading edges, like so many other problems involving UHTCs, faced numerous hurdles. Moreover, in classic materials science fashion, addressing one problem, such as making a material tougher, required trade-offs such as reducing hardness or increasing vulnerability to oxidation. It was like trying to solve one of those sliding tile puzzles, in which moves simultaneously depend on and block one another. Most vexing of all, before we could solve many of those puzzles, advances were needed in processing technologies, materials chemistry, sintering, and other areas.



S. M. Johnson, et al., *Recent Developments in Ultra High Temperature Ceramics at NASA Ames.*

In the late 1990s and early 2000s, two NASA flight experiments, SHARP-B1 and SHARP-B2 (Slender Hypervelocity Aerothermodynamic Research Probes), exposed ultrahigh-temperature ceramics to actual atmospheric reentry conditions. SHARP-B2 consisted of a nose cone (*left*) bearing four small, sharp, leading-edge fins, or *strakes (circled in yellow)*, made up of these ceramics, including some with the same formulations as those produced and tested by the authors' group. A close-up view (*right*) shows a strake made of (*from left to right*) a hafnium diboride–silicon carbide composite, a zirconium diboride–silicon carbide composite, and a composite of zirconium diboride, carbon, and silicon carbide.

We began by studying how processing conditions and additives affected zirconium diboride ceramics' strength and *fracture toughness*—how well the materials resist breaking once a crack appears. We chose these materials based on previous studies identifying their favorable properties, low density compared with some other UHTCs, and lower cost than hafnium-based ceramics. One breakthrough came when we optimized the dispersion of silicon carbide particles to our zirconium diboride: We nearly doubled the strength of the ceramics, raised their fracture toughness by about 50 percent, and became the first lab to report zirconium diboride-based ceramics with strengths exceeding 1,000 megapascals (very few ceramics cross that strength threshold, which is on par with the pressures that deform the strongest steels).

At the same time as our research was starting at Missouri S&T, NASA took notice of UHTCs. When the space agency flew its Slender Hypervelocity Aerothermodynamic Research Probes (SHARP-B2), a September 2000 mission to evaluate whether sharp leading edges could survive the searing temperatures then endured by blunt-body aerospace vehicles, zirconium diboride numbered among the ceramics tested on the four sharp-edged testing strakes adorning its nose cone (*see figure above*). Here again, the need to solve several problems at once presented itself: UHTCs such as zirconium diboride ceramics are brittle, which resulted in failures during the SHARP-B2 flight. The failures were exacerbated by manufacturing problems such as large grain sizes, which often accompanied the high temperatures and pressures needed back then to achieve full densification.

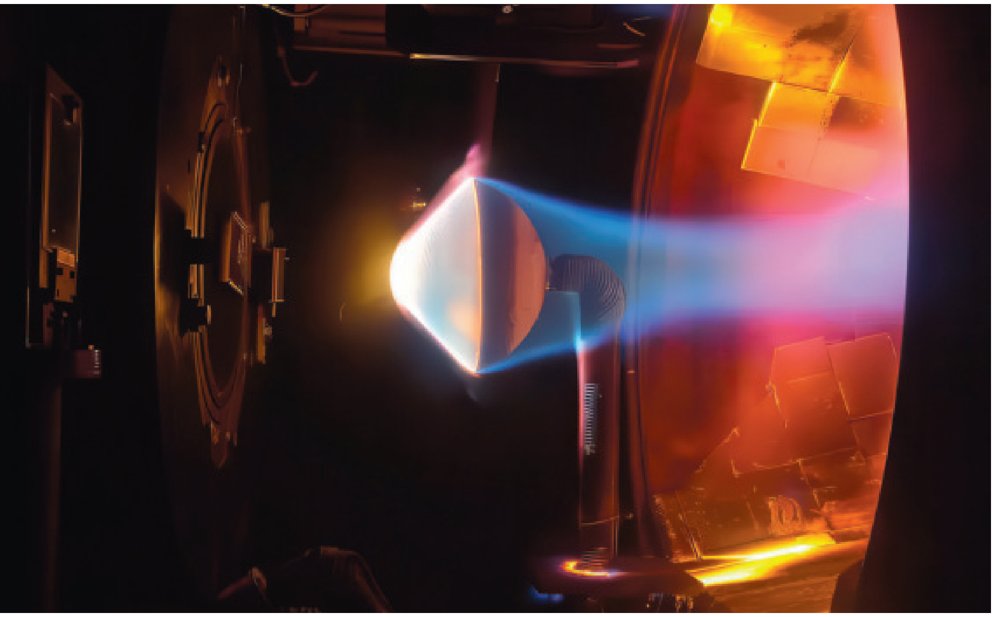
We needed a solution that could not only address these concerns but could do so in useful sizes and shapes. Producing one tiny sample with desired qualities is an achievement, but producing materials that maintain desired characteristics across necessary length scales, from the microscopic to the size of a component or wing edge, posed a greater challenge. With this in mind, we examined a coextrusion process—squeezing two or more materials through a single die to produce structured materials (think striped toothpaste). Coextrusion let us control a ceramic's structure at multiple length scales. Through this technology, we produced ceramics that could better resist thermal shock (damage or stress caused by rapid temperature changes), a key susceptibility caused by the brittleness and poor heat conduction characteristic of UHTCs, bringing us closer to our goal of developing a wing-edge material suitable for hypersonic flight.

Very few ceramics cross that strength threshold, which is on par with the pressures that deform the strongest steels.

Refining Densification

Inspired by insights regarding how particle size and surface chemistry affect densification (gained in part from our serendipitous furnace controller accident), our research progressed through the 2000s and into the 2010s. We noticed that impurities introduced during powder processing could actually improve materials' mechanical properties at room temperature. For example, the media we used to reduce the size of ceramic particles (to improve densification) contained tungsten carbide particles that, when combined with zirconium diboride, increased the ceramic's strength.

Density is not always a desirable trait, particularly in aerospace vehicles, which



Cesar Acosta/NASA

Whether they are meant to endure the rigors of hypersonic flight, the soaring temperatures of atmospheric reentry (on Earth or other planets with atmospheres), or the extreme conditions within a nuclear reactor, ultrahigh-temperature materials need to be tested to their limits. This sample is being tested for its thermal properties at NASA's Aerodynamic Heating Facility, much as it might be tested at the authors' lab. The facility, part of the Arc Jet Complex at the Ames Research Center in California, gathers data on thermal protection systems for space probes and human-carrying spacecraft.

must balance every ounce of force and thrust. But for UHTCs, densification—removing voids and pores from the initial powder compact, thereby making it stronger and more resistant to its external environment—is essential. By 2012, our lab had demonstrated that we could use pressureless sintering to obtain fully dense ceramics with grain sizes on the order of 5 micrometers or less (about the size of a human blood cell). This advance was novel and notable at a time when pressure-sintering processes often saw grains growing to much larger sizes during densification.

Impurities introduced during processing could improve mechanical properties.

Encouraged, our group delved deeper and found that certain solid-state reactions (chemical reactions between solid materials that occur without melting) offered a side benefit: Those reactions that involved reducing agents such as carbon, boron carbide, or tungsten carbide removed surface oxide impurities and enhanced densification. Essentially, by mixing these substances with ceramic powders, we had devised a kind of "scale remover" that cleaned undesirable layers from ceramic surfaces and encouraged particles to meld together.

To assess how a given elevated temperature range will affect UHTCs, our laboratory uses both custom-built and commercial instruments. These tools measure mechanical, thermal, and electrical properties from room temperature up to 2,000 degrees (a sort of minimum threshold for us) or higher. Measuring these properties provides valuable usage data for engineers and designers, but we view it as only the first step; we strive to understand the fundamental behavior that controls the effects we witness. For example, we use precisely calibrated testing machines and sensors to apply controlled forces, measure the conventional fracture properties (how materials crack or break), and link those findings to the composition and microstructure using fracture mechanics. Materials scientists routinely conduct such analysis at room temperature to identify strength-limiting flaws, typically defects such as cracks, pores, or grain size. We number among the few groups that extend this scrutiny to ultrahigh temperatures.

Our research continues to benefit from our knowledge of microstructure development and densification behavior and how chemical reactions during processing produce ceramics with superior properties. Pressureless sintering also opens vast new opportunities for building UHTCs through additive manufacturing, the method used by 3D printers. With pressureless sintering, labs no longer must squeeze ceramic powders into shaped molds under high pressures. Instead, parts can be made in the desired shapes, resulting in cheaper UHTCs and dispensing with most of the expensive machining that used to follow densification.

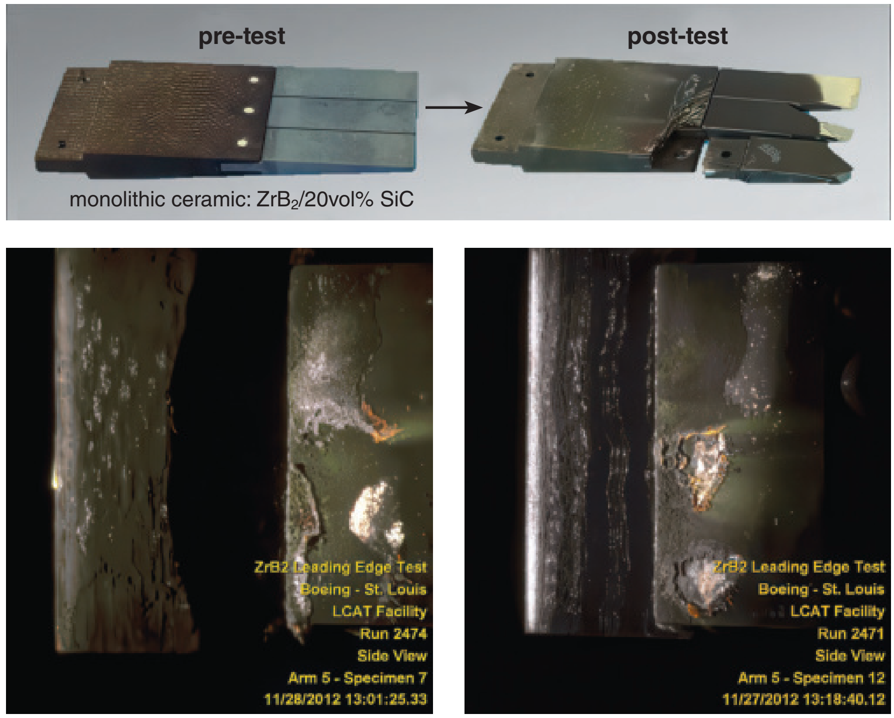
Resisting Oxidation

Materials exposed to extremely high temperatures face threats far beyond melting and thermal shock, as should be clear by our repeated mentions of oxidation (which here refers to a chemical reaction that degrades boride and carbide ceramics by converting the outer part of the material into gases or weak oxide scales). As encapsulated in Swedish scientist Svante Arrhenius's eponymous equation, the rates of chemical reactions and processes such as oxidation grow exponentially as environmental conditions heat up. This rule applies to UHTCs: Below about 1,000 degrees, zirconium diboride experiences only slow oxidation, but the rates increase by orders of magnitude as temperatures increase. Above 1,500 degrees or so, evaporation, sublimation, and, eventually, ablation can lead to rapid failure in a material. Consequently, we have worked through numerous studies to boost oxidation resistance in various environments, such as air and high-velocity plasmas.

One typical method for making oxidation-resistant ceramics involves adding hard silicon carbide particles. Silicon carbide has useful mechanical and thermal properties at elevated temperatures. In short, it resists oxidation, is hard (meaning it can alter the path of cracks without breaking), and is thermally stable (meaning it keeps its properties, performance, and structure at high temperatures). Although adding silicon carbide can improve the oxidation behavior of UHTCs such as zirconium diboride at intermediate temperatures (800–1,600 degrees), silicon carbide itself undergoes active oxidation above 1,600 degrees. Porous layers can form, compromising the protection and mechanical integrity of the protective surface scale (oxide layer).

