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The New Race to the Moon

Florence Nightingale, Data Explorer

DISCOVERIES FROM THE DEEP SEA

What the ocean is teaching us about life—on Earth and beyond

INSIDE

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SEAFLOOR SURPRISES

GHOSTLY BIOLUMINESCENCE

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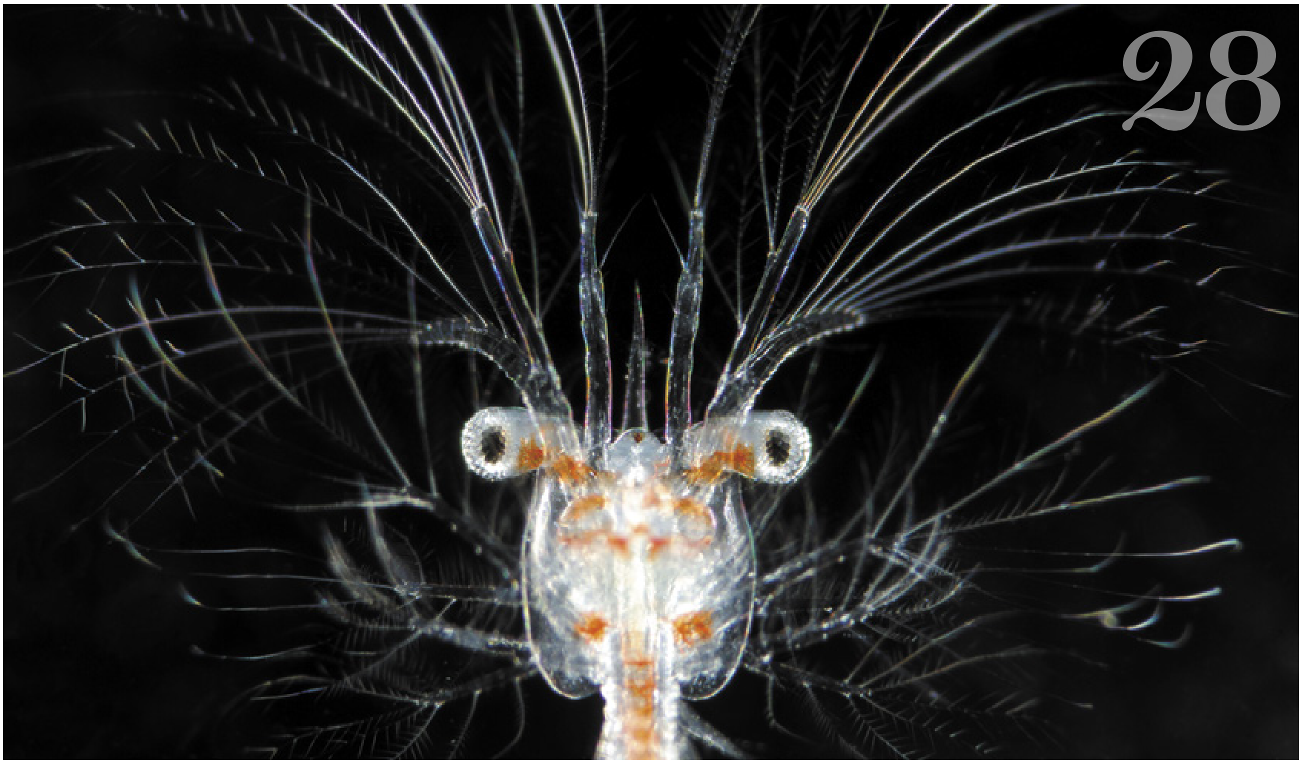
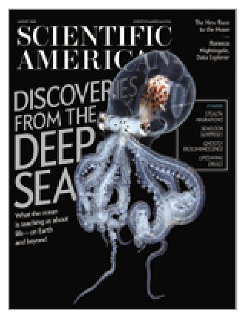


Solvin Zankl/NPL/Minden Pictures (*deep sea shrimp, Sergestes species*)



ON THE COVER
The wunderpus octopus is transparent when it is a juvenile and becomes reddish or rust-colored with white bands as it matures. The adult, only nine inches long or so, lives in the sand in relatively shallow water and can change its appearance to ward off predators. **Photograph by Yung-Sen Wu.**

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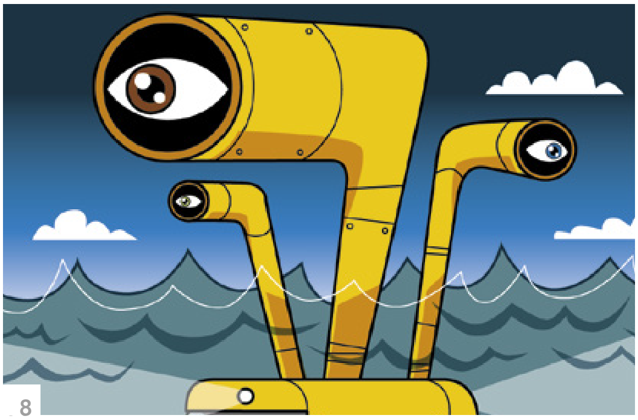

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FROM THE EDITOR

Laura Helmuth is editor in chief of *Scientific American*. Follow her on Twitter @laurahelmuth

Sea Surprises

We humans may think of ourselves, or possibly beetles, as typical Earthlings, but to a first approximation, life on Earth exists in the sea. And what spectacular life! Our special package on the oceans is teeming with images of eerie, delicate, elaborate, glowing and occasionally kind of frightening creatures that have rarely been seen by terrestrial species. The in-depth report, which starts on page 28, was guided by sustainability senior editor Mark Fischetti along three main themes: mystery, discovery and surprise.

One of the most common abilities on Earth is a mystery we're just now solving: bioluminescence. As author Michelle Nijhuis shares on page 30, recent surveys show that most organisms in the ocean are able to glow. This ability evolved independently across phyla, using different chemical processes and for different purposes, transmitting light-based messages even on the seafloor.

Ocean creatures live much more three-dimensional lives than people realized, surging vast distances from the deep ocean toward the surface in search of food. This "diel migration"—by an estimated 10 billion tons of animals—moves carbon and other elements through the oceans and the world, as contributing editor Katherine Harmon Courage explains on page 48. The stunning images for this story and throughout the package were gathered by photography editor Monica Bradley.

Sea-dwelling creatures are exposed to a lot of pathogens, and they have evolved an astonishing variety of chemical defenses to protect themselves. These chemicals have the potential to treat human diseases, and as science journalist Stephanie Stone reports on page 56, some have been turned into treatments for various types of cancer, chronic pain and COVID, with many more deep-sea drugs in development.

The textbook view of the oceans stratifies them into layers according to depth. As Fischetti describes on page 65, that's just one way to slice it. Scientists are increasingly realizing that other qualities are just as important for understanding ocean zones: salinity, light, color, temperature, even life-forms. The eye-opening graphics by Skye Moret and *Scientific American* senior graphics editor Jen Christiansen offer a new inspiring view of the ocean.

Mystery, discovery and surprise. As deep-ocean biologist Timothy Shank writes on page 70, the ocean is full of diverse life, unexpected chemistry and weird physics—and there's still so much to learn.

You may have heard that we know more about the surface of the moon than the structure of the seafloor, but as Fischetti details on page 40, with new marine mapping and the release of private data, that soon won't be true (if it ever was).

What's next for the moon? There's a race among nations and various billionaires to send missions, and possibly people again, to the moon, which is a lot more difficult than sending a rocket to space. Author Rebecca Boyle reports on page 72 that scientists are cautiously optimistic—there's a lot of research to be done on the moon, and new partnerships with private companies could actually lead to an exciting time of lunar exploration.

Clear, dramatic graphics have the power to change the world. Florence Nightingale launched the modern era of public health and public health messaging with her depictions of death and disease during the 1853–1856 Crimean War. They helped to revolutionize medical practices around the world and saved countless lives (*page 78*). Our graphics editors at *Scientific American* are always striving to present complex, mind-bending and sometimes invisible phenomena using engaging graphics, building on Nightingale's work. SA

Illustration by Nick Higgins

April 2022

> **"I do not read *Scientific American* for the book reviews, but I recognize one that is beautifully written."**
>
> ROBERT HUNT *SOUTHERN METHODIST UNIVERSITY*

FLIGHT OF THE NAVIGATORS

"The Quantum Nature of Bird Migration," by Peter J. Hore and Henrik Mouritsen, describes the biophysical underpinnings of how the animals navigate. This article is fascinating. I believe that Earth's magnetic north pole shifts position every so often. How would this affect the ability of birds to migrate successfully?

Steven Sverdlik *Dallas, Tex.*

Radio-frequency (RF) transmitters are increasingly attached to birds to track their movements. The sizes of transmitters and the methods of attaching them have had unfortunate physical impacts on birds, which are gradually being addressed through design improvements. But in light of the eye-opening findings presented in Hore and Mouritsen's article, it seems we also need to be concerned about RF fields generated by tracking transmitters and how those fields might impact birds' supremely delicate natural compass.

Mike Alexander *Palo Alto, Calif.*

THE AUTHORS REPLY: To answer Sverdlik: Earth's magnetic field does indeed shift, and pole reversals occur from time to time (the last one was almost 800,000 years ago). We know that birds are capable of calibrating their magnetic compass with information from the sun. If they do this every day, it does not matter where the magnetic poles are. No one knows what happens during a reversal. If it took place instantaneously, birds would be none the wiser because their compass is not sensitive to the polarity of the magnetic field. But the reversal typically takes several thousand years, during which time the local magnetic field intensity can be very much smaller than it is today. Perhaps the birds would simply rely on other directional cues until the magnetic field settled down again.

In response to Alexander: Tracking devices usually employ frequencies well beyond 100 megahertz, which are very unlikely to affect the birds' magnetic compass. Frequencies within the range that can affect their compass could indeed falsify results. Usually the transmitters are active only intermittently and for very short periods, however. Therefore, even if they used the critical frequencies, there might be no significant effect on the birds' orientation.

CRITICAL ACCLAIM

I do not read *Scientific American* for the reviews, but I recognize one that is beautifully written. Omar El Akkad's review of Emily St. John Mandel's novel *Sea of Tranquility* under the heading "Half-Lived Years" [Recommended] is a piece that can stand alone as an essay on our times and the literature emerging from them. He should be commended for it.

Robert Hunt
Director of Global Theological Education, Perkins School of Theology, Southern Methodist University

CLOSE SOLAR ENCOUNTERS

"The Threat of Solar Superflares," by Jonathan O'Callaghan [December 2021], discusses instances within the past 10,000 years in which immense flares from the sun have caused geomagnetic storms on Earth, including the massive 1859 Carrington Event and a far stronger storm around A.D. 775.

It should be noted that at the National Oceanic and Atmospheric Administration's Space Weather Workshop in April 2014, one of the main topics was about a near miss that actually occurred in July 2012: a large coronal mass ejection was detected passing Earth by the STEREO-A satellite. It was suggested that it could have had a much larger impact than the Carrington Event. The 2012 event missed us by one week.

Steve Senger *Prince George, British Columbia*

DON'T SLEEP ON THIS OFFER

In "Nap Like a Genius," Bret Stetka writes about recent research on Thomas Edison's practice of jolting himself from the edge of sleep to boost creativity. I tried Edison's sleep-interruption technique by holding a copy of *Scientific American* as I started a nap, waiting to reach the N1 stage. When the magazine fell to the floor, I woke with a revelation: "It's time to renew your subscription." The true genius appears to lie within your subliminal marketing department.

Jay Lynch *Pittsburgh, Pa.*

TRAUMA AND THERAPY

In "The Long Shadow of Trauma" [January 2022], Diana Kwon describes the history of the stigmatized diagnosis of borderline personality disorder (BPD) and the question of whether it should be recast as a trauma-related condition. As two psychologists who have treated many traumatized and BPD patients and supervised hundreds of psychotherapists in training, we appreciate the clarity and depth of Kwon's reporting. Not every aspect of this complex topic could possibly be addressed in one article, but there are two points we feel are important to emphasize.

First, one of American clinical psychologist Marsha Linehan's most brilliant insights about the treatment of BPD is that psychotherapists themselves must receive support and supervision to be effective treatment providers. BPD patients are difficult. Psychotherapists are human. Very often, they, too, have been traumatized and invalidated, and they may retaliate against patients who "invalidate" them by failing to improve in treatment. The hostility toward these patients mentioned in the article is not only the consequence of a difference in the therapist's theoretical approach; it is a consequence of the therapist's countertransference left untreated.

Second, a psychiatric diagnosis is based on a model of disease entities causing illness. In the case of viruses, this model is clearly useful. In the case of psychological pain, the entity-based model may be helpful in supporting less blame and shame, and more compassion, from society in general.

For the purpose of effective treatment, however, diagnoses are poor guides. Models based on continua, such as the intensity of the individual's experienced trauma and invalidation, genetic and temperamental vulnerability, etcetera, may be more accurate and useful. As Peggy Wang, a person who'd been diagnosed with both BPD and complex post-traumatic stress disorder, was quoted as noting in Kwon's article, "The labeling is not the issue."

Lake McClenney and Rob Neiss *California*

LOW-TEMP MAINTENANCE

The keep-cool reflective paint described in "Cool Color," by Sophie Bushwick [Advances; August 2021], looks like a useful product for those of us living in a hot, sunny climate. Bushwick quotes materials scientist Yuan Yang noting that manufacturers of such material will need to figure out "how to make sure that the paint stays white after 30 years of use." That problem is easily solved by any householder: every five to 10 years, wash the surface and repaint it—*voilà!*

John Grabinar *Beersheba, Israel*

ERRATA

In "Constructing the World from Inside Out," by György Buzsáki [June 2022], the opening illustration should have been credited to Stefania Infante, not Islenia Milien.

"Discrimination Is Heartbreaking," by Jyoti Madhusoodanan [Innovations In: Health Equity; June 2022], incorrectly said that Shivani Patel's work has focused on tribal communities in rural India for the past two decades. Her work focuses on community health issues across the country.

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Next Frontiers

Exploration is fundamental to science and a fundamental human trait

By the Editors

Schoolbooks typically present explorers as intrepid individuals who, at the behest of colonizing leaders, sail wooden ships to new lands, ride on horseback across uncharted mountains or slash their way through the jungle. But today most explorers who are making fundamental discoveries are scientists. And whether the frontiers are minuscule, like the human genome, or massive, like our deepest oceans, we still have much left to learn about planet Earth. The quests that modern scientists pursue rival anything in a history book or an adventure novel.

Exploration is science in its most basic form—asking questions of the natural world and, we hope, using the answers for the betterment of everything on Earth.

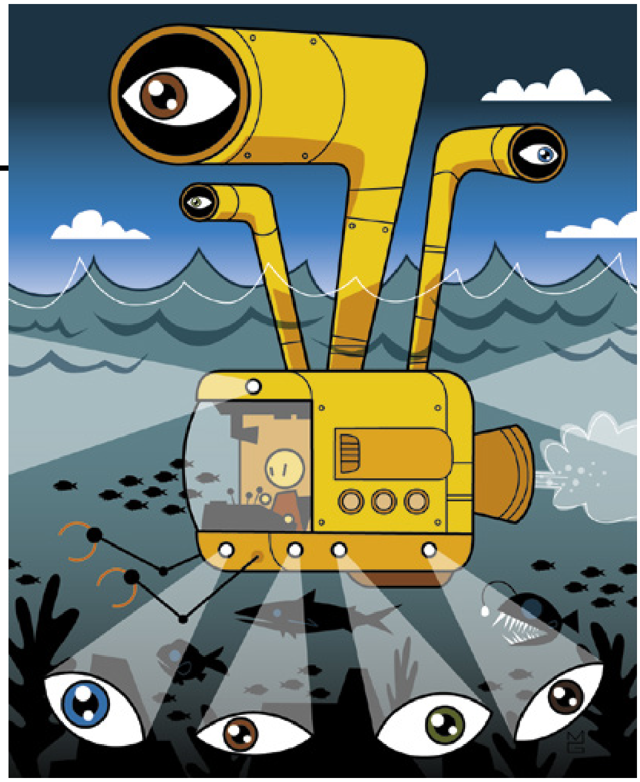
Some unknown territories are emergent: human consciousness or why trillions of bacteria floating on the ocean suddenly glow in unison across more than 100 square miles. Frontiers can be cultural, too, and we must explore with respect.

Exploration has great value. It inspires us, widens our knowledge and gives us hope for a better future. And the practical payoffs can be plenty. Some are even lifesaving. Scientists who spent decades exploring what was in the atmosphere found that over time the concentration of carbon dioxide was rising. Without that discovery, we humans would now be living like the proverbial frog in a pot of gradually heating water, unsure why the environment around us is changing, and slowly boiling to death.

In the early 2000s Katalin Karikó and Drew Weissman of the University of Pennsylvania were studying fundamental molecules called messenger RNA (mRNA) in humans and realized that a few adjustments could prevent the molecules from causing inflammation. Then, in 2017, Weissman and Norbert Pardi, also at Penn, discovered how to modify mRNA to neutralize an invading virus. When COVID struck, Pfizer-BioNTech and Moderna rapidly created two powerful vaccines for the virus—using mRNA. Weissman says he and his co-explorers met several unexpected hurdles, but each one made them only more determined to convert their discoveries into something helpful.

The human drive to overcome challenges is an essential aspect of the human drive to explore. As Robert Ballard, who discovered the wreck of the RMS *Titanic* in 1985 and was part of the team that found the first deep-sea hydrothermal vents, told us recently: "The ocean is a formidable place. I was almost killed several times. But the human spirit is indestructible." Ballard turned 80 in June and in May spent two weeks on an expedition in the Pacific Ocean.

That drive to take on challenges often spurs innovation. Technological advances have always helped the intrepid, and the inventions keep coming. Early human submersibles that reached the bottom of the deepest ocean trenches made the trip just once, stressed by the enormous pressures there. But eventually a more stress-resistant deep-submergence vehicle, the *Limiting Factor,* allowed investor and undersea explorer Victor Vescovo to reach trench bottoms numerous times.



Now there are roughly 4,000 autonomous Argo floats across the world's oceans that dive down to 2,000 feet and resurface every 10 days, gathering data about basic physical traits such as water temperature, salinity and pressure. Programmable vessels greatly expand our reach and reduce the risk to the people involved in exploration, allowing for the kind of discovery that the human body might limit. The Argo consortium will also deploy dozens of sensors every year that will gather biological and chemical data, leading to new observations about marine life.

Other institutions plan to deploy swarms of autonomous underwater vehicles that will search the seas in unison, sending data to guide ships that forward the information to researchers on shore, who then can redirect the swarms. Ocean research groups have made it a priority to openly share their discoveries and data with the public, to be more inclusive of people who live along waters being explored, and to inspire the next generation of young scientists. Anyone can go along for the ride—we can all be explorers.

Many commercial ventures are involved in exploration. Maybe one day you'll put on your virtual-reality goggles, connect with an online adventure company and rent a video-equipped remote vehicle that explores the Great Barrier Reef from above for several hours at your direction. Or the desert at the height of bloom. Or a rain-forest canopy.

Captain James T. Kirk began each episode of the original *Star Trek* television series by saying, "Space, the final frontier." Not necessarily. We still have plenty to discover right here on Earth, and we eagerly await surprises from the newest worlds we find. SA

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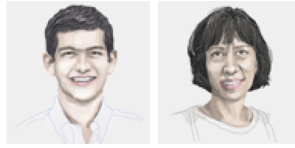
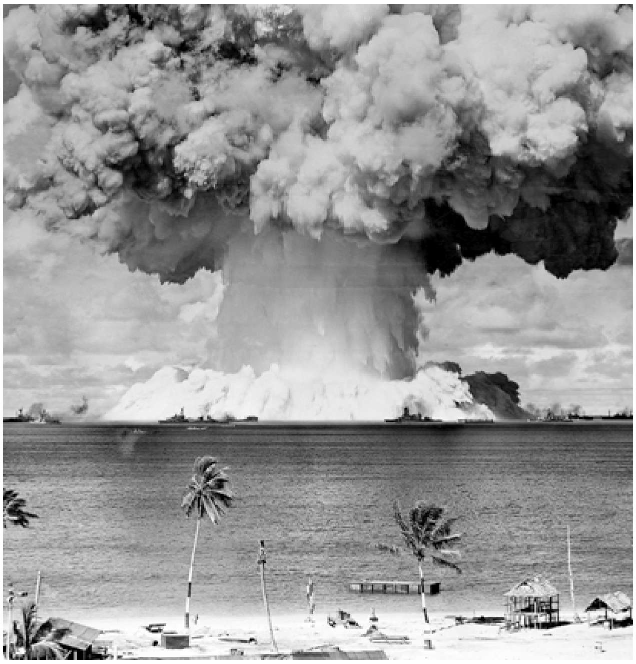
Illustration by Martin Gee



Hart Rapaport is a researcher at Columbia University's K=1 Project, Center for Nuclear Studies. **Ivana Nikolić Hughes** is a senior lecturer in chemistry at Columbia University. She is president of the Nuclear Age Peace Foundation.



Clean Up the Marshall Islands

Restoring the islands is a matter of environmental and social justice

By *Hart Rapaport* and *Ivana Nikolić Hughes*

Russia's placement of its nuclear arsenal on high alert during the war in Ukraine has unearthed fears of nuclear holocaust. As governments across the world consider their own roles in lessening the risk of nuclear war, the U.S. cannot excuse itself. We should talk about stemming a future nuclear impact, but equally important is reckoning with our past.

Between 1946 and 1958 the U.S. nuclear testing program drenched the Marshall Islands with firepower equaling the energy yield of 7,000 Hiroshima bombs. Cancer rates have doubled in some places, displaced people have waited decades to return to their homes, and radiation still plagues the land and waters of this Pacific island nation. The U.S. must prioritize the restoration of these islands and the resettlement of their people as a matter of human rights and environmental justice. What the U.S. has done so far is simply not enough.

The tests most gravely affected four atolls in the north of the nation: Bikini (*seen here in 1946*), Enewetak, Rongelap and Utirik. In the first two cases, members of the U.S. military resettled communities prior to testing, whereas people on Rongelap and Utirik left after fallout from tests reached them. Today only Enewetak and Utirik have substantial permanent populations; refugees from Bikini and Rongelap are still unable to return home safely.

In addition, the structural integrity of the Runit Dome, a concrete shell covering more than 100,000 cubic yards of nuclear waste on an island of Enewetak Atoll, is at risk because of rising sea levels. Leakage from the dome will likely increase, and higher tides threaten to break the structure open.

To better understand the effect of nuclear testing on the islands, scientists at the Department of Energy have conducted a wide range of studies. We believe their work has missed critical pieces. Rather than taking simple, direct measurements of gamma radiation, the DOE has consistently relied on simulations. Still, the military has notably cleaned up some parts of Enewetak Atoll.

For several years our group has gone to the Marshall Islands to research the fallout of this nuclear testing. We have published our findings to ensure that independent information exists to safeguard the well-being of affected communities.

Considerable contamination remains. On islands such as Bikini, the average background gamma radiation is double the maximum value stipulated by an agreement between the governments of the Marshall Islands and the U.S., even without taking into account other exposure pathways. Our findings, based on gathered data, run contrary to the DOE's. One conclusion is clear: absent a renewed effort to clean radiation from Bikini, families forced from their homes may not be able to safely return until the radiation naturally diminishes over decades and centuries.

Beyond plutonium and uranium, strontium 90 is a radioisotope of concern in the Marshall Islands. It can cause leukemia and bone and bone marrow cancer and has long been a source of health concerns at nuclear disasters such as Chernobyl and Fukushima. Despite this, the U.S. government's published data don't speak to the presence of this dangerous nuclear isotope.

We have tested sediment from two bomb craters in the northern Marshall Islands and found consistently high values of strontium 90. Although detecting this radioisotope in sediment does not neatly translate into contamination in soil or food, the finding suggests the possibility of danger to ecosystems and people.

More than that, cleaning up strontium 90 and other contaminants in the Marshall Islands is possible. Congress should appropriate funds, and a research agency, such as the National Science Foundation, should initiate a call for proposals to fund independent research with three aims. We must first further understand the current radiological conditions across the Marshall Islands; second, explore new technologies and methods already in use for future cleanup activity; and, third, train Marshallese scientists, such as those working with the nation's National Nuclear Commission, to rebuild trust on this issue.

Through the collective work of dozens of researchers rather than a small group of scientists at the DOE, remediation efforts across the world will benefit. The Marshallese people and other affected communities have told us for decades just how dangerous nuclear weapons are. Let's heed their warnings before it is too late. SA

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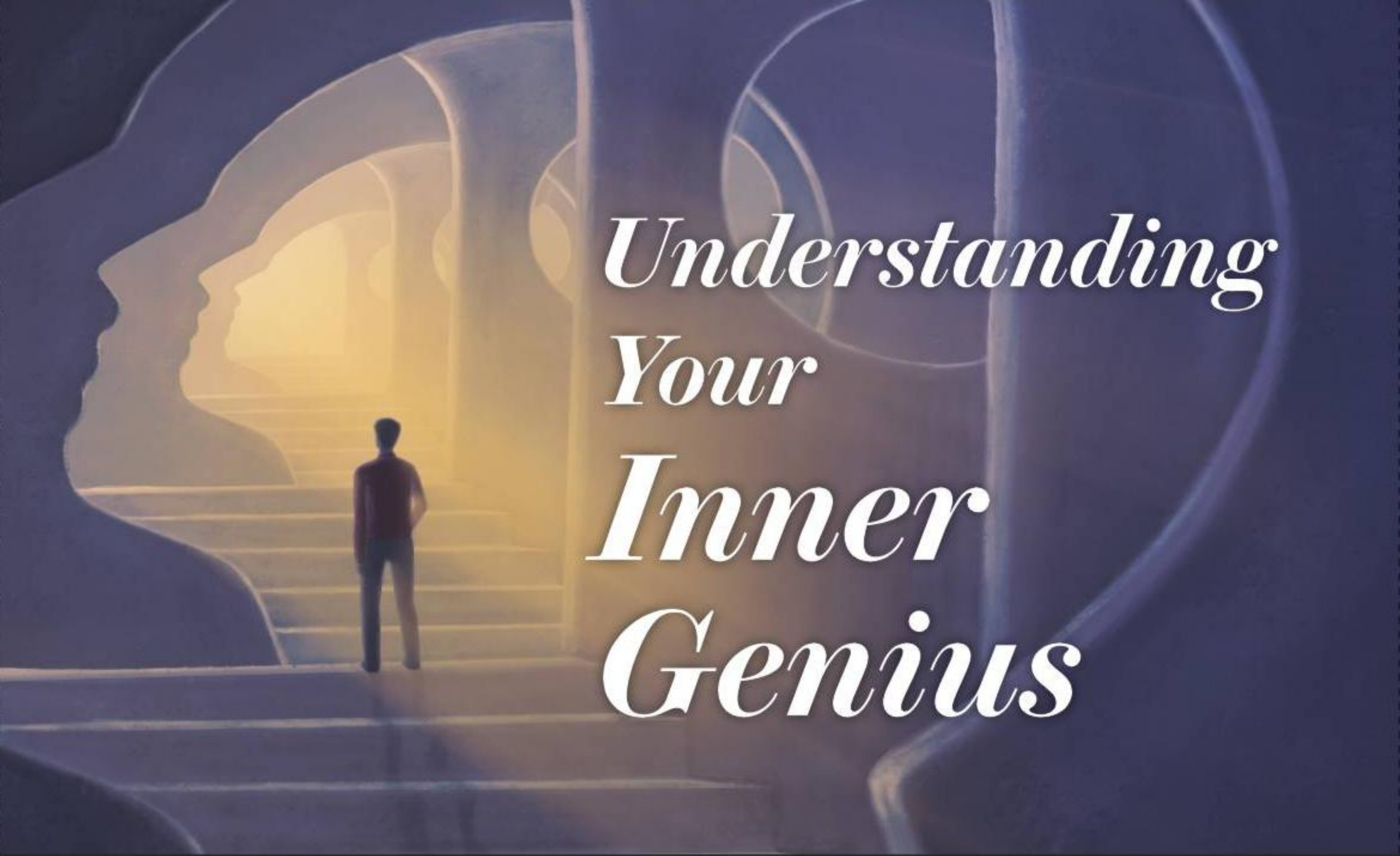

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The molecule psilocybin is found in hallucinogenic "magic mushrooms."

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- The first plants sprout in soil brought back from the moon
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- AI aids diagnosis of devastating olive tree disease

PHARMACOLOGY

Mushrooms' Legal Trip

As psilocybin research ramps up, the drug's status under the law is shifting

Magic mushrooms are undergoing a transformation from illicit recreational drug to promising mental health treatment. Numerous studies have reported positive findings using psilocybin—the mushrooms' main psychoactive compound—for treating depression as well as smoking and alcohol addiction, and for reducing anxiety in the terminally ill. Ongoing and planned studies are testing the drug for conditions that include opioid dependence, PTSD and anorexia nervosa.

This scientific interest, plus growing social acceptance, is contributing to legal changes in cities across the U.S. In 2020 Oregon passed statewide legislation decriminalizing magic mushrooms, and the state is building a framework for regulating legal therapeutic use—becoming the first jurisdiction in the world to do so. For now psilocybin remains illegal and strictly controlled at the national level in most countries, slowing research. But an international push to get the drug reclassified aims to lower barriers everywhere.

After a flurry of research in the 1950s and 1960s, psilocybin and all other psychedelics were abruptly banned, partly in response to their embrace by the counterculture. Following the 1971 United Nations Convention on Psychotropic Substances, psilocybin was classed in the U.S. as a Schedule I substance—defined as having "no currently accepted medical use and a high potential for abuse." Psilocybin production was limited, and a host of administrative and financial burdens effectively ended study for decades. "It's the worst censorship of research in history," says David Nutt, a neuropsychopharmacologist at Imperial College London.

Despite these legal hurdles, the current research resurgence has seen Nutt and others exploring how psilocybin changes the brain's connectivity patterns: reducing connections within the usual networks while increasing links between less connected regions. Just this year a study showed that treatment involving psilocybin led to sustained network alterations, which seemed to correlate with reduced depression symptoms. Two organizations are beginning final rounds of trials for psilocybin's use for depression, which could lead to the substance's first approval by the U.S. Food and Drug Administration.

As news of psilocybin's promise spreads, several U.S. cities have passed measures decriminalizing magic mushrooms. This is not the same as legalization; the molecule and the mushrooms themselves remain illegal, but prosecuting people for their possession or use is deprioritized or discouraged.

In 2019 Denver voters passed a ballot measure that prohibits using city money to prosecute people for magic mushroom–related offenses. City councils soon took similar steps in Oakland and Santa Cruz in California and in Ann Arbor, Mich. In November 2020 voters in Washington, D.C., passed a ballot measure making natural psychedelics one of law enforcement's lowest priorities. Cities and counties in Michigan, Massachusetts, California and Washington State have followed suit.

As part of Oregon's legislation, the state health authority created a scientific advisory board to recommend regulations for psilocybin service centers, such as designating mushroom species and preparations to use and production standards to follow. These centers, which can apply for licenses starting next January, will not claim to treat depression but will aim to improve general well-being.

"My worry is that people won't necessarily get that distinction … and turn up with horrible, treatment-resistant depression, expecting an expert in treating that condition," says Johns Hopkins University psychiatrist Natalie Gukasyan, who led a recent psilocybin trial.

Oregon's advisory board is determining how best to train facilitators and screen clients for risk factors, such as a family history of schizophrenia or bipolar disorder. "All our decisions revolve around consumer safety," says Oregon State University mycologist Jessie Uehling, who chairs the board's product subcommittee. "We want to know that we're avoiding all the potential risks and creating the safest environment for people." The centers will focus on fungi and natural preparations rather than the synthetic psilocybin used in clinical trials so far, Gukasyan notes.

Regardless of local decriminalization, U.S. researchers must still abide by federal Schedule I regulations. The International Therapeutic Psilocybin Rescheduling Initiative, a coalition of research and advocacy organizations, aims to get the World Health Organization to conduct a review of the relevant evidence for reclassifying the drug. "It's inconceivable the WHO could now say psilocybin doesn't have medical value. It can work where other drugs have not," Nutt says.

Various laws already facilitate research and treatment in some countries. Canada classifies magic mushrooms as Schedule III, so penalties are lower, and certain research and trials are granted exceptions. A Canadian charity called TheraPsil has a fast-track process for end-of-life psilocybin therapy.

Some countries such as Jamaica never made magic mushrooms illegal, although the psilocybin molecule often is. Research is limited in most of these places, but many have thriving "psychedelic retreat" industries that are not medically regulated. The Netherlands has specifically banned the mushrooms—but its laws don't mention the psilocybin-containing lumps of underground material that eventually sprout them, better known as truffles. This loophole has paved the way for numerous therapeutic retreats, but little organized research.

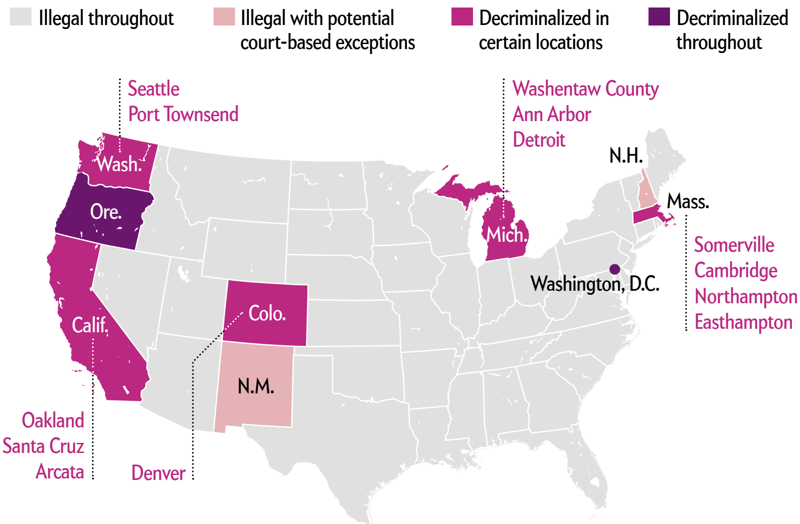
Portugal has famously decriminalized all drugs. Some countries ban the mushrooms but not their spores, because the latter do not contain psilocybin. Others simply do not enforce their laws on magic mushrooms.

