VOLUME 246 AUGUST 2024 NUMBER 02

NATIONAL GEOGRAPHIC

ROLEX AND NATIONAL GEOGRAPHIC
PERPETUAL PLANET AMAZON EXPEDITION

DAWA YANGZUM SHERPA,
INTERNATIONAL
MOUNTAIN GUIDE

FRANCESCO SAURO, EXPLORER

CRISTIAN DONOSO, EXPLORER

GHISLAIN BARDOUT,
EXPLORER

WHAT DO THEY SEEK?

Explorers, adventurers, scientists. Men and women who always broadened the horizons, for all humankind to share. Rolex was at their side when they reached the deepest point in the oceans, the highest summits of the Earth, the deepest jungles and both poles. But now that we know, more than ever, that our world has its limits, why do they continue to venture out there, again and again? Certainly not for kudos, accolades, or an ephemeral record. What they truly seek is to understand more intimately how complex and delicate our planet is, to document its change and how together, we can affect it for the better. So as long as they need it, we will be at their side. Because today, the real discovery is not so much about finding new lands. It's about looking with new eyes at the marvels of our planet, rekindling our sense of wonder, and acting to preserve our pale blue dot in the universe…
Doing our very best for a Perpetual Planet.

#Perpetual

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Perpetual Planet
Initiative

ROLEX

FROM *the* EDITOR

NATHAN LUMP

WHEN MY HUSBAND and I lived in Seattle, we noticed something peculiar on our house's deck overlooking Puget Sound. In one spot, there was a continual accumulation of what looked to my eye to be mouse poop. But it was both on the deck's floorboards *and* on the exterior wall of the house. We couldn't figure it out.

When a pest control company came to investigate, they knew instantly what it was: bats. The design of our house—its steeply pitched roofline with deep overhangs—had created a perfect place for them to roost. It was a favorite launchpad for bats to conduct their nighttime forays to hunt insects.

We didn't try to deter them. Bats occupy an important place in our ecosystems, and watching them fly out into our little valley every evening soon became one of my favorite activities. In many ways, bats are an evolutionary marvel, and what we are continuing to learn about them is the subject of a fascinating feature this month.

We also have a look at the renaissance of France's iconic river, the Seine, just in time for the Olympics; the science of inflammation; and more.

I hope you enjoy the issue.

MARK THIESSEN

CONTENTS

ON THE COVER

SUBSCRIBER EDITION Brown University professor Sharon Swartz releases an Egyptian fruit bat into a wind tunnel to study the mechanics that allow it to fly.
Photograph by NICHOLE SOBECKI

NEWSSTAND EDITION A reflection of the Eiffel Tower appears in the early morning waters of the Seine, which is undergoing a decade-long rehabilitation.
Photograph by TOMAS VAN HOUTRYVE