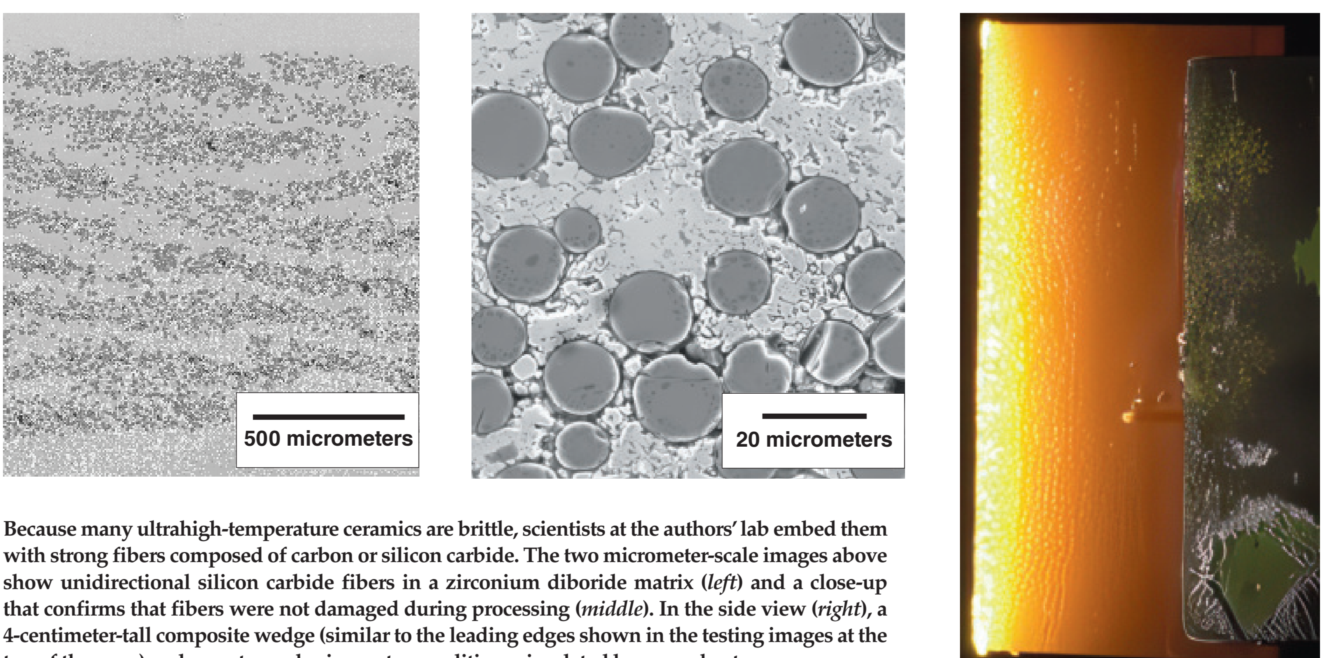
Oxide scales can act as helpful barriers by stopping oxygen from reaching the ceramic and slowing further reactions. Scales are ubiquitous when borides and carbides are exposed to air, even at room temperature. These scales can have positive or negative impacts. For example, the scale that accumulates on starting particles from natural oxidation processes inhibit densification, and oxidation at high temperatures or hypersonic speeds can cause damage or failure of parts. Indeed, the zirconium diboride powders that we use to make ceramics have native oxide layers on their surfaces. We found that, when we processed and heated the powder, the impurities clumped together, producing weak spots that became strength-limiting flaws above 1,800 degrees. This finding implied that we could strengthen zirconium diboride at elevated temperatures by improving processing and synthesizing starting powders of greater purity.

Our laboratory has explored other promising options to improve oxidation resistance at ultrahigh temperatures. For example, we have experimented with adding transition metals that dissolve into the ceramic matrix. When these dissolved species react in oxidizing environments, the result is a ceramic that actually becomes more refractory. As shown on the following page, when we combine zirconium diboride with transition metals such as tungsten, molybdenum, and niobium, a dense region forms that blocks oxygen diffusion and improves oxidation resistance (we call it the "dark layer"). Despite this progress, improving oxidation behavior remains among the great challenges facing all UHTCs, and UHTC matrix composites are an emerging research and development area.



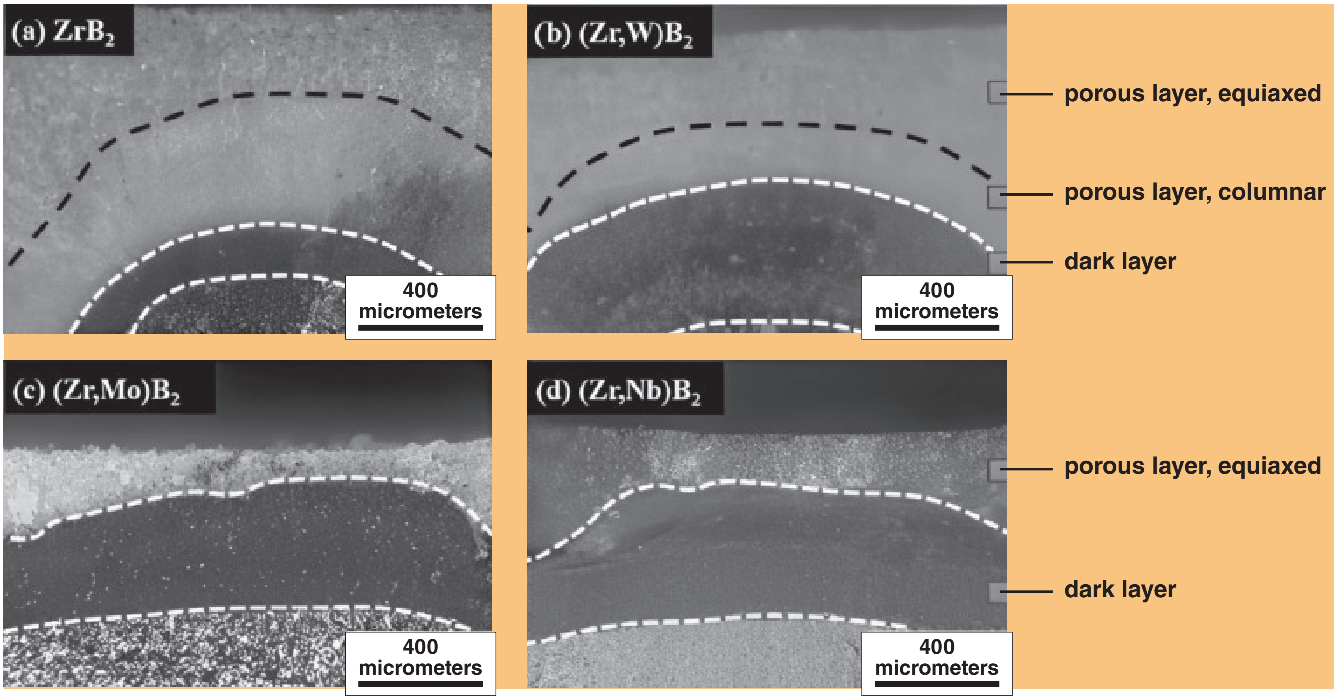
Lai, B. J., M.S. Thesis, Missouri S&T, used with permission; NASA

Images show the protective potential of fiber reinforcement and innovative matrices. The leading edge (*top*) was made of unreinforced zirconium diboride–silicon carbide ceramic and failed due to thermal shock, which caused the sharp ends to crack and fall off. The two other leading edges (*bottom left and right*) were reinforced with high-strength continuous silicon carbide fibers. The first, made from conventional zirconium diboride–silicon carbide, was damaged and receded. The second, improved in the authors' lab by changing the matrix to zirconium diboride and zirconium disilicide, proved more durable and performed far better in simulated hypersonic flight.



Because many ultrahigh-temperature ceramics are brittle, scientists at the authors' lab embed them with strong fibers composed of carbon or silicon carbide. The two micrometer-scale images above show unidirectional silicon carbide fibers in a zirconium diboride matrix (*left*) and a close-up that confirms that fibers were not damaged during processing (*middle*). In the side view (*right*), a 4-centimeter-tall composite wedge (similar to the leading edges shown in the testing images at the top of the page) endures atmospheric reentry conditions simulated by an arc heater.

Lai, B. J., M.S. Thesis, Missouri S&T, used with permission



Lai, B. J.,. M.S. Thesis, Missouri S&T, used with permission

Cross sections show the layering in oxidized zirconium diboride (*a*) and zirconium diboride-based ceramics containing tungsten (*b*), molybdenum (*c*), and niobium (*d*). Equiaxed layers are composed of grains that are roughly the same size, whereas columnar layers comprise grains that are elongated in rows that grow perpendicular to the surface. These micrographs show the formation of an oxide layer (*labeled as dark layer*) that might act as a protective barrier to further intrusion of oxygen, thereby limiting harmful oxidation.

Brittleness is another critical issue that we address in our laboratory. We try to guard against the catastrophic failure that brittle materials such as ceramics can experience by using high-strength fibers to fabricate ceramic matrix composites that are more damage tolerant. Think of a material that splinters but maintains some integrity, like a piece of wood, as opposed to a material that suddenly and catastrophically fails, like a pane of glass. Our group has investigated examples that use a zirconium diboride-based matrix combined with silicon carbide or carbon fibers. Conceptual wing leading edges made from these composites can resist atmospheric reentry conditions simulated by an arc heater for up to 10 minutes without losing significant amounts of material. This capacity offers hope that these materials may one day provide sufficient protection for hypersonic flight applications.

This disordered composition helps ceramics stand up to high temperatures, withstand stresses, and resist corrosion.

Compositionally Complex Ceramics

If mixing one or two materials into a UHTC for their desirable qualities could pay dividends, how much greater might the possibilities grow by drawing from a wider menu, or compositional space, of five or more elements? Such is the thinking behind *compositionally complex ceramics*. Also called high-entropy ceramics, these fine-tunable materials could revolutionize several application areas, such as reentry vehicles, rocket nozzles, turbine blades, and next-generation nuclear reactors, as well as numerous electronic, magnetic, and optical devices.

The descriptor "high entropy" refers to how such approaches can produce a single, stable crystal structure composed of randomly distributed atoms. This disordered composition produces an entropic stabilization effect that helps ceramics stand up to high temperatures, withstand stresses, and resist corrosion and wear. Essentially, the randomness of the mix resists unwanted changes such as alterations in how atoms are arranged in crystals (which can cause cracking or strength loss), segregation (separating like substances from one another, akin to oil and water, lowering toughness and conductivity), and decomposition (breaking materials down into simpler substances).

For UHTCs, the entropy effect can also potentially increase melting temperatures. Our laboratory has shown that reaction-based processing (processing materials via chemical reactions at high temperatures) could improve thermal conductivity and material strength at elevated temperatures. With this in mind, our group established a unique niche: using carbothermal and boro/carbothermal reduction reactions (chemical reactions in which a substance gains electrons—in this case, using carbon and boron) to produce compositionally complex, ultrahigh-temperature carbide and boride ceramics, including zirconium diboride-based ceramics. In brief, we mixed oxide precursor powders with carbon (carbothermal reaction) and then partially transformed the resulting carbide into a boride via reduction (boro/carbothermal reduction).