The 1971 U.N. treaty has a clause allowing countries to exempt traditional Indigenous uses of psychedelic plants. Indigenous people in some South American countries have used psychedelics for centuries and have fought governments for their right to engage in related ceremonies. There is even a religious organization in New Mexico, the Oratory of Mystical Sacraments, that claims members can legally use magic mushrooms in certain circumstances.

"This idea that psilocybin is helpful for mental health conditions is not a new one. There are thousands of years of history of efficacious treatment; it's just in a different knowledge format," Uehling says. "We're trying hard here in Oregon to honor that knowledge system."

Public perceptions of psilocybin are changing, and as increasing interest generates more evidence, this trend looks set to accelerate. "It's a thrilling time to be a mycologist," Uehling says. Many are waiting to see what happens in Oregon, she adds: "Other states will come up with variations on—hopefully—what we get right, and also on what needs to be changed." *—Simon Makin*

Psilocybin Status in the U.S.



Graphic by Amanda Montañez

yod67/Alamy Stock Photo

BIOLOGY

Dazzling Defenses

Beetles' shifting colors offer both camouflage and warning

Flashy iridescent shells might not seem like the best evolutionary strategy for bugs trying to avoid hungry birds. But in recent years biologists have shown that iridescence—lustrous shifts in color, depending on the angle of view—can actually camouflage green jewel beetles among sun-dappled leaves. And now a study published in *Animal Behavior* suggests iridescence has another protective quality: birds seem to be innately wary of these color changes.

The study authors say this is the first time iridescence, as opposed to simple glossiness or bright colors, has been shown to deter predators. "It's actually the changeability, the very hallmark of iridescence, that is important for this protective function," says Karin Kjernsmo, a researcher at the University of Bristol in England and the study's lead author.

To test how birds reacted to iridescent beetles' varying colors, Kjernsmo and her colleagues set out glossy, color-shifting *Sternocera aequisignata* jewel beetle shells, along with artificial glossy and matte green shells and a color-shifting shell with matte varnish. They baited the shells with mealworms, then offered this buffet to day-old domestic chicks.

The chicks scarfed down mealworms under matte green shells, but they hesitated when encountering glossy shells and both color-changing types. A previous study showed that birds shy away from glossiness, but the specific avoidance of shifting colors was not previously documented, the researchers say.

Johanna Mappes, a University of Helsinki biologist who worked on the earlier study but was not involved with the new one, praises the way Kjernsmo's team controlled for each type of shell finish, "especially creating matte iridescence signals—it's really genius."

The new findings suggest iridescence is an evolutionary two-for-one deal: it helps the jewel beetles hide, but it also scares off predators that manage to spot them. Kjernsmo speculates that this might help explain why so many insects are iridescent—it "allows them to be protected in many different contexts."

This hypothesis might also explain why these beetles evolved to use iridescence rather than a more typical warning color such as bright red or orange, often used by insects that have poison as a backup defense. For this jewel beetle species, which does not have chemical defenses, the extra attention drawn by traditional warning colors might not be worth it; better to blend in when possible.

More research is needed to discern why iridescence frightens birds. The beetles might be mimicking other iridescent insects that do have chemical defenses, the researchers suggest, or the changes might simply confuse predators—if a beetle's color shifts, a predator might not be able to classify it as safe or dangerous.

—Kate Golembiewski

ANIMAL BEHAVIOR

Buzzkill

Common farm fungicide makes male mason bees unappealing to females

Like the opposite of a good perfume, a chemical humans use to protect crops may have the unexpected side effect of making certain bees less attractive to mates, potentially threatening populations of these crucial pollinators.

The common pesticide fenbuconazole is classified as relatively safe for bees because it specifically targets fungi (which are taxonomically very different from bees) and because exposure to it does not typically kill bees directly. Previous research had found that insecticides deemed "low risk" for bees can still impact their development, feeding behavior and learning; fungicides such as fenbuconazole had not been studied as extensively but were thought less likely to be harmful.

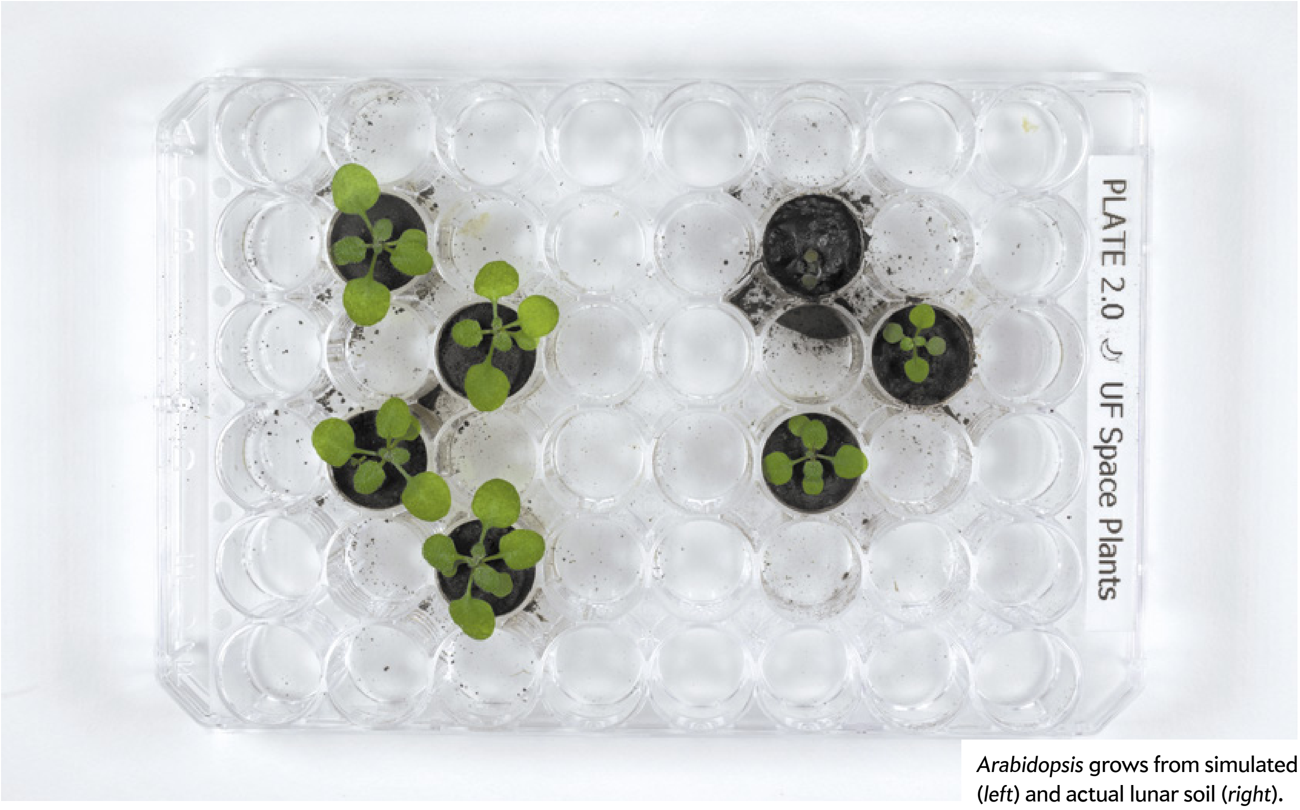
Samuel Boff, lead author of the new study in the *Journal of Applied Ecology*, and his colleagues wanted to know whether fenbuconazole—typically applied to wheat, apples and grapes—might subtly affect bees. "We did [the study] because this fungicide is used often," says Boff, an ecologist at the University of Würzburg in Germany. "We did not expect to find an effect."

But there was, in fact, a surprising effect: fenbuconazole exposure altered two distinct components of male horned mason bees' courtship ritual. A male typically vibrates his thorax alluringly and also relies on his scent to attract females. Exposure to the fungicide lowered the vibrational frequency (possibly by influencing muscle contractions) and additionally altered the males' chemical profiles, changing their scent. Females seemed put off by these changes; they preferred unexposed males. The study authors speculate that such female mating avoidance could reduce populations of horned mason bees and other species with similar mating systems.

Cerez/EyeEm/Getty Images

The study "is important because it's giving us a mechanism for decline," says Susan Willis Chan, a bee researcher at the University of Guelph in Ontario, who was not involved with the study. "It's a great paper." Boff hopes his team's findings will prompt more scrutiny of fungicide use and possibly lead to alternative pest-control methods.

—Darren Incorvaia



Arabidopsis grows from simulated (*left*) and actual lunar soil (*right*).

UF/IFAS/Tyler Jones

SPACE SCIENCE

One Small Sprout

Scientists grow first-ever seedlings in Apollo moon dirt

Twelve grams of the moon arrived at Robert Ferl's laboratory in an undecorated UPS box.

Ferl, a horticulturist at the University of Florida, had waited more than a decade for that moment. The small box of dirt, postmarked from NASA, held some of the last remaining unopened samples of moon dust, called regolith, collected by *Apollo* astronauts. Despite months of practice, Ferl recalls, he lifted the sample with trembling hands. "It's freaky, scary stuff," he says. "I mean, what happens if you drop that?" Ferl and his team were about to become the first researchers to grow plants in actual lunar soil.

The experiment was green-lit as part of a lunar research boom fueled by NASA's Artemis program, which aims to send humans back to the moon later this decade. This time around NASA wants to build an outpost there as a dress rehearsal for future voyages to Mars. Scientists anticipate such longer missions will require a sustainable source of food. "All of human exploration has been driven by the ability to keep crews fed," says Gil Cauthorn, an Osaka, Japan–based researcher with the Astrobotany International Research Initiative.

Ferl's recent work, published in *Communications Biology*, offers an important first step in that journey, ultimately proving that plants can grow in moon soil. The seedlings failed to truly thrive, however, indicating that any future lunar farmers will need to fertilize their regolith.

To test the moon soil, Ferl and his team divvied up the samples into 12 pots of 900 milligrams apiece and planted seeds from *Arabidopsis thaliana,* a hardy relative of mustard and cabbage. All the seeds successfully germinated, but the seedlings had difficulty with the next growth stage: establishing a healthy root system. The Apollo sprouts were stunted and stressed, not only by the salt- and metal-rich regolith but also by its lack of water and microbes.

Helpful microbes are among the most important components of any soil used for planting. "They play a huge role," says Gretchen North, a plant physiological ecologist at Occidental College, who was not involved in the study. Symbiotic bacteria help plants regulate growth hormones, fight off pathogens, minimize environmental stress and absorb crucial nutrients such as nitrogen. Lunar regolith lacks a natural microbiome, and so the plants struggled to take in nutrients and manage stress.

Plus, regolith can become extremely dense, like cement, when water is added. "It's difficult to get that stuff to not become a rock," says Cauthorn, who was not involved in the new study.

Adding extra nutrients or composting crops to foster microbe growth could improve plants' prospects. And North, who has studied plant growth in simulated Martian conditions, suspects the moon still offers more fertile ground than the Red Planet's rusty soil. That's because Martian regolith is full of perchlorate, an oxidative compound that can be harmful to plants and animals alike.

Ferl hopes to continue studying how life might take hold in otherwise barren soils, with an eye toward both boosting humanity's prospects off the planet and improving agriculture in nutrient- and water-depleted soils here at home. But for now he and his fellow researchers are grateful to experiment with one of the only bits of lunar soil on Earth. "For us," he says, "it was—and continues to be—a real privilege." —*Joanna Thompson*

VISUAL SCIENCE

Sight Unseen

Researchers restore electrical activity in human retinas after death

Few biological facts seem as irrevocable as brain death. It has long been assumed that when we die, our neurons die with us. But a new study on the neuron-packed tissue of the eye is beginning to challenge that dogma.

In the new work, researchers restored electrical activity in human retinas—the light-sensitive neural tissue that sits at the back of our eyes and communicates with our brains—from recently deceased organ donors. This achievement, reported in *Nature*, offers a better way to study eye diseases such as age-related macular degeneration, a leading cause of vision loss and blindness. It could also lay the groundwork for reviving other types of neural tissue and perhaps—one day—for retinal transplants.

Most retina studies are done in animals, primarily mice. But mouse retinas lack the macula, a key region found in human eyes that picks out fine details, so they are not an ideal model. Human eye tissue from autopsies often takes hours to obtain and is dead before scientists can study its function. But what if you could revive it?

When Yale University researchers showed in 2019 that rudimentary electrical activity could be restored in pig brains after death, University of Utah vision scientist Frans Vinberg, Scripps Research retinal surgeon Anne Hanneken and their colleagues were inspired to study whether retinal tissue could also be restored postmortem.

For the study, the researchers first tested how long mouse retinas could send electrical signals after the animals were euthanized. They were able to restore this activity up to three hours later—and found that a lack of oxygen was the main factor in irreversible loss of function. They then investigated human eyes that the researchers obtained from organ donors very soon after brain or cardiac death. The scientists transported the eyes to the laboratory in a container that supplied oxygen and nutrients, then exposed the retinal tissue to dim light and measured electrical signals generated by the tissue. They were able to reestablish electrical activity in light-sensitive cells called photoreceptors, as well as in the neurons these cells connect to, in the donor eyes—if the eyes were obtained less than 20 minutes after death. Of course, the eyes could not "see," because they were not connected to a brain, Hanneken notes.


Close-up of the retina in a human eye

stanley45/Getty Images

But the results showed it was possible to restore not just individual retinal cells but the communication between them.

"What's most exciting is this really could become a model for studying visual physiology in human retinas, in health and in aging and in disease," says Joan Miller, chief of ophthalmology at Mass Eye and Ear and ophthalmology chair at Harvard Medical School, who was not involved with the new study. Macular degeneration, for example, has so far been difficult to study because living human eye tissue has been impossible to access. Using this new technique, scientists could study healthy and diseased donor eyes to understand their function and test treatments.

The team's findings also suggest it may be possible to revive other types of neural tissue. "The retina is a window to the brain, so if you can restore communication in the retina after death, it makes you pause and consider what kind of communication you might be able to recover in the brain," Hanneken says. The study additionally raises the prospect of retinal transplants, although those are likely still very far off, the researchers say.

This new work illustrates the importance of donor tissue to basic science. "We are very thankful for the donors and their families," Vinberg says. "We hope this will encourage people … to check that box in their driver's license and also be willing to donate tissues for research." *—Tanya Lewis*

ECOLOGY

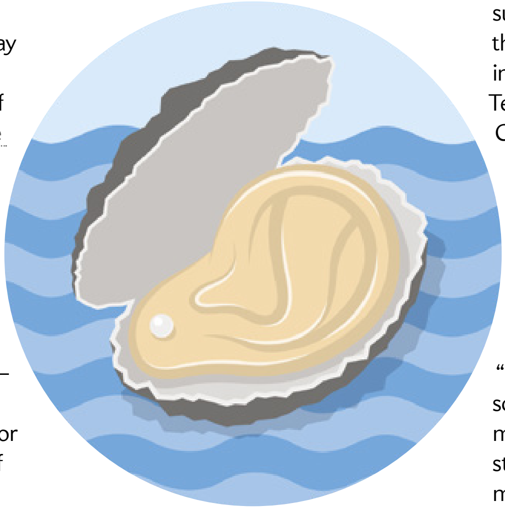
Oyster GPS

Shrimp sounds could lure baby bivalves to build new reefs

Oyster reefs once carpeted much of the seafloor, filtering water, stabilizing shorelines and providing habitats for a vast array of life. But in the past 200 years net-dragging fishing boats have destroyed most of these reefs around the world. Now, in the *Journal of Applied Ecology*, researchers at Australia's University of Adelaide reveal a curious fact that may help rebuild such formations: baby oysters follow the sounds of shrimp.

Australian flat oysters' microscopic larvae drift in currents and swim with hairlike cilia, searching for a hard surface—ideally a thriving reef made of shells from other oysters—to cement themselves to for the rest of their lives. If no established reef is nearby, the babies float aimlessly over the sandy seafloor; only a lucky few find homes on stray rocks. Conservation scientists have tried to start new reefs by introducing limestone boulders for larvae to settle on, but most remain lost at sea.

Previous studies demonstrated that other sea creatures can navigate toward the sounds of healthy ecosystems—sounds that have become increasingly rare as reefs fall silent and ships dominate the ocean soundscape. Oysters lack ears but sense sound vibrations, so the team wondered if the larvae could follow a sonic beacon of their own: the crackle of snapping shrimp.



These reef-dwelling creatures snap their claws to unleash jets of water that stun prey, producing a staticky-sounding, 210-decibel cacophony—as loud as a rock concert. In their laboratory and in an ocean experiment, the scientists found that oyster larvae navigated toward recorded shrimp sounds and settled on hard surfaces nearby. Larvae had difficulty locating those surfaces without the sounds playing or with boat noise disrupting them.

The researchers say luring oyster larvae to potential reef sites could offer an alternative to expensive, labor-intensive measures such as sending divers to ferry larvae to their new homes. "There is a cost and effort in raising oysters," notes marine scientist Terry Palmer of Texas A&M University–Corpus Christi, who works on oyster conservation but was not involved with the study. He says the new method might be useful in conjunction with providing surfaces for reef building, especially in areas with relatively few of the animals.

And this sound technique might eventually help more than just oysters. "They're really the building blocks of the southern reefs," says University of Adelaide marine biologist Brittany Williams, the study's lead author. Where oysters go, more life will follow. And although tricking larvae into settling on a lifeless reef might seem like a cruel bait and switch, rest assured: the plankton and algae that oysters eat are nearly omnipresent in the water, so the bivalve trailblazers won't starve while they wait for the rest of the reef community to arrive. *—Kate Golembiewski*

Illustration by Thomas Fuchs

PALEONTOLOGY

Water Launch

Pterosaurs could have vaulted into flight from the water

Ever since pterosaur fossils were discovered more than two centuries ago, paleontologists have wondered how these gawky-looking reptiles launched themselves into the air. Experts have recently focused on a "quad launch" hypothesis, which envisions pterosaurs rocking back and forth on their arms to jump into the air using a pole vault-like motion, whether from land or water. Direct physical evidence of this technique has been elusive, but now a small pterosaur from the Jurassic rocks of Germany is helping solve the mystery.

The sparrow-sized fossil, described by Natural History Museum of Los Angeles paleontologist Michael Habib and his colleagues in *Scientific Reports*, features unusually well-preserved bones and skin impressions of a pterosaur type called an aurorazhdarchid. The paleontologists used a process known as laser-stimulated fluorescence to detect the fossilized tissues, including a wing membrane and webbed feet. Analyzing these structures let the researchers determine how the pterosaur could have used them to take off.

Prior research indicates pterosaurs were not strong swimmers, Habib notes—so this fossil's soft tissues "are best interpreted as water-launch adaptations" rather than swimming gear. These structures offer the first physical evidence that pterosaurs could take off using quad launch, he says; until now the best evidence came from biomechanical models of skeletons. The skin impressions along the arms suggest that, when folded, the pterosaur's wings could help the reptile push off from the water's surface. The researchers found that the wings and webbed feet combined would have been enough to propel the animal from a resting position.

Most modern birds use their muscular legs to spring into the air. But pterosaurs had different proportions and would have behaved differently, says University of Edinburgh pterosaur researcher Natalia Jagielska, who was not involved in the new study. Knowing that soft tissues like the pterosaur's can be preserved in the fossil record, Jagielska adds, "is a great reason for scanning other exquisitely preserved fossils with lasers and seeing if they can tell us a different story." —*Riley Black*

Fossil showing pterosaur skeleton and soft tissues

"Quadrupedal Water Launch Capability Demonstrated in Small Late Jurassic Pterosaurs," by Michael Pittman et al., in *Scientific Reports*, Vol. 12; April 21, 2022

Clark Little

FLUID DYNAMICS

Science in Images

By Joanna Thompson

Imagine the perfect ocean wave: a wall of water swells and curls in on itself before breaking dramatically near the shore. Catching such a wave would be any surfer's dream—and the physics underneath its churning surface is just as mind-blowing as the ride.

As an ocean wave coils, it creates a hollow tube made of spinning water. If you could peek under the surface, you would see numerous small, thin twisters known as rib vortices looping around this primary vortex. Scientists have only recently begun to investigate why and how these beautiful, delicate secondary eddies form.

"Basically there's a separation that occurs," says Christine Baker, a fluid mechanics researcher at the University of Washington. When a wave begins to break, tiny aerated regions along the leading edge cause a few streams to separate from the main vortex. These streams twist themselves into rib vortices as they pick up momentum.

"We often make the analogy of a figure skater," says Jim Thomson, an oceanographer at the University of Washington. Initially a wave's rib vortices are wide bands of water that twist slowly like figure skaters spinning with their arms outstretched. But as the wave travels forward, Thomson explains, its ribs corkscrew into thin filaments—an effect similar to when figure skaters tuck in their arms. "They rotate faster and faster," he says. This rotation stretches the separation between the main vortex and its mini vortices as they loop and grow.

Baker's work uses a combination of computer calculations and physical experiments to investigate how these vortices sweep trash and pollution from the shore out into the ocean. Until the past decade or so few people in the scientific community paid much attention to rib vortices, partly because they are difficult to photograph, the researchers say—the ephemeral twists require a high-resolution camera and precise timing to capture. In addition, modern computer simulations are finally complex enough to model them. "We often don't study things or see things until we have the tools to do so," Thomson says.

To see more, visit **ScientificAmerican.com/science-in-images**

ENVIRONMENT

Branching Out

AI takes on a disastrous olive tree disease

An aggressive plant pathogen that wipes out olive trees is projected to cost Italy billions of euros over the next 50 years. *Xylella fastidiosa*—a bacterium named for its pickiness when grown in the laboratory—was detected in southern Italy in 2013. It is now designated a "quarantine organism" in the European Union: infected trees, some hundreds of years old, must be cut down to prevent the disease from spreading in places such as Italy's Apulia region.

"We are obliged to destroy *Xylella*-positive plants, but people in Apulia don't want to destroy them," says Valeria Scala, a plant pathologist at Italy's Council for Agricultural Research and Economics. As scientists, she says, "we have to live between two worlds." So Scala and her colleagues are looking for ways to fight *Xylella* without killing every infected tree. Using a machine-learning algorithm to sift through the trees' metabolic data, they are learning which trees tend to get sicker than others—and how to choose trees to treat instead of chopping them down. The work is detailed in *Frontiers in Plant Science*.

Xylella makes complex fatty acids called lipids to use as key signaling molecules, and the trees manufacture their own lipids in response to infection. The researchers collected twig samples from 66 trees and used their algorithm to compare lipid profiles along with infection status, tree variety, and whether each tree had been treated with Dentamet, a metallic mixture that relieves *Xylella* symptoms but is not a cure.

The team found that one particular lipid type appeared at greater concentrations in infected plants. An olive variety native to hard-hit Apulia showed higher levels of this lipid when infected than did a widespread variety known for its hardiness. For both tree types, Dentamet kept infected individuals' lipid levels lower.

Study co-author Massimo Reverberi, a molecular plant pathologist at Sapienza University of Rome, says the two tree varieties behaved a bit like people with stronger or weaker immune systems fighting off the flu. "Our hypothesis is that it's 'personal' in some ways," he says. Further developing the algorithm could help the researchers diagnose infection severity by measuring lipid concentrations. Less severe infections could then be managed with Dentamet, and only the worst cases would have to be culled. Knowing how trees respond to *Xylella* infection will also direct the search for additional treatments and identify more resistant tree varieties, Scala adds.

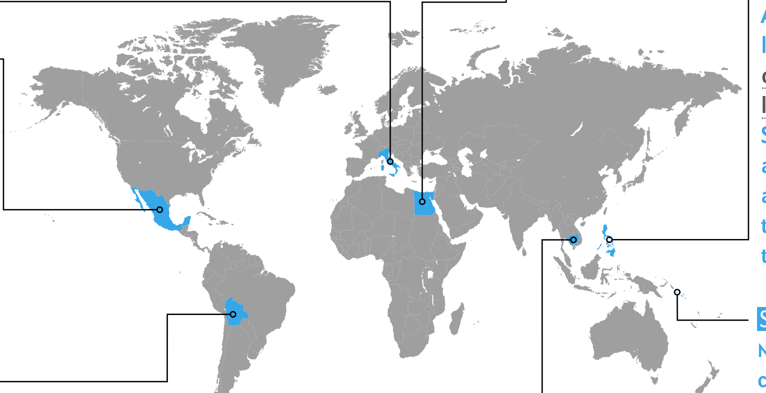
University of Salento chemist Francesco Paolo Fanizzi, who was not involved in the new study, says it represents "a promising methodology that could give some relief to this painful economic situation in the southern part of Apulia." "We have to survive together with bacteria," he adds. —*Maddie Bender*

Cosimo Calabrese/Getty Images

IN THE NEWS

Quick Hits

By Joanna Thompson



MEXICO
Although the annual monarch butterfly migration has been in decline for three decades, entomologists confirmed that eastern monarchs' wintering grounds in Mexico increased in area by 35 percent since last year. The insects may be adapting to climate change, experts suggest.

ITALY
For the first time, scientists retrieved a human genome from volcanic ash–encrusted remains found in the ancient city Pompeii. They identified the individual as a man in his 30s, with markers for spinal tuberculosis, and they also analyzed the bones of an accompanying woman over 50.

EGYPT
New analysis of a space rock found in the desert in 1996 suggests it was forged in a rare "type Ia" supernova explosion. The violent event most likely occurred some 4.6 billion years ago on the outskirts of our solar system.

PHILIPPINES
A species of *Pyralidae* moth last recorded in 1912 was discovered in a passenger's luggage in the Detroit airport. Several moth larvae had apparently stowed away in a bag of medicinal tea, which the traveler purchased in the Philippines.

BOLIVIA
Using lidar, a laser-based remote sensing technology, archaeologists uncovered traces of 11 Indigenous villages from 1,500 years ago. These settlements were connected by a complex series of roads and bridges to two large, previously known cities called Landivar and Cotoca.

CAMBODIA
Cambodian environmental officials have asked the public to stop picking carnivorous, distinctively shaped "penis plants." These rare, insect-consuming plants are found only in shallow, nutrient-poor soils in some of the country's remote mountain regions.

SOLOMON ISLANDS
NASA satellite imaging captured activity indicating multiple eruptions from the underwater volcano Kavachi. In addition to being geologically active, the site is home to a thriving shark population—earning it the superb nickname "sharkcano."

For more details, visit www.ScientificAmerican.com/aug2022/advances

My Father Flies into a Hurricane

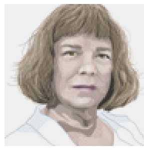
They fly from the Caribbean sun into
the storm's spiraling arms; their turbo prop
jolts and shudders. Across his window, streaks
of rain begin. They're flying into darkness,
the plane all fumes and metal shell, he thinks,
as they head for the eye. All along, they're dropping
instruments to map vertically
pressure, temperature, wind direction
and speed, data in three dimensions plus time.

He's read about these trips: to enter the gyre's
racket of wind and rain, the crew harness
themselves in place. Between them and death,
two pilots' strength—no parachutes; ejecting
futile in winds like these. He's wanted to feel
how frail humans are against the force
of atmosphere, to feel its energy,
a bow to what he's studied all these years:
his, the fifth American doctorate

in meteorology. The War made the field:
so many forecasts crucial to success in invasions
or bombing raids. He judged jet stream effects,
then returned, afterwards, to equations—physics
of air and water, the way they interact—
but he's wanted to go inside the living fact.
The Center called him once the storm had blown
past St. Lucia, Haiti, Jamaica, its eye
sliding between Cuba and the Yucatán.

Towards the eye wall, the storm grows wild—
winds strongest, noise loudest, no turning
around. He wonders why he's left the ground
as the plane pulls, jerks, falls and climbs
in the hurricane's judder and thrash. Updraft
(pressed hard against his seat) and down
(dropping many feet abruptly; his stomach
turning). Stowed gear rattles at the latches.
Updraft (harder, longer) and down (harness

cuts into his shoulders as he's thrown about).
He wants out; he wishes he hadn't asked.
And just as he thinks he can't stand more,
they're through the wall, which rises behind,
a cliff of cloud, steeper than a stone canyon
and deeper. They turn in the light, sun overhead
in the calm, open space inside the eye,
then spiral down to look for a sailboat reported
lost. No way to see a thing so small



Sandy Solomon lives in Nashville, Tenn., where she is writer in residence in the Creative Writing Program at Vanderbilt University. Her poetry collection, *Pears, Lake, Sun,* received the Agnes Lynch Starrett Prize from the University of Pittsburgh Press. Her poems have also appeared in the *New Yorker,* the *New Republic,* the *Times Literary Supplement,* and many other publications in the U.S. and the U.K.

in such high waves. He's surprised how tiny the plane's
whirring sounds after the din in transit.
He thinks of how, on the ground, birds sing
in this brief reprieve. But here he can see the edge:
the plane must turn into the hurricane
again, cross the wall, cross into
disturbance, only now they know:
this one's big. They've got air pressure
readings lower than any *they've* seen.

A category five, they reckon, and strengthening:
winds hitting 190 miles per hour.
They cut through the wall, adrenaline high.
No escape. Only the wind's unholy
engine, its sharp shifts in all directions.
So long as the pilots' combined strength can keep
the plane level and on course (they fight for control),
so long as the plane holds together (it cracks
and creaks), so long, he thinks, as his nerve holds …

But unlike the first half of this flight, when chaos
deepened the further they went, now however
wild the wind, they know it lessens; the battering
eases. They cross into sun: below them, glints
on the ocean's surface. But since they've mapped the winds,
crossed the eye wall, over and back, they know
more. Which saps pleasure in rediscovered
calm. He finds his body's damp—shirt soaked
and stinking; he finds standing again an effort.

On his wall he's hung the storm's huge spiral
and the date: August 7, 1980.
From space, the satellite registered its shape—
almost fetal, outsized head around
an eye, wisps of arms as if a sonogram
had gathered this "Allen" before landfall,
his massive fetch, the sum of possible destructions;
the given: thrum of wind and roiling waters
and the taken, 269 souls.

Fifth then among Atlantic hurricanes
on record, that's the flight he asked to join.
And why, I wonder, do I imagine him now?
Perhaps I fancy a kind of bliss at the core
of disorder—a blue-sky temporary respite:
assurance that all this trouble will blow over.
How then can we account for ourselves, my father
and I, then and now, as we cut across asphalt
to head home through tangles of evening traffic?
As if nothing has happened.

NASA/Science Source

Claudia Wallis is an award-winning science journalist whose work has appeared in the *New York Times, Time, Fortune* and the *New Republic.* She was science editor at *Time* and managing editor of *Scientific American Mind.*

Unequal Diabetes Care

U.S. screening guidelines miss too many people of color

By Claudia Wallis

Rahul Aggarwal was in medical school when he got the surprising news that his mother—a fit woman in her 40s—had been diagnosed with type 2 diabetes. "I always thought of diabetes as a disease of people at higher weights and with certain lifestyle practices," he recalls, "but my mom was an Indian American woman with a healthy weight and good diet and exercise practices." Aggarwal, now a clinical fellow at Beth Israel Deaconess Medical Center in Boston, began thinking about how diabetes seems to disproportionately affect certain ethnic and racial groups. Those musings were the seed of an eye-opening study published earlier this year in the *Annals of Internal Medicine.* It quantified diabetes risk in minority groups to determine if current screening recommendations are equitable. Spoiler alert: they are not.

The current standard was released in 2021 by the U.S. Preventive Services Task Force (USPSTF), which issues evidence-based guidance on disease prevention. The recommendation is to test adults aged 35 to 70 for diabetes if they are overweight or obese, defined as having a body mass index (BMI) of 25 kg/m^2 or more. Aggarwal and his collaborators looked at the lowest-risk individuals eligible for screening under that rubric: 35-year-olds who are just barely overweight (with a BMI of 25). Within this cohort about 1.4 percent of white Americans have blood glucose levels in the diabetic range, so the researchers were shocked to find that the rate was about double for Hispanics and even higher among Black and Asian Americans. They concluded that to detect diabetes equally across all these groups, you would need to test Asian Americans with a BMI of 20 and Black and Hispanic individuals with a BMI of just 18.5—measures considered to be in the healthy range.

In a second analysis, the investigators looked at diabetes prevalence by age and concluded that to match the efficacy of screening white people at 35, providers would need to screen Hispanic Americans at 25, Asian Americans at 23 and Black Americans at 21. Medicine has been eliminating race-based scoring that made some tests, such as an assessment of kidney function, less sensitive to disease in Black people. But in the case of diabetes screening, the one-size-fits-all standard may be the problem.

Because diabetes is a complex disease involving diet, life habits, genetics and psychosocial factors, it's not easy to say why vulnerability would vary among demographic groups. There is some evidence that Asian Americans have more abdominal fat at lower body weights than do people of other ethnicities, which raises risk. "A lot of studies suggest it's better to measure the waist-hip ratio instead of using BMI [to assess risk]," says Quyen Ngo-Metzger of the Kaiser Permanente Bernard J. Tyson School of Medicine. Chronic stress has also been linked to diabetes risk, she says, and that could include the stress of experiencing racism.