ENVIRONMENT

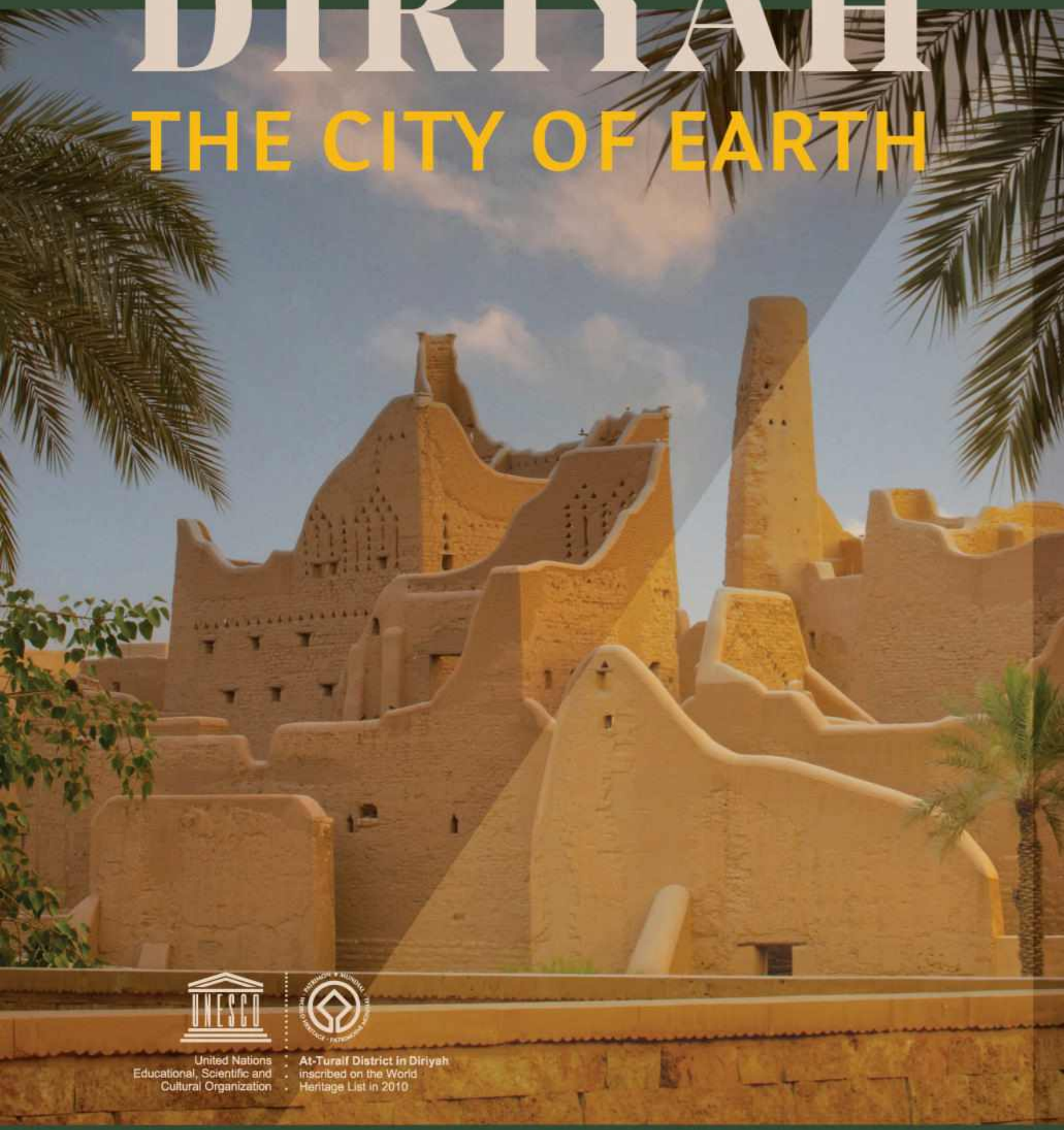
"I was grateful for the opportunity and luck to enjoy such A UNIQUE MOMENT and to be in this fantastic place under a starry sky *without light pollution*."

MARCIO ESTEVES CABRAL, *Photographer*

In this panoramic image stitched from nine exposures, the Milky Way hovers above a field of *Paepalanthus* wildflowers in Brazil's Cerrado region.