These reduction-based methods offer advantages such as wide compositional flexibility, lower oxygen impurity contents, lower densification temperatures, and better microstructure development control. Through these methods, our group has demonstrated that compositionally complex carbides and borides better retain their strengths under higher temperatures than conventional carbide and boride ceramics that contain only one transition metal. By extending these methods, we have also produced dual-phase, compositionally complex ceramics that contain both boride and carbide phases, and that show promise for further control over microstructure and properties. (To materials scientists, a *phase* refers to a region within a material—here, a ceramic—that has its own unique crystal structure and chemical makeup.)

When combined, each phase brings its own advantages: Here, the boride phase might harden the ceramic (reducing the likelihood of scratches or dents) and help it resist oxidation, whereas the carbide phase might make it tougher (better able to absorb impacts or deform without breaking) and better at protecting structures from heat. Our group's other significant advances in this area include verifying computational predictions concerning the thermochemical stability of new compositions, as reported in our recent *Nature* paper, along with discovering novel superhard ceramics such as a boride containing equal amounts of hafnium, molybdenum, titanium, vanadium, and tungsten.

Research Challenges

The enormous promise of UHTCs should motivate intensive research for many years given the many fundamental scientific questions that remain unanswered and the applied research and development needed to put these materials into widespread application. As for our group, our potential future research activities include UHTC matrix composites; additive manufacturing, better known as 3D printing; and materials that transfer heat more efficiently.

Composites that use UHTCs as a protective matrix for high-strength fibers (ultrahigh-temperature ceramic matrix composites, or UHTCMCs) could potentially overcome the issues of brittleness and added weight confronting ceramics through composite design strategies such as fiber reinforcement or optimized microstructures. Unfortunately, compared with some other countries, the United States has engaged in comparatively little research into these composites. Some promising directions include developing new high-strength fibers that are more refractory than current silicon carbide fibers and more resistant to environmental degradation than carbon fibers.

Devising robust methods to produce desired shapes is a key step to enabling wider use of UHTCs.

Manufacturing UHTCs into useful components remains challenging. Most research studies produce dense ceramics using *spark plasma sintering* (squeezing powder into a solid using heat and electricity) or hot pressing (exactly what it sounds like), but neither mold-based method lends itself to affordably making parts with complex shapes; instead, both make simple geometric shapes that then require expensive and complex machining processes to produce components with the desired shapes. Engineers have found ways to densify some UHTCs using pressureless sintering, which can make shaped parts that require little finish machining. Devising robust methods to produce desired shapes by additive manufacturing is a key step to enabling wider use of UHTCs.

These materials are only now making their way from research labs to industrial uses, but these are still early days. Whatever the challenges, however, past successes by our group and our colleagues make us confident that we have only begun to tap the full potential of UHTCs.

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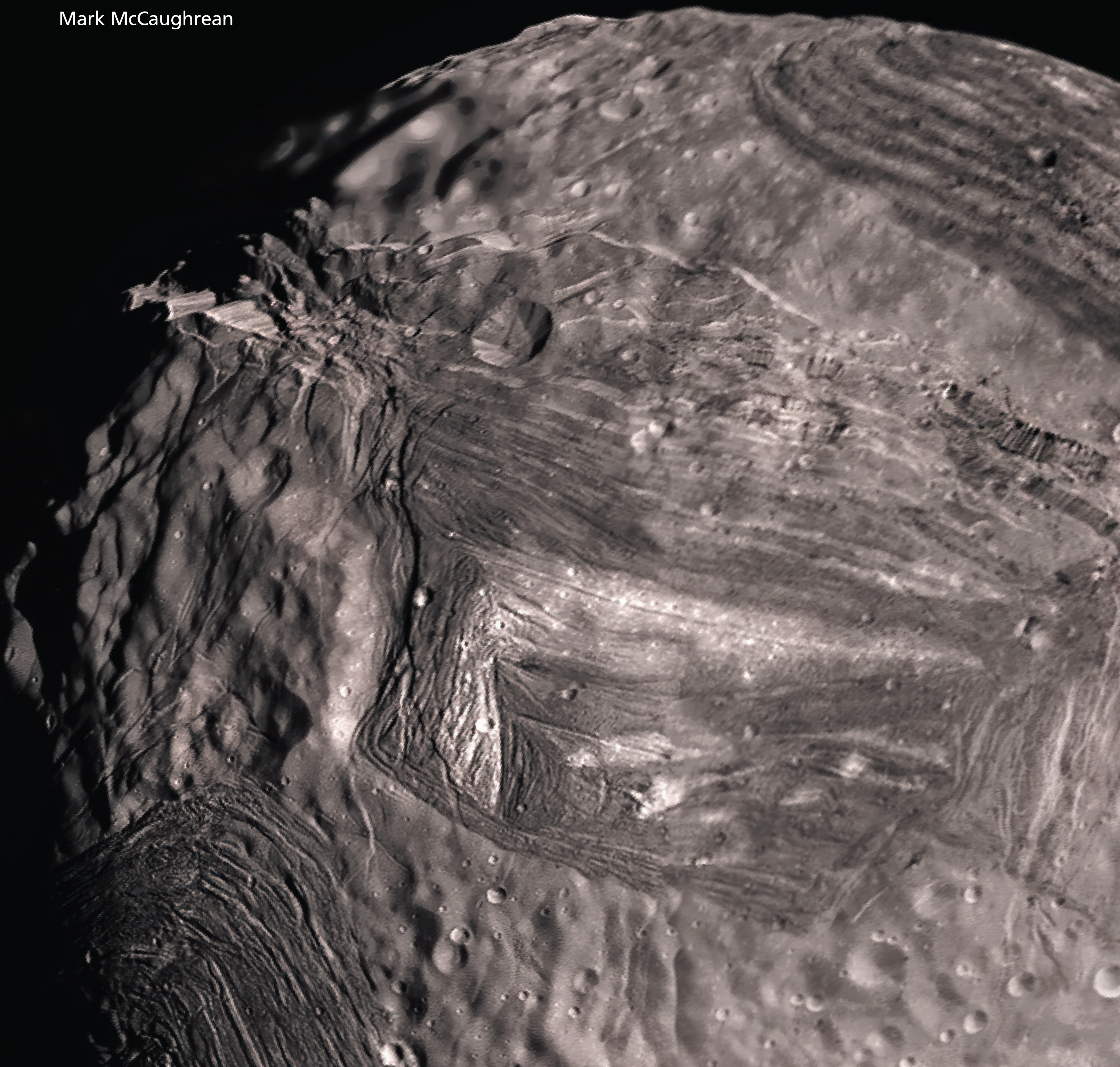
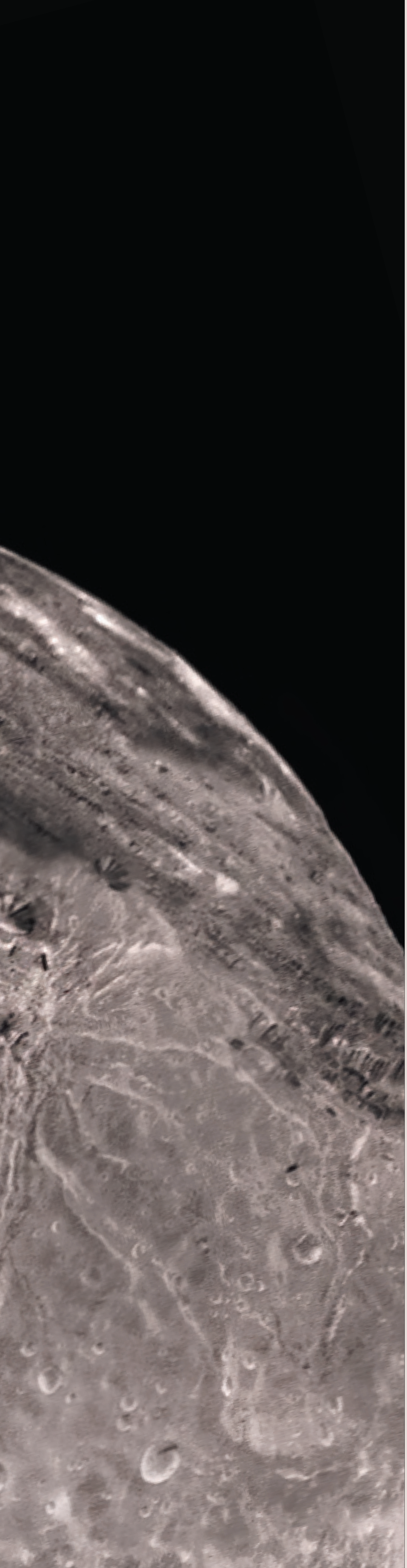
Space Tourism

A trip through the Solar System would not be complete without visiting these out-of-this-world locales.

Mark McCaughrean





Voyager 2/NASA, JPL-Caltech/image processing Jason Major, CC BY-NC-SA

Extraterrestrial Vacation

Imagine that it's possible to cross vast gulfs of space-time on journeys to amazing locations in our Solar System, the Milky Way, and deep space, that you'll survive the extreme conditions you'll find out there, and that you'll be able to see the invisible and discover a panoply of wonders through magical, multiwavelength goggles.

For me, it's just as remarkable that we have the curiosity and technology to explore and study those places without needing to go ourselves. We've sent robot avatars close to the Sun, to planets, moons, asteroids, and comets, and to the edge of interstellar space. Beyond that, our telescopes capture light from across the electromagnetic spectrum, allowing us to see new stars and planets forming, the event horizons of black holes, and even the birth of the universe 13.8 billion years ago.

As an astronomer, I've been privileged to use some of the largest telescopes on Earth and off it, and to travel to other worlds vicariously through the eyes of robotic spacecraft. For this article, I have compiled some must-see destinations in our Solar System, so pack your protective gear and imagination into your spacecraft. Pick a destination . . . and go!