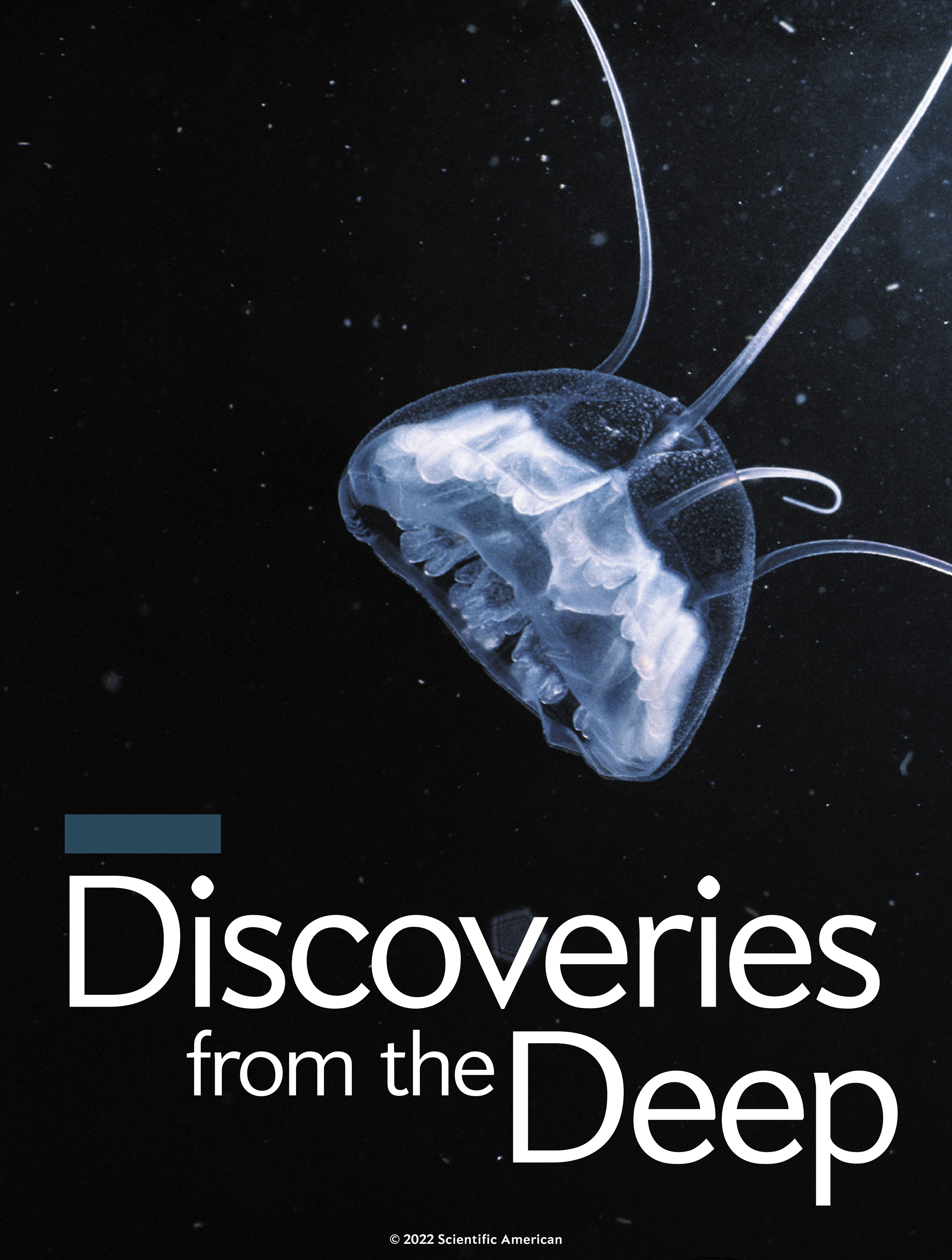
Ngo-Metzger, who was the USPSTF's scientific director from 2012 to 2019, notes that "most studies of diabetes were done in middle-aged white individuals," and that's what screening standards were based on. She argues that they should be revised. "The study found that you would miss so many Blacks, Hispanics and Asians when you use these guidelines. I think it's a disservice."

The USPSTF is unlikely, however, to revisit its guidelines soon, usually waiting three to five years, says Michael J. Barry of Massachusetts General Hospital, a task force vice chair. The USPSTF is committed to health equity, he says, but it needs more evidence that altering its recommendations would result in better long-term outcomes for patients—an issue the new study does not address.

Still, it seems obvious that detecting—and treating—diabetes earlier in communities where it is often missed would lead to improved health. Harvard University cardiologist Dhruv Kazi, senior author on the *Annals* study, points out that diabetes takes an outsize toll on Americans of color. "Black individuals with diabetes are more than twice as likely to end up on dialysis than white individuals with diabetes," he notes. They are also more likely to lose limbs and vision to undertreated diabetes. Kazi attributes these tragic disparities to "structural" inequities such as poor access to health care, high-quality food and opportunities for exercise.

Like Ngo-Metzger, Kazi would like to see screening guidelines better reflect individual risk factors that include race and ethnicity. Without such changes, he says, insurers may refuse to cover diabetes testing in people who have a BMI below 25 or who are younger than 35. Fixing larger social inequalities would require major changes, Kazi concedes, "but making screening more equitable is a good place to start." SA

Illustration by Fatinha Ramos



Discoveries from the Deep

Advances in robotics, sensing and genomics are accelerating discovery in the darkest ocean depths. Scientists are finding a more sophisticated, life-filled place than they ever expected

"Put a human in the sea, and they are pretty useless," says marine ecologist Kelly J. Benoit-Bird of the Monterey Bay Aquarium Research Institute. "They can't breathe. They can only see as far as the end of their outstretched arm. They can't make any sense of the sounds they hear."

Maybe that's why, since humans have been on Earth, the sea has been an enigma to us. The oceans cover 71 percent of Earth's surface, and by volume they provide 99 percent of the planet's living space. Yet we still know little about the life within.

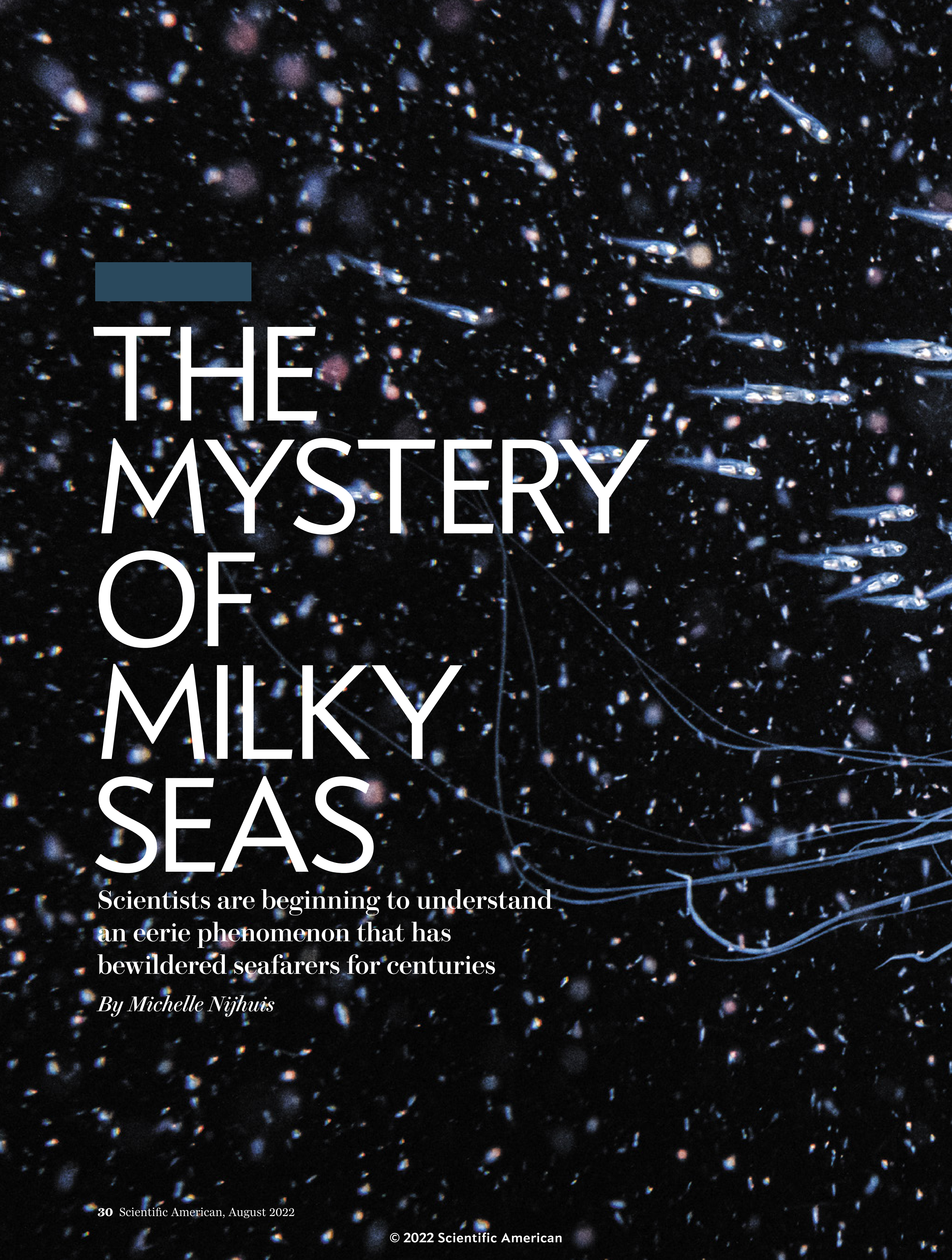
That's changing, rapidly. Aided by autonomous underwater vehicles, advanced sensing technology and fast, mobile genome-sequencing machines, scientists and explorers are finding all kinds of inspiring surprises. We've assembled some of the most fascinating recent discoveries, from the sea's surface to the seafloor.

—Mark Fischetti, Senior Editor

TINY NAVIGATORS

Zooplankton fill the seas, but they don't just drift along with the currents, as once was thought. They react and move as water conditions change, driving the ocean's food web and much of its daily life.

Flip Nicklin/Minden Pictures



THE MYSTERY OF MILKY SEAS

Scientists are beginning to understand an eerie phenomenon that has bewildered seafarers for centuries

By Michelle Nijhuis

MANY MARINE CREATURES emit light, providing one clue as to why the sea's surface can sometimes appear ghostly white.

Michelle Nijhuis is author of ***Beloved Beasts: Fighting for Life in an Age of Extinction*** (W. W. Norton, 2021), a history of the modern conservation movement. She lives in Washington State.

ON JANUARY 30, 1864, THE CONFEDERATE WARSHIP CSS *ALABAMA* ENTERED WHAT its captain described as a "remarkable patch of the sea." The *Alabama,* sailing southwest along the Horn of Africa, was one of several Confederate vessels cruising the world's oceans during the U.S. Civil War, weakening the Union by raiding its merchant ships. Formidable pirates though they were, Captain Raphael Semmes and his crew were spooked by the sea they encountered that January evening. "At about eight P.M., there being no moon, but the sky being clear, and the stars shining brightly, we suddenly passed from the deep blue water in which we had been sailing, into a patch of water so white that it startled me," Semmes recounted in a memoir.

At first he thought that the pale, constant glow indicated a submerged ridge, but a weighted line the crew dropped over the gunwale sank for 600 feet without hitting bottom. "Around the horizon there was a subdued glare, or flush, as though there were a distant illumination going on, whilst overhead there was a lurid, dark sky," Semmes wrote. "The whole face of nature seemed changed, and with but little stretch of the imagination, the *Alabama* might have been conceived to be a phantom ship, lighted up by the sickly and unearthly glare of a phantom sea." The *Alabama* traveled through the eerie water for several hours, finally exiting the patch as abruptly as it had entered it.

Semmes's firsthand description is one of the earliest reliable accounts of such a sea, and it has become a valuable, though inadvertent, contribution to science. Now, after combining dozens of historical reports with state-of-the-art satellite data, researchers are close to solving one of the ocean's most persistent mysteries—its vast, ephemeral displays of ghostly living light.

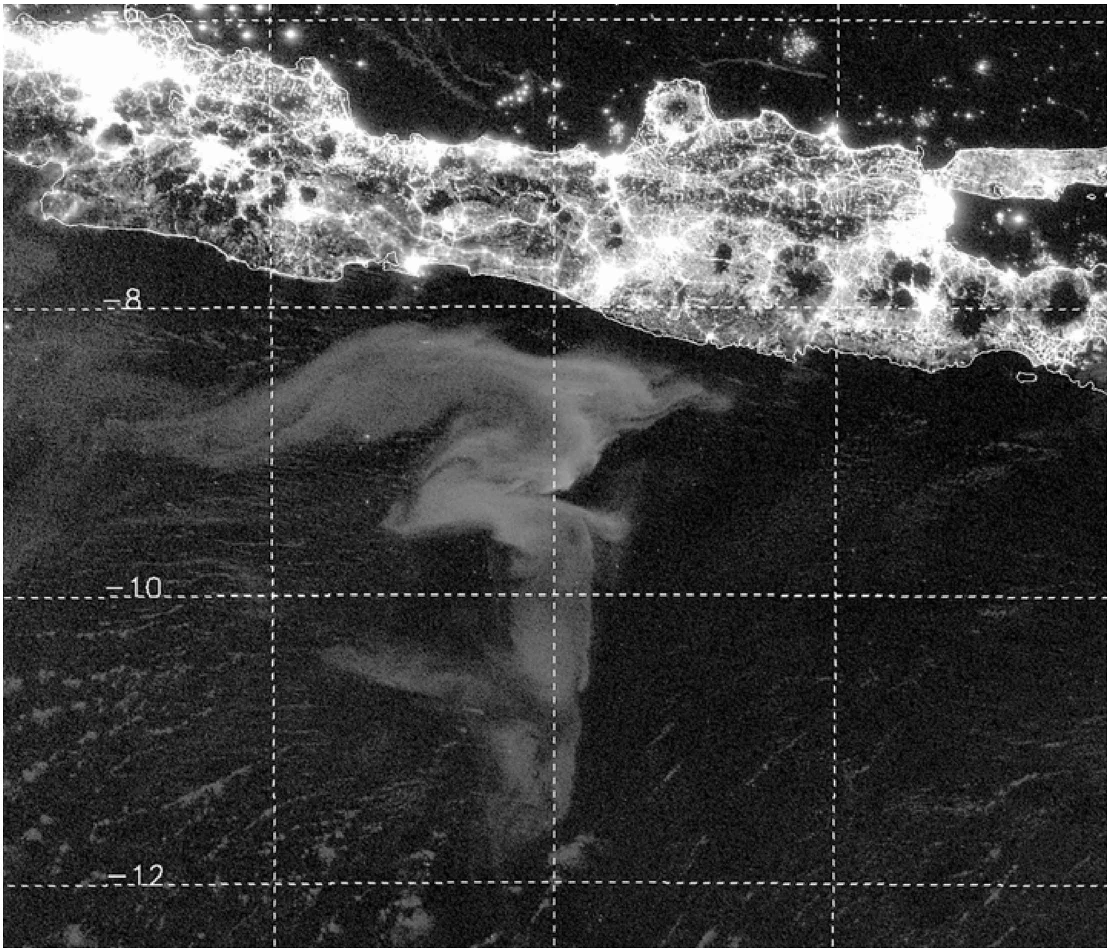
SILENT DREAD

THE COLD RADIANCE emitted by fireflies, some species of fungi and various sea creatures is called bioluminescence. Although it is one of the oldest subjects of scientific study, it is also among the most elusive. Mentions of animal light appear in ancient poetry and songs from many cultures. In the third century B.C.E., Aristotle noticed that if he struck the surface of the sea with a rod, the water sometimes produced a bright blue flash. Three hundred years later Pliny the Elder described light-emitting species of mollusks, jellyfish and mushrooms, adding that the Black Forest of central Europe was rumored to glow with bioluminescent birds (such rumors, though often repeated, were unfortunately never confirmed).

Around 1370 Egyptian zoologist Al-Damiri included bioluminescent insects in his zoological dictionary. And in 1492, during his fateful approach to the Bahamas, Christopher Columbus observed glimmers of light in the ocean—an occurrence that scientists now surmise was produced by bioluminescent marine worms of the genus *Odontosyllis,* which periodically rise to the water's surface en masse to perform a circular mating "dance." In the late 1800s, after centuries of speculation, scientists confirmed that bioluminescence results from an oxidation reaction between an enzyme and its substrate within animal and plant cells. Basic questions remained, however: no one knew what prompted different organisms to glow or what purpose the light might serve.

Most accounts of bioluminescence, on land and at sea, describe blue-green flashes and gleams, sometimes stimulated by disturbance, as with Aristotle's rod. But reports such as that of Captain Semmes suggested a very different phenomenon. The seawater plied by sailors was suffused with steady white light, not bluish bursts, and the glow often stretched for miles. These "milky seas" were rare enough, and strange enough, that people widely considered them to be tall tales—more plausible than mermaid encounters, perhaps, but just barely so. Herman Melville, in his 1851 epic *Moby-Dick,* por-

Henley Spiers/Minden Pictures (*preceding pages*)



A MILKY SEA sprawling across almost 40,000 square miles of ocean south of Java in summer 2019 was captured by sensitive night-vision satellites; it lasted 45 days.

NOAA/Colorado State University/CIRA

trayed them as bad omens, describing a mariner's "silent, superstitious dread" on entering a "midnight sea of milky whiteness," as if "shoals of combed white bears were swimming round him." In Jules Verne's novel *Twenty Thousand Leagues Under the Sea,* written almost two decades later, the fictional submarine pilot Pierre Aronnax is less perturbed by his voyage through a milky sea in the Bay of Bengal, calmly informing his assistant that "the whiteness which surprises you is caused only by the presence of myriads of infusoria, a sort of luminous little worm, gelatinous and without color."

Verne's pilot was on the right track, but it would be more than a century before science began to catch up with science fiction. In July 1985 a U.S. Navy research vessel encountered a milky sea off the Arabian Peninsula. The scientists onboard, who were conducting a broad study of marine bioluminescence, were equipped for this stroke of luck, and they quickly collected seawater samples for inspection. In addition to the dinoflagellates, copepods and other types of plankton associated with the familiar, flashing displays, the samples contained bioluminescent bacteria. The researchers suggested that milky seas occurred after algae colonies on the water's surface bloomed and died. When the dead algal cells ruptured, they released lipids subsequently consumed by bacteria, which then multiplied furiously, eventually becoming concentrated enough to produce a continuous glow.

Finally, milky seas had been established as a scientific phenomenon with a biological cause. But to understand where, when and exactly why they occurred, researchers needed more data than serendipity could provide.

SAILING OVER SNOW

FOR THE U.S. NAVY, marine bioluminescence is a practical concern because a patch of bright seawater can outline a submarine, turning it into an easy target. In the early 2000s Steven Miller, an atmospheric scientist then at the Naval Research Laboratory in Monterey, Calif., began to wonder whether satellite sensors could detect bioluminescence from above. The only sensors capable of observing visible light at night were those in the Operational Line Scan (OLS) system that flew on U.S. Air Force satellites. Miller knew that most surface displays of marine bioluminescence were much too small to register on the sensors, so, on a whim, he searched the Internet for mentions of widespread bioluminescence. He turned up a description of milky seas on the Web site Science Frontiers, an idiosyncratic catalog of "unusual & unexplained" happenings then maintained by physicist William R. Corliss.

Miller, his curiosity piqued, began to collect eyewitness accounts. Among them was a relatively recent report from a British merchant ship, the SS *Lima,* which had sailed through a milky sea along the Horn of Africa on January 25, 1995. "The bioluminescence appeared to cover the entire sea area, from horizon to horizon," read the *Lima*'s log entry, "and it appeared as though the ship was sailing over a field of snow or gliding over the clouds."

When Miller pulled up the OLS images from the *Lima*'s location on that date, he initially saw nothing. But when he zoomed in, he saw a faint, comma-shaped smear. "It looked like a finger smudge, but it moved as I moved the figure," he remembers. Miller found that the edges of the smudge matched the coordinates noted in the ship's log as it entered and exited the milky sea, which covered nearly 5,500 square miles. When he examined OLS images from the days immediately before and after the *Lima*'s encounter, he found the same smudge, rotating counterclockwise in concert with local ocean currents. "Okay," Miller thought, "we *can* see bioluminescence from space."

Miller got in touch with Steven Haddock, a marine biologist at the nearby Monterey Bay Aquarium Research Institute (MBARI), to share his findings. Like Miller, Haddock had never seen a milky sea firsthand, but he was familiar with the phenomenon, especially because one of his mentors, marine biologist Peter Herring (now retired), had cataloged hundreds of descriptions of milky seas dating back to Captain Semmes and the *Alabama*. Haddock, who primarily studies bioluminescence in jellyfish, had spent much of his career trying to get as close as possible to bioluminescent organisms using crewed or remotely operated deep-sea submersibles. He and Miller began to collaborate.

Although the OLS detection from 1995 had been something of a fluke—the product of Miller's persistence and a fortuitous satellite position—Miller hoped a new, more sensitive low-light visible-spectrum instrument called the day-night band (DNB) sensor would allow a systematic survey of milky seas. The sensor, launched in 2011, now rides on two satellites more than 500 miles above Earth's surface, each orbiting the planet daily. More than 100 times as sensitive as the OLS, the DNB can easily pick up the gleam of a milky sea. But it can also pick up the faint "airglow" produced by the absorption of ultraviolet light in the upper atmosphere, some of which is reflected by clouds. "There were clouds everywhere. The airglow is emitting upward, and sometimes it makes this really diffuse, widespread veil of light," Miller explains. Differentiating bioluminescence from these other phenomena, he adds, "took us many years of looking at what seemed like very noisy imagery."

Thanks to the long history of sightings by mariners, Miller and Haddock knew that the occurrences of milky seas peaked in winter and summer and that they were most often reported in the northwestern Indian Ocean, where both the *Alabama* and the *Lima* had encountered them, as well as around Indonesia, in particular near the island of Java and in the Banda Sea. Narrowing his search to these seasons and locations, Miller analyzed DNB data collected on moonless nights from 2012 through 2021, eventually identifying a dozen events that were not clouds or airglow, were invisible during the day and drifted with the currents over multiple nights. One 2019 event, detected just south of Java, was visible for at least 45 nights and covered almost 40,000 square miles—an area the size of Kentucky. Its multiweek persistence suggests that the DNB sensor could be used to dispatch researchers to newly formed milky seas in time to conduct dives in them. "[There's] only so much you can do from spaceborne measurement," Miller says. "You can't get into the water, you can't see the vertical structure of the glow within water, you can't sample the critters, you can't measure the detailed chemistry. [For] all these things, you need to be in the middle of it to truly understand."

While Miller waits for the chance to be in the middle of a milky sea, he continues to expand his collection of sightings. A recent addition comes from Sam Keck Scott, who in the summer of 2010 helped to sail a restored Dutch ketch from Malta to Singapore, crossing the Arabian Sea. One evening in late July, as Scott began his watch, he noticed an odd radiance in the air. After a few minutes he realized that even though the sky was completely dark he could see the boat's sails and hull; the entire ocean had brightened and seemed to be shining from within. Scott and his crewmates sailed through the milky sea for about four hours, exiting it even more suddenly than they had entered. "We knew it was bioluminescence of some kind, but it was on this wild, wild scale, unlike anything I'd ever seen before," Scott recalls.

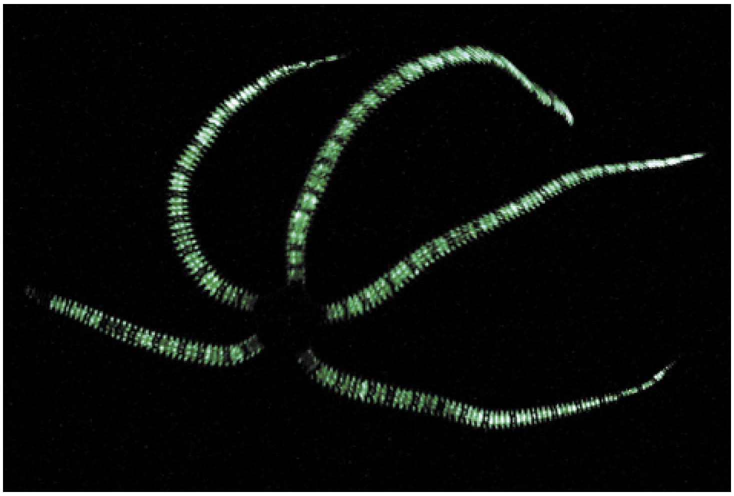
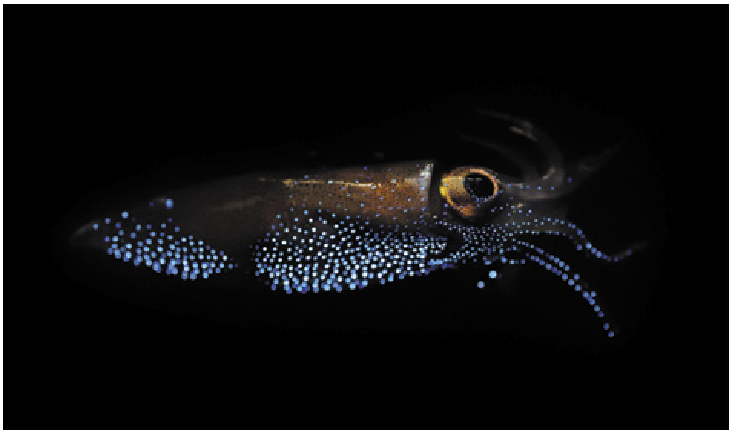
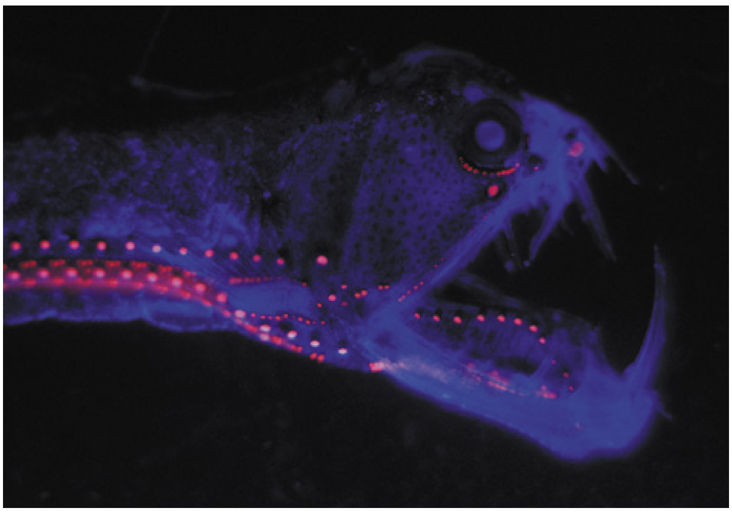
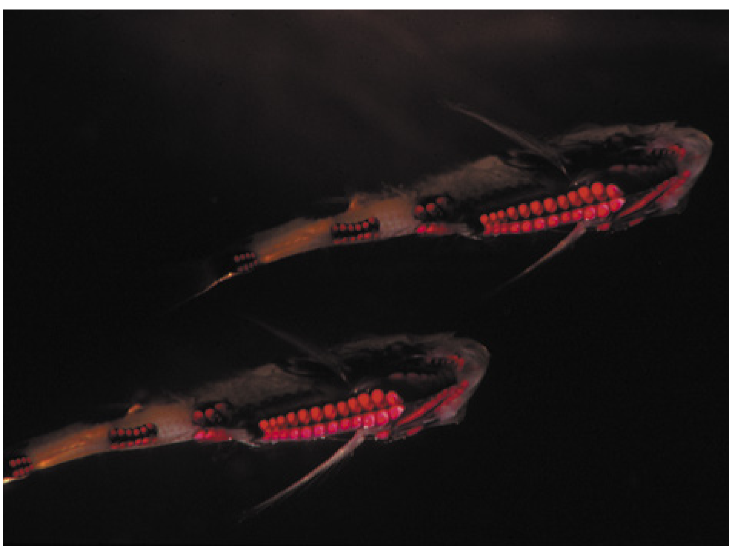
BURGLAR ALARM

FROM A DISTANCE, scientists have proposed various hypotheses about how milky seas form. Investigators on the 1985 navy expedition theorized that the bioluminescent bacteria they collected had congregated around an algal bloom. Other sleuths have since suggested that the steady glow results from "quorum sensing," the ability of bacteria to communicate through chemical signaling. Once their density is high enough to produce a perceptible collective glow, they sustain a continual shine. But why? Some biologists think bioluminescence in other marine organisms helps them attract food or mates or functions as a kind of burglar alarm, flashing when they are under attack in hopes of attracting the predators of their predators. The glow of quorum sensing in bacteria may act as a different invitation: when a colony runs low on food in the open water, it may glow to encourage nearby fish to come and consume the bacteria, consequently sustaining the bacteria in their guts.

The decade of DNB data complicates the idea that milky seas occur most frequently in winter and late summer. The peaks in milky-sea formation do appear to be strongest in the northwestern Indian Ocean when winter and summer monsoons trigger phytoplankton blooms by bringing deep, cold, nutrient-rich water to the sea surface. Farther east, however, milky seas may be set up by the Indian Ocean Dipole, an El Niño–like pattern of sea-surface temperatures associated with cool, dry conditions and strong winds in the eastern Indian Ocean between

DEEP-SEA inhabitants produce an amazing array of bioluminescence to communicate, attract mates or prey, or confuse predators. Counterclockwise from top left: a green brittle star; a firefly squid whose underside glows to camouflage it against the water above when seen by enemies below; a viperfish; two hatchetfish; a dragonfish; and the belly of a pearlside. Dots along the belly are photophores—organs that produce light through chemical reactions or symbiotic bacteria.

Jerome Mallefet/Minden Pictures; David Shale/Minden Pictures; David Shale/Minden Pictures; Jerome Mallefet-FNRS/Minden Pictures; Jerome Mallefet-FNRS/Minden Pictures; Solvin Zankl/Minden Pictures (*clockwise from top left*)

May and October. The satellite data also suggest an explanation for why the glow occasionally seems to extend to some depth, creating the perception among mariners that their ship is suddenly floating in light: Miller found that several milky seas occurred in the relative calm between large ocean eddies, where a combination of currents and temperature gradients can isolate a column of seawater from the surrounding ocean, putting it at a standstill. Such conditions, he hypothesizes, could foster superdense bacterial populations whose quorum sensing extends vertically as well as horizontally to adjacent colonies, magnifying the depth and breadth of the resulting milky sea.

Miller and Haddock hope the DNB sensors' ability to detect—and, in time, perhaps predict—milky seas will allow researchers to quickly head out to the ocean and collect samples to test hypotheses. Until then, milky seas are unlikely to give up their lingering mysteries.

EVERYWHERE AGLOW

THE SECRETS of milky seas persist in part because much larger questions remain about the nature, function and extent of bioluminescence itself. Since most bioluminescent organisms live in the ocean, many at great depths, observing bioluminescence firsthand has required considerable resources—and not inconsiderable risk. Marine biologist Edith Widder, who founded the Ocean Research and Conservation Association in 2005, began her pioneering bioluminescence studies in the 1980s. She recounts her numerous and occasionally hair-raising submersible experiences—including a life-threatening leak at a depth of 350 feet—in her 2021 book, *Below the Edge of Darkness.* "I've spent a lot of my career in submersibles, operating in the dark" because only very recently have cameras been able to perceive both the light and the color of bioluminescence, she told me. "It's absolutely, breathtakingly beautiful, and finally [other people are] getting to see it."

Widder and other researchers who have managed to take deep-sea voyages have known for decades that bioluminescence is a common ability. But the first reliable estimate of its occurrence came in 2017, when Haddock and Séverine Martini, then a postdoctoral researcher at MBARI and now at the Mediterranean Institute of Oceanography, published an analysis of 17 years of video observations collected by remotely operated vehicles off the California coast. From more than 350,000 observations, which included more than 500 groups of organisms, taken at depths from just below the surface to nearly 13,000 feet, Martini and Haddock concluded that at least three quarters of the organisms were capable of bioluminescence. The percentage remained remarkably consistent at different ocean depths. In a 2019 study, they found that about a third of the organisms living on the ocean floor are bioluminescent. Martini identified a carnivorous sponge that was not only new to science but the first documented case of bioluminescence in its phylum.

Given that the ocean is the largest living space on the planet, the two analyses suggest that bioluminescence is one of the predominant ecological traits on Earth. "It's not something far away that you'll never see in your life," Martini says. "At sea, everything is glowing—you just have to pay attention." For Martini, Haddock, Widder and the few other marine bioluminescence researchers, the pervasive glow only increases their interest in its ecological functions, evolutionary history, chemistry and genetics—and their excitement about the high-definition underwater cameras and advanced genetic sequencing that offer new ways of accessing a once all but inaccessible world.

Humans have benefited greatly from bioluminescent species. Medical and biological researchers frequently use green fluorescent protein, which biologists isolated from bioluminescent jellyfish in the 1960s, as a visual marker of proteins and the components of living cells. Widder is using bioluminescent bacteria to identify pollution hotspots in Florida's Indian River Lagoon, one of the most diverse estuaries in North America. Fertilizer and pesticide runoff from farms and lawns, as well as leakage from sewage and septic systems, has been poisoning the lagoon for decades, and the pollution has accumulated in its sediments. Because most pollutants interfere with bacterial respiration and therefore with bacterial bioluminescence, Widder and her colleagues have taken sediments from the lagoon and mixed them with bioluminescent bacteria in the lab to determine the relative concentrations of pollutants throughout the lagoon—knowledge that helps in monitoring, mitigation and restoration efforts.

Although applications are expanding, the ability of marine organisms to benefit from their own bioluminescent capacity is under threat. The rush to mine valuable metals from the ocean floor is expected to tremendously impact not only the seabed but the entire deep sea, where the water is typically clear enough for bioluminescent organisms to communicate with one another across hundreds of feet. When robotic mining vehicles scrape the seafloor, they kick up clouds of sediment. After machines pump collected material to the surface and remove the fist-sized, metal-rich nodules, they dump the remaining mud and silt back into the sea, again clouding once transparent water—inevitably disrupting communication among the bioluminescent organisms and interfering with their ability to find food and mates.

"In the context of ocean ecology and ocean health, it's important to understand how widespread and widely used [bioluminescence] is," says Haddock, who co-authored a 2020 paper on the ecological effects of deep-sea mining. "If you do something that's going to affect that process, it's going to have all these ripple effects that we can only now start to appreciate." The glowing seas that so terrified generations of mariners have taken no victims and left no traces; the cloudy seas created by humans, however, could permanently dim the ocean's light. ■

FROM OUR ARCHIVES

Luminous Animals. Thomas R. R. Stebbing; *Scientific American Supplement,* November 30, 1895.

scientificamerican.com/magazine/sa

David Shale/Minden Pictures

THE BLACK SEADEVIL, which lies in wait as deep as 13,000 feet, has a transparent lure rising from its head. Bacteria living inside the lure glow to attract prey. It is unclear how the fish controls the emissions.

ANGEL, MONSTER

When sea angels hunt, they transform into monsters. The free-swimming slugs, less than an inch long, store six jellylike “arms” known as buccal cones inside their heads (*left*). When they sense prey—for example, a nearby sea butterfly—muscles in their core contract, causing the arms to shoot out (*right*) and grab the target, in milliseconds. They can also tear a victim’s body out of its shell for easier consumption.