DIRIYAH

THE CITY OF EARTH



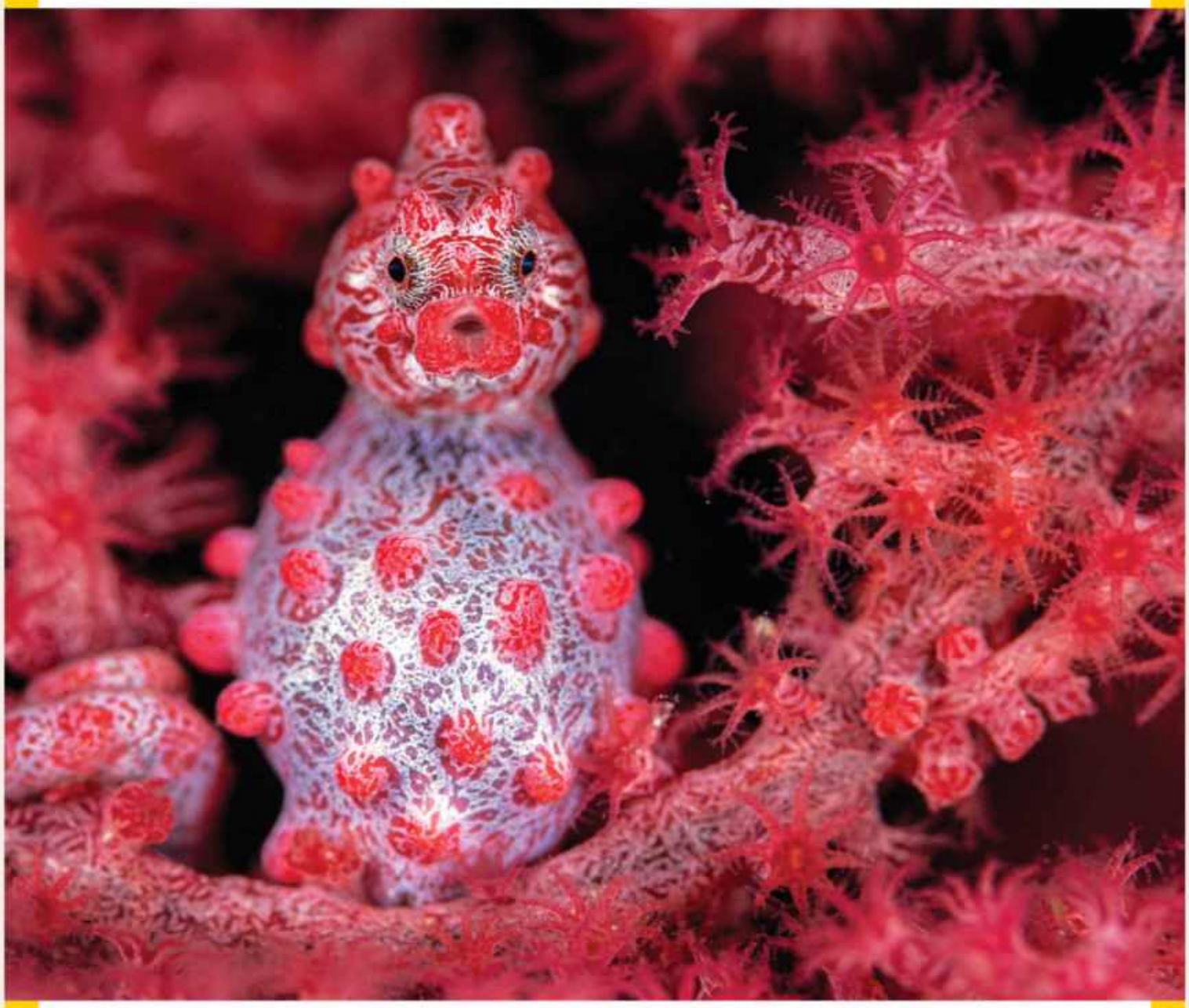
United Nations
Educational, Scientific and
Cultural Organization

At-Turaif District in Diriyah
inscribed on the World
Heritage List in 2010

At-Turaif,
UNESCO World Heritage Site
The birthplace of the Kingdom
A 300-year-old legacy

DIRIYAH.SA

Only in Saudi



ANIMALS

"After *a week of checking out* multiple sea fans for the best examples of pygmy seahorses and coral polyps, I shot this photo at 6 a.m. That's when everything FINALLY CAME TOGETHER."

BYRON CONROY, *Photographer*

Only about half an inch high, a pygmy seahorse—male and pregnant—gazes out from a maze of coral polyps in Indonesia's Lembeh Strait.