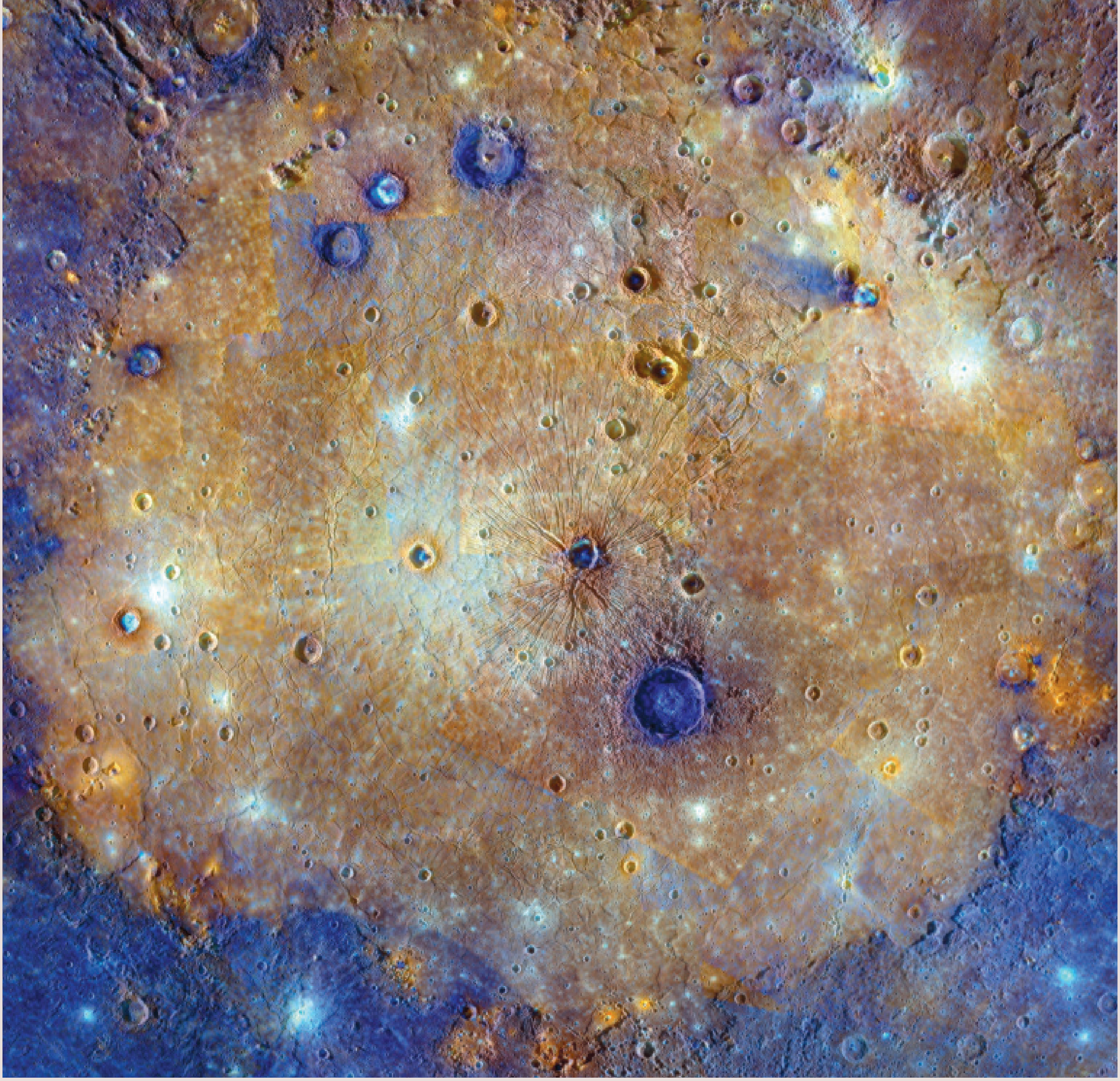
Mark McCaughrean is an astronomer who studies the birth of stars and planets. As the former senior advisor for science and exploration at the European Space Agency, he has worked on many space missions, including the Rosetta spacecraft and the Hubble and James Webb Space Telescopes. He is also the cofounder of Space Rocks, an organization that celebrates space exploration and the art, music, and culture it inspires through public events and more. This article is adapted from the book **111 Places in Space That You Must Not Miss** *© Emons Verlag GmbH 2025. Mastodon: @markmccaughrean@mastodon.social*

Miranda

MIRANDA IS ONE OF THE MOST fascinating moons of Uranus, all of which are named for characters in works by Alexander Pope or William Shakespeare, in this case the latter's comedy *The Tempest*. Discovered in 1948 by astronomer Gerard Kuiper, Miranda is just 470 kilometers in diameter. It's the smallest moon that's roughly spherical in the whole Solar System, which means it has enough mass to keep it flexible internally and allow gravity to pull it into a ball, whereas smaller moons tend to be irregular. But once you get here, you'll find that it's all the departures from spherical that make Miranda so interesting.

From above, you'll see rugged and fractured terrain, a patchwork quilt delineated and crossed by faults, gorges, ridges, and craters. Some regions look as though they've had a giant garden rake pulled through them. One possible explanation for the rough surface is that Miranda suffered one or more huge impacts in its early history, causing it to break up and then badly reassemble under its own gravity. Or it may have been kneaded, heated, and reshaped over billions of years by tidal forces, thanks to Uranus and some of its other moons. It's even possible that a subsurface water ocean was involved and is still liquid.

Descend to the surface, and you'll discover perhaps the most remarkable feature on Miranda: the giant cliffs of Verona Rupes. Although estimates of the height of this escarpment vary wildly from 5 to as much as 20 kilometers, they're probably the highest sheer cliffs in the Solar System and are sure to attract gawkers. Future space BASE jumpers might also want to visit this moon after conquering the Cliffs of Hathor on Comet 67P/Churyumov–Gerasimenko. (*See page 307.*) Falling from 10 kilometers up, you'll take more than eight minutes to reach the surface. But Miranda is large enough that you'll land at about 140 kilometers per hour, so you'll need to activate a giant airbag to cushion your landing.



MESSENGER/NASA, Johns Hopkins University Applied Physics Laboratory, Carnegie Institution of Washington

Caloris Basin

AS YOU DESCEND TOWARD THE scorching surface below, the vast scale of the Caloris Basin will quickly become apparent. Spanning over 1,500 kilometers across—10 percent of the circumference of Mercury—this giant crater was created almost four billion years ago when an asteroid at least 100 kilometers in size struck the closest planet to the Sun.

The impact created two broken rings of mountains and cliffs up to 2 kilometers high, while the basin itself was flooded with lava escaping from the interior of the planet. In the billions of years since the impact, the region has been struck again by numerous smaller asteroids and meteorites, making other craters. Several of the younger craters have groups of strange, irregular depressions with bright floors and rims known as *hollows*, which are probably caused by sublimation of sulfur compounds brought closer to the surface by the more recent events.

Now turn on your gas sensors, and you'll discover that Mercury has an extremely thin atmosphere that, as on Earth, includes hydrogen, helium, and oxygen. There are also sodium, potassium, and calcium, volatile elements that should have been removed by the intense heat of the Sun long ago. So where are they coming from today? The Caloris Basin is a rich source for these elements, and it's thought that they emerge from the hollows in the young craters, as well as from material brought to the surface in the past few hundred million years in explosive volcanic events similar to the one that buried Pompeii.

As you start your journey home, take a look back at Mercury. If the conditions are right, you'll see a giant yellow tail extending up to 24 million kilometers from the planet. Atoms in the thin atmosphere are blown into this tail by the strong sunlight, which then causes the sodium in particular to glow, giving it that characteristic streetlight hue.

The Cliffs of Hathor

STANDING ON A PROMONTORY jutting from the top of the Cliffs of Hathor, you're nervous. It's 900 meters down to the boulder-strewn floor of Hapi Valley below, the same height as El Capitan in Yosemite National Park. You reach to check your parachute one last time and momentarily panic when you remember that you don't have one. But what good would it do anyway? There's no atmosphere here to slow you down. Help!

Relax. You're on 67P/Churyumov–Gerasimenko, the comet explored by the European Space Agency's Rosetta spacecraft from 2014 to 2016. It's a loosely packed ball of ice, dust, and organic molecules, and at just 4 kilometers across, the gravity at the top of the cliffs is less than 0.001 percent of that on Earth. So just follow your guide's instructions: gently fall forward and enjoy the ride. After all, it's going to take a while—about 90 minutes—to reach the bottom.

That leaves you plenty of time to take in the spectacular scenery offered by the Cliffs of Hathor, named for the Egyptian sky deity, and also to contemplate the oddities of BASE jumping on a comet. Its center of gravity isn't directly below you, so you'll be drawn across the valley. Also, the gravity decreases by 50 percent as you descend and the comet rotates every 12.4 hours around an axis through Hapi, further complicating your timing and trajectory. All quite head spinning.

But the valley floor is approaching now, and you need to get ready to land. It's easier than you think. After falling all that way, your touchdown speed will be only 1.3 kilometers per hour, a slow amble. The next question is whether you're up for the expert challenge: leaping back to the top of the cliffs again. The feat involves no more effort than jumping onto a paperback book on Earth, but jump too fast and you'll escape altogether from the comet's weak pull, leaving you to drift inexorably out into the Solar System.

Rosetta/ESA, OSIRIS Team/image processing Mark McCaughrean, CC BY-SA

ESA/DLR/FU Berlin/Andrea Luck

Olympus Mons

IT'S SUNRISE AND THERE'S A light frost of water ice on the ground. You're standing in the middle of what appears to be a large crater with high cliff walls that rise to 3 kilometers and span a distance of 30 to 40 kilometers around you in all directions. But looks can be deceiving, as you're actually in the *caldera*—volcanic depression—at the top of Olympus Mons, the largest volcano in the Solar System.

Olympus Mons is located just off the western edge of the Tharsis Plateau on Mars, home to several other enormous shield volcanoes, and everything about it is gargantuan, including the caldera at its summit. Spanning over 600 kilometers in diameter and covering a region roughly the size of Poland, the volcano gradually but inexorably rises to 21 kilometers above the plains around it. That's more than twice the height of Maunakea, Earth's tallest volcano when measured from its ocean floor base. Even parts of the escarpment at the outer edge of Olympus Mons reach heights almost as tall as Mount Everest.

To the north and west, the terrain is chaotic, thanks to debris from huge lava-fueled landslides off the volcano that extended as far away as 1,000 kilometers. Scientists believe that Olympus Mons was surrounded by an ocean when the first landslides occurred billions of years ago, and that other landslides have happened more recently. The continuous activity has grown the volcano progressively over eons and is one explanation for its enormous size.

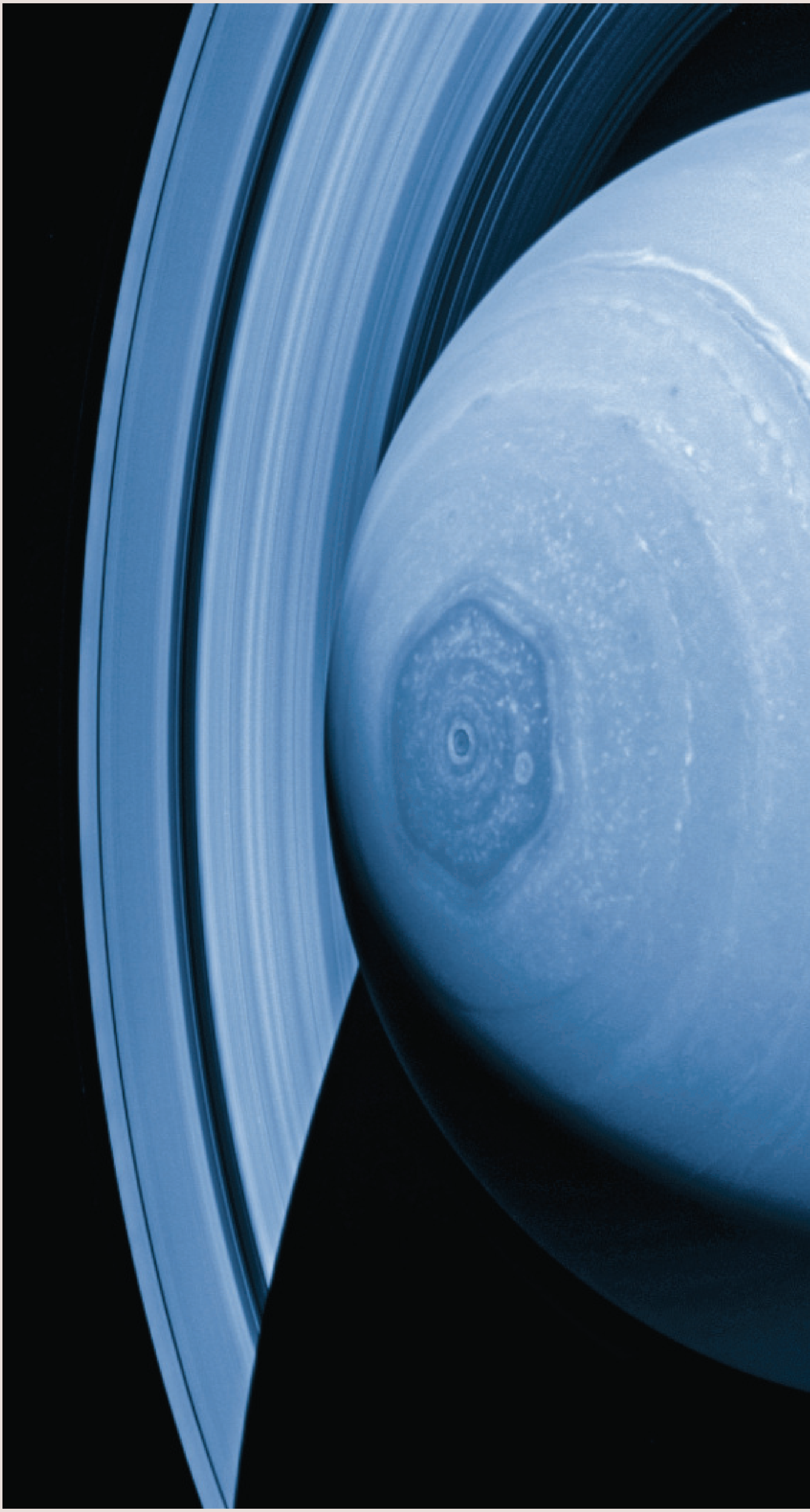
Mars lacks Earth's plate tectonics, so the mountain has stayed fixed over the same hot spot under the martian crust, growing ever larger with every eruption. The volcano might still be active but is dormant these days. Analysis of lava flows on its flanks suggests that they emerged between 115 million and just 2 million years ago, a mere blink of the eye in geological terms. So, watch for new activity as you plan your hikes on the giant volcano.