Alexander Semenov

Mark Fischetti is a senior editor for sustainability at *Scientific American.*

EVERY INCH OF THE SEAFLOOR

High-tech mapping is finding surprising underwater formations everywhere

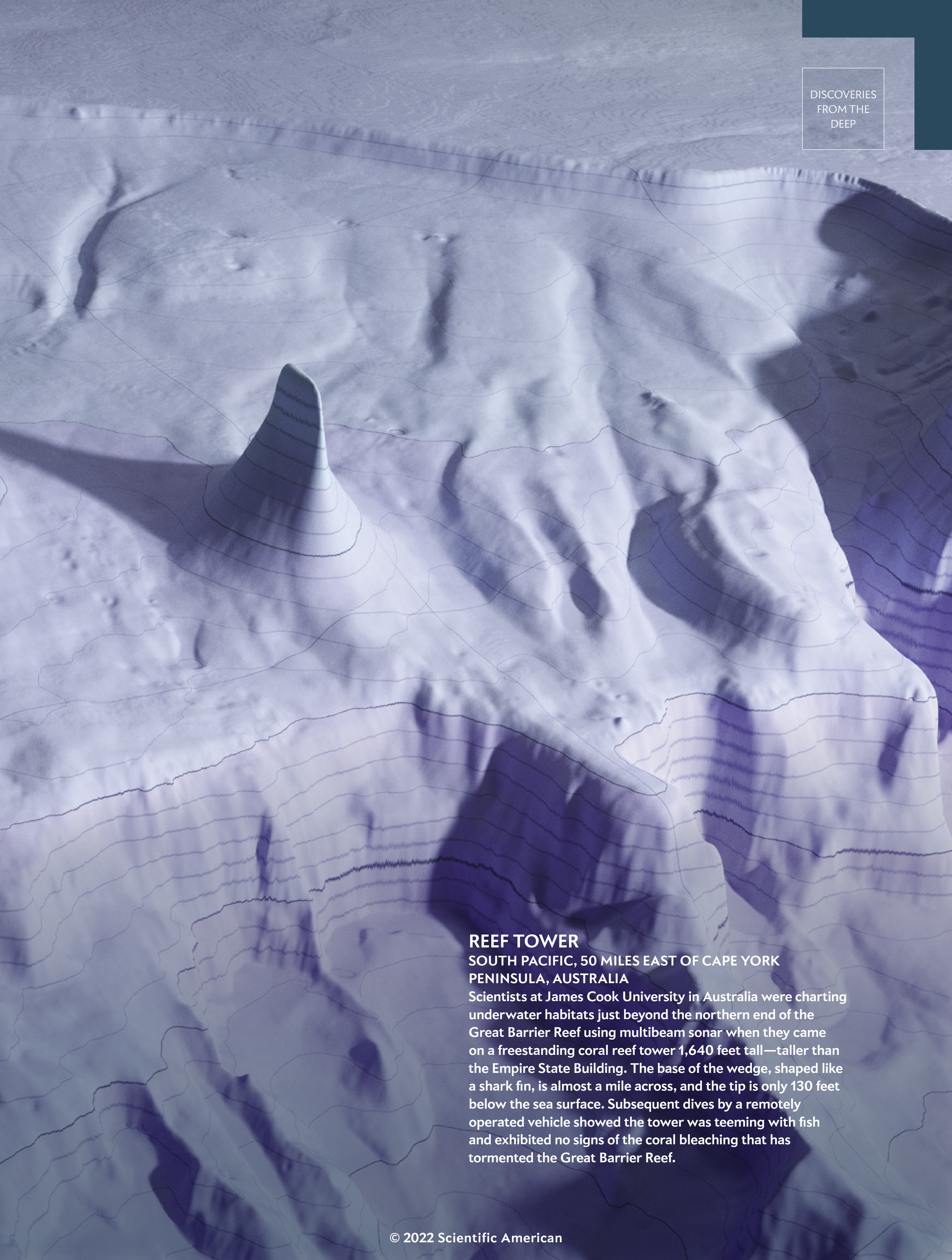
By Mark Fischetti

Illustrations by Maceij Frolow

OCEANOGRAPHERS ARE FOND OF SAYING THAT WE KNOW MORE ABOUT THE MOON'S SURFACE THAN we do about Earth's seafloor. It's true. As of 2017, only 6 percent of the global seabed had been mapped, typically by ships with sonar instruments sailing back and forth in straight lines across a local section of sea.

But since then, nations have become eager to chart the seafloor within their own "exclusive economic zones," which reach 200 nautical miles from their shores, in part to look for critical minerals they can scrape up using big mining machines. The other push is Seabed 2030—an effort to map Earth's entire seafloor by 2030, run jointly by the Nippon Foundation and the nonprofit General Bathymetric Chart of the Oceans.

The goal is to collect and stitch together mapping done by governments, industries and research institutions everywhere. Public release of previously private bathymetric data is helping to widen the areas plotted. And uncrewed, remotely operated vehicles fitted with sonar that can zoom around underwater for days at a time are speeding the pace of mapping. By June 2022 an impressive 21 percent of the world's seafloor had been charted. The more experts map, the more surprises they find—such as the three unexpected, unusual formations revealed here.



REEF TOWER

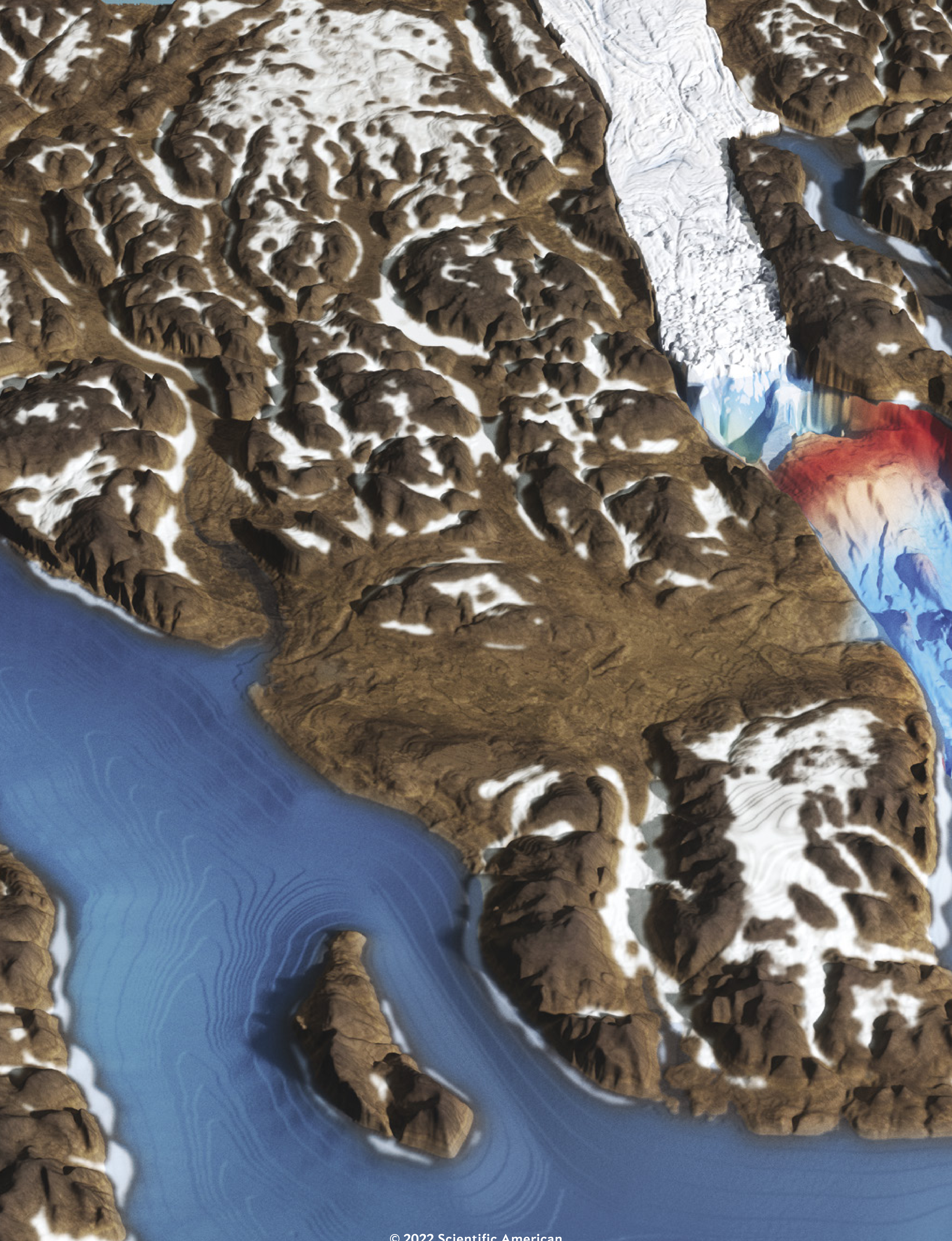
SOUTH PACIFIC, 50 MILES EAST OF CAPE YORK PENINSULA, AUSTRALIA

Scientists at James Cook University in Australia were charting underwater habitats just beyond the northern end of the Great Barrier Reef using multibeam sonar when they came on a freestanding coral reef tower 1,640 feet tall—taller than the Empire State Building. The base of the wedge, shaped like a shark fin, is almost a mile across, and the tip is only 130 feet below the sea surface. Subsequent dives by a remotely operated vehicle showed the tower was teeming with fish and exhibited no signs of the coral bleaching that has tormented the Great Barrier Reef.

MILLION MOUNDS CORAL PROVINCE

NORTH ATLANTIC, 100 MILES EAST OF GEORGIA, U.S.

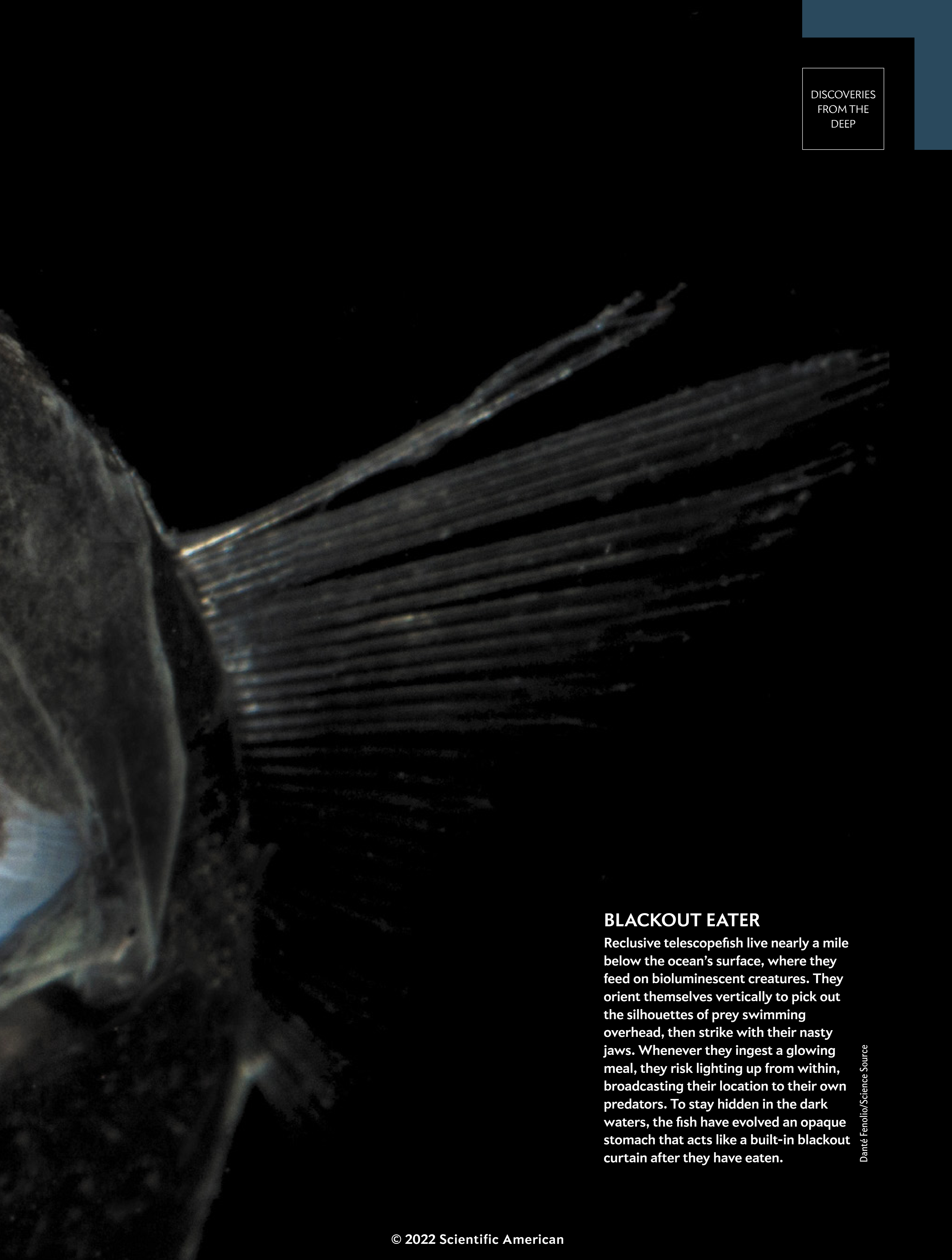
Investigators at the National Oceanic and Atmospheric Administration have finished mapping the "million mounds" deep-sea province. Thousands of coral mounds, each 30 to 300 feet high, blanket 11,000 square miles of ocean floor, making it the largest deep-sea coral ecosystem ever discovered. At a depth of 2,000 to 2,600 feet, the seafloor receives no sunlight, so the white corals don't house symbiotic algae that give shallow reefs their color. When old corals in the mounds die, their skeletons provide the foundation for new corals; some mounds have been growing for thousands of years.



RYDER GLACIER SILL

ARCTIC OCEAN, SHERARD OSBORN FJORD, NORTHWESTERN GREENLAND

Geologists at Stockholm University were puzzled about why the front edge of Ryder Glacier, at the Sherard Osborn Fjord, was losing less ice than the faces of other Greenland glaciers. Using multibeam sonar on an icebreaker in the fjord, they discovered two parallel sills of bedrock (*red*), separated by a basin, that cross the fjord. The inner sill, about 3.8 miles across and 1,600 to 1,900 feet high, blocks relatively warm Atlantic Ocean water from reaching the glacier and melting its underside, slowing the glacier's demise.



BLACKOUT EATER

Reclusive telescopefish live nearly a mile below the ocean's surface, where they feed on bioluminescent creatures. They orient themselves vertically to pick out the silhouettes of prey swimming overhead, then strike with their nasty jaws. Whenever they ingest a glowing meal, they risk lighting up from within, broadcasting their location to their own predators. To stay hidden in the dark waters, the fish have evolved an opaque stomach that acts like a built-in blackout curtain after they have eaten.

Danté Fenolio/Science Source

STEALTH MIGRATIONS

Trillions of tiny animals may be coordinating their daily movements in ways that affect every organism on the planet

By Katherine Harmon Courage

TRILLIONS OF ZOOPLANKTON migrate every night from the ocean's depths up to the surface and back. Each species has its own rhythm, which can vary based on age, season and sex.

Katherine Harmon Courage is an independent science journalist and contributing editor for *Scientific American.* She is author of *Octopus! The Most Mysterious Creature in the Sea* (Current, 2013) and *Cultured: How Ancient Foods Feed Our Microbiome* (Avery, 2019).

EVERY EVENING AROUND THE WORLD TRILLIONS OF ZOOPLANKTON, MANY SMALLER THAN a grain of rice, hover hundreds of feet below the surface of the sea, waiting for their signal. Scientists long considered these tiny animals to be drifters, passive specks suspended in the ocean, moved by the whims of tides and currents. And yet, just before the sun disappears, the swarms begin to rise on a clandestine journey to the surface.

As they climb, clusters of other zooplankton join in: copepods, salps, krill and fish larvae. The multitudes remain near the surface at night, but just as the first beams of morning light begin to cascade across the sea, they are already turning back down to the deep. As sunset and sunrise slide from east to west every 24 hours—across the Pacific Ocean, then the Indian, the Southern and the Atlantic—swarm after swarm make the same upward journey, retreating as daylight returns.

Humans are mostly unaware of this daily aquatic movement, known as diel vertical migration, but it's the largest routine migration of life on Earth. Current estimates indicate some 10 billion tons of animals make these excursions every day. Some of them ascend from more than 3,000 feet below. It's an astonishing feat. For a quarter-inch fish larva, making a one-way vertical trip of 1,000 feet is the equivalent of a human swimming more than 50 miles—in just an hour or so. During the trip these animals pass through zones of ocean where the conditions are wildly different. At 1,000 feet the water is roughly 39 degrees Fahrenheit—maybe 20 degrees colder than the surface—and the pressure is about 460 pounds per square inch, more than 30 times what it is up top. Why would huge numbers of tiny animals make such an arduous trip every day?

The short answer is to eat—and to avoid being eaten. During the day vulnerable zooplankton hide from predators such as squid and fish in the dark depths. When night begins to fall, they rush to the surface to feed on phytoplankton—the microscopic aquatic plants that live in the top few hundred feet of water—under cover of night.

But this is just the prevailing wind of vertical migration. There are all kinds of crosscurrents and eddies. Now, with increasingly sophisticated sonar, underwater autonomous vehicles and advances in DNA sequencing, researchers are starting to understand those details. The specifics will help answer questions that have implications for the oceanic food web, the global carbon budget and the very nature of life on Earth.

DANCES OF THE DEEP

EARLY RECORDINGS of diel migration date to World War II, when ships and submarines using sonar to sweep the oceans for enemy subs detected something odd—parts of the seafloor seemed to be moving up and down, creating a deep "scattering layer" that reflected the sonar signals. The layer fluctuated twice a day by as much as 3,000 feet—shifts that seemed to defy logic. In 1945 oceanographer Martin Johnson embarked on a research ship to sample plankton at various times and depths over 24 hours. "From these preliminary observations there appears to be some direct correlation of the planktonic animals with the scattering layer," Johnson wrote. The proposal that the layer was composed of living creatures raised more questions than it answered, however.

Answering those questions proved difficult. The animals

tonaquatic/Getty Images (*preceding pages*) involved are tiny, their passage happens in the dark and the deep ocean is tough to access. Tracking swarms of flea-size organisms through the lightless depths is trickier than following migrating whales across hemispheres. By the 1990s researchers had learned enough to describe the diel migration as a cloud of organisms rising and falling in unison. Higher-resolution sonar picked up individual clusters of animals and more subtle movements up and down. Even today, though, sonar-based surveys can't distinguish which tiny animals are on the move. Sampling the zooplankton, as Johnson did, can haul up the organisms for identification, but it blurs the nuances of time and location that could indicate where each animal was in its journey.

Despite these challenges, new research is revealing hidden intricacies of the mass migration. For one thing, the process is intimately tied to what's happening in the skies. When the sun is absent for weeks at a time during polar winters, some of these animals realign their migrations with cycles of the moon. Solar eclipses can cue them to start swimming toward the surface. Zooplankton living below 1,000 feet, where light intensity is just 0.012 percent of what it is at the surface, may shift their vertical position by as much as 200 feet as passing clouds change the trace amounts of light reaching them, explains Deborah Steinberg, chair of biological sciences at the Virginia Institute of Marine Science. She realized this during a research cruise, even though the light changes at the surface were not apparent to her or her colleagues. "From our perspective on the ship, every day of the cruise was overcast, gray and drizzly," she and her colleagues noted in a 2021 paper. But the zooplankton somehow registered the subtle changes in light far underwater.

Autonomous vehicles equipped with cameras and collection devices that allow them to pair images with chemical signatures from the water column have begun to offer new, animal's-eye views of migration. For example, Kelly J. Benoit-Bird of the Monterey Bay Aquarium Research Institute (MBARI) in California and Mark Moline of the University of Delaware sent an autonomous underwater vehicle 1,000 feet down into the Catalina Basin off southern California to take sonar measurements of vertically migrating zooplankton. The echoes it returned were stunning: they revealed that the zooplankton were organized in well-defined clusters, tightly assembled by kind and migrating together in carefully timed ascents.

"We need to start thinking about this not just as a bulk process but as an individual and species-by-species sort of thing," Benoit-Bird says of vertical migration. And the adventurous zooplankton are not alone in the nightly commute. "So many animals use this as a strategy," Benoit-Bird says. Octopus, lanternfish, siphonophores and other motley deep-sea creatures also make the nightly trek to avoid their own predators and to find food—in their case, the other migrators.

PLANTS ON THE MOVE

ANIMALS MIGHT not be the only ones making routine vertical migration. Kai Wirtz is a professor and ecosystem modeler at Helmholtz-Zentrum Hereon's Institute of Coastal Systems in Germany. In 2016 Wirtz and his colleagues were looking to describe how the distribution of different phytoplankton matched up with different ocean environments. But he noticed that the circulation of ocean water alone wouldn't bring enough nitrogen and phosphorus from the depths to feed the ocean's vast and essential blanket of phytoplankton at the surface.

Scientists had known for decades that many species of phytoplankton can move—some by changing their buoyancy by shedding fats or changing their dimensions and others by whipping their tail-like flagella. Wirtz mulled this over as he looked more broadly at the oceans' profile: the top is filled with sun but few nutrients. The bottom does not get enough sunlight for photosynthesizers to live on, yet it harbors an abundance of nutrients. So, he thought, why *wouldn't* these plants use their evolved locomotive abilities to commute between the two spaces? In fact, he says, "there is not an easy other explanation."

By Wirtz's estimates, it's possible that half of marine phytoplankton species undertake a regular vertical migration of dozens to 100 feet, shuttling nutrients from below and solar energy from above. These microscopic organisms might take hours, days or even weeks to complete the journey, some reproducing along the way, thereby allowing their descendants to carry on the mission. This idea presents a radical change in how scientists might think of phytoplankton, which they often consider as more of a chemical compound than individual living organisms with varied behaviors.

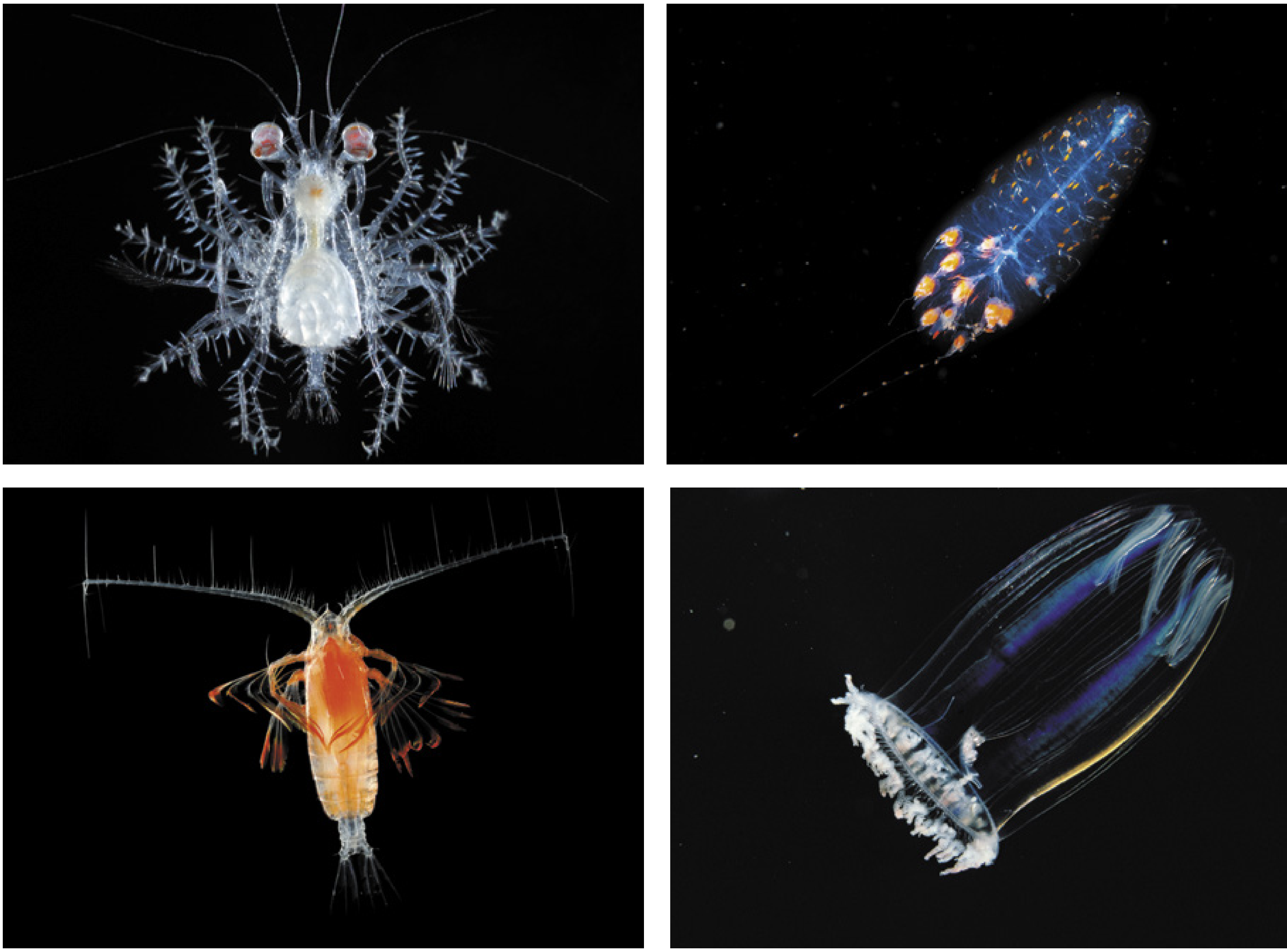
> To pinpoint which species are moving when and where, scientists are combing the water column for the genetic traces of transitory organisms.

Laboratory work confirms not only that marine plants move vertically but also that their behavior is more sophisticated than we had thought. One team at Washington State University set up 6.5-foot-tall saltwater tanks with dinoflagellate phytoplankton, then introduced predatory copepods to one of the tanks. When the scientists replicated typical day-night light cycles, they saw the hungry copepods making the traditional nighttime ascent and daytime descent. The phytoplankton in both tanks did the opposite—swimming up during the "sunlit" day and down at night, probably to maximize their sunlight exposure and minimize their risk of being eaten by the night-feeding zooplankton.

To the researchers' amazement, though, they saw that the single-celled plants in the tower with the copepods routinely retreated even deeper than usual at night, putting more distance between themselves and the enemies above. No one knows how the phytoplankton sense their predators' behavior. But as the researchers noted in their paper in *Marine Ecology Progress Series,* "This newly reported behavioral response … could have important ecological consequences."

ALTERING THE CARBON BUDGET

ONE CONSEQUENCE of phytoplankton migration is the extent of climate change. In 1995 Steinberg and other scientists were try-



THE ZOOPLANKTON MENAGERIE comprises a wild array of tiny animals. Clockwise from top left: A crab larva known as a megalopa from the Atlantic Ocean; a blue and orange plankton from the Canary Islands; a sea butterfly also from the Canary Islands; an arrow worm, found in all oceans, from the surface to the deep; a blue bioluminescent plankton from the Arctic Ocean; and a buglike copepod from the Atlantic deep sea, common in tropical regions.

Solvin Zankl/Minden Pictures; Sergio Hanquet/Minden Pictures; Sergio Hanquet/Minden Pictures (*top row, left to right*); Solvin Zankl/Minden Pictures; Flip Nicklin/Minden Pictures; Sinclair Stammers/Minden Pictures (*bottom row, left to right*)

ing to piece together the global carbon budget—the amount of carbon dioxide emitted into the atmosphere and the amount pulled from it, in part by marine ecosystems. The numbers weren't adding up; more carbon was disappearing from the ocean surface than they could account for. Then Steinberg got a look into the darkness.

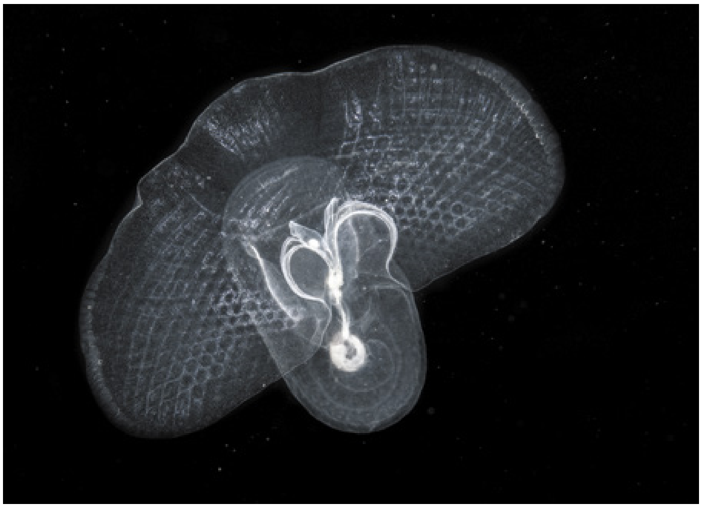
As part of her research, done at the Bermuda Institute of Ocean Sciences, Steinberg would often dive during the daytime, and she became well versed in the local fauna. But then she got to take a night dive. She plunged off the side of a small boat above 13,000 feet of dark water and soon found "it was a totally different community. I was in the water with animals of every single kind," she recalls, her voice still ringing with excitement more than a quarter of a century later. That night was her cue to change direction and start studying diel migration. And she had an inkling that it might hold part of the carbon answer.

On the ocean's surface, phytoplankton suck an enormous amount of carbon dioxide from the atmosphere, but they release much of it right back into the air, often within days. As migrating zooplankton swim up at night and eat these marine plants, they become a kind of biological conveyor, transporting carbon down into the deep sea, where it can get sequestered for hundreds or thousands of years.

To study this crucial movement of carbon, Michael Stukel, a plankton and marine biogeochemistry researcher at Florida State University, spends a lot of time peering through a microscope at zooplankton's fecal pellets. Individual excretions are small, but when they happen on such an enormous scale, they take on global biogeochemical significance.

Fecal pellets from vertical migrators, rich in carbon, descend through the water column. They are joined by other sinking biological particles, creating "marine snow" that slowly drops to the deep seafloor. Together with the swimming zooplankton carrying their carbon-loaded dinners back down with them, this global sequestration of carbon means the planet is "not as hot as it otherwise would be," Stukel says.

Estimates of the amount of carbon sequestered by migrating



organisms vary widely because so much about the diel migration remains a mystery. Better data will improve climate models, which in turn will improve understanding of how climate change will alter these organisms' behaviors—and, subsequently, the climate again. "You run into these big questions for humanity, for climate, that we can't answer, and a fair number of them relate to these migrators," says Ken Buesseler, a senior scientist at the Woods Hole Oceanographic Institution.

BALANCING ACT

ANSWERS TO THE REMAINING big questions about these migrators are likely to come from work such as that happening in Kakani Katija's lab at MBARI. There she's adding stereoscopic cameras and vision algorithms to autonomous vehicles so they can carefully track the movements of specific migrators. She can now train a vehicle and turn it loose to locate an animal and trail it for hours.

Katija's team is training the technology on gelatinous creatures such as siphonophores, which look like ghostly worms. Because these animals have semitransparent tissue and move quickly and unpredictably, siphonophores are hard for an autonomous vehicle to keep sight of, but that's what Katija wants: "We're trying to understand how to make these systems more robust," she says. To capture usable images and video, the team needs a robot that can swim and produce light—both of which could easily interfere with their subjects' behavior. "That's a huge concern," Katija acknowledges. One stealthy strategy is to use red light, which most of these creatures can't see, and a cruising mode that minimizes turbulence. Researchers are also turning to satellites in space that can observe the density of animals that come up to feed at night without the risk of disturbing them. Equipped with lidar—laser-based remote sensing technology—they can peer into the water as far down as 65 feet.

To pinpoint which species are moving when and where, scientists are also combing the water column for the genetic traces of transitory organisms. One team dropped large seawater-sampling bottles at various depths from its research ship as it drifted in the Gulf of Mexico. At the same time, the researchers were taking sonar readings of the life below. From the samples, they sequenced strands of DNA to deduce what organisms had been where—and when. The results, published in 2020, revealed poorly resolved spots in the concurrent sonar readings. Although sonar data suggested fish and other relatively large targets accounted for much of the moving biomass, the DNA indicated that copepods and gelatinous zooplankton had a much greater presence.

What researchers need most, they agree, is a global network of ocean monitors that can watch these processes day in and day out to more fully understand the ocean's systems before humans further disrupt them. For example, large-scale fishing has been done almost exclusively in the ocean's surface layer, augmented more recently by bottom trawling. But now some countries, including Norway and Pakistan, are issuing commercial fishing permits for the middle swath of ocean, in part to suck in the diel migrators and process them into food for farmed fish and for fish oil.

Expanding dead zones and rising oxygen-minimum zones in ocean water are also squeezing these animals out of livable daytime habitats. And climate change is decreasing the mixing of water layers in the open ocean, bringing fewer nutrients to phytoplankton. Fewer phytoplankton means less food for migrating zooplankton. All of which means the scientists studying these animals are under growing pressure. "It's not often that we have the chance in history to understand a system before it's exploited," Benoit-Bird says. "I feel like we're kind of racing against the clock."

To better understand the movements of trillions of copepods, krill and other elusive migrators, this summer Benoit-Bird and her colleagues will return to sea. She hopes their expedition with underwater robots, sonar, imaging and environmental DNA can help them learn how these tiny animals self-organize during the day—rising and falling, tightening and loosening in swarms to stay connected with networks of other species.

In the meantime, the sun will continue to rise and set. As it does, an untold number of animals will follow the underwater tides of darkness and light, eating, excreting and modulating the very balance of elements on our planet. SA

FROM OUR ARCHIVES

The Basis of Aquatic Life. Leon Augustus Hausman; December 1924.

scientificamerican.com/magazine/sa

INTIMIDATOR

A female blanket octopus unfurls her iridescent cape. Scientists suspect that the membranous webbing helps to deter would-be predators by making the octopus appear larger and more intimidating. The female can grow to six feet long and up to 40,000 times heavier than the male, which is smaller than a Ping Pong ball—one of the most extreme sex differences in the animal kingdom.