SELENA GOMEZ STEVE MARTIN MARTIN SHORT

Parental Control Advised

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SCIENCE

"This image is a celebration of the often OVERLOOKED BEAUTY in the simplest things around us. Who knew sugar syrup could look like an *abstract painting* in a museum of modern art?"

DIEGO GARCÍA, *Photographer*

Captured with a camera-mounted microscope under polarized light and magnified 25 times, crystallized sugar syrup looks nothing like the pancake topping.

AUGUST

CULTURE

"Branding at Forty Mile Colony is ABSOLUTE ORGANIZED CHAOS. Men and women weave around each other—as well as the horses, cattle, ropes, and *red-hot brands*—in harmony to get the work done."

TIM SMITH, *Photographer*

Members of Hutterite religious colonies work together in Montana to place identity marks on calves. Hutterite livelihood relies heavily on agriculture.

NATIONAL GEOGRAPHIC EXPLORERS

These contributors have received funding from the National Geographic Society, which is committed to illuminating and protecting the wonder of our world.

Nichole Sobecki, p.16

An Explorer since 2021, the Nairobi-based photographer specializes in humanity's connection to the natural world. She documented cheetah trafficking through Somaliland for our August 2021 issue and Sudan's ancient past and uncertain future for the January 2022 magazine. This month her feature spotlights the mysterious world of bats.

Tomas van Houtryve, p.58

His work spans photography, filmmaking, and art installations. Based in Paris, he's focused recently on the Seine, for this issue, and the rebuilding of Notre Dame, the subject of his 2022 cover story. He became an Explorer this year.

Mary Winston Nicklin, p.58

"The Seine's stories are infinite," says the Franco-American journalist, who lives in Paris and traveled the length of the river to research this month's story on the vast cleanup of the famed waterway.

James Gorman, p.16

A former science reporter for the *New York Times,* he has written numerous stories about bat flight and bat life. He now competes with big brown bats for use of his front porch in upstate New York.

Ferris Jabr, p.88

Making his home in Portland, Oregon, Jabr is the author of *Becoming Earth: How Our Planet Came to Life.* The feature on shell formation is his second for the magazine, after a 2022 story on soil ecology.

CLOCKWISE FROM TOP LEFT: MARK THIESSEN, NGM STAFF; MARCO CASINO; RYAN G.; KATE HOOPER GORMAN; MARY WINSTON NICKLIN

A

This photographer-artist c
English botanist Ann

ANNA ATKINS, NEW YORK PUBLIC LIBRARY (TOP); HUGH TURVEY

A cyanotype from Atkins's work on British algae (top) inspired the shell images made by Turvey (above). His previous work for *National Geographic* includes specialized imaging of elephant skulls, iPhones, and pythons.

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DIFFERENT LIGHT

combines the pioneering work of 19th-century
na Atkins with modern x-ray technology.

RAY ARTIST Hugh rvey is obsessed with e inner workings of ngs. The aim of his art: "peel back the layers" the physical world and ow it in "a different nt." For this month's ry on the science shells (page 88), the ndon resident com- ned two techniques to just that. To see inside e shells, he layered ay film, which exposes erior densities, with anotypes. The latter is a camera-free technique of placing objects on salt-treated paper that turns blue when exposed to UV light and water (aka blueprinting). Avoiding inverted images was a challenge. Turvey found himself ditching the digital world for the darkroom and playing with chemicals, which he hadn't done in years. It was quite slow going, he says, but the "old-school, analog process was just a joy."

BATS

A

LOVE

STORY

DAZZLING IN FLIGHT, MYSTERIOUSLY RESISTANT TO DISEASE, VITAL TO ECOSYSTEMS AROUND THE GLOBE—BATS ARE A SCIENTIFIC WONDER.

WORDS BY JAMES GORMAN

PHOTOGRAPHS BY NICHOLE SOBECKI

How do bats fly? Scientists at