North Polar Hexagon

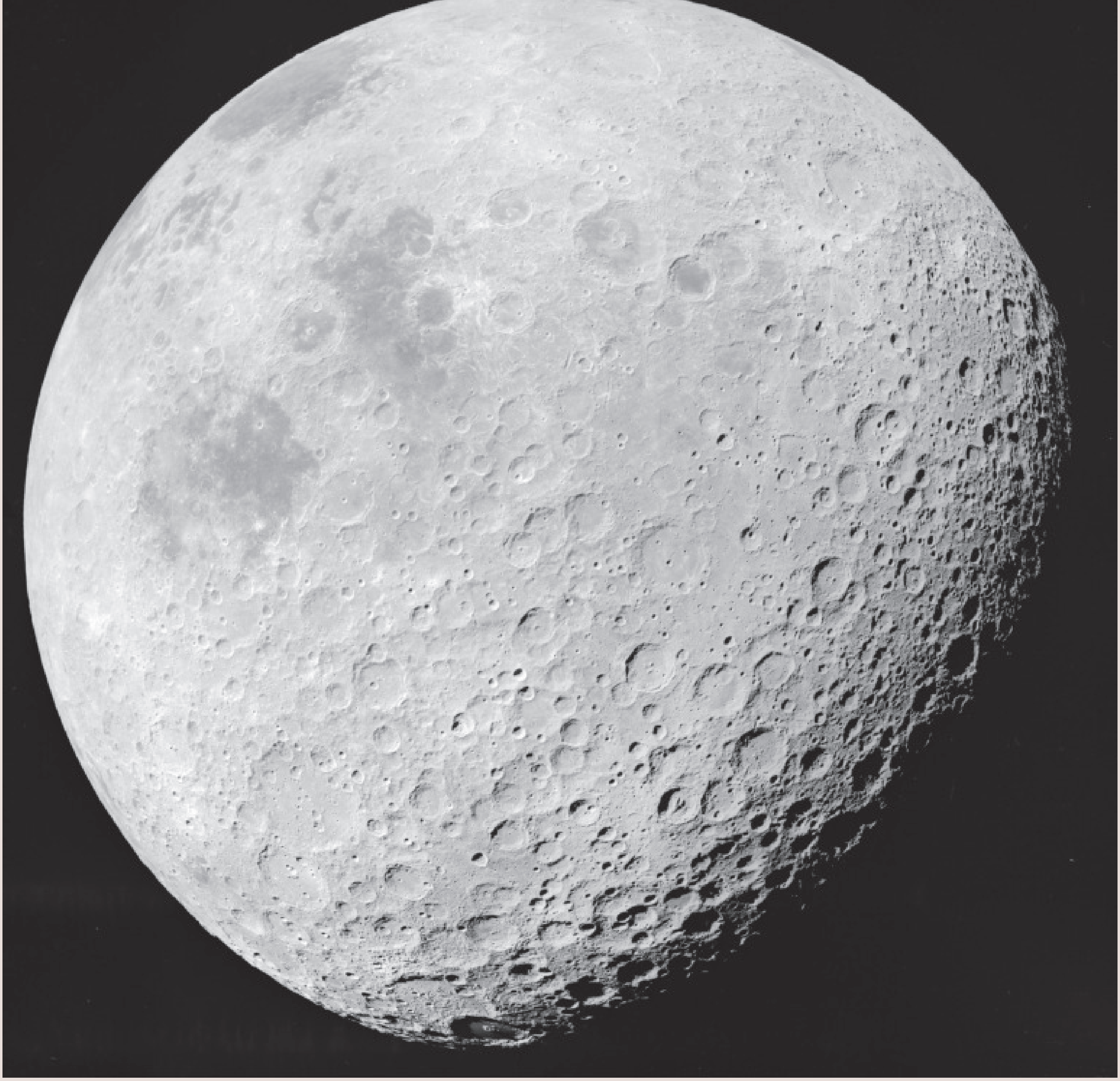
VISITORS TO SATURN OFTEN focus on its equatorial regions to view the planet's magnificent ring system. Beneath the rings at these latitudes, Saturn's upper atmosphere is a set of belts and zones in a bland, beige palette, and the uppermost clouds made of ammonia ice at around −250 degrees Celsius are battered by ferocious winds reaching 1,800 kilometers per hour. Warmer cloud decks of ammonium disulfide and water ice lie hundreds of kilometers deeper.

The rings might receive most of the attention, but the real excitement takes place in Saturn's polar regions, particularly in the north. As your eye moves to higher latitudes, you'll see small storms drifting poleward, and there will be clearer stripes and dark spots. And then suddenly, at around 78 degrees north, you'll notice something quite bizarre surrounding the pole: an enormous hexagon spanning 29,000 kilometers, each of the six sides larger than Earth's diameter. Inside the hexagon are many storm systems, large and small, and as you move closer to the pole itself, ragged clouds hurtle around a giant vortex at speeds of up to 600 kilometers per hour at the edges. Imagine yourself in the calm, 9,000-kilometer-wide center of this cyclone, looking at its eyewall descending more than 100 kilometers into Saturn's atmosphere.

But what about that weird hexagon? The most likely explanation is that there's a powerful jet stream around the pole that creates a strong gradient in the wind speed. Combine that with rotational forces from Saturn's short, 10.5-hour day, and you get atmospheric waves that meander up and down in latitude. The same thing happens to Earth's jet streams, but on Saturn the waves settle into a stable, six-sided polygon around the pole. Try to time your visit during the northern summer solstice, which happens every 29 years, to see the hexagon change in color from blue to golden as seasonal hazes accumulate over it.



Cassini/NASA, JPL-Caltech, Space Science Institute/image processing Mark McCaughrean, CC BY-SA



Apollo 16/NASA, JSC, ASU/image processing Mark McCaughrean, CC BY-SA

Far Side of the Moon

IF YOU'RE SEARCHING FOR SOME peace and quiet away from our home planet, then look no further than the far side of the Moon. It's less than 400,000 kilometers away and yet completely hidden from noisy Earth.

We see only one side of our nearest companion. Soon after it formed, the Moon became *tidally locked*, meaning that its orbital period around Earth matches the rotational period around its axis. As a result, one side of the Moon is permanently facing Earth (apart from slight wobbles, called *librations*), and the other is concealed. But Pink Floyd notwithstanding, it's not dark on the far side, at least no more so than on the near side. Both sides experience a fortnight of scorching daylight that reaches up to 120 degrees Celsius followed by a frigid two weeks of night that plummets down to −171 degrees.

The far side is more heavily cratered and has few of the large, dark *maria*, or "seas," found on the near side. When the Moon formed, it was at just 5 to 10 percent of its current distance from Earth. This proximity to our hot, young planet affected the composition of the Moon's near side, resulting in a thinner crust that was more easily penetrated by asteroid impacts. The deep punctures released hot lava that smoothed craters and created maria. The far side's thicker crust prevented asteroids from reaching the Moon's interior but left the surface pockmarked with craters.

The only humans to have seen the lunar far side are 24 of the Apollo astronauts, and then only from above as all crewed landings were on the near side. In 2024, the Chinese spacecraft Chang'e 6 landed and returned samples from the far side, and there's discussion about building a radio observatory there. Because the far side is shielded from the blare of Earth's incessant technological chatter, the faintest cosmic whispers would become audible.

Thanks to tidal locking, the Moon is receding from Earth at 3.8 centimeters per year, so every day you delay, the longer the journey will get. ■

Scientists' Nightstand

The Scientists' Nightstand, American Scientist's *books section, offers reviews, review essays, brief excerpts, and more. For additional books coverage, please see our* Science Culture *blog channel online, which explores how science intersects with other areas of knowledge, entertainment, and society.*

ALSO IN THIS ISSUE

THE MIND ELECTRIC: A Neurologist on the Strangeness and Wonder of Our Brains. By Pria Anand.
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CLAMOR: How Noise Took Over the World and How We Can Take It Back. By Chris Berdik.
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ONLINE

On our *Science Culture* blog:
www.americanscientist.org/blogs/science-culture

The Costs of Being Sally Ride

Book review editor Jaime Herndon reviews the documentary film *Sally* from writer, director, and producer Cristina Costantini.

NASA

Crossroads of Science and Fiction

Michael L. Wong

AMAZING WORLDS OF SCIENCE FICTION AND SCIENCE FACT. Keith Cooper. 224 pp. University of Chicago Press, 2025. $22.50.

When *Star Trek* first aired in 1966, it posited a universe bursting with planetary possibilities—a bold move at a time before anyone knew of a single planet beyond our Solar System.

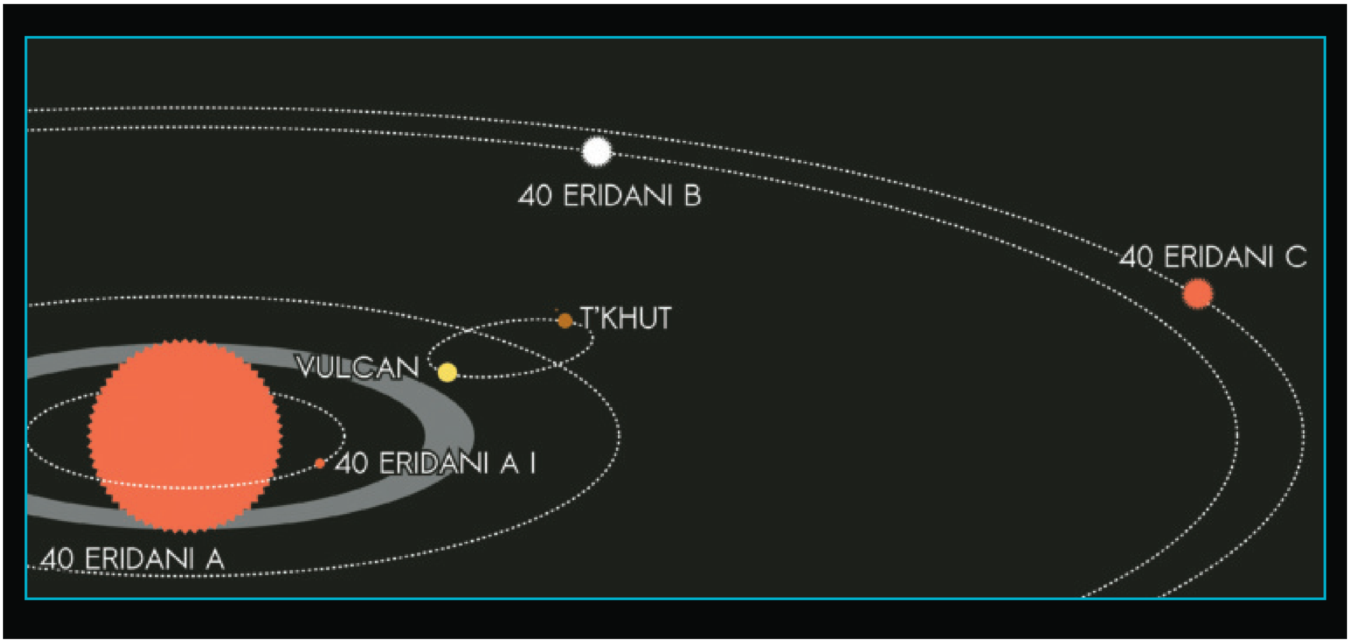
Nearly 60 years later, we now know for sure that we live in such a universe. Astronomers have discovered roughly 6,000 exoplanets, worlds orbiting other stars. Statistically speaking, our galaxy alone must be home to hundreds of billions of planets, many of which are bound to resemble Earth in their size, mass, and temperature. In other words, there really is a strange new world to visit every week—if only we had warp drive.