Mike Bartick

HEALING WATERS

Compounds that sea creatures make to defend themselves could yield lifesaving medicines

By Stephanie Stone

Photographs by Devin Oktar Yalkin

RESEARCHERS from the Scripps Institution of Oceanography wade through seagrass beds near San Diego (*opposite page*). The scientists collect microbes there for study and store them in ultracold freezers at their lab (*this page*).

Stephanie Stone is an award-winning science journalist and video producer who covers biodiversity, sustainability and human health. She is a co-founder of *bioGraphic* magazine.

AFTER COMPLETING SIX LONG ROUNDS OF chemotherapy, 75-year-old Pedro R. L. received the news he and his family had been hoping for: his chronic lymphocytic leukemia was in complete remission. But while his body was still recovering, he contracted COVID-19. He was admitted to the Quirónsalud Madrid University Hospital on January 30, 2021. Initial treatments failed, and by February 25 he had developed severe pneumonia. That's when his doctor, Pablo Guisado, recommended they try plitidepsin, a potent antiviral compound in a phase 3 clinical trial for treating hospitalized COVID patients.

Plitidepsin comes from a place few drugmakers would have predicted: the seafloor around Es Vedrá, an uninhabited rocky island off the southwestern coast of Ibiza, Spain. Back in 1988, Madrid-based pharmaceutical company PharmaMar organized an expedition to the storied site, an abrupt outcrop thought to have inspired Homer's tale in *The Odyssey* about singing sirens luring sailors to their death. While diving on a reef packed with purple corals and red sea fans, scientists pulled a comparatively uninspiring invertebrate creature from a rocky slope 36 meters deep—a translucent, pale-yellow tunicate, *Aplidium albicans,* that resembled a wad of discarded facial tissues.

The researchers were interested in tunicates because they filter-feed on plankton by continuously drawing water through their barrel-shaped bodies. Along with their food, they pull in viruses and other pathogens, so they need strong chemical defenses to fight off infectious organisms—and that makes them promising sources for medicines.

By 1990 PharmaMar had isolated a compound from the *A. albicans* specimen that was active against both cancer and virus cultures. PharmaMar pursued the cancer angle because cancer drugs tend to be more profitable than antivirals. After decades of research and testing, in 2018 Australia approved plitidepsin as a treatment for multiple myeloma.

When the COVID pandemic hit, company scientists quickly proved that plitidepsin was effective against SARS-CoV-2 in both laboratory cultures and mice, and it outperformed competing antivirals in preclinical, head-to-head trials. In 2020 PharmaMar launched a phase 1-2 clinical trial for hospitalized COVID patients that concluded in 2021. The results were dramatic: 74 percent of the patients with moderate disease recovered fully within a week of their first dose. The phase 3 trial is due to finish by December. In May, PharmaMar

virologist Jose Jimeno said plitidepsin appeared to be superior to other COVID antivirals. Its impact on Pedro R. L. was impressive; after two courses of treatment, his pneumonia and the rest of his symptoms had cleared completely.

Today, worldwide, there are 21 approved drugs that were sourced from the sea, most of them isolated from invertebrates. Another tunicate, *Ecteinascidia turbinata,* which attaches to submerged mangrove roots, yielded the molecular mixture that led to Yondelis, a sarcoma and ovarian cancer drug, and Zepzelca, which targets small-cell lung cancer. A black sponge that encrusts tidal pool rocks in southern Japan, *Halichondria okadai,* produced a drug, now marketed as Halaven, to treat late-stage breast cancer. And a venom peptide from a cone snail, *Conus magus,* led to Prialt, a chronic pain drug.

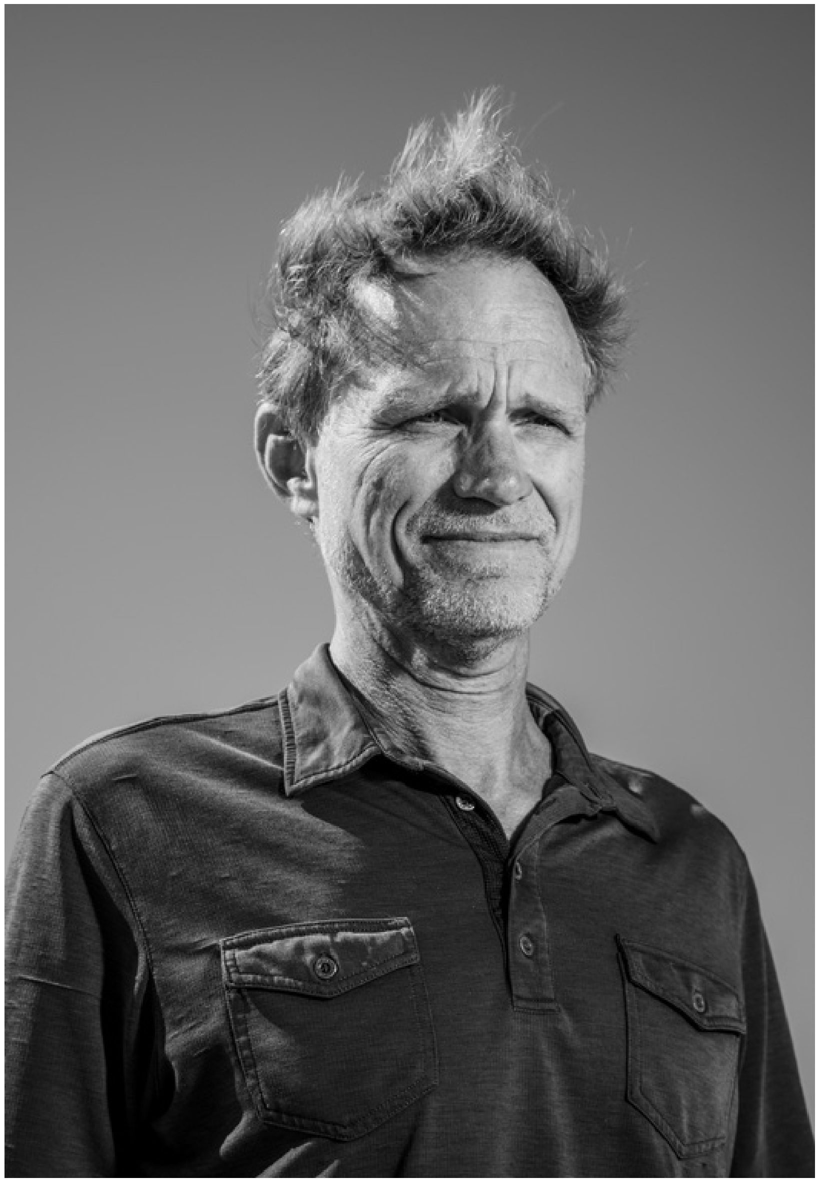
Corals, sea slugs, marine worms and mollusks have also yielded promising compounds. "For the past 600 million years these invertebrates have been living in this microbial soup that's like a petri dish," says marine ecologist Drew Harvell of Cornell University, explaining their need for robust defenses. An average liter of seawater contains about one billion bacteria and 10 billion viruses. Although scientists first assumed most marine invertebrates evolved their own weapons, they have learned over the past few decades that the majority of these defensive substances are actually produced by microbes

FREEZER RACKS house 18,000 microbe strains collected over 30 years. Scientists grow the strains in cultures, test their biological properties and may sequence their genomes looking for exploitable genes.

living symbiotically within the creatures' tissues. Last year, for instance, a team led by Samar Abdelrahman of the Georgia Institute of Technology tested five species of sea slugs from the Red Sea and found bacteria that produced antibacterial, antifungal and anticancer agents.

Drug discovery scientists—who for decades focused on land-based biology because it was more familiar and easier to access—now widely recognize that microbes, which dominate the ocean's biological diversity, are the most likely sources of marine-derived medicines. Of 23 new drugs currently in clinical trials, 16 are produced by microbes, and another four come from invertebrates that probably owe their resilience to symbiotic microbes. In recent years scientists have isolated thousands of promising compounds from marine microbes, the diversity of which reflects the vast variability of marine conditions. "On land, microbes dry out; they have trouble maintaining a fluid balance," Harvell says. "But the oceans are a much more permissive, welcoming environment."

Yet for most approved marine drugs, the process has taken decades, partly because of insufficient funding and partly because isolating, testing and producing large quantities of novel compounds is time-consuming. Fortunately, recent advances in genomics, chemistry and computation are enabling scientists to be more targeted and efficient in the search for lifesaving medicines from the sea.



GENE TARGETS

IN 1989 Paul Jensen brought sediments from the Bahamian seafloor back to his lab at the Scripps Institution of Oceanography to mine them for medically useful bacteria. It wasn't easy. His first challenge was to grow marine bacteria in lab conditions that are, at best, an approximation of those in the ocean. Then, when some species grew, he had to persuade them to produce at least a few of the molecules in their arsenal, even though they weren't subject to the same stimuli they would face in their natural environment.

Despite these hurdles, Jensen eventually discovered a new species of bacteria, *Salinispora tropica,* that produced a novel cancer-killing molecule. That compound, now marketed as marizomib, has just completed a phase 3 trial as a drug for glioblastoma, the deadly brain cancer that claimed the lives of John McCain and Beau Biden. It is currently awaiting approval from the Food and Drug Administration. Marizomib is a powerful example of the potential for marine bacteria to yield new medicines, but the process took more than three decades, motivating Jensen and others to look for better approaches.

By the early 2000s genomics had transformed their work. The first full genome sequences for marine microbes, including *S. tropica,* revealed that species that produced just a few compounds in lab cultures could usually make many more; some of them had dozens of compound-encoding gene clusters in their DNA. Within a few years metagenomics—the process of sequencing the DNA of entire communities of organisms in a sample—revealed still more hidden potential. Scientists started to find compound-encoding gene clusters in species they hadn't even cultured in the lab.

Today Jensen is also looking directly for molecules instead of the microbes that produce them. On four occasions over the past year, postdoctoral researchers on his team have waded into the seagrass beds off San Diego's Point Loma peninsula to submerge sheets of tiny, absorbent beads, called resins, that pull organic molecules out of seawater. Back in the lab, Jensen analyzes the samples for bioactive compounds—chemicals that can act on a living organism.

He already has a hit: a compound with an unusual carbon skeleton that includes a group of enzyme-reactive molecules Jensen thinks could act "as something like a warhead." This novel structure might function very differently than existing medicines do. "I think it's

going to kill cells," Jensen predicts. "Now we're hoping to get a sense of what its target might be."

Next, he will need to match the compound to its producer. Enormous databases of marine microbial genomes and bioactive compounds, along with the computing power necessary to correlate them, are enabling scientists to link chemicals to genes efficiently. Katherine Duncan, a marine microbial chemist at the University of Strathclyde in Glasgow, is a pioneer of this approach, which she calls pattern-based genome mining. The technique has become possible only recently. "We just haven't had the tools to compare data sets of this size," she says.

Duncan is now using this technique to analyze dark sediment cores pulled from the ocean floor 4,000 to 4,500 meters deep off the coast of Antarctica. The early results are tantalizing: The samples include at least two new species of marine bacteria, *Pseudonocardia abyssalis* and *Pseudonocardia oceani,* that produce antimicrobial compounds. On land, members of the same genus live symbiotically with fungus-growing ants, producing antibacterial and antifungal molecules that deter pathogens from invading the ants' fungal gardens. It's not a stretch to imagine that the marine cousins could yield anti-infective drugs.

One of the greatest challenges scientists such as Duncan and Jensen face is figuring out which molecular discoveries warrant the most attention. Nadine Ziemert, a microbiologist at the University of Tübingen in Germany, has developed a tool to help researchers mine genomes in a more targeted way by looking for resistance genes. Any organism that produces a toxic molecule must have some mechanism for protecting itself from its own weapon—usually by making a modified copy of the toxin's cellular target that can resist its attack.

PAUL JENSEN (*left*) has been investigating ocean compounds for potential drugs for decades. A researcher from his lab (*right*) dips a sheet studded with absorbent resin beads that can pull organic molecules out of seawater.

Ziemert's tool, called the Antibiotic Resistant Target Seeker, allows researchers to access a database of more than 10,000 bacterial genomes—or upload their own—and run a search for resistance genes related to specific cell functions. The database will become more valuable as it grows, especially as researchers accelerate their work to sequence the genomes of species from extreme, underexplored environments. Ziemert's target seeker has shown such promise that start-up company Hexagon Bio has built a similar tool to mine fungus genomes for promising compounds.

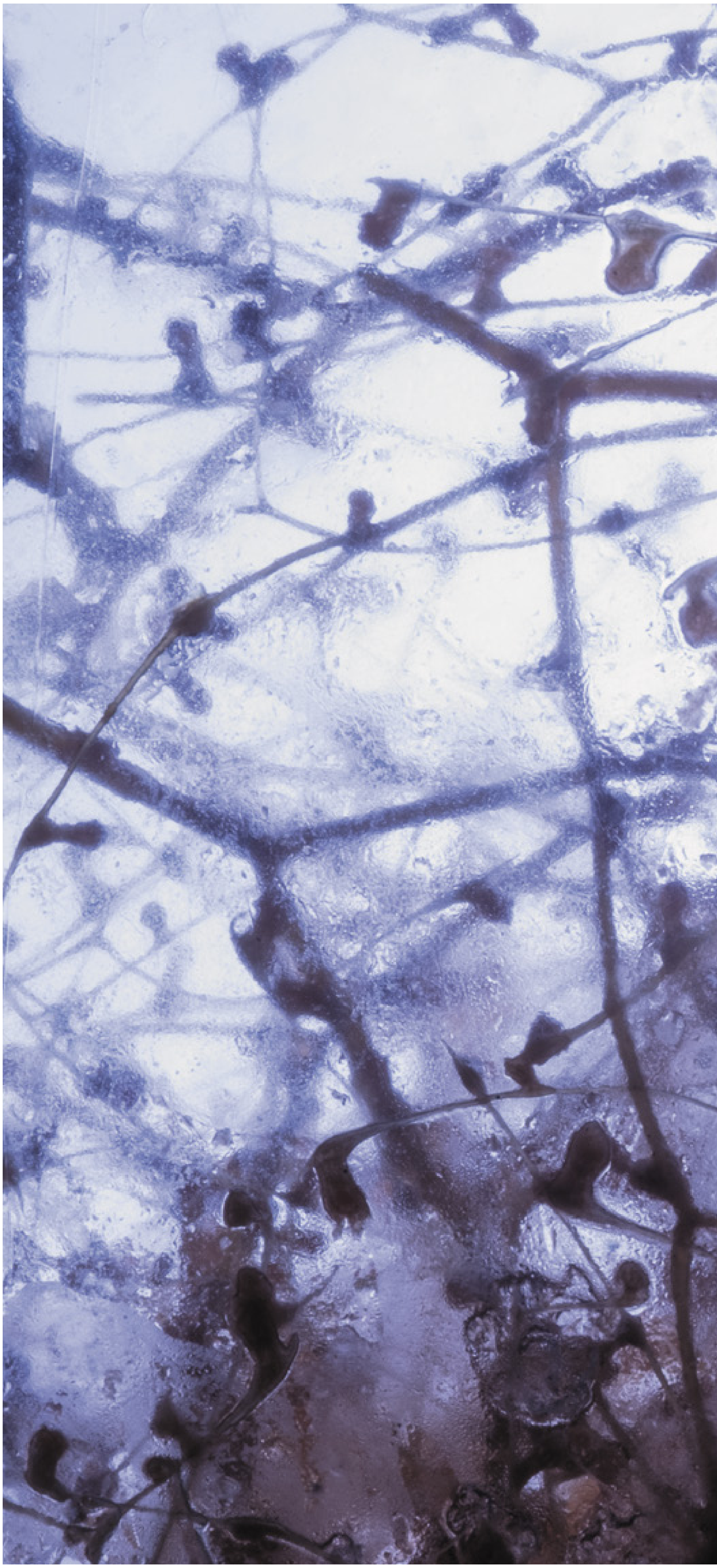
NEW ANTIBIOTICS

TARGETED GENOME MINING couldn't come at a better time. The COVID pandemic has highlighted the need for a deeper pool of drugs to treat emerging infectious diseases. There is also a desperate need for new drugs to treat established diseases. Many bacterial infections, including pneumonia, tuberculosis, gonorrhea, blood poisoning and various foodborne diseases, have become harder—and in some cases, impossible—to treat because of rising microbial resistance to antibiotics. Public health officials widely recognize antibiotic resistance as one of the gravest threats facing humanity.

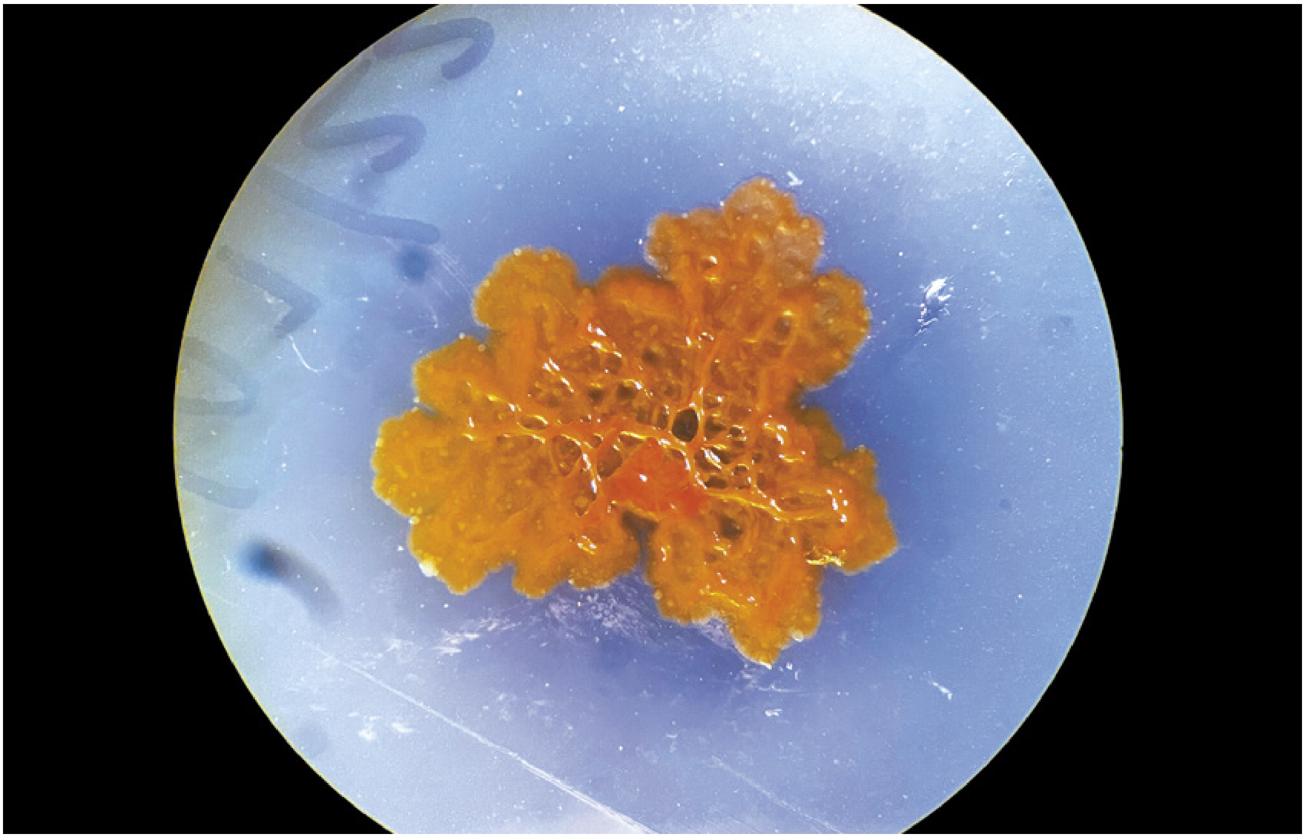
Because almost all antibiotics come from terrestrial microbes, it seems clear that marine microbes, which are greatly understudied, hold the potential to address this crisis. University of Sydney chemist Richard Payne is particularly excited about their ability to treat tuberculosis, caused by *Mycobacterium tuberculosis*. "Over the last 10 years TB has been the greatest killer among infectious diseases," Payne says, "and with all the efforts that have gone to COVID, we've gone backward with our control of TB." An antibiotic that targets a different TB protein than past drugs is needed.

That's exactly what Payne found in a bacterium from Shinyang Beach on Jeju Island, South Korea, a horseshoe of white sand on a small peninsula best known for its ideal windsurfing and kitesurfing conditions. The compound, ohmyungsamycin A, prevents *M. tuberculosis* from properly disposing of its waste proteins, ultimately killing the cell. And when Payne created a set of chemical analogs—slightly altered, chemically synthesized molecules that could be produced in volume—one of them was so potent that it completely sterilized a lab-grown tuberculosis colony in three days. The drug has already proved effective in infected zebra fish and is moving on to trials in mice.

Finding and developing new antibiotics have largely fallen to academics in recent decades because the drugs sell at such low prices that pharmaceutical companies lack the financial incentive to pursue them. The same math applies to treatments for many neglected tropical diseases, including malaria. In 2012 Scripps chemist William Gerwick isolated a molecule called carmaphycin B from a tuft of cyanobacteria growing on a boat's mooring line in a Curaçao harbor. He chemically synthesized a set of analogs that he tested against cancer cells, a frequent first line of research.



A MARINE invertebrate recently captured by a submersible in the deep sea off southern California (2,500 meters down) remains frozen, waiting to be identified.



SALINISPORA bacteria from the sea, cultured in a lab dish, produce a cancer-killing molecule marketed as marizomib that has just completed phase 3 trials as a drug for glioblastoma, a deadly brain cancer.

The results were not spectacular, so Gerwick turned his attention to other projects. Recently, however, a colleague suggested that they test his analogs on malaria parasites, and this time the outcome was striking. "One of them was exquisitely reactive against malaria," Gerwick says. Moreover, it wasn't toxic to human cells.

Gerwick now has funding to explore carmaphycin B as a new antimalarial drug. Whether or not it eventually becomes an approved medicine, the discovery is a reminder about the possibilities stored in the thousands of bioactive marine compounds scientists have already identified.

Carmaphycin B is also a reminder that technological advances alone won't deliver new drugs; serendipity and a willingness to capitalize on it are often required. On the day that Gerwick's former student Joshawna Nunnery collected the cyanobacteria from the mooring line, she was supposed to be diving elsewhere. But when her lab mate and diving partner contracted dengue fever, she had to cancel those plans and resorted to snorkeling near the research station instead.

Opportunities to capitalize on such serendipity are increasing as investment in ocean exploration grows. On a recent expedition to the central Pacific Ocean's Phoenix Islands archipelago onboard the Schmidt Ocean Institute's research vessel, *Falkor,* Anna Gauthier became one of the first scientists to sample deep-sea bacteria from the islands. Gauthier, a doctoral student at Harvard University, planned to conduct immune response experiments during the expedition, so she didn't immediately freeze bacteria she pulled from the sea, which is the usual practice. Instead she started culturing the organisms onboard the ship.

The technique provided an unintended benefit: survivorship was far higher than in traditional, lab-based cultures of defrosted specimens. Eighty percent of the bacteria she grew were so different from those typically encountered by mammals that they didn't trigger an immune response from mammalian cells. The finding, though still far from leading to a medical advance, has tantalizing potential for immunotherapies and vaccines.

The promise of new lifesaving medicines, paired with rising public health crises, offers tremendous motivation for scientists such as Duncan in Glasgow. "I know people who have been on last-line antibiotics and were resistant," she says. "My grandma died from sepsis. Everyone has stories like that."

Duncan hopes those stories may change within the next decade. "The marine environment is hugely undiscovered," she marvels. The next plitidepsin is out there in the ocean. It might already be in a lab. SA

FROM OUR ARCHIVES

Can We Save the Corals? Rebecca Albright; January 2018.

scientificamerican.com/magazine/sa

DYNAMIC SEAS

How the ocean organizes itself

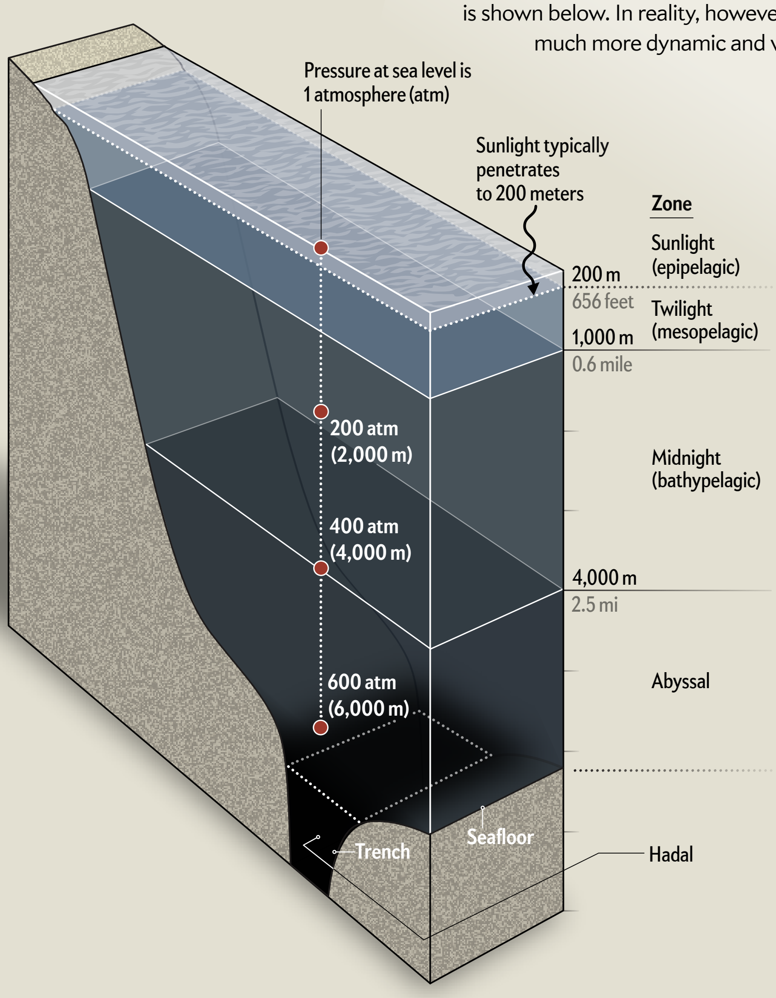
Editor: Mark Fischetti

Graphics: Skye Moret and Jen Christiansen

Consultant: Kelly J. Benoit-Bird, Science Chair, Monterey Bay Aquarium Research Institute

THE CLASSIC PROFILE

Numerous diagrams depict the ocean as a layer cake made up of five standard zones that are defined by depth and are uniform worldwide. The typical cross section, which is admittedly handy, is shown below. In reality, however, the ocean is much more dynamic and varied.

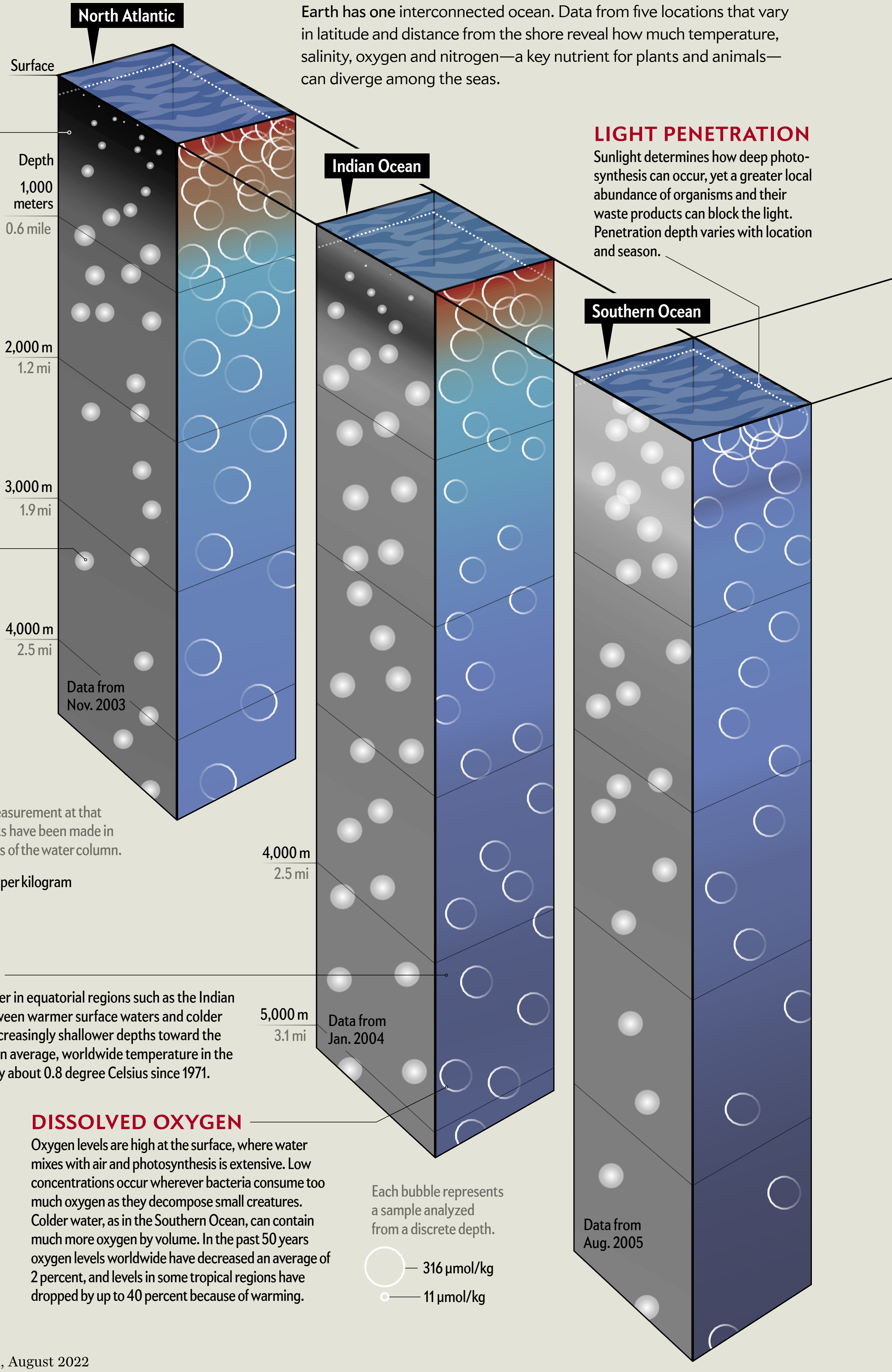


SEARCH "OCEAN ZONES" ONLINE, AND YOU will see hundreds of illustrations that depict the same vertical profile of the sea. The thin, top layer is the "sunlight" or epipelagic zone, which receives enough light for photosynthesis by phytoplankton, algae and some bacteria. Below it is the twilight zone, where the light fades but is still strong enough for some animals to see by and where many animals make their own light through bioluminescence. Next is the midnight zone, with no measurable light, followed by the relentlessly cold abyss. Finally, there are the incredibly deep seafloor trenches known as the hadal zone, named after Hades, Greek god of the underworld.

In this classic view, the amount of light and the water pressure—which increases steadily with depth—largely define which creatures live where. Those factors are important, but so are water temperature, salinity, amounts of oxygen and nitrogen, and the changing currents. Data collected worldwide have revealed that ocean dynamics, and ocean life, are far more complex than we thought, surprising us again and again as we explore.

A New View of the Sea

Earth has one interconnected ocean. Data from five locations that vary in latitude and distance from the shore reveal how much temperature, salinity, oxygen and nitrogen—a key nutrient for plants and animals—can diverge among the seas.



SALINITY

The North Atlantic is the saltiest ocean, particularly near the surface. Trade winds carry away evaporating moisture, and there are influxes of very salty water from the Mediterranean Sea and from the Arctic, where salt is left behind when water freezes.

Salinity, in practical salinity units (psu)

33.2 Low — 36.7 High

NITROGEN

Surface water tends to be low in nitrogen because the element is consumed by the many photosynthesizing phytoplankton there. In the Southern Ocean, water that is more uniformly dense from top to bottom helps to distribute nitrogen evenly.

Each sphere indicates a measurement at that depth; more measurements have been made in the top few hundred meters of the water column.

42.7 micromoles per kilogram

0.04 µmol/kg

TEMPERATURE

Warm water reaches deeper in equatorial regions such as the Indian Ocean. The transition between warmer surface waters and colder deep waters happens at increasingly shallower depths toward the poles (Southern Ocean). On average, worldwide temperature in the top 700 meters has risen by about 0.8 degree Celsius since 1971.

0.5°C 32.9°F Cold — 26.1°C 79.0°F Hot

LIGHT PENETRATION

Sunlight determines how deep photosynthesis can occur, yet a greater local abundance of organisms and their waste products can block the light. Penetration depth varies with location and season.

DISSOLVED OXYGEN

Oxygen levels are high at the surface, where water mixes with air and photosynthesis is extensive. Low concentrations occur wherever bacteria consume too much oxygen as they decompose small creatures. Colder water, as in the Southern Ocean, can contain much more oxygen by volume. In the past 50 years oxygen levels worldwide have decreased an average of 2 percent, and levels in some tropical regions have dropped by up to 40 percent because of warming.

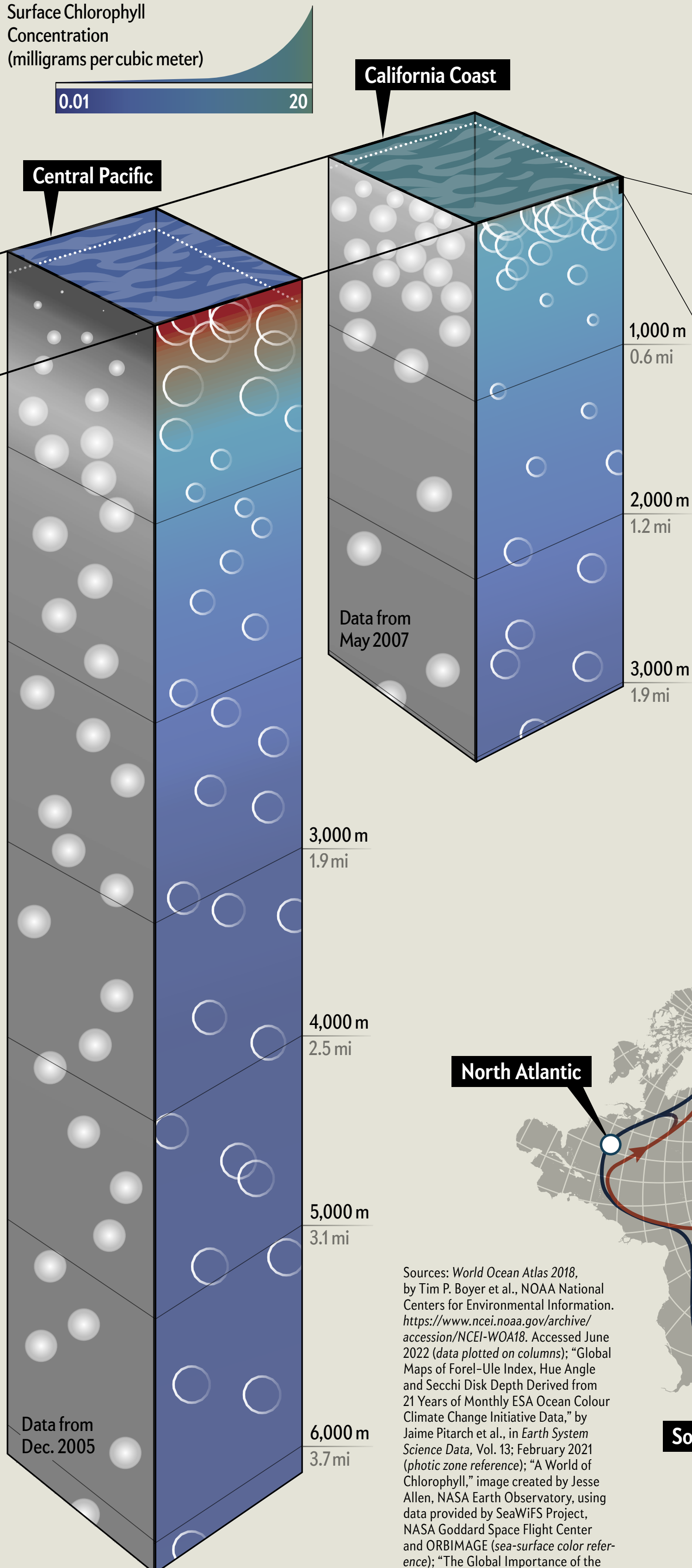
Each bubble represents a sample analyzed from a discrete depth.

316 µmol/kg

11 µmol/kg

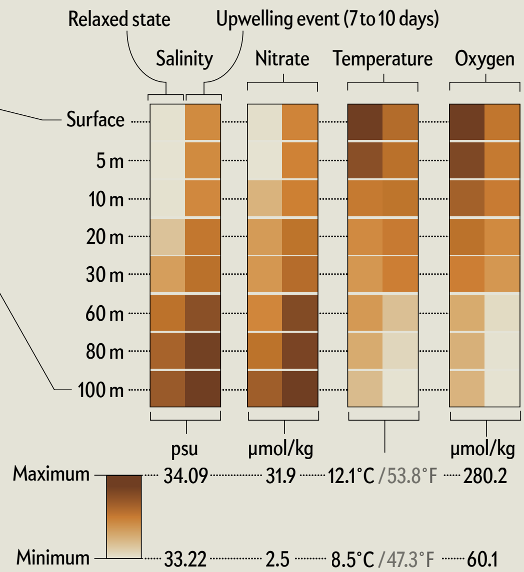
SURFACE COLOR

“Aqua blue” is an appealing vision, but the ocean’s surface color varies quite a bit globally. A greater concentration of phytoplankton full of chlorophyll, for example, adds more green. And the more biologically productive a region is, the less clear the water.



UPWELLING

The ocean varies in time as well as space. On the western coasts of continents, steady winds along the shore, in combination with Earth’s rotation, can push surface water out to sea, letting deep water rise. This “upwelling” along California’s coast brings cold water rich in nutrients such as nitrate to the surface, where it fuels phytoplankton blooms, which consume oxygen. The winds tend to last for seven to 10 days before relaxing, allowing surface water to warm again.

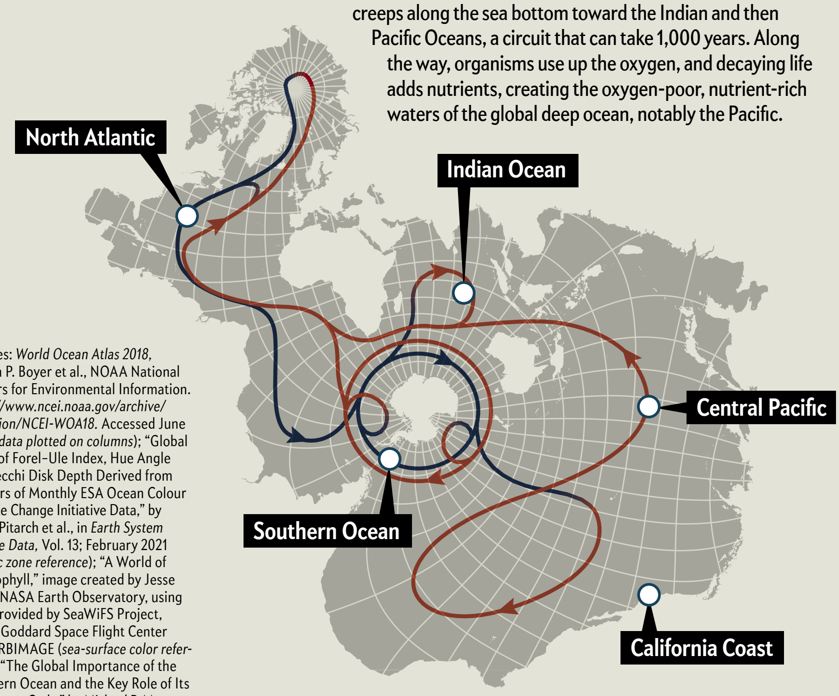


THRIVING LIFE

Water deeper than the sunlight zone accounts for more than 90 percent of Earth’s living space. It is home to the largest animal communities on the planet—largest in biomass and in numbers of individuals. Scientists estimate that the dark seas may hold a million undescribed species.

CONVEYOR BELT

Gigantic masses of water with the same density slowly circulate along an established route. Cold, salty water near the North Atlantic surface—rich in oxygen but low in nutrients—sinks and creeps along the sea bottom toward the Indian and then Pacific Oceans, a circuit that can take 1,000 years. Along the way, organisms use up the oxygen, and decaying life adds nutrients, creating the oxygen-poor, nutrient-rich waters of the global deep ocean, notably the Pacific.



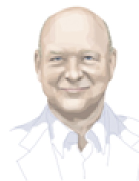
Sources: *World Ocean Atlas 2018*, by Tim P. Boyer et al., NOAA National Centers for Environmental Information. *https://www.ncei.noaa.gov/archive/accession/NCEI-WOA18*. Accessed June 2022 (*data plotted on columns*); “Global Maps of Forel-Ule Index, Hue Angle and Secchi Disk Depth Derived from 21 Years of Monthly ESA Ocean Colour Climate Change Initiative Data,” by Jaime Pitarch et al., in *Earth System Science Data*, Vol. 13; February 2021 (*photic zone reference*); “A World of Chlorophyll,” image created by Jesse Allen, NASA Earth Observatory, using data provided by SeaWiFS Project, NASA Goddard Space Flight Center and ORBIMAGE (*sea-surface color reference*); “The Global Importance of the Southern Ocean and the Key Role of Its Freshwater Cycle,” by Michael P. Meredith, in *Ocean Challenge*, Vol. 23; 2019 (*global ocean conveyor belt reference*)

DIVE KINGS

King penguins nest in massive colonies—sometimes with hundreds of thousands of birds—on sub-Antarctic islands. They do not build nests. Instead they keep each egg warm on the top of their feet. The males take the first incubation shift, which can last for weeks, while the females venture to the sea for a well-earned meal. Measuring about three feet tall, the kings are the second-largest of all penguins, eclipsed only by the emperors.

Tui De Roy/Minden Pictures

Timothy Shank is a biologist, director of the Molecular Ecology and Evolution Lab at Woods Hole Oceanographic Institution, and co-leader of the Deep-Ocean Genomes Project.



TURNING THE TIDE

Discoveries keep revising our long-held views of life

By Timothy Shank

FOR MORE THAN 50 YEARS DEEP-SEA EXPLORATION HAS BEEN A CONTINUOUS FOUNT OF DISCOVERIES that change how we think about life in the ocean, on dry land and even beyond our planet. Consider the following three events.

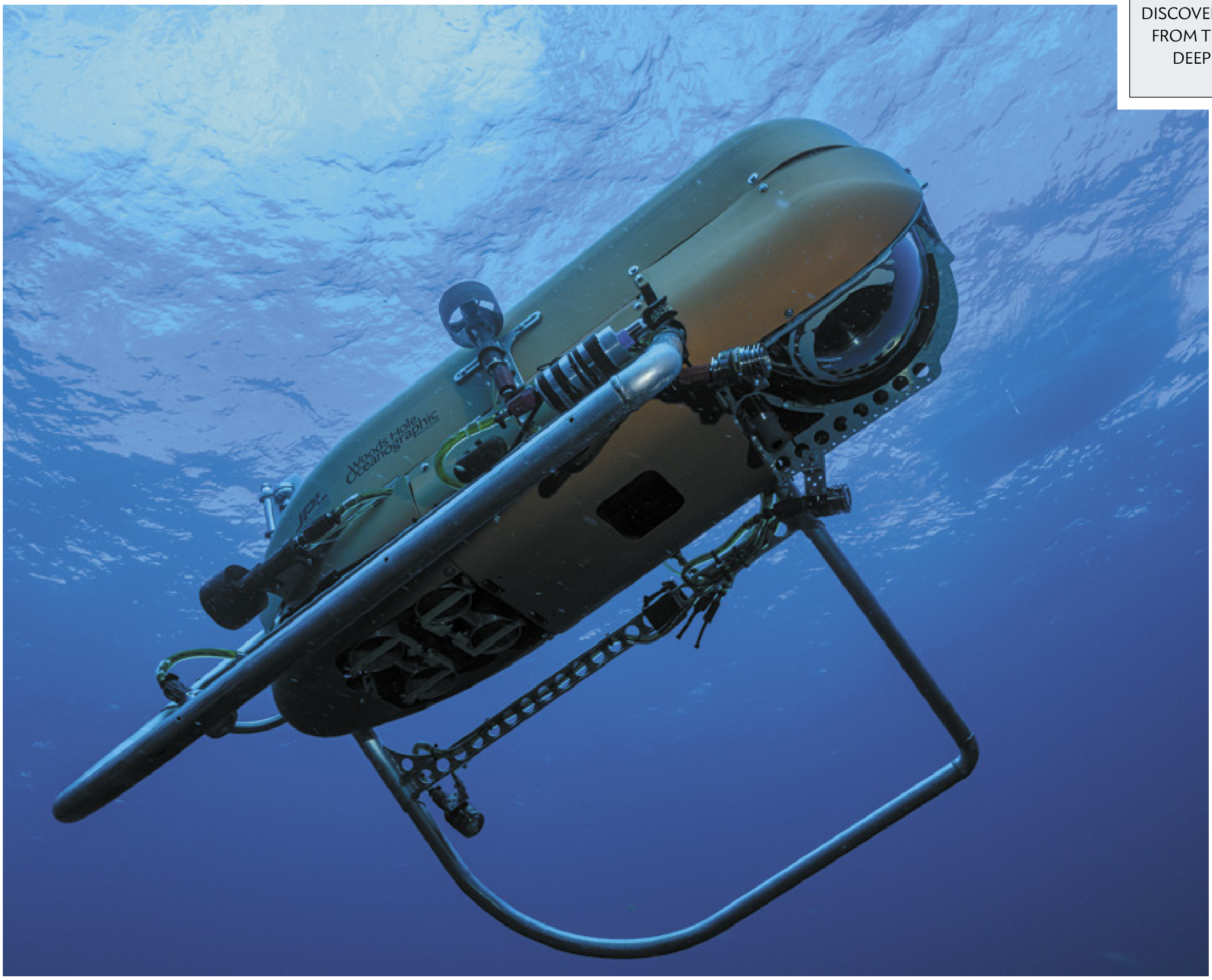
On October 16, 1968, a cable tethering the submersible *Alvin* to a research ship located 100 miles off Nantucket broke. The sub sank to the seafloor more than 5,000 feet below; the crew of three escaped safely. Nearly a year later, when a team brought *Alvin* back to the surface, the biggest surprise was that the crew's lunch—bologna sandwiches and apples in a plastic box—was strikingly well preserved. Bacteriological and biochemical assays proved it. Someone even took a bite. Subsequent experiments in the Woods Hole Oceanographic Institution laboratory where I'm writing this article found that rates of microbial degradation in the retrieved samples were 10 to 100 times slower than expected. This discovery, and others, led to the conclusion that metabolic and growth rates among deep-sea organisms were much slower than those of comparable species at the ocean's surface.

In 1977 scientists diving in the restored *Alvin* made another historic discovery—the first in-person observations of life around hot, hydrothermal vents rising from the seafloor. This sighting overturned the long-held view that our entire planetary food web was built on photosynthesis—using sunlight's energy to convert carbon dioxide and water into complex carbohydrates and oxygen. The hydrothermal organisms, and the entire ecosystem, thrived in pure darkness, converting chemicals in the vent fluid into life-sustaining compounds through a process we now call chemosynthesis.

If that revelation wasn't surprising enough, an expedition I was part of in 1993 exposed an earlier mistaken belief. We had discovered a significant hydrothermal vent ecosystem on the East Pacific Rise. The system had been destroyed by a seafloor eruption just a few years earlier, yet it had already been bountifully recolonized. A bologna sandwich might decay so slowly in the deep that you could eat it a year later, but it turned out that biological processes in the deep sea could be extremely fast as well.

Each new ocean discovery that disrupts old dogma reinforces a much larger truth: the ocean is far more complex—and much more intertwined with our own lives—than we ever imagined. For much of the 20th century, for example, scientists maintained that the deep ocean was a harsh, monotonous place of perpetual darkness, frigid temperatures, limited food and extreme pressure—conditions that should make complex forms of life impossible. But new tools for observing, sensing and sampling the deep ocean, such as increasingly sophisticated underwater vehicles with high-definition camera systems, have demonstrated that biodiversity in the darkest depths may rival that of rain forests and tropical coral reefs. These missions have further revealed that the depths are far from uniform; like kangaroo habitat in Australia and tiger lands in Asia, they are home to evolutionarily distinct biogeographic regions.

We are beginning to appreciate how connected these realms are to our own. The rapid three-dimensional change of conditions such as temperature, salinity and oxygen concentration in the deep ocean and the currents and eddies that establish the boundaries of these provinces are expected to fundamentally change as the effects of human activity reach ever farther below



THE ORPHEUS from the Woods Hole Oceanographic Institution is designed to maneuver autonomously and in swarms of vehicles at the deepest depths and to land to collect samples on the fly.

Evan Kovacs/© Woods Hole Oceanographic Institution

the surface. Already lobsters are moving to deeper, colder waters and molting at different times of the year. Commercially important groundfish such as cod and haddock are migrating poleward in search of more suitable habitat.

We are seeing that the ocean's biogeographic boundaries are neither immutable nor beyond the imprint of humans. In studies, more than half of sampled hadal organisms—those living in the deepest parts of the ocean, beyond 20,000 feet—had plastics in their gut. PCBs, which were banned in the U.S. in 1979 and phased out internationally as part of the Stockholm Convention beginning in 2001, are also common in tissues of animals from the extreme bottoms of the sea.

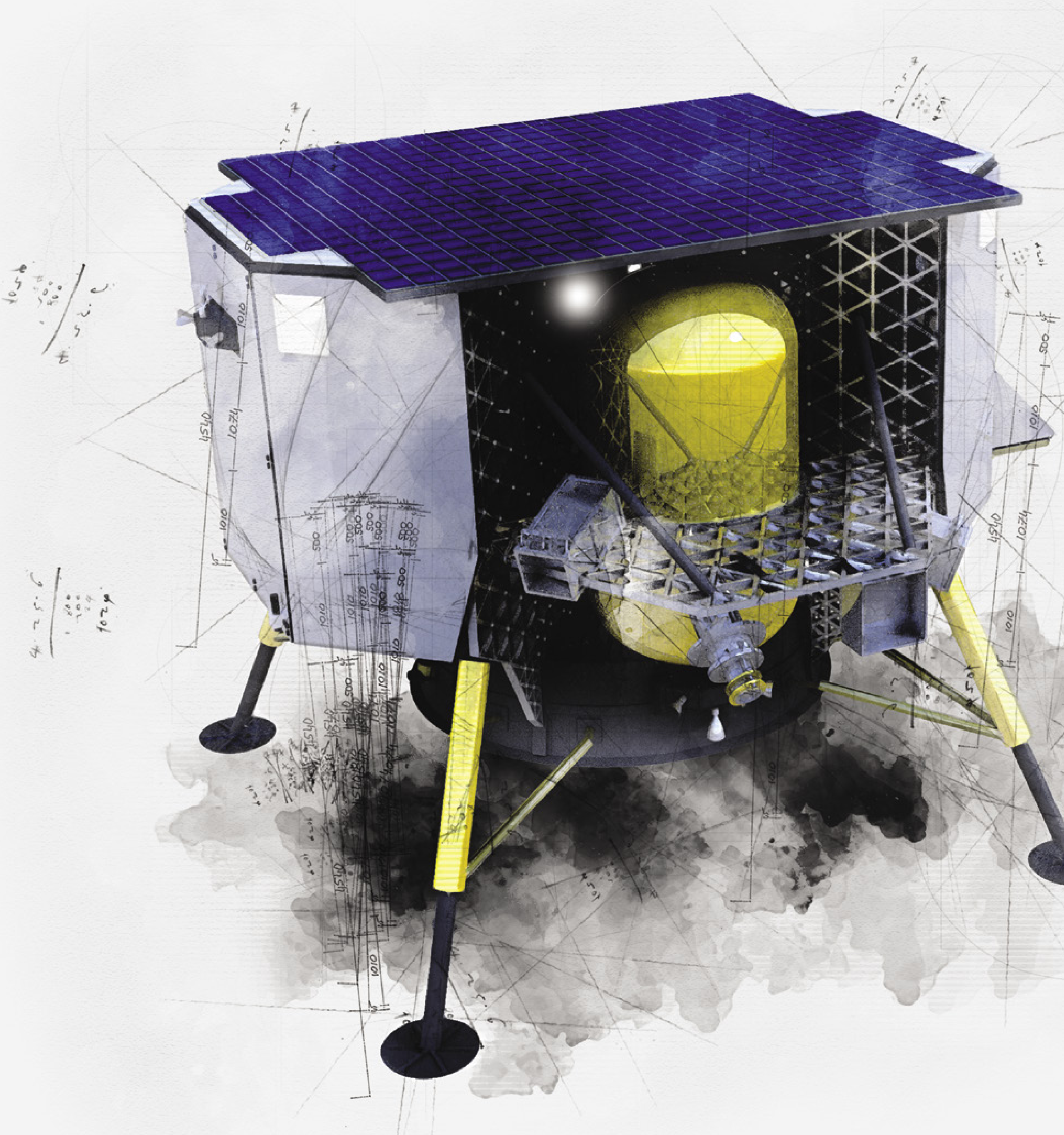
We are also starting to learn that life in the deep might have things to teach us. Deep-sea fish produce biomolecules called osmolytes that permit cellular functions, such as the precise folding and unfolding of proteins, to proceed unimpeded by crushing water-column pressures exceeding 15,000 pounds per square inch. Medical researchers have determined that some of these molecules could help treat Alzheimer's disease, which is characterized by misfolded proteins. In addition, decoding the genes that govern traits we see in deep-sea animals, such as those that stave off errors in DNA replication, transcription and translation, might be used in therapies for cancer and other afflictions.

The greatest paradigm that ocean exploration may tear down is that Earth represents the sole example of life in the universe. Life might have existed on Mars when it hosted liquid water, and the fact that Earth and Mars have shared ejected material in the past means we could have exchanged the building blocks of life. But the discovery of chemosynthetic life on Earth and the more recent finding of perhaps 13 liquid-water oceans underneath the icy shells of moons such as Jupiter's Europa and Saturn's Enceladus—places that may have been too distant to have shared life-bearing material with Earth in the past—raise the possibility of a second, independent genesis of life. And if life can form twice in one solar system, then it could be anywhere we look in the heavens. SA

FROM OUR ARCHIVES

Team Players. Jeffrey Marlow and Rogier Braakman; November 2018.

scientificamerican.com/magazine/sa



ASTROBOTIC'S Peregrine lander is due to launch to the moon by the end of 2022. It will carry a mix of science experiments and private payloads.

The New Race to the Moon

Commercial spacecraft are vying to land on the lunar surface, but can they kick-start a new space economy?

By Rebecca Boyle

Illustrations by Don Foley

Rebecca Boyle is an award-winning freelance journalist in Colorado. Her forthcoming book *Walking with the Moon: Uncovering the Secrets It Holds to Our Past and Our Future* (Random House) will explore Earth's relationship with its satellite throughout history.

ONE DAY LAST DECEMBER, JOHN WALKER MOOSBRUGGER, A 25-YEAR-OLD project manager for the lunar robotics start-up Astrobotic, sat in front of the company's clean room and watched as an instrument older than him was attached to a moon lander. The vehicle, called Peregrine, was a four-legged, foil-wrapped canister as big as a hot tub. The instrument—Surface and Exosphere Alterations by Landers, or SEAL—was a shoebox-sized sensor designed to study how a spacecraft's landing disturbs moon dust. Peregrine is scheduled to launch later this year—and it is just one of many missions that private companies are scrambling to send up after years of preparation. Since its founding in 2007 as a scrappy competitor for the now defunct Google Lunar XPRIZE, Astrobotic had been working on its lander and signing deals with companies that wanted to put instruments on it, planning for a launch eventually. But in 2018 NASA came calling with a funding scheme that would turn Astrobotic into one of several moon ferries by the middle of this decade. Since then, Walker has been readying payloads like SEAL. "All of a sudden, in late October, [NASA representatives] started showing up," Walker says. "Everything got very real."

Sometime in the next four or five months, the first American moon missions in half a century will make a return to Earth's satellite. The arrivals won't be human—at least not yet—and they won't even be government-built. The coming lunar fleet will consist of private spacecraft carrying science experiments and other cargo for paying customers, including NASA. Astrobotic's Peregrine lander is due to ride on United Launch Alliance's new Vulcan Centaur rocket, scheduled to make its inaugural voyage before the end of 2022. Competing lunar start-up Intuitive Machines is set to launch its lunar lander, Nova-C, on a SpaceX Falcon 9 rocket, also by the end of this year. A dozen more firms are expected to follow in the next six years, carrying cargo that ranges from a magnetometer and supplies for a future lunar base camp to small amounts of cremated human remains.

These will be just the latest firsts in a gradual ramping up of the commercial space economy. SpaceX launched its first rocket in 2006, and since 2012 it and other private companies such as Northrop Grumman have been flying cargo to the International Space Station—and more lately, crew. In 2021 the long-delayed era of regular private space tourism arrived as billionaires and celebrity customers started riding rockets into near-Earth space.

But going to the moon is a much taller order. Rockets that can reach the moon must burn more fuel than normal launches to escape Earth's orbit and enter a lunar trajectory, and the journey takes about three days, as opposed to a few minutes to reach Earth orbit. Although companies such as SpaceX have plans for crewed ships to the moon, none have made it past the prototype phase, so for now the new moon race is being pioneered by small companies such as Astrobotic.

NASA has not gotten out of the spacecraft business; its Artemis program, a sister to the Apollo missions, aims to return humans to the lunar surface by 2025. The agency has been working on its own new moon rocket, the Space Launch System, since 2011, and scientists still plan new missions under its planetary exploration programs. But outsourcing these smaller, near-term missions to industry is part of NASA's modern strategy of paying private companies to take on some of the load. NASA officials say a commercial lunar market will increase competition, drive down prices and ensure people will keep going back to the moon regardless of who occupies the White House. For their part, the companies hope that their NASA-subsidized cargo deliveries will jump-start a new economic boom, the way the transcontinental railroad spurred Western development in 19th-century America. This time the rush would be for moon metals, water and helium—materials that could become precious if rockets were to start launching out into the solar system from a lunar base station.

In the meantime, science missions that have been lingering for years or otherwise had little chance of reaching space are poised to make it to the moon. The SEAL instrument, for example, is a spare copy of one built in 1996 for a different mission. It didn't fly then, but now, thanks to this private-public moon rush, it should get its chance.

Lunar scientists are watching this activity with a mixture of skepticism and hope. "I'm still pretty early in my career, and this is the second or third time I've been told we're going back to the moon," says Angela Stickle, a planetary scientist at Johns Hopkins University's Applied Physics Laboratory. "But I think it is real this time. The launches are on the books, they've been paid for, and that's something we've never had before."

Of course, the sustainability of any private enterprise depends on making money, and the prospects for a gold rush on the moon are still speculative. Is there really a lasting market for commercial lunar landers? That depends on who you ask—and on what the new fleet of robots is able to pull off.

PRIVATE MOON MISSIONS ARE ARGUABLY THE INEVITABLE NEXT STEP IN a process that NASA set in motion 17 years ago, with the creation of the Commercial Orbital Transportation Services (COTS) program. COTS was NASA's plan to pay private companies to develop ships that could fly to the space station after the retirement of the space shuttles. NASA spent $500 million over five years to help SpaceX and Orbital Sciences develop new rockets and cargo ships. The program was a success, leading to new reusable launchers and vehicles that reliably bring supplies to the space station. SpaceX has since completed 156 launches of Falcon 9 rockets, developed with NASA seed money, and in 2020 the company began flying human astronauts to the station, too.

The commercial cargo program's legacy may have been on Thomas Zurbuchen's mind in December 2017, when the Trump administration announced a program aimed at returning to the moon. Trump wanted to send astronauts there by 2024, and Zurbuchen, the astrophysicist in charge of NASA's science mission directorate, saw an opportunity to add to NASA's science budget at the same time. He began asking, "Whatever happened to the companies that competed in the ill-fated Google Lunar XPRIZE?"

The competition, which Google and the XPRIZE Foundation created in 2007, would have awarded $20 million to the first privately financed moon lander. The program ended after a decade without a winner; getting to the moon was just too difficult and expensive to make the comparatively meager purse worthwhile. One former competitor, an Israeli start-up called SpaceIL, eventually made it to the moon, albeit with an unplanned crash landing in April 2019. But in vying for the prize, several companies had built lander prototypes and rovers that could theoretically deliver all kinds of cargo to the moon, in some cases much more cheaply than a traditional NASA mission. They included Astrobotic, another outfit called Moon Express, and even smaller firms such as Micro-Space. After the competition ended, many of these companies continued working on their landers, rovers and instruments, in Astrobotic's case even lining up customers for eventual trips.

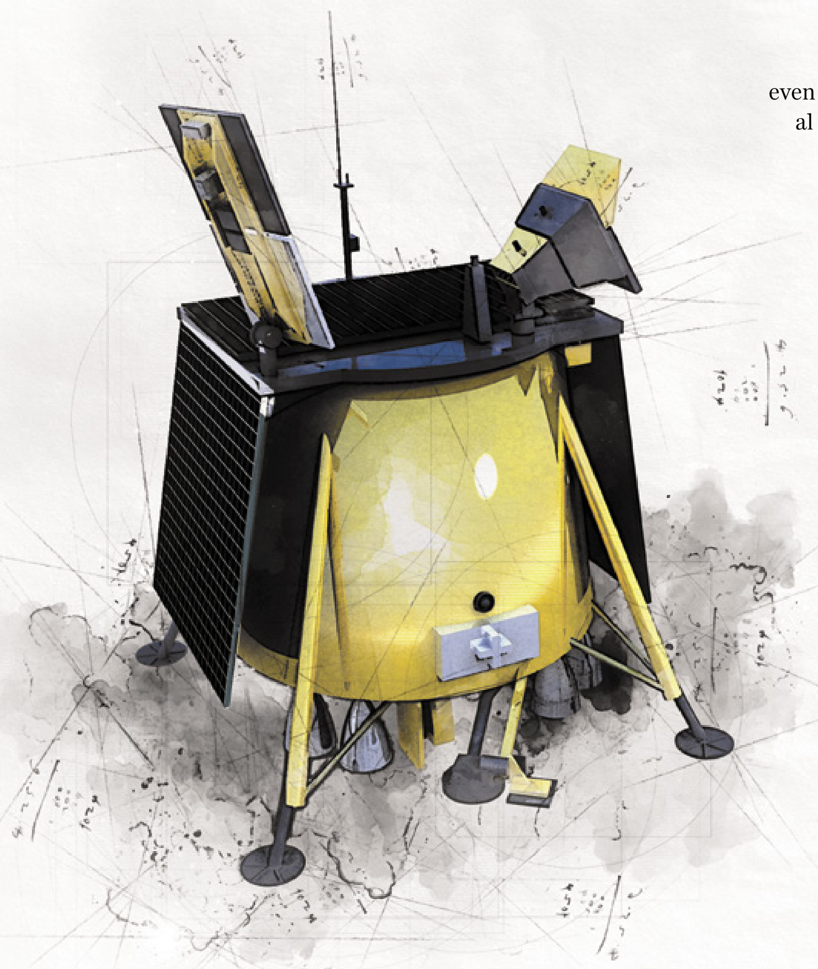
Eyeing those companies and the success of COTS, NASA created the $2.6-billion Commercial Lunar Payload Services (CLPS) program in 2018, arguing that a high-risk, high-reward scheme would enable more science for NASA's dollar while encouraging a fledgling lunar marketplace to take off. Under CLPS—usually called "clips"—NASA pays private companies to build landers, rovers and other instruments and to carry science experiments on them. This time, Zurbuchen figured, the odds were probably better than in 2007: lunar technology was more advanced, and there were more rockets capable of making the trip to the moon.

Geopolitics also helped CLPS get off the ground. Zurbuchen was able to secure that $2.6 billion in part because of Trump's moon ambitions and in part because of American fears of China's rise in space. In December 2020 a Chinese lander and rover arrived at the moon's south pole, collecting samples that were later returned to Earth. "We have every reason to believe that we have a very aggressive competitor in the Chinese, going back to the moon with taikonauts," NASA administrator Bill Nelson said in November 2021, referring to Chinese astronauts. "And it's the position of NASA, and I believe the United States government, that we want to be there first." Suddenly, Lunar XPRIZE competitors such as Astrobotic were back in the game, carrying the fire for American space interests. "In 2018 there was a Chinese lunar mission and zero U.S. lander missions on contract," says Dan Hendrickson, vice president of business development at Astrobotic. "Fast-forward to 2021: there are now seven American lunar lander contracts in place. It's a sea change."

NASA missions typically fall into one of three classes. Flagship missions such as the Mars rovers or the James Webb Space Telescope take up the most money and the most attention. They are usually decades-long, multibillion-dollar projects run by teams of scientists and engineers from across the space agency and university partners. Missions that are slightly smaller fall into a class called New Frontiers, and they are capped at $850 million. The Discovery missions are the leanest, with a cost cap of $450 million. Launching any of these missions requires years of planning and preparation, and not every mission is chosen; scientists may try for a good portion of their career before landing a Discovery mission or getting an instrument on a New Frontiers spacecraft.

The CLPS program is different. A single commercial lander might carry a dozen payloads that have nothing to do with one another. Scientists who would otherwise spend years preparing a Discovery mission proposal could instead submit a simple science instrument for a CLPS mission, meaning faster scientific return for less money. "You don't have to spend 15 years building a spacecraft when you can do it in two," Stickle says.

As of April 2022, CLPS had awarded contracts for seven deliveries from four companies: Astrobotic, Intuitive Machines, Firefly Aerospace and Masten Space Systems. Astrobotic's Pere-



FIREFLY AEROSPACE hopes its Blue Ghost spacecraft will be among the first private vehicles to reach the moon.

grine and two Intuitive Machines Nova-C landers are up first, scheduled to launch in late 2022.

"We went from 50 years of nothing going to the moon to seven deliveries scheduled over the next three and a half years," Chris Culbert, who manages the CLPS program at the NASA Johnson Space Center, said at a panel discussion in November 2021.

EXPERIMENTS WON'T BE THE ONLY CARGO ON THE FIRST PRIVATE LUNAR missions. Astrobotic's manifest includes items from, among others, the Mexican Space Agency, which is launching the first lunar instruments from Latin America; a Japanese company called Astroscale, sending a time capsule of messages from children around the world; and two firms promising to fly cremated human remains to the lunar surface on behalf of family members who want a celestial send-off for their loved one.

But if the missions land safely, they will also pull off a lot of science, possibly answering some of the most urgent questions we still have about the moon. Researchers debate how exactly our satellite formed, and when. They question the nature of moonquakes, weathering by the solar wind, and the extent and nature of lunar water. Scientists don't know for sure why the moon's near side and far side appear so different. Solving these riddles about the moon would help us understand how people might live and work there someday. But even more broadly, investigating these questions will help us understand how Earth and its companion formed, how the sun evolved, and perhaps even whether a body like the moon is vital for the eventual origin of life.

The first few CLPS experiment awards went to scientific instruments that were simple and cheap. In some cases, NASA looked for spares like SEAL that were sitting on a shelf, maybe canceled from previously proposed missions or left over from other spacecraft. Robert Grimm, a planetary scientist at the Southwest Research Institute, who is building multiple instruments to fly on different landers, says one agency official joked with him, "We're so desperate for payloads, we'll send rocks back to the moon."

On its first mission, set for the fourth quarter of 2022, Astrobotic's Peregrine Lunar Lander will carry two dozen payloads—including the SEAL instrument—to Lacus Mortis, a hexagonal lava plain on the northeastern face of the moon's near side. One of Intuitive Machines' Nova-Cs will carry six payloads to Oceanus Procellarum, a vast dark plain on the western edge of the moon. The other is set to bring a mass spectrometer and a drill called PRIME-1 that will extract and sample lunar ice from the south pole region. Later missions will attempt more daring sites with more interesting geological features and will bring instruments to study the moon's magnetic field and geology, among other goals. Astrobotic even won a $199.5-million contract to deliver a large rover called VIPER, a major science mission that will prospect for water at the south pole in 2023.

David Blewett is a planetary scientist at the Johns Hopkins University Applied Physics Laboratory whose mission was selected in June 2021 for a 2024 flight. His project, called Lunar Vertex, will investigate the magnetic anomaly in a region called Reiner Gamma, which contains a bright surface marking shaped like a tadpole. The swirl has been known since the Renaissance, but scientists debate how it formed. Some theories suggest the moon's magnetic field changed the motion of the surface dust, whereas another postulates that a collision with a comet's tail modified the lunar surface. Lunar Vertex will study the paisley-pattern area for about one lunar day—13 Earth days—to determine the swirl's magnetic properties, origin, and more.

Under the traditional NASA mission-selection process, Lunar Vertex would have been part of a $450-million spacecraft. Instead it's flying for $30 million as one of a handful of instruments onboard the scrappy Intuitive Machines lander. The hardware itself is also cheaper and simpler than a typical planetary science mission—Nova-C is a slender five-footed hexagon about the size of a British telephone booth. Brett Denevi, a planetary scientist at the Applied Physics Laboratory, is overseeing the design of the mission's camera. "For Lunar Vertex, the detectors are literally like cell-phone camera detectors," she says.

Grimm has instruments heading to the Schrödinger basin, an impact crater on the far side that features a peak ring—a plateau or secondary ring inside a crater's rim that is a hallmark of large impacts. The Schrödinger mission will carry a lunar seismometer—the first to land on the moon since Apollo and the first on the far side—along with a drill, to study the inside of the moon. Grimm says they will provide a fuller picture of the moon's interior heat and structure, helping to resolve how the satellite came to be.

Other experiments scheduled for launch in the next six years will study how spacecraft landings affect lunar regolith, scouring spacecraft and habitats. They will investigate the radiation environment on the moon; study its carbon dioxide, methane and other volatile substances; search for water ice; and monitor radio waves at the surface, informing plans for radio telescopes to be built on the moon in the future. All these missions will answer key research questions, demonstrate new technologies, prepare scientists and astronauts for eventual human arrivals, and, if industry partners get their wish, stimulate a new kind of lunar economy.

THE INVESTORS AND ENTREPRENEURS WORKING IN THIS ITERATION of the private space industry aren't all motivated by scientific curiosity, of course. They're out to make money, from lunar resources and the proliferation of people and businesses interested in those resources. But the value of that lunar material is still hypothetical.

Take lunar water, which may be plentiful inside permanently shadowed craters. With time and effort, the water theoretically could be split into its constituent parts, oxygen and hydrogen, to be used for rocket fuel. Yet mining lunar water will be profitable only if the moon eventually hosts an active launch pad that allows a solar system exploration economy to arise. Furthermore, creating the infrastructure to convert water to rocket fuel on another celestial body will be difficult, even if the market for it exists.

Most investors say there's money to be made on the moon long before it becomes a mining outpost, though. "If that was the whole story, then I'd be very nervous," says Chad Anderson, managing partner at venture capital firm Space Capital, which invested in Astrobotic in 2016. Anderson tracks investment in space-related enterprises and says that $258 billion has been poured into 1,688 such companies since 2013, evidence that venture capitalists see ample opportunity beyond the bonds of Earth.

Anderson says this wave of experiments could lead to a profitable cycle in which the first instruments make promising finds, leading to more questions and ultimately to new interest from prospectors who want to locate and extract whatever the moon has to offer. "The CLPS program is a very elegant way of stimulating a market and stimulating multiple companies in a market," he says. "In a mining analogy, an economy builds around people going out to look for gold, and you're going to start selling them picks and shovels and overalls." In the moon's case, the shovels are things like communications capability and solar power, which are commodities a lander provider can sell for a fee.

Hanh Nguyen, a graduate student at the London School of Economics who studies public policy with an interest in the commercial space industry, says government funding might spur a new market. "I think as the government provides opportunity for some companies to develop their products," she says, "other companies will see a need for services or products they can fill in."

SpaceX had a built-in customer base, however, including other countries' governments—Nguyen noted that one of its early clients was Malaysia—and American agencies such as the Defense Department. For the moon, potential commercial customers are not quite so obvious, says Matthew Weinzierl, a professor at Harvard Business School who studies the economics of space. "What's the big upside?" he says. "Where is the big demand going to come from, for visions of a marketplace on the moon with people walking around? That's exactly the tension I wrestle with and, I'm guessing, people in the industry wrestle with. There are definitely people hoping that tourism, manufacturing, things like that will pan out." Yet Weinzierl adds that Earth is full of unfettered capital, and space offers one new place to park it.

LUNAR SCIENTISTS TEND TO BE OF TWO MINDS ABOUT THE PROSPECT OF cheap, frequent private flights to the moon. Several leading lunar researchers are calling for more transparency and better planning. "I think there are mixed feelings," Stickle says.

Since Apollo, lunar exploration has relied on a sometimes awkward symbiosis between the jingoism and swagger inherent in human spaceflight and the more goal-oriented, pragmatic approach of scientific exploration. "The interesting thing about lunar science is that it often does get caught up in these bigger issues that are not necessarily driven by science," Denevi says. Even those who are excited to get their experiments on the first private flights acknowledge that CLPS could undercut big, bold NASA lunar missions. Some scientists I spoke with pointed to this as the elephant in the room, noting that the numerous small CLPS missions might not allow for the kind of science that can be done best with a larger mission.

Community leaders are trying to prepare their colleagues for the opportunities CLPS poses while remaining aware of possible pitfalls, says Amy Fagan, chair of the Lunar Exploration Analysis Group and a lunar scientist at Western Carolina University. Some lunar scientists are thinking a few steps ahead of CLPS, either because they're concerned about hurting their chances for a NASA Discovery mission or because they're just eager to do more.

The flip side, Fagan says, is that CLPS may be more resilient in the face of budget cuts or politics than larger and more expensive purely governmental projects. So far the Biden administration has adopted the Artemis program begun under Trump and has continued funding CLPS contracts, which surprised some lunar scientists who are accustomed to shifting political winds whenever a new president takes office. "It's tremendous that we had an administration change and yet Artemis is still there," Fagan says. "Clearly, there's a recognition that it's important to go back to the moon."

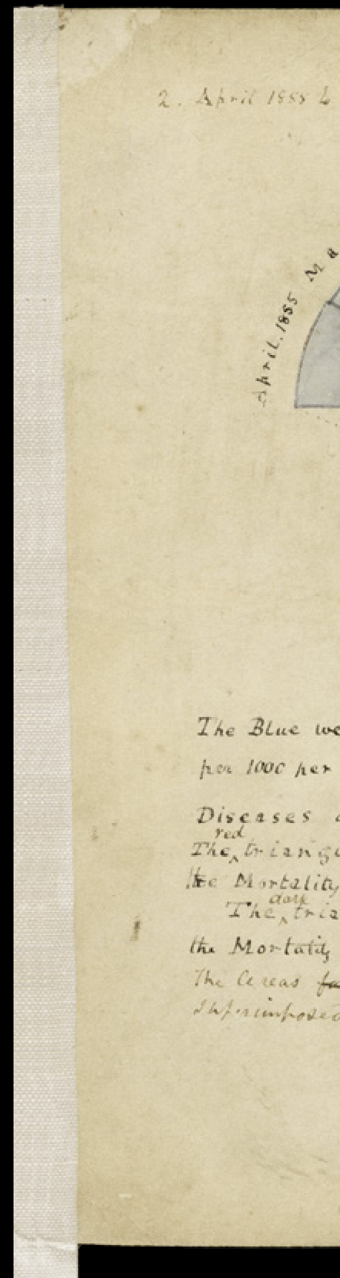
Whereas Apollo was a demonstration of American brainpower and geopolitical might, these new missions half a century later will showcase the country's present version of government-subsidized capitalism, ultimately sharing the control—and the credit—with entrepreneurs. Scientists who just want to understand more about Earth's companion world should get their answers no matter who launches the ships. The moon, silent and foreboding as ever, will not discriminate. SA

FROM OUR ARCHIVES

Missions to the Moon. Set Reset; July 2019.

scientificamerican.com/magazine/sa

RJ Andrews is a professional data storyteller. He is editor of the Information Graphic Visionaries book series and author of its volume on Florence Nightingale. Visit VisionaryPress.com to learn more and follow him on Twitter @infowetrust



HISTORY OF SCIENCE

Florence Nightingale's Data Revolution

The celebrated nurse improved public health through her groundbreaking use of data storytelling

By RJ Andrews

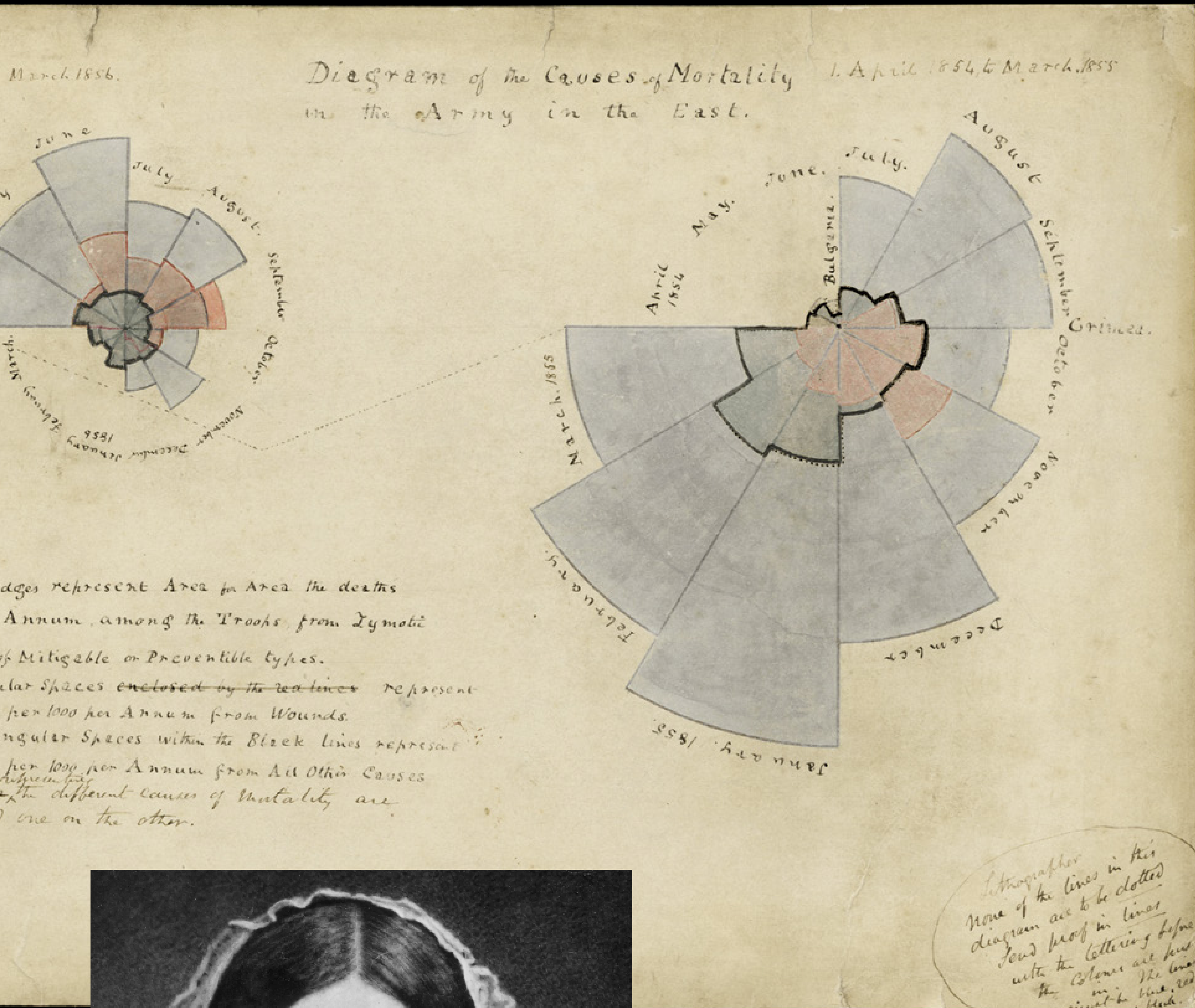
IN THE SUMMER OF 1856 FLORENCE NIGHTINGALE SAILED HOME FROM WAR FURIOUS. AS THE NURSING administrator of a sprawling British Army hospital network, she had witnessed thousands of sick soldiers endure agony in filthy wards. An entire fighting force had been effectively lost to disease and infection. The "horrors of war," Nightingale realized, were inflicted by more than enemy bullets.

Nightingale had earned the moniker "Lady with the Lamp" by making night rounds on patients, illuminated by a paper lantern. She was serving in the Crimean War, where Britain fought alongside France against the Russian invasion of the Ottoman Empire. The causes of the soldiers' torment were numerous: incompetent officers, meager supplies, inadequate shelters, overcrowded hospitals and cruel medical practices.

Nightingale arrived back in London determined to prevent similar suffering from happening again. It would be an uphill slog. Many government leaders accepted the loss of common soldiers as inevitable. They wrongly believed, for example, that communicable diseases were caused by unavoidable realities—the weather, bad diet and harsh work conditions. And the poor quality of army data made it impossible to know exactly how soldiers died. Patient outcomes varied depending on whether you asked the officer who lost fighters, the ferryman who shuttled the sick, the doctor who treated invalids or the adjutant who buried bodies.

Resolute, Nightingale set out to sway the minds of generals,

British Library Imaging Services; Hulton Archive/Getty Images (*Nightingale*)



DRAFT DIAGRAM

Surviving drafts of Nightingale's diagrams give a rare peek into her team's creative process. Drawn by government clerks, these drafts show how the team refined original ideas to improve information design. They also reveal that the mechanical precision of the final lithographs was not present in the original references. This early sketch gives a preview of one of Nightingale's most famous graphics (*shown in its final form on page 84*), which reveals how army deaths from preventable diseases (*blue*) outnumbered hospital deaths from wounds (*red*).

FLORENCE NIGHTINGALE was photographed in London a few months after returning home from war. At around this same time, she began working with data and charts.

medical officers and parliamentarians. Their poor data literacy muted statistical arguments that could have oriented them toward the facts. Nightingale, with her quantitative mind, had to persuade people with common understanding but uncommon standing. Her prime target throughout this effort was the head of the British Army, Queen Victoria.

With public attention drifting away from the concluded war, Nightingale knew that the opportunity for reform was fleeting. She worked 20-hour days, mostly behind the scenes, writing letters, wrangling data and publishing anonymously. She did not do it alone—a circle of experts, including statesmen, statisticians and scientists, united with her to break the policy makers' inertia and ineptitude. The team focused its campaign on promoting sanitary reform: fresh air, clean sewers and less crowding.

Nightingale's key persuasion tactic was to convey statistics in exciting ways. I recently conducted the first in-depth study of how Nightingale created and used data visualization, and I share my research in the forthcoming book *Florence Nightingale, Mortality and Health Diagrams* (Visionary Press). I studied correspondence that details Nightingale's information-design process, hand-drawn draft diagrams never before seen by the public and a complete catalog of her information graphics. We can now appreciate better than ever what an innovator Nightingale was and how her techniques foreshadowed how data graphics would become essential to public understanding and debate today.

Recognizing that few people actually read statistical tables, Nightingale and her team designed graphics to attract attention and engage readers in ways that other media could not. Their diagram designs evolved over two batches of publications, giving them opportunities to react to the efforts of other parties also jockeying for influence. These competitors buried stuffy graphic analysis inside thick books. In contrast, Nightingale packaged her charts in attractive slim folios, integrating diagrams with witty prose. Her charts were accessible and punchy. Instead of building complex arguments that required heavy work from the audience, she focused her narrative lens on specific claims. It was more than data visualization—it was data storytelling.

Nightingale's stories showcased how poor sanitation and overcrowding caused unnecessary death. She constructed her arguments from easy-to-understand comparisons. For instance, Nightingale brilliantly framed army mortality by contrasting it with civilian mortality. She showed how, for example, peacetime soldiers living in army barracks died at higher rates than civilian men of similar ages. Her graphics made it impossible to deny the realities represented by the data: army administration needed dramatic reform.

Nightingale's diagrams received broad coverage in the press. Within months after the first batch was published, the issue of overcrowded barracks was debated in both houses of Parliament, which moved to reform the sanitary conditions of the army. This resolution was backed by four subcommissions focused on sanitary construction, health codes, a military medical school and military statistics. Within a couple of years the quality of British Army data soared under the leadership of a Nightingale ally. The new data-collection operation—eventually lauded as the best in Europe—also proved the success of the sanitary reforms: mortality from preventable disease among soldiers declined to less than that in the comparable civilian population. Nightingale celebrated this milestone with a final Crimean War diagram, published in 1863.

Her campaign's biggest impact on civilian public health took another decade to materialize. The reforms Nightingale fought for were finally codified in the British Public Health Act of 1875. The legislation established requirements for well-built sewers, clean running water and regulated building codes. The law and the precedent it set worldwide would be driving forces—along with the development of vaccines that conferred immunity to diseases and artificial fertilizer that boosted crop yields—in doubling the average human life span during the following century. SA

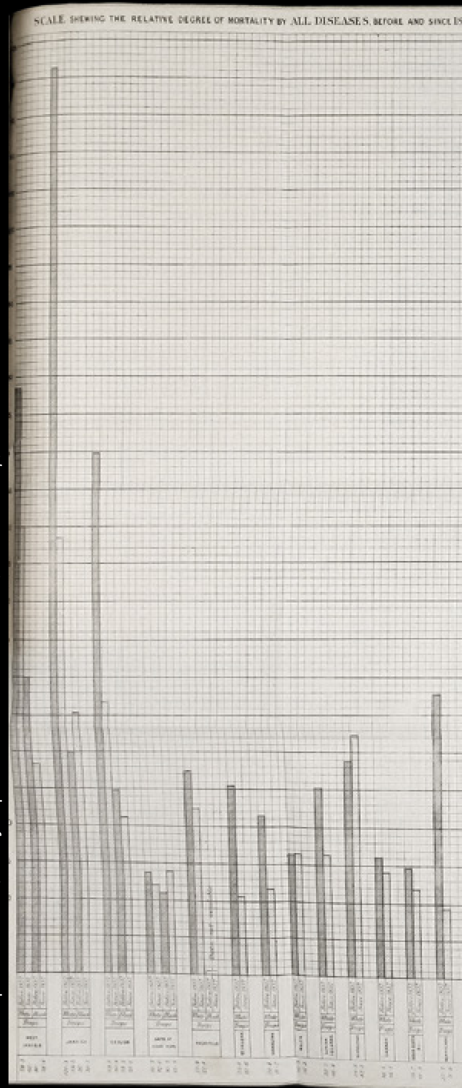
FROM OUR ARCHIVES

Florence Nightingale. I. Bernard Cohen; March 1984.

scientificamerican.com/magazine/sa

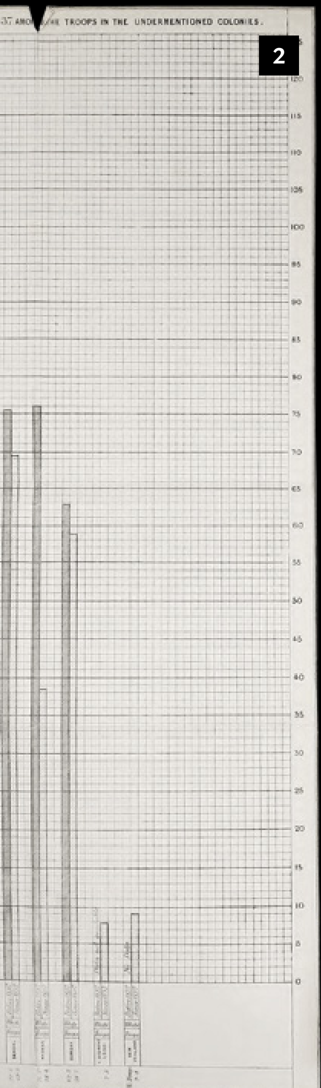
CONTEXT

Nightingale's firsthand experiences in the Crimean War drove her passion for health reform. Here she leads a group on horseback to view the siege of Sevastopol (*1*), the Crimean War's culminating conflict. Nightingale's graphics departed from the standard visualizations of the time, such as this black-and-white bar chart of soldier mortality (*2*). In contrast, her charts (*3*) amplified the data story by comparing soldier (*red*) and civilian (*black*) mortality rates using horizontal bars, making the chart's labels easier to read. Nightingale's letters reveal that she was the one who designed the chart form, data and text.



Wellcome Collection; Internet Archive *archive.org/details/b21365210*; UCLA Library Special Collections, History & Special Collections for the Sciences (*clockwise from top*)


1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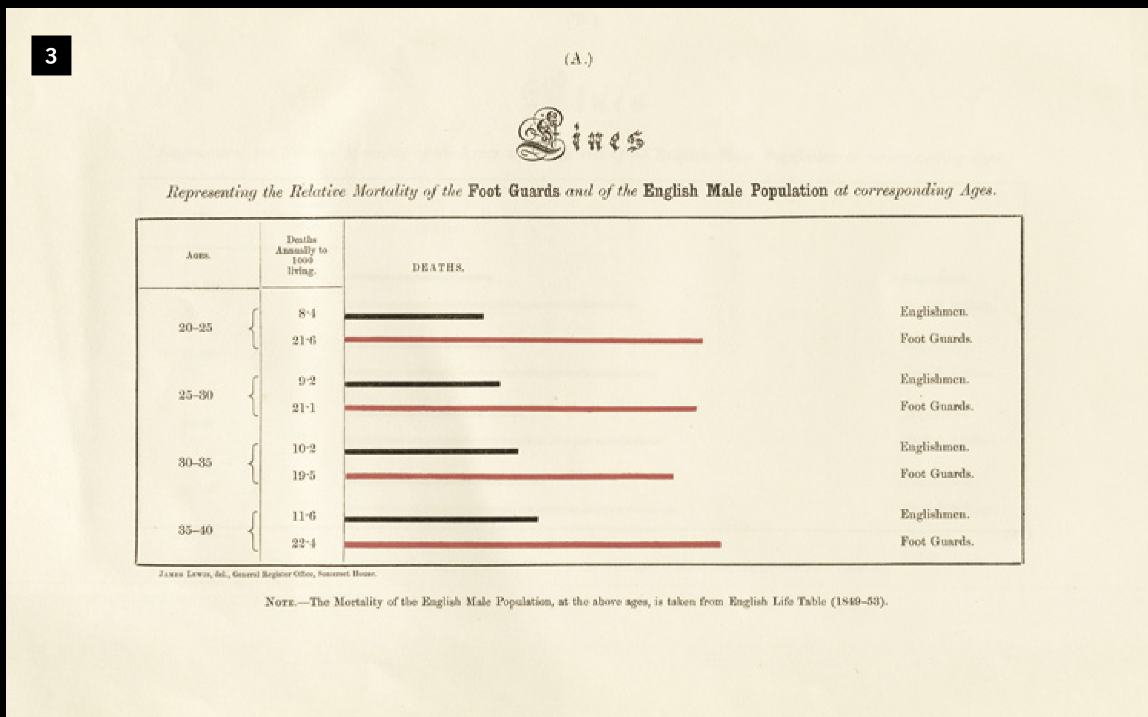
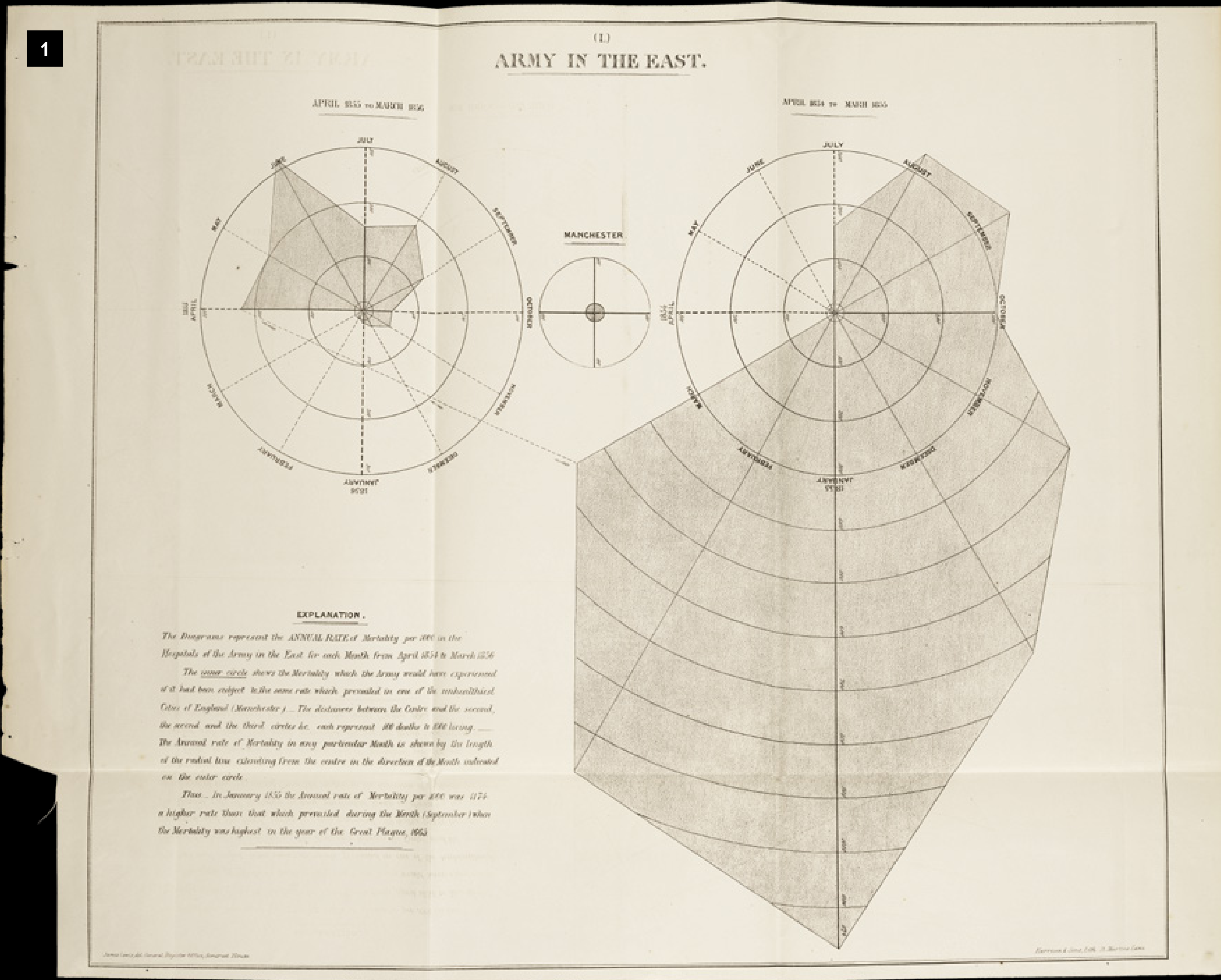
AMONG THE TROOPS IN THE UNDERMENTIONED COLONIES.


3
(A.)
Lines
Representing the Relative Mortality of the Foot Guards and of the English Male Population at corresponding Ages.
Ages.
Deaths Annually to 1000 living.
DEATHS.
20–25
8·4
21·6
25–30
9·2
21·1
30–35
10·2
19·5
35–40
11·6
22·4
Englishmen.
Foot Guards.
James Lewis, del., General Register Office, Somerset House.
Note.—The Mortality of the English Male Population, at the above ages, is taken from English Life Table (1849–53).

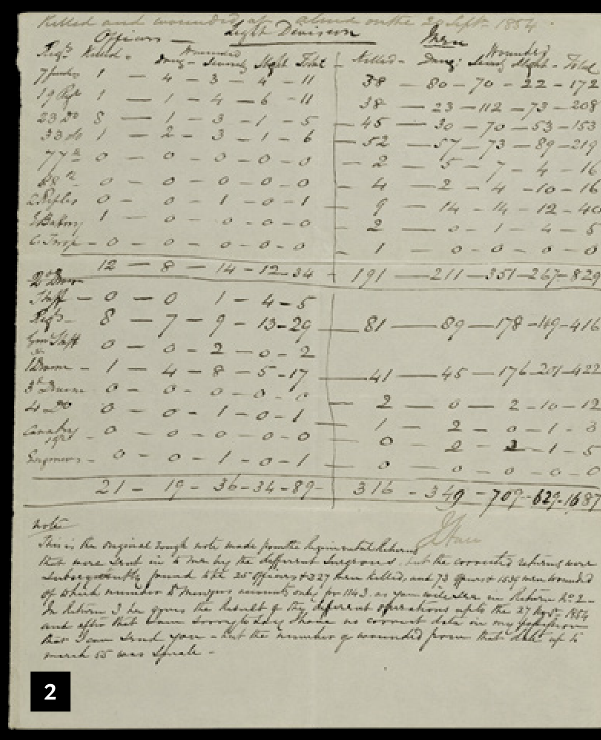


DATA CRAFTWORK

Nightingale collaborated with physician and medical statistician William Farr on her first batch of diagrams. They included bar charts, area charts and circular diagrams (*1*). This diagram shows the British Army's monthly mortality rate across the war. The small circle at the center of the composition represents the mortality rate for similar groups in the city of Manchester, England, where living conditions and general health were poor at the time, which helped readers grasp the extreme mortality rate in the army.

HANDS-ON LEADER

The civilian data came from Farr's vaults at the General Register Office (GRO). The army data were assembled from half a dozen sources who had recorded deaths during the war. An extant army record (*2*) indicates the nonstandardized data that Nightingale helped to wrangle. Farr's team of GRO clerks assisted with data analysis; they also drafted the diagrams. Nightingale managed and funded diagram lithography, printing and distribution. Her edits, which survive in correspondence and on diagram drafts, reveal a leader engaged with the project from conception through production. Although these first diagrams attracted attention, the circular diagrams contained a visual encoding flaw that caused large values to appear overexaggerated. Nightingale and her team corrected the mistake in their second batch of graphics.