In the absence of physics-defying, faster-than-light propulsion, we have two tools of exploration at our disposal: astronomy and imagination. Keith Cooper's new book, *Amazing Worlds of Science Fiction and Science Fact*, investigates how these two tools are intertwined in our understanding of our planet-filled cosmos. Science and science fiction exist in a symbiotic relationship: Cosmic discoveries open new realms for storytelling, and boundary-pushing narratives inspire researchers to probe ever further and imagine realities that just might be crazy enough to be true.

Amazing Worlds is structured around chapters dedicated to different classes of planets depicted in science fiction, such as desert worlds, ocean worlds, ice worlds, worlds that orbit more than one star, and worlds with no sun at all. Cooper picks notable examples of each kind of planet, using them as vehicles of the imagination to provide an accessible way to understand the basic principles of planetary environments. Those principles furnish readers with a foundation for exploring more abstract studies within exoplanet science.

In his chapter "Lands of Sand," Cooper uses the planet Arrakis from Frank Herbert's *Dune* novels and their multiple on-screen adaptations to discuss the processes that influence a planet's climate, such as the greenhouse effect, the ice–albedo feedback loop, and the carbonate–silicate weathering cycle. He then uses these concepts to explain how planetary scientist Yutaka Abe at the University of Tokyo and his colleagues have modeled the climates of Arrakis-like worlds. The models constructed by Abe and his colleagues demonstrate that drier worlds should maintain their habitability under a wider range of conditions than ocean-covered worlds. This counterintuitive finding means that "planets like Arrakis may greatly outnumber planets like Earth," writes Cooper, before providing an informative sidebar about the great lengths that life must go to, in order to adapt to harsh desert environments. He concludes the chapter with a prescient reminder: "We're lucky to have Earth, and we should never take her for granted."

Indeed, for all our efforts, we have yet to find another truly Earthlike planet, though scientists are currently working on technologies that might enable that momentous discovery. (*See "Earth 2.0 Could Be Just Around the Corner," May–June 2024.*)



Shisma/Wikimedia Commons

This illustration shows the 40 Eridani system, as depicted in the books *Star Trek: Star Charts* and *The Worlds of the Federation*. Vulcan is fictional, but the larger star system of which it is a part, 40 Eridani, is very real. This system is only 16.5 light-years from Earth and can be seen with the naked eye. If Vulcan were real, it would be located in what would be the inner edge of 40 Eridani A's habitable zone, and due to this proximity it wouldn't be visible from Earth.

Instead, we have populated our scientific catalog of exoplanets with true anomalies. Gassy worlds lighter than cotton candy, like the "super-puff" Kepler-51. Scathing oceans of lava, such as CoRoT-7b, whose surface could be hotter than 1,000 degrees Celsius. Skies with clouds of gemstones, the natural precipitates in the atmospheres of worlds like WASP-121b. "No matter how bizarre planets are in science fiction, astronomical history has shown that the universe can throw at us planets even more bizarre than anything we could have dreamed of," Cooper writes. These discoveries, in turn, populate the skies of science fiction with even more fantastical settings, allowing storytellers to draw on the ever-expanding science of exoplanets.

For example, Cooper explores how author Charlie Jane Anders was inspired by recent discoveries of tidally locked exoplanets—worlds where one hemisphere experiences perpetual day, and the other, endless night. Tidal locking is common for worlds that orbit close to their host stars, resulting in scores of exoplanets without our familiar sunrises and sunsets. How would one know when to sleep and when to be awake? Anders populates her fictional tidally locked planet with one society that imposes a strictly regulated curfew, and another that embraces the chaos of timelessness. "I really just started obsessing about once you confront the idea of maintaining sleep schedules, how far are you willing to go into social control?" she tells Cooper. Cultural contemplation has been part of science fiction since its inception. By transporting us far from the here and now, it invites us to critique our own society from a different angle. Now, thanks to the exotic exoplanets astronomers have found, science fiction has a plethora of strange new vantage points to play with.

Science fiction typically reflects not only the current cultural zeitgeist, but it also takes a freeze-frame of our current scientific knowledge. Despite all of our searching, we have not yet confirmed conditions conducive to life on any exoplanet, much less irrefutable evidence of life itself. Hence, contemporary science fiction is adapting to the idea that intelligent life might be rare in the universe.

Some of the most striking parts of *Amazing Worlds* come through the inclusion of Emma Puranen, an astrobiologist, historian, and ethicist who studies the portrayal of exoplanets in science fiction over time. "Puranen's research suggests that planets that are home to indigenous technological species are not written about as frequently as before," Cooper writes. He continues,

> When exoplanets existed only in our imagination, it was easy to

Cultural contemplation has been part of science fiction since its inception. By transporting us far from the here and now, it invites us to critique our own society from a different angle.

conjure up fictional societies to inhabit them because storytellers could make those fictional exoplanets as hospitable as they wanted. Now that we know of thousands of exoplanets, none of which, at the time of writing, are known to be habitable like Earth, it's harder to picture worlds upon which societies—either human or alien—could thrive.

The influence flows both ways. Exoplanet researchers draw on ideas from fiction in choosing what to look for. A fun example is the search for a planet around 40 Eridani A, the home star of the fictional planet Vulcan in *Star Trek*. Scientists looked with special interest there, and in 2018 thought they had found a planet. But newer studies suggest the planet was an illusion—an artifact in the data likely due to star spots.

Cooper further illustrates how science fiction propels scientists such as Amaury Triaud, an astronomer with more than a hundred exoplanet discoveries to his name. Triaud was involved in the discovery of the TRAPPIST-1 system, for instance, which contains seven roughly Earth-sized exoplanets orbiting a dim, red star some 40 light-years away. Early in Triaud's career, Swiss science fiction writer Laurence Suhner consulted Triaud on the science of circumbinary planets for her *QuanTika* trilogy. "Funnily enough, I wasn't working on circumbinary planets at the time, and now I am," Triaud tells Cooper. "In so many strange ways, science fiction becomes reality!" Planets with multiple suns are a staple of science fiction. Now, thanks in no small part to Triaud and his colleagues, researchers are actually finding them, learning which of the imagined possibilities align with observed reality.

Through its examination of planets built for entertainment, *Amazing Worlds* offers an engaging survey of the latest results in exoplanetary science. And through his conversations with scientists and writers, Cooper demonstrates how entwined imagination and ingenuity are at the forefront of astronomical understanding. If there's anything that exoplanets have taught us, it's that we must expect the unexpected. And if there's anything that science fiction can do for science, it's to help us do just that.

Michael L. Wong is a NASA Sagan Postdoctoral Fellow working at the Carnegie Institution for Science's Earth and Planets Laboratory. An astrobiologist and planetary scientist, Wong studies the emergence of life, planetary habitability, and how to look for signs of life beyond Earth. In his spare time, he hosts Strange New Worlds: A Science and Star Trek Podcast.

A Neurologist's Tale

Dawn M. McBride

THE MIND ELECTRIC: A Neurologist on the Strangeness and Wonder of Our Brains. Pria Anand. 288 pp. Washington Square Press, 2025. $28.99.

The Mind Electric: A Neurologist on the Strangeness and Wonder of Our Brains by Pria Anand is a book of stories: stories about the function and dysfunction of the human brain; stories about patients with neurological disorders; stories about the current and historical cultural contexts in which these disorders have been described and explained; and stories about Anand herself, as she trained as a neurologist and became a mother. In her own story, she shows the reader how she became the doctor she is today, by rejecting some of the training she received and learning to listen to the stories her patients tell.

Anand begins the book with the story of her grandfather: showcasing his personality, describing his adventures in Los Angeles and how he met his wife, and finally, about his physical decline due to motor dysfunction near the end of his life. Weaving together his story with an introduction to neurological organization and function, Anand sets the reader up for what to expect from the rest of the book: stories of patients—both her own and those from historical records—and the disorders they experienced. These stories help the reader understand the complex workings of the human brain and show how doctors are able to identify the brain's dysfunction through their patients' stories.

Each chapter is centered around a particular behavior or experience that is essential to our everyday functioning, such as sleep, pain, motor control, the vestibular senses, and language. Within each chapter, Anand describes these behaviors or experiences with examples of both typical development and function and the different forms of dysfunction seen in patients. She shares stories of how each disorder has been studied, named, and explored, often including the cultural context in which the disorder has been examined. She pairs these stories with seminal research studies for each topic. For example, to illustrate how our brains are primed for language, Anand writes, "In one study, a group of pregnant women read a children's story aloud—a passage from *The Cat in the Hat*, for instance—twice each day, in a quiet place where their voice was the only sound. In the hours and days after birth . . . the newborns overwhelmingly chose to hear the story they knew over the unfamiliar one." The brain works in amazing ways, even before birth.

Woven between patient stories are Anand's critiques of the medical establishment's treatment of patients, from the language used in medical notes to the showmanship in which doctors have engaged.

In some instances, the tales are mysteries, with Anand revealing clues leading to the discovery of the cause of the disorders she describes. In other cases, the anecdotes are medical dramas about patients Anand has treated. But she takes care never to objectify the patients, unlike how Jean-Martin Charcot, a French doctor in the 1800s who specialized in "hysteria" in women, entertained Parisians with his "museum of curiosities," exploiting the pain of these individuals. Anand's compassion for her patients and their pain is clear throughout the book, even—and perhaps especially—in cases where a patient's behavior was unusual or unexplained.

Anand also delves into lay explanations of the disorders she explores through a variety of cultural lenses. From India, to Guinea in sub-Saharan Africa, to a tiny island off the coast of Colombia, the reader is given a firsthand account of each of these communities based on her work and studies. About her time in Guinea, she writes: "From patients and their families at Hôpital Ignace Deen, though, I learned about other ways to make sense of epilepsy. I learned that epilepsy can be caused by the devil or by *djina*, invisible spirits who inhabit the sea and the forest . . . I learned that epilepsy comes at night, in black shadows and dark birds and bad dreams." In relating these stories and beliefs about the neurological disorders she treats, Anand draws a parallel between the explanations doctors propose for the symptoms they see in their patients and the explanations laypeople give to these symptoms. Although only one is based in science, both types of stories are based on the knowledge one has and the attention given to the patients themselves.

Woven between patient stories are Anand's critiques of the medical establishment's treatment of patients, from the language used in medical notes to the showmanship in which some doctors have engaged. These critiques are part of her own story of how she became the doctor she is today. While writing about the numbing of emotion and the sleep deprivation she experienced during medical school, she also points out that "in some ways, the power imbalance inherent in medical practice derives from the ways in which doctors control their patients' narratives. We arbitrate which stories are important and which don't matter, which are true and which are false, as if we were omniscient rather than subjective beings, as if our training somehow excises the humanity, the personal, from our practice."

By the end of the book, Anand reveals herself as a skilled yet empathetic neurologist who is also a gifted storyteller. Early in the book she writes that she wants to "both honor and contend with these stories within stories—the ones we tell about our minds, and the ones our minds tell us—in all their wonder, strangeness, and heartbreak." Her book does exactly that.

Dawn M. McBride is a professor of psychology at Illinois State University. Her research explores topics in human memory and forgetting. She has published more than 40 peer-reviewed articles and has authored textbooks on research methods, statistics, cognition, and introductory psychology.

Reconsidering Our Soundscapes

K. Anthony Hoover

CLAMOR: How Noise Took Over the World and How We Can Take It Back. Chris Berdik. 272 pp. W. W. Norton & Co., 2025. $29.99.

In our everyday lives, noise is so widespread that we often ignore it—much to our detriment, as science journalist Chris Berdik writes in his newest book, *Clamor: How Noise Took Over the World and How We Can Take It Back*. Berdik describes noise as one of the most ubiquitous pollutants in our daily experience, showing few signs of abating. Noise affects what we can hear, how we feel, our health, our ability to learn, and even our longevity.

Berdik suggests that our current approach to noise—the typical focus on decibels and how loud something is—not only minimizes the full impact of noise on humans and on nature, but also brushes aside decades of work toward a more comfortable environment. He interviews designers, musicians, and scientists to better understand our various soundscapes, with the hope of creating more peaceful environments.

The book is split into two parts. Part one covers what and how we hear and how we respond, as well as the effects of noise on nature and the environment. A primary theme is that the true concern is less about the number of decibels and more about the quality and duration of sound, for both humans and animals. He writes, "As with underwater environments, the most harmful sounds in terrestrial ecosystems are not necessarily the loudest but rather the most persistent."

Part two explores how to transform the soundscapes in our learning, work, and recreational spaces. This aim necessitates a new understanding of sound: Although a quiet environment can be a goal, noise can also be transformed into something pleasant. Many sounds are design choices, such as sounds from electronic devices, and can be changed. Berdik writes about efforts that have been underway in research, architectural design, product development, and urban planning toward more comfortable acoustic environments.

A common problem is that we tend to try to fix problematic noise, rather than anticipating and addressing sound in our designs of buildings, cities, and products. With some special exceptions such as concert halls, designers typically merely try to satisfy regulations rather than offer an acoustically satisfying environment.

Berdik writes about the concept of "soundscape," a term that is often applied to environmental noise. A major principle when it comes to soundscapes is that there aren't any bad sounds, but there can be wrong sounds at the wrong times. For instance, urban noise has been a problem for millennia: Nighttime chariot driving was prohibited in ancient Rome to protect citizens' sleep. These days, almost conversely, electric vehicles have become so quiet, especially at slow speeds, that some sounds must be added so that pedestrians can hear them as they approach. The challenge is designing vehicle sounds that properly alert pedestrians without inordinately contributing to a noisy environment.

But noise is not always bad; in some cases, the right noise can actually be desirable. For example, studies in the 1950s and 1960s showed that the biggest complaints in offices and workplaces were less about the levels of ambient sound and more about the lack of privacy, both from being overheard and from being distracted by others.

One result was the almost-heretical concept of *masking systems*, which use small loudspeakers to slightly increase the background sound level as if an office building's HVAC were running a little more vigorously. Masking, often incorrectly called "white noise," is now ubiquitous and has become big business because these systems can be very beneficial. However, they must be properly adjusted so that they are effective, without becoming an additional annoyance.

Humans aren't the only ones affected by noise: Animals of all types are also dealing with increased noise from the modern world, making it harder to communicate and avoid danger.

Humans aren't the only ones affected by noise. Animals of all types are also dealing with increased noise from the modern world, making it harder to communicate and avoid danger. Perhaps the biggest measurable impacts are on underwater creatures. Aquatic animals perceive and use sound for a wide range of behaviors, including attracting mates, finding food, and avoiding predators. Underwater loudness can interfere with all of these things, but that's not the only danger to some of these animals. Intense underwater sound can actually cause temporary hearing loss for many kinds of marine animals, and although auditory sensory cells can regenerate in some fish, amphibians, and birds, the same cannot be said for whales and dolphins, or for humans.

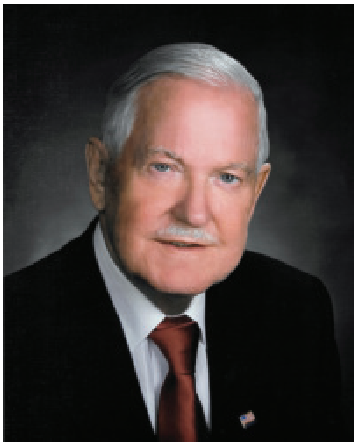
Changes to propulsion systems, combined with streamlined hulls and drag-reducing coatings on ships, can help quiet ship noise, but these changes come at a high financial cost—one at which many companies balk. But the noise pollution issue needs to be addressed industry-wide, not just by one or two companies, to truly make a difference. Berdik also reminds the reader that the issue does not have a one-size-fits-all solution: "A more tailored and adaptable approach to reducing underwater noise would focus on protecting the soundscapes of critical areas such as coral reefs, spawning grounds, and migration corridors, and that degree of specificity will require a lot more long-term listening."

Berdik covers a lot of environments and soundscapes and puts forth many ideas in *Clamor*, sometimes to the detriment of a more in-depth examination of problems and their solutions. One could easily write a book solely on the effects of noise pollution on the physical health of humans, for example, or on the effects of noise on children in the classroom. Answers are few and far between, but maybe that's not the real goal of this book. Perhaps, as Berdik writes, the goal is simply about "expanding our ambitions for sound." In other words, looking at our subjective "definitions" of things like sound, noise, and music. For example: sound happens when you mow your lawn; noise happens when your neighbors mow their lawns; and music happens when your neighbors mow your lawn.

Noise can be quite subjective and any attempt to organize, quantify, and deal with noise is, by necessity, complicated and multifaceted. *Clamor* is an accessible introduction to the topic of noise and noise pollution, as well as a primer on how to see noise in a different way so that we can begin to change our soundscapes accordingly.

K. Anthony (Tony) Hoover has served as a principal consultant on over 2,100 projects in architectural acoustics. He has lectured widely, has written and contributed to books and publications, is frequently retained as an expert witness, and has received numerous design awards.

Dr. Hans D Baumann, Leading A Life of Purpose



On March 25, 2025, Hans D. Baumann, Ph.D., P.E. passed away at home in West Palm Beach, Florida. He was 94. His passing marks the end of an era.

His professional career, spanning nearly 70 years, began in his native Germany in the early 1950s. The contributions to his chosen field are vast and varied, and his dedication to advancing the state-of-the-art is unsurpassed.

Preferring the practical over the political, Hans was never shy about steering away from the crowd in order to get to the underlying fundamentals, or to resolve a conflict with a practical approach. Getting to the physical truths of process control was of key importance to him. In that spirit, Hans pioneered many, what are today, fundamental concepts relating to valve sizing and valve noise prediction.

His most recent efforts resulted in the development of novel, physics-based noise prediction methods, known as the ABC Method. His scientific and engineering appetites were insatiable, right to the end.

Early in his working career, he was able to work at a foundry, as well as at a tool and die maker. These experiences were to prove invaluable in his ability to design practical and cost-effective control valves.

"My aim is simple: to eliminate any unnecessary features and focus on cost-effective designs" **– H. D. Baumann**

Dr. Baumann received an industrial engineering education in Germany and then studied under U.S. Government sponsorship at Western Reserve University, and later at Northeastern University, culminating in a Ph.D. in Mechanical Engineering from Columbia Pacific University.

During his professional career, he personally designed or directed the development of over 30 valve lines. One of them, the famous "CAMFLEX" valve and its derivations, is produced in eight countries where over three million units have been sold.

He is credited with over 150 U.S. and worldwide patents and has published over 200 papers and articles in addition to co-authoring seven handbooks on valves and instrumentation.

He began his professional career at Welland & Tuxhorn, working as Engineering Manager. In 1958, he moved to the United States to work for Masoneilan Company as Development Engineer. From there, he progressed to Director of Engineering at A.W. Cashco in Illinois, Manager of R&D at Worthington S/A in France, and Corporate Vice-President of Masoneilan International, Inc. In 1977, while working as an international consultant, he determined it was time to form his own control valve manufacturing company, H. D. Baumann Assoc. Inc. After selling his company to Emerson Electric, he worked for Fisher Controls as Senior Vice President.

He served as a director of the ISA Standards & Practices Department Board, Chairman of the ISA75.11 Committee, U.S. Technical Expert for IEC Committee SC/65B/WG9, was a Member of the ASME Bioprocessing Equipment Executive Committee, and Chairman of the Equipment Subcommittee on Seals, and was the former Standards Chairman for Control Valves for the Fluid Controls Institute (FCI).

His professional affiliations include: *Honorary Member of International Society of Automation (ISA), Life Fellow of the American Society of Mechanical Engineers (ASME), Honorary Life Member of the Fluid Controls Institute (FCI), and member of Sigma Xi, the Scientific Research Society.*

Some notable awards for his control valve designs include: seven *Vaaler Awards,* the *ISA UOP Technology Award,* the *ISA Chet Beard Award,* a Gold Medal from Germany, and prizes from France and Japan. He was named by *InTech* magazine one of the *50 Most Influential Industrial Innovators,* was named *Entrepreneur of the Year* by the New Hampshire High Technology Council, as well as being inducted into the *Process Automation Hall of Fame.*

Hans lived purposefully; he lived authentically; he lived fully. He was very generous, sharing his knowledge, his experience, and his success. He was ever the gentleman, in manner and appearance.

He will be greatly missed, but his legacy will live on.

"I would advise students and graduates alike to make more use of their brain and imagination." **– H. D. Baumann**

Sigma Xi Today

A NEWSLETTER OF SIGMA XI, THE SCIENTIFIC RESEARCH HONOR SOCIETY

Spring 2025 GIAR Awards

Sigma Xi has awarded 61 student research grants for the spring 2025 cycle of its Grants in Aid of Research (GIAR) program. Since 1922, the Society's GIAR program has been funding research for undergraduate and graduate students, and currently awards grants biannually in the fall and spring.

This year's Committee on Grants in Aid of Research, along with a panel of guest reviewers, evaluated hundreds of applications across most research disciplines. Chaired by Shawn Ellerbroek, the committee awarded grants to 10 undergraduate students, 14 master's students, and 37 doctoral students. Grant amounts ranged from $300 to $5,000, and a total of $120,090 was awarded.

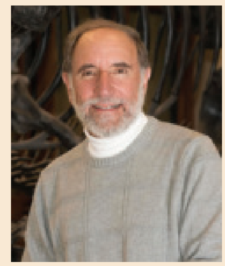
Visit **sigmaxi.org/GIAR-recipients** to view the names and research projects of the spring 2025 awardees.

Visit **sigmaxi.org/GIAR** to learn more about the program, read stories from past recipients, and submit applications for future grants. The deadline for fall grant applications is October 1, 2025.

Sigma Xi Today is managed by Jason Papagan and designed by Chao Hui Tu.

From the President

Hamjambo from Kenya!



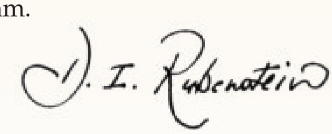
This summer, I spent time in the field in Kenya, where I studied zebra–livestock interactions and their impact on human livelihood and endangered species sustainability. And while I was excited to return home, I knew there was growing concern waiting for me over the unstable future of federal research funding in America. Like it or not, many scientists in our country have been thrown into a chaos that threatens the foundations of our scientific research enterprise.