Killed and wounded at Alma on the 20 Sept 1854

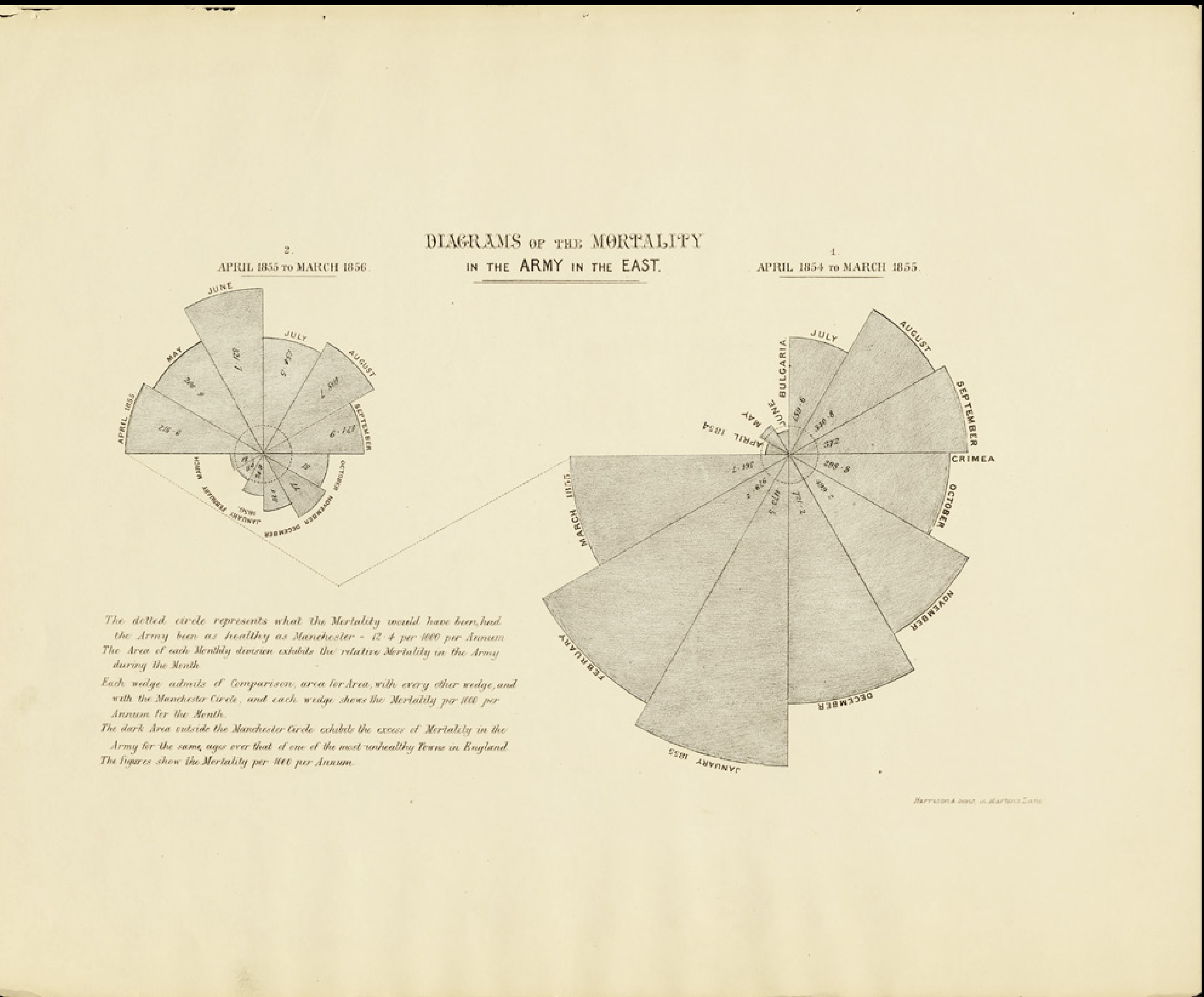
Light Division

Regts	Officers Killed	Wounded Dang.	Severely	Slight	Total	Men Killed	Wounded Dang.	Severely	Slight	Total
7 Fusilrs	1	4	3	4	11	38	80	70	22	172
19 Regt	1	1	4	6	11	38	23	112	73	208
23 do	8	1	3	1	5	45	30	70	53	153
33 do	1	2	3	1	6	52	57	73	89	219
77th	0	0	0	0	0	2	5	7	4	16
88th	0	0	0	0	0	4	2	4	10	16
2 Rifles	0	0	1	0	1	9	14	14	12	40
Battery	1	0	0	0	0	2	0	1	4	5
C. Troop	0	0	0	0	0	1	0	0	0	0
	12	8	14	12	34	191	211	351	267	829
2d Divn										
Staff	0	0	1	4	5					
Regts	8	7	9	13	29	81	89	178	149	416
Gen Staff	0	0	2	0	2					
1st Divn	1	4	8	5	17	41	45	176	201	422
3d Divn	0	0	0	0	0	2	0	2	10	12
4 Do	0	0	1	0	1	1	2	0	1	3
Cavalry 1st	0	0	0	0	0	0	2	2	1	5
Engineers	0	0	1	0	1	0	0	0	0	0
	21	19	36	34	89	316	349	709	829	1687

Note

This is the original rough note made from the Regimental Returns that were sent in to me by the different Surgeons, but the corrected returns were subsequently found that 25 officers & 327 men killed, and 73 officers & [illegible] men wounded of which number Dr [illegible] accounts only for 1143. as you will see in Return No. 2 — In Return 3 he gives the result of the different operations up to the 27 Novr 1854 and after that I am sorry to say I have no correct data in my possession that I can send you — but the number of wounded from that date up to March 55 was small —

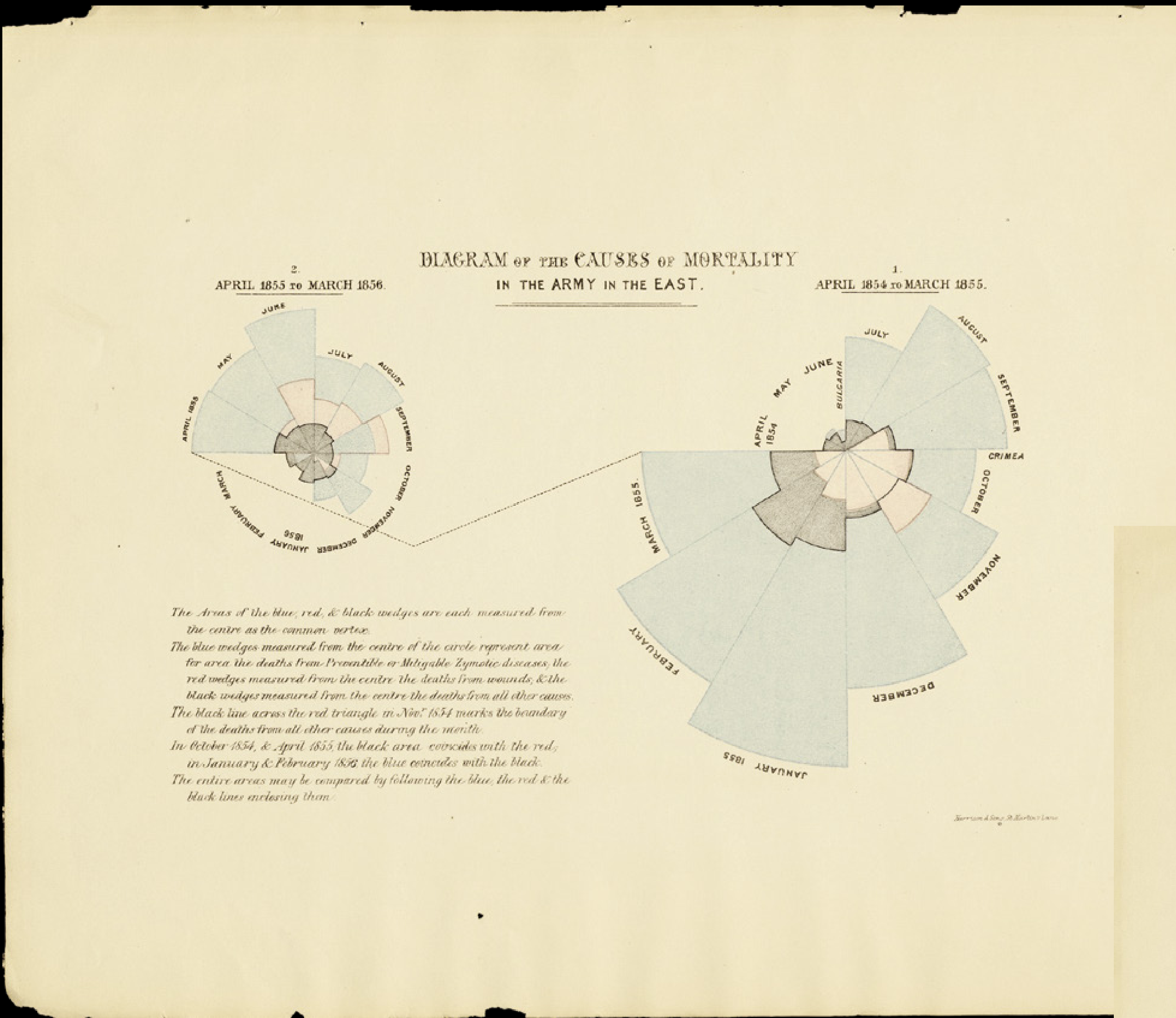
UCLA Library Special Collections, History & Special Collections for the Sciences (*top*); Wellcome Collection (*bottom*)



DATA STORYTELLING—THE PROBLEM

Nightingale's second batch of visualizations was her most stunning graphic achievement. The three-diagram set was originally issued in a confidential report to Queen Victoria. After the sanitation reformers were attacked in an anonymous pamphlet, Nightingale and her team repackaged the diagrams with a final rebuttal for public consumption. These graphics form a narrative that exposed the problem (too many deaths), revealed its cause (preventable disease) and offered lifesaving solutions (sanitary reform). The first diagram, shown here, emphasizes the problem by comparing the monthly rate of army mortality across two years (*radiating wedges*) with the average mortality rate in the city of Manchester (*inner circle*).

Harvard Library



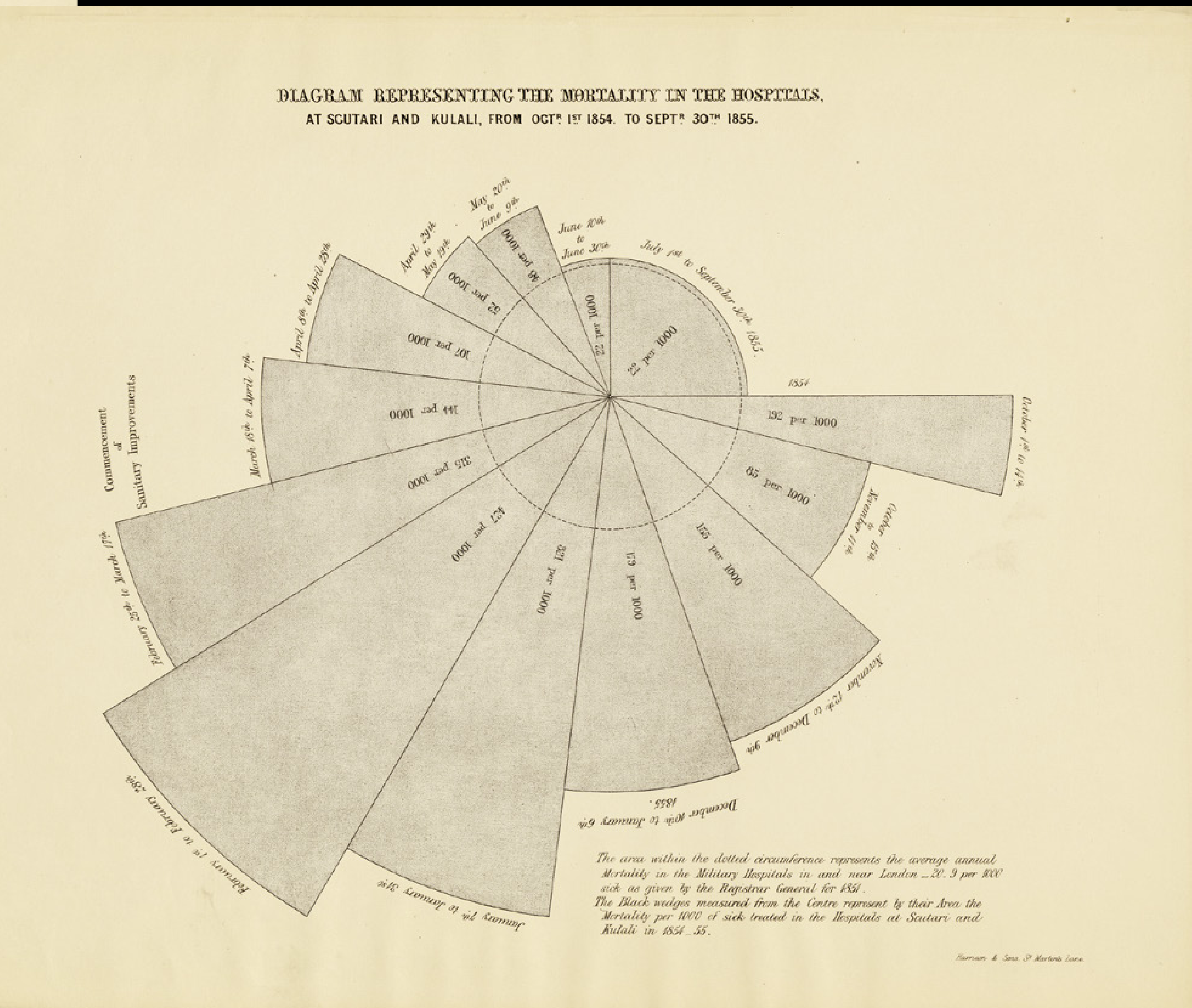
DATA STORYTELLING—THE CAUSE

Nightingale's best-known diagram is this colorful depiction of causes of mortality, illustrated by overlapping wedges. Part of the chart's enduring success is attributable to its strange yet interesting form; others at the time presented similar data in conventional line graphs, to little effect. As the middle story element of her visual argument, it elevated two comparisons. The first shows that deaths from preventable diseases (*blue*) greatly outnumbered hospital deaths from wounds (*red*). The second comparison, repeated from the first diagram, is between the first year (*right*) and second year (*left*) of the war. It shows that mortality declined significantly between the two years, which are linked by a jagged line, and encourages readers to wonder what occurred to make such a difference.

Harvard Library

DATA STORYTELLING—THE SOLUTION

The third diagram completed the story by focusing attention on the moment when a team of sanitation engineers began fixing Nightingale's hospital. The mortality rate decreased greatly with the "commencement of sanitary improvements." In her quest to highlight sanitary reform in this graphic, Nightingale left out other factors that probably played a role, including a reduction in hospital overcrowding and the end of a miserably cold winter. Furthermore, the sanitary improvements to the hospital did not magically happen in one day; they were the result of several months of work clearing filth, rebuilding sewers and installing ventilation flues. The radiant diagram is an information-design wonder: its wedge angles vary to accommodate the different record-collection periods for its source data.



Creating Our Sense of Self

One brain region helps people maintain a consistent identity

By Robert Martone

We are all time travelers. Every day we experience new things as we travel forward through time. As we do, the countless connections between the nerve cells in our brain recalibrate to accommodate these experiences. It's as if we reassemble ourselves daily, maintaining a mental construct of ourselves in physical time, and the glue that holds together our core identity is memory.

Our travels are not limited to physical time. We also experience mental time travel. We visit the past through our memories and then journey into the future by imagining what tomorrow or next year might bring. When we do so, we think of ourselves as we are now, remember who we once were and imagine how we will be.

A study, published in the journal *Social Cognitive and Affective Neuroscience* (*SCAN*), explores how one particular brain region helps to knit together memories of the present and future self. When people sustain an injury to that area, it leads to an impaired sense of identity. The region—called the ventral medial prefrontal cortex (vmPFC)—may produce a fundamental model of oneself and place it in mental time. When the region does so, this study suggests, it may be the source of our sense of self.

Psychologists have long noticed that a person's mind handles information about oneself differently from other details. Memories that reference the self are easier to recall than other forms of memory. They benefit from what researchers have called a self-reference effect (SRE), in which information related to oneself is privileged and more salient in our thoughts. Self-related memories are distinct from both episodic memory, the category of recollections that pertains to specific events and experiences, and semantic memory, which connects to more general knowledge, such as the color of grass and the characteristics of the seasons.

SREs, then, are a way to investigate how our sense of self emerges from the workings of the brain—something that multiple research groups have studied intensely. For example, previous research employed functional magnetic resonance imaging (fMRI), a method that uses blood flow and oxygen consumption in specific brain areas as a measure of neural activity, to identify regions that were activated by self-reference. These studies identified the medial prefrontal cortex (mPFC) as a brain region related to self-thought.

This area, the mPFC, can be further divided into upper and lower regions (called dorsal and ventral, respectively), and it turns out that each one makes different contributions to self-related thought. The dorsal section plays a role in distinguishing self from other and appears to be task-related, whereas the ventral section, the vmPFC, contributes more to emotional processing.

In the *SCAN* study, the researchers used the self-reference effect to assess memories of present and future selves among people who had brain lesions to the vmPFC. The scientists worked with seven people who had lesions to this area and then compared them with a control group made up of eight people with injuries to other parts of the brain, as well as 23 healthy individuals without brain injuries. By comparing these groups, the scientists could investigate whether brain lesions in general or those to the vmPFC specifically might affect SREs. All people in the study underwent a thorough neuropsychological evaluation, which confirmed that they were within normal ranges for a variety of cognitive assessments, including measures of verbal fluency and spatial short-term memory. The researchers then asked the participants to list adjectives to describe themselves and a well-known celebrity, both in the present and 10 years in the future. Later, the participants had to recall these same traits.

The researchers discovered that people in their control group could recall more adjectives linked to themselves in the present and future than adjectives linked to the celebrity. In other words, scientists found that the self-reference effect extends to both the future and the present self. Although there was some variation in the group—people with brain injuries to areas other than the vmPFC were somewhat less able to recall details about their future self when compared with healthy participants—the self-reference effect still held true.

Results were distinctly different, however, for the participants with injuries to the vmPFC. People with lesions in this area had little or no ability to recall references to the self, regardless of the context of time. Their identification of adjectives for celebrities in the present or future was also significantly impaired when compared with the rest of the participants' responses. In addition, people with vmPFC lesions had less confidence about an individual's ability to possess traits than other people in the study. All of this evidence points to a central role for the vmPFC in the formation and maintenance of identity.

The new findings are intriguing for several reasons. Brain lesions can help us understand the normal function of the region involved. Lesions of the vmPFC are associated with altered personality, blunted emotions, and a number of changes in emotional and executive function. Injury to this area is most often associated with confabulations: false memories that people recite to listeners with great confidence. Although it may be tempting for someone to view confabulations as deliberate or creative falsehoods, people who tell them actually are unaware that their stories are false. Instead it is possible their confusion could stem from misfunctioning memory retrieval and monitoring mechanisms.

Robert Martone is a research scientist with expertise in neurodegeneration. He spends his free time kayaking and translating Renaissance Italian literature.

More broadly, the study helps us understand how self-related memories—recollections key to maintaining our core sense of identity—depend on the function of the vmPFC. But what about our past selves? Curiously, in previous studies that asked people to consider their past selves, there was no more activation of the mPFC than when considering someone else. Our past selves seem foreign to us, as if they were individuals apart from us.

One idea that scientists have put forward to understand this distinction is that perhaps we are not very kind in our judgments of our past selves. Instead we may be rather critical and harshly judgmental of our previous behavior, emotions and personal traits. In these situations, we may use our past primarily to construct a more positive self-image in the present. Put another way, because we may recognize flaws in our past self's behavior, we tend to distance ourselves from the person we once were.

Bringing the present and future into the spotlight, then, is central to understanding the way our brain and thoughts build our current identities. In many ways, it makes sense that the mPFC is important in this process of recalling present details and imagining future ones that build on our recollections. The prefrontal cortex, including the mPFC and its subdivisions, forms a network in the brain that is involved in future planning. That network also includes the hippocampus, a brain structure that is central to episodic memory formation and that can track moments as sequential events in time. In past work, researchers have found that manipulating the activity of the hippocampus alters creative and future imaginings, which suggests an important role for brain structures supporting memory in imagining the future. In fact, although we often think of memory as the brain's accurate and dispassionate recording device, some scholars have characterized it as a form of imagination.

Future thought is a vital component of being human. Its importance in our culture is embodied in the mythological figure and pre-Olympian god Prometheus (whose name means "forethinker"), patron of the arts and sciences. According to Greek legend, he shaped humans out of clay and bestowed them with fire and the skills of craftsmanship. These are acts that illustrate the power of imagining a novel future. Although there is debate as to whether thinking about the future is an exclusively human feature—birds such as Western Scrub-Jays, for example, appear to anticipate and plan for future food needs—it is clear that future thought has played a significant role in human evolution. This ability may have contributed to the development of language, and it has a key part in human interactions, where the vmPFC is central to evaluating and taking advantage of social context.

Now, thanks to this new research, we have a better idea than ever about the way a small region within our brains is able to build and hold this core ability to maintain our identity. SA

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Illustration by Zoe Liu

NONFICTION

Sad Species

Are humans really the smartest animals?

Review by Darcy B. Kelley

Would we, as a species, be better off if we were more like other animals? I suspected I'd enjoy reading Justin Gregg's tour of this question when he opened with a quote from *Pyramids,* by Terry Pratchett, a book in one of my favorite science-fiction series: "Mere animals couldn't possibly manage to act like this. You need to be a human being to be really stupid."

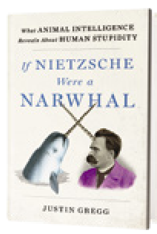
Gregg, an expert on animal cognition, explores what human foibles reveal about animal intelligence by invoking philosopher Friedrich Nietzsche. Nietzsche's conundrum, as Gregg sees it, is that he both envied cows and pitied them for the same reason: cows do not have an awareness that they will die. Nietzsche was both an intellectual genius and a mental wreck—the latter overcoming the former when, so the story goes, he witnessed a horse being whipped in Turin, Italy, and subsequently suffered a psychotic break. The premise here is that being unhappy is the price our species pays for intelligence. But how do we know if other animals are actually happier?

Gregg cheekily points out that even the scientists (who are generally considered smart humans) who devote their careers to creating artificial intelligence can't agree on what intelligence is. Humans basically "know it when we see it" and regard intelligence as a positive trait. We often look outward for extraterrestrial signs of intelligence by seeking messages or signals that come from faraway planets. Curiously, we don't do very well with this search on our own planet.

Let's take lying: an overdeveloped human trait that is often employed for advantage. Gregg argues that the key feature of lying is intention. Although there is certainly evidence of deception throughout the animal kingdom, our species has the supposedly superlative abilities of language and "theory of mind." But do they serve us well? Are we better off? Gregg dives into a fascinating discussion of the downsides, running from Jane Austen ("we have daily proof") to the modern onslaught of disinformation. From here he compares our species with others in terms of "death wisdom" and mortality and later considers the happiness of bees, as well as what it means to foresee the future.

The book is a snappy read but lingers: it left me wondering why we don't respect signals of intelligence from other species—and more deeply consider how our own intelligence works against us.

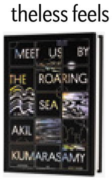
Darcy B. Kelley is Harold Weintraub Professor of Biological Sciences at Columbia University.



If Nietzsche Were a Narwhal:
What Animal Intelligence Reveals about Human Stupidity
by Justin Gregg. Little, Brown, 2022 ($29)

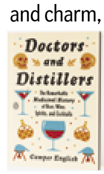
IN BRIEF

Meet Us by the Roaring Sea:
A Novel
by Akil Kumarasamy.
Farrar, Straus and Giroux, 2022 ($27)



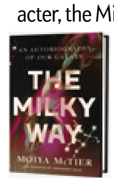
Set in a future of eye scans, carbon credits and advanced AI, Akil Kumarasamy's new novel nonetheless feels surprisingly like home—even as it tests the boundaries of self and story. Its protagonist, grieving the recent death of her mother, throws herself into translating a little-known Tamil manuscript about 17 medical students who strove to achieve radical compassion during the Sri Lankan Civil War (dating to 1983–2009). This and her other portals to shared experience—the omnipresent television, a new drug that transfers memories—dissolve the barriers of being into a dizzying alchemy of past and present, love and truth, death and memory. —*Dana Dunham*

Doctors and Distillers:
The Remarkable Medicinal History of Beer, Wine, Spirits, and Cocktails
by Camper English.
Penguin Books, 2022 ($18, paperbound)



Your favorite cocktail may very well have its roots in medicine of generations past. With immense wit and charm, author Camper English traces millennia to explore how civilizations used fermented and distilled beverages to do everything from hydrating the workforce to fending off the Black Death. English takes a tongue-in-cheek approach to his subject matter, resulting in wildly compelling stories, such as how Buckfast, a tonic wine created by monks to treat colds and influenza, became the "U.K.'s version of Four Loko." It is every bit as entertaining as it is educational. —*Mike Welch*

The Milky Way:
An Autobiography of Our Galaxy
by Moiya McTier.
Grand Central Publishing, 2022 ($27)



Moiya McTier assumes the role of cosmic interpreter to let our galaxy tell her own story. As a character, the Milky Way is a cross between a Greek goddess and GLaDOS, the artificially superintelligent computer system from the Portal video-game series. She gossips about other galaxies, teaches us about her past and imparts a primer on astrophysics, all the while relishing every opportunity to throw shade on humankind's egocentrism and closed-mindedness. McTier—who in 2021 became the first Black woman to graduate from Columbia University's astronomy Ph.D. program—dedicates the book "to everyone who's been made to feel that they're not 'sciencey enough.'" —*Maddie Bender*

Illustration by London Ladd

Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and co-author of *Discerning Experts* (University of Chicago, 2019).

Wishful Thinking in Climate Science

Influential carbon-reduction models rely on tech that doesn't exist

By Naomi Oreskes

At last year's Glasgow COP26 meetings on the climate crisis, U.S. envoy and former U.S. secretary of state John Kerry stated that solutions to the climate crisis will involve "technologies that we don't yet have" but are supposedly on the way. Kerry's optimism comes directly from scientists. You can read about these beliefs in the influential Intergovernmental Panel on Climate Change (IPCC) Integrated Assessment Models, created by researchers. These models present pathways to carbon reductions that may permit us to keep climate change below two degrees Celsius. They rely heavily on technologies that don't yet exist, such as ways to store carbon in the ground safely, permanently and affordably.

Stop and think about this for a moment. Science—that is to say, Euro-American science—has long been held as our model for rationality. Scientists frequently accuse those who reject their findings of being irrational. Yet depending on technologies that do not yet exist is irrational, a kind of magical thinking. That is a developmental stage kids are expected to outgrow. Imagine if I said I planned to build a home with materials that had not yet been invented or build a civilization on Mars without first figuring out how to get even one human being there. You'd likely consider me irrational, perhaps delusional. Yet this kind of thinking pervades plans for future decarbonization.

The IPCC models, for instance, depend heavily on carbon capture and storage, also called carbon capture and sequestration (either way, CCS). Some advocates, including companies such as ExxonMobil, say CCS is a proven, mature technology because for years industry has pumped carbon dioxide or other substances into oil fields to flush more fossil fuel out of the ground. But carbon dioxide doesn't necessarily stay in the rocks and soil. It may migrate along cracks, faults and fissures before finding its way back to the atmosphere. Keeping pumped carbon in the ground—in other words, achieving net negative emissions—is much harder. Globally there are only handful of places where this is done. None of them is commercially viable.

One site is the Orca plant in Iceland, touted as the world's biggest carbon-removal plant. Air-captured carbon dioxide is mixed with water and pumped into the ground, where it reacts with the basaltic rock to form stable carbonate minerals. That's great. But the cost is astronomical—$600 to $1,000 per ton—and the scale is tiny: about 4,000 tons a year. By comparison, just one company, tech giant Microsoft (which has pledged to offset all its emissions), produced nearly 14 million tons of carbon in 2021. Or look at carbon capture at the Archer Daniels Midland ethanol plant in Illinois, which, since 2017, has been containing carbon at a cost to the American taxpayer of $281 million (more than half the total project cost); at the same time, overall emissions from the plant have increased. And the total number of people employed in the project? Eleven. Meanwhile numerous CCS plants have failed. In 2016 the Massachusetts Institute of Technology closed its Carbon Capture and Sequestration Technologies program because the 43 projects it was involved with had all been canceled, put on hold or converted to other things.

It's obvious why ExxonMobil and Archer Daniels Midland are pushing CCS. It makes them look good, and they can get the taxpayer to foot the bill. The Infrastructure Investment and Jobs Act, passed last year, contained more than $10 billion for efforts to develop carbon-capture technologies. In contrast, the act contained merely $420 million for renewable energy—water, wind, geothermal and solar.

Scaling up solar and wind is going to cost money and will need to be supported by effective public policies. The big question is, Why can't we get those programs? One reason is the continued obstructive activities of the fossil-fuel industry. But why do scientists accept this hand-waving? My guess is that, frustrated by the inability of elected officials to overcome the political obstacles, researchers think that getting around the technological obstacles will be less difficult. They may be right. But by the time we know if they are, it may be too late. SA

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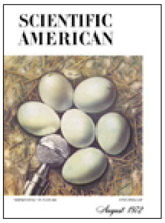
Illustration by Katie Louise Thomas

50, 100 & 150 YEARS AGO

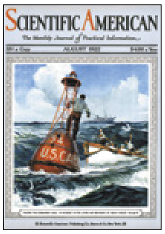
INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Mark Fischetti

AUGUST



1972



1922

1872

1972 Creation Science

"The stage is being set for the mandatory teaching of divine creation as a scientific theory on the same footing as evolution in the public schools of California. In 1969 the State Board of Education modified a new 'science framework' for kindergarten through the 12th grade to require that recommended textbooks present more than one hypothesis for the origin of the universe, matter, life and man. The guidelines make it clear that the other hypothesis is to be creation."

1922 Topographers Hike a Lot

"Last year a good many of the keen-eyed engineers and their assistants making maps for the United States Geological Survey covered 12,311 square miles of territory, making the total mapped since the work began in 1879 equal to 43 percent of the country, exclusive of Alaska: 1,301,136 square miles. The engineers are estimated to have tramped an aggregate of approximately nine million miles, for the average amount of walking varies, from five miles for every square mile surveyed in ordinary country to ten or more miles in rough country."

Locomotive Rings True

"A piano seems out of place in a locomotive workshop, yet there is no better way of discovering cracks and defects in the parts of locomotive machinery than by striking the metal with a hammer and comparing the noise of the vibrations with piano notes. If the metal rings harmoniously with the piano note, all is well; the least flaw will result in a discord. Defects that are hardly noticed by the ordinary method of hammering are at once evident when the piano test is employed. A locomotive that rings true all over is certainly fit for service."

Mount Everest, Almost

"A few days ago the cables published a dispatch from General C. G. Bruce. It reads: 'Three members of the Everest expedition, Mallory, Somerville and Norton, on May 21 reached an altitude of 26,800 feet, the highest ever reached by man, and just 2,200 feet below the summit. To have got so far in a climb which was merely a kind of preliminary reconnaissance is a very fine achievement and seems to augur well for the final effort.' The London *Times* notes, 'The prospect of reaching the summit seems now much less a forlorn hope than it did.'"

During a subsequent 1924 attempt to scale the peak, George Mallory and his partner, Andrew Irvine, disappeared, last seen less than 1,000 feet from the summit. Mallory's body was not found until 1999.

1872 Electric Lighthouses

"The following are the electric lights in England and France with the dates they were erected: Dungeness, January 1862; Cape La Heve, France, South Light, December 1863, North Light, November 1866; Cape Grisnez, France, February 1869; Souter Point, England, January 1871; South Foreland, England, January 1872. It is interesting to see, says *Nature,* that England took the lead in adaptation of electric illumination to lighthouse purposes. (We believe that in the United States there is no lighthouse in which the electric light is employed.)"

Acorn Elegance

"An acorn suspended by a piece of thread within half an inch of the surface of water in a hyacinth glass will, in a few months, burst and throw a root down into the water and shoot upwards its straight and tapering stem, with beautiful little green leaves. A young oak tree, growing in this way on the mantelshelf, is a very elegant and interesting object."

Mineral Water Inquiry

"It would be a most desirable study for a physician of experience to tour our most renowned mineral waters, and to accurately ascertain their real merits. Most of the published descriptions are by proprietors, hotel keepers, or those in their interest, who are only concerned to brag as loudly as possible about the virtues of particular sources. Certain it is that the prolonged use of any mineral water in health or disease is of doubtful efficacy."

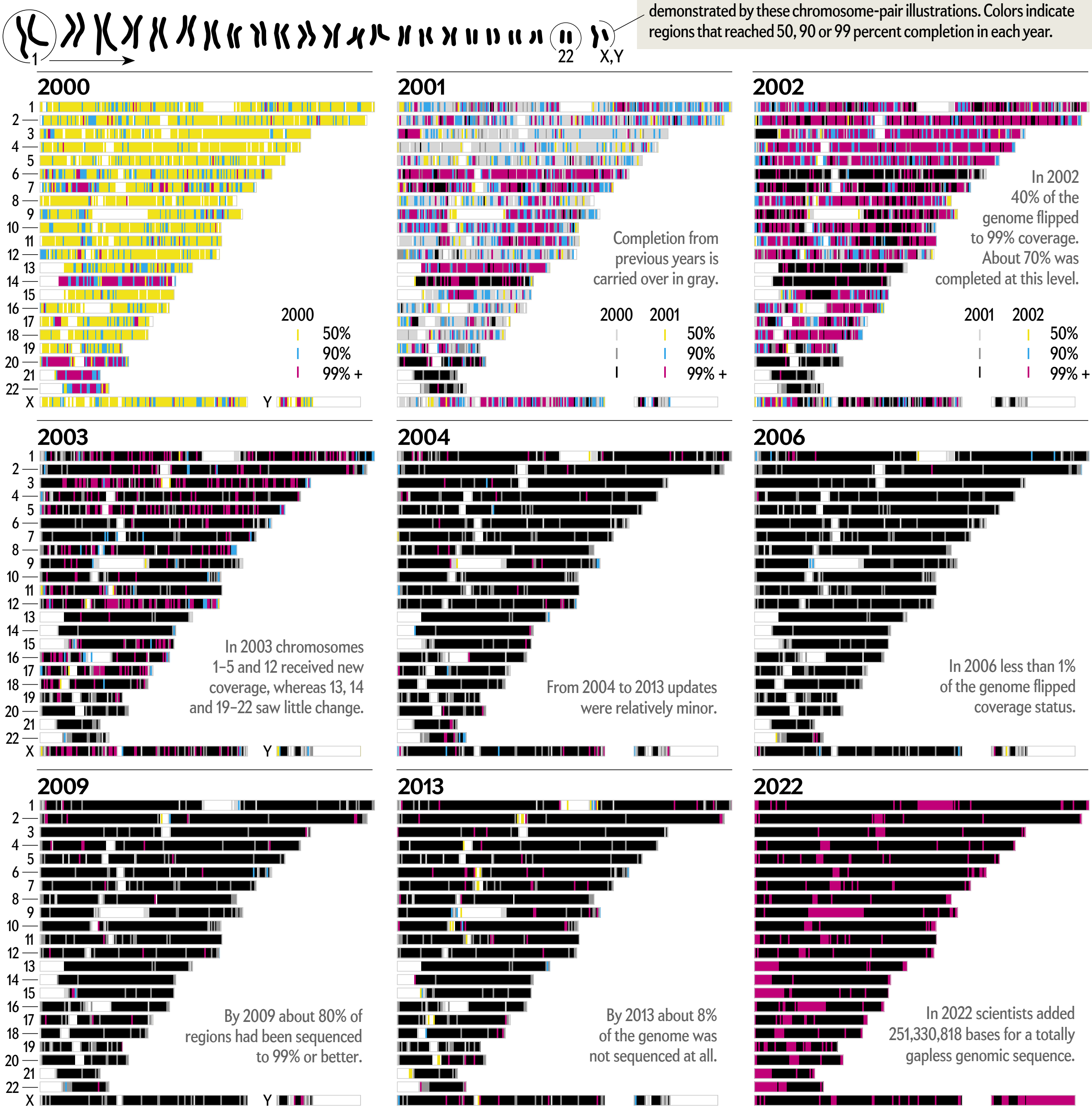
1922, GASOLINE: "In 1904, when the automobile was just coming into its own, gasoline represented an eighth of the refiner's business; today it is between a quarter and a third. Kerosene, which constituted practically 60 percent of the output, is now less than one eighth. Heavy fuel oil, which shares the internal-combustion field with gasoline and competes with coal in the raising of steam, has leaped from 16 to 55 percent."

Scientific American, Vol. 127, No. 2; August 1922

GRAPHIC SCIENCE

Text by Clara Moskowitz | Graphic by Martin Krzywinski

In the horizontal bars below, each of the 22 numbered human chromosomes and two sex chromosomes (X, Y) are divided into regions (*thin vertical stripes*) of 1,000,000 bases, or nucleotides. Different bar lengths reflect the chromosomes' varying physical lengths, as demonstrated by these chromosome-pair illustrations. Colors indicate regions that reached 50, 90 or 99 percent completion in each year.



Sources: UCSC Genome Browser; "The Complete Sequence of a Human Genome," by Sergey Nurk et al., in *Science*, Vol. 376; April 2022

3,117,275,501 Bases, 0 Gaps

After 22 years, scientists have deciphered our genetic code

The human genome is at last complete. Researchers have been working for decades toward this goal, and the Human Genome Project claimed victory in 2001, when it had read almost all of a person's DNA. But the stubborn remaining 8 percent of the genome took another two decades to decipher. These final sections were highly repetitive and highly variable among individuals, making them the hardest parts to sequence. Yet they revealed hundreds of new genes, including genes involved in immune responses and those responsible for humans developing larger brains than our primate ancestors. "Now that we have one complete reference, we can understand human variation and how we changed with respect to our closest related species on the planet," says geneticist Evan Eichler of the University of Washington, one of the co-chairs of the Telomere-to-Telomere consortium that finished the genome.