Given this current state of affairs, Sigma Xi must serve as a bright beacon helping guide the scientific ship between the Scylla and Charybdis of ignorance and malfeasance. One important step in this direction will be for Sigma Xi to have a successful and illuminating 2025 International Forum on Research Excellence (IFoRE), our signature annual event celebrating the pursuit and practice of research excellence. IFoRE's theme this year—Science and Society: Crafting a Vision for a Sustainable Tomorrow—is truly timely, and it reflects our shared responsibility as scientists and engineers to ensure that research advances the well-being of humanity and our planet.

As it became clear that funds for many of our members were being cut or even terminated, Sigma Xi's board realized that attendance at an in-person interdisciplinary gathering could be limited. Accordingly, Sigma Xi decided that this year's conference would be held virtually. Our integrated online platform will offer easy, one-stop access via web browser or mobile app, with the ease and familiarity of Zoom meetings and webinars. By cleverly using chat rooms and having student presentations transformed into "speed talks," we are confident that lively, engaging, and illuminating conversation will ensue.

IFoRE's agenda this year is tightly packed with compelling sessions, many of which focus on artificial intelligence, science policy, disease transmission, the overall improvement of human health, and much more. We are excited and expect that every IFoRE session will provide actionable insights, spark new ideas, and inspire excellence in research and scholarship in ways that chart a course for a better future.

Registration is currently open at experienceIFoRE.org. In addition to the ease and flexibility of attendance, our new virtual format offers extremely affordable rates, including discounts for students and Sigma Xi members. Whether you are a seasoned researcher or a rising scientist, we hope you will join us virtually from October 30 to November 1, 2025, and contribute your voice and vision to this year's program.



Daniel Rubenstein

FACES of GIAR: Jana Woerner

Grant: $500 in Fall 2022
Education level at time of the grant: PhD student

Project Description: My collaborators and I applied tracking collars to all adult spotted hyenas (*Crocuta crocuta*) living in the same social group in the Maasai Mara National Reserve in Kenya at the beginning of 2023. These collars recorded fine-scale GPS locations, accelerometer and magnetometer data, and all vocalizations, allowing us to monitor these individuals around the clock for several weeks. The overall research project focuses on how communication drives coordination of collective behaviors, such as resource acquisition and defense. I am specifically interested in the social dynamics that affect group hunting in spotted hyenas. Group hunts are often more successful than solo hunts, and bigger prey items are hunted only in groups. However, spotted hyenas live in fission–fusion societies with strict dominance hierarchies that determine access to all resources. Higher-ranking hyenas can easily steal food from lower-ranking conspecifics, so hyenas spend most of their time alone or in small subgroups to avoid intraspecific competition while foraging. Hyenas are highly efficient hunters, so each individual can choose when to hunt in a group, and with whom. Using the data collected with the help of this grant, I will investigate the drivers of this individual participation in group hunts.

How did the grant process or the project itself influence you as a scientist/researcher? This was one of the first grant proposals that I wrote for my project, so it helped me define my goals and hypotheses clearly. The relatively short proposal requirements also forced me to write succinctly, something that I often struggle with. The project itself has confirmed my passion for performing fieldwork, studying wildlife, and using technology to improve our current understanding of the world.

What advice would you give to future applicants? Have somebody outside of your discipline read your proposal to make sure it is accessible to a broad audience.

Where are you now? I am currently working with my collaborators at the Max Planck Institute of Animal Behavior in Konstanz, Germany. We are still processing and analyzing the enormous amounts of data collected by our tracking collars, and we have already found some interesting patterns when it comes to hunting and food stealing in hyenas. I will return to Michigan State University later this year to finish my PhD.
Students may apply for Sigma Xi research grants by March 15 and October 1 annually at **sigmaxi.org/giar**.

New Sigma Xi Chapter Established at India's Christ University

On July 4th, Sigma Xi installed its newest chapter at Christ University in Bengaluru, Karnataka, India. The ceremony was held in person and celebrated the new chapter's officers, members, and commitment to growth and advancement of the university's research enterprise. It also established Sigma Xi's very first India-based chapter.

Sigma Xi fellow and past president Dr. Robert T. Pennock presided over the ceremony, which also included a video message from current president Dr. Daniel I. Rubenstein. The chapter's founding members are Mrs. Athulya S., Dr. Beulah Matcha, Dr. Gowtham Sanjai S., Dr. Michael T. Moses, Dr. Sarath K. Chandra, Dr. Shibu K. Mani, and Dr. Vinay Jha Pillai.

Since its founding in 1969, Christ University has been committed to academic excellence, interdisciplinary research, and innovation. As one of India's leading institutions, the School of Engineering and Technology serves its students by fostering cutting-edge research and development in various engineering disciplines. The new chapter will amplify the university's commitment to fostering a culture of research and innovation while enhancing its efforts to promote interdisciplinary research and scientific collaboration. With the university's rapidly growing research profile, the officers look forward to the benefits of collaboration and research recognition that the new chapter will present to its founding and future members.

2025 Sigma Xi Award Winners

Sigma Xi, The Scientific Research Honor Society is proud to announce several 2025 Award Winners. Presented annually by the Society's Prizes and Awards program, the following awards recognize exemplary achievement in science and engineering. Recipients are presented with the awards at the International Forum on Research Excellence (IFoRE), where many will serve as keynote speakers. More information on additional awards and recipients can be found at **sigmaxi.org/awards**.

John P. McGovern Science and Society Award

Freeman Hrabowski
ACE Centennial Fellow
President Emeritus, The University of Maryland, Baltimore County

For their work championing initiatives in leadership development, STEM education, workforce advancement, and civic engagement and playing a pivotal role in improving science and mathematics education, with a strong focus on increasing minority participation and success in these fields.

The John P. McGovern Science and Society Award is presented to an individual who has made an outstanding contribution to science and society. The award consists of a medal and a $5,000 honorarium. Recipients are publicly recognized and presented the award at the International Forum on Research Excellence, powered by Sigma Xi.

William Procter Prize for Scientific Achievement

Alessandro Sette
Professor, La Jolla Institute for Immunology
Adjunct Professor, University of California, San Diego

For understanding basic mechanisms of antigen recognition and immunity, predicting immune activity, and developing interventions against cancer, infection, autoimmunity, and allergies.

The William Procter Prize for Scientific Achievement is presented to a scientist who has made an outstanding contribution to scientific research and has demonstrated an ability to communicate this research to scientists in other disciplines. The award includes a $5,000 honorarium, a $5,000 grant to a young colleague of the recipient's choice, and a bronze statue.

Moses and Dorothy Passer Award *Inaugural Award

Meghan Barrett
Assistant Professor of Biology, Indiana University Indianapolis

For being a pioneering leader in entomology as related to the ethical treatment of insects in research and production (i.e., farming) contexts.

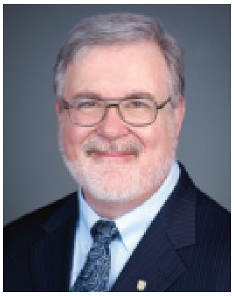
The Moses and Dorothy Passer Award recognizes individuals for their contributions to promoting integrity in science. The objective of this award is to promote individual and collective efforts to strengthen the integrity of scientific research. The award comes with a $1,000 honorarium and an invitation to speak at Sigma Xi's annual IFoRE conference.

Lawrence M. Kushner Memorial Award *Inaugural Award

Ryoto Tamura
Assistant Professor of Neurosurgery, Keio University School of Medicine, Japan

For their work on neurosurgical and translational approaches to patients with brain tumors.

The Lawrence M. Kushner Memorial Award supports a member of Sigma Xi in advancing the technology transfer aspects of their research, projects, products, or work. The $1,250 award is presented annually to a student member or early-career professional on an alternating basis.



Walston Chubb Award for Innovation

Richard J. Spontak

Distinguished Professor of Chemical & Biomolecular Engineering, North Carolina State University

For their groundbreaking discovery that the anionic block polymers he developed—originally described as charged thermoplastic elastomers (TPEs)—possess inherent antimicrobial properties and can continuously self-sterilize. This innovation addresses a critical global need for effective microbial inactivation methods that do not contribute to antimicrobial resistance, a challenge that has grown more urgent in the wake of the COVID-19 pandemic and the rise of drug-resistant pathogens.

The Walston Chubb Award for Innovation is designed to honor and promote creativity among scientists and engineers. The award carries a $4,000 honorarium and an invitation to give a lecture at the International Forum on Research Excellence, powered by Sigma Xi.

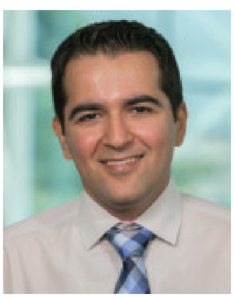
Dr. Philip J. Wyatt Technology Transfer Award *Inaugural Award

Santiago Perez-Lloret

Senior Researcher, CONICET
Assistant Professor of Neurophysiology, University of Buenos Aires

For developing a computer vision, artificial intelligence–based algorithm to assess motor dysfunction symptoms in Parkinson's disease.

The Dr. Philip J. Wyatt Technology Transfer Award promotes the commercialization of scientific research for the health, security, or economic betterment of society. The award is presented annually and includes a $7,500 honorarium.



Young Investigator Award

Amir H. Gandomi

Professor of Data Science, Data Science Institute at University of Technology Sydney

For advancing AI for social good, applying data-driven solutions to public health, sustainability, and smart cities to enhance safety, resilience, and well-being.

Awarded annually, Sigma Xi's Young Investigator Award recognizes excellence within 10 years of a researcher's highest earned degree. This year's award is given for excellence in life and social sciences and includes a $5,000 honorarium.

Evan Ferguson Award

Rudy L. Ruggles, Jr.

Vice Chairman, J. Craig Venter Institute
Adjunct Scientist

The Evan Ferguson Award has been presented annually since 2008 in recognition of outstanding service to Sigma Xi and its mission. The recipient is recognized with a plaque and a lifetime subscription to *American Scientist*.

Quite Simply The World’s Most Advanced Sunglasses May Save Your Life

The sun rises and sets at peak travel periods. During the early-morning and afternoon rush hours, many drivers find themselves temporarily blinded while driving directly into the glare of the sun. **Deadly accidents are regularly caused by such blinding glare**, with danger arising from reflected light off another vehicle, the pavement, or even oily windshields that can make matters worse. Yet motorists struggle on despite being blinded by the sun’s glare that causes countless accidents every year.

NASA Technology

Eagle Eyes® has been working on perfecting these sunglasses for two decades and has finally achieved it. Many overpriced designer sunglasses can actually blur your vision by allowing harmful UV and blue light rays in, but thanks to a team of NASA physicists and scientists, **Eagle Eyes’ revolutionary technology allows you to see the world like you’ve never seen it before**. Looking to nature for inspiration, these NASA scientists discovered how eagles can distinguish their prey from their surroundings with utmost precision while protecting their eyes from harmful UV rays and blue light. Scientists then adapted this natural process into lens technology that, in turn, led to the founding of Eagle Eyes Optics,™ the leader in stylish, high-performance eyewear that protects and enhances vision under any light condition.

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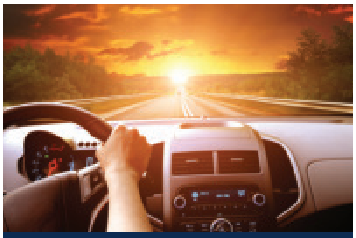
Eagle Eyes Optics Eyewear has set these breakthrough polarized, Trilenium® lenses into the best frame material on the market. **At just over ½ ounce**, these titanium superlight frames layered in 22 karat gold are some of the strongest, lightest and most flexible frames ever designed. And of course, the aviator style is amazingly good looking.



A study by the National Highway Traffic Safety Administration showed that **74% of crashes** occurred on clear, sunny days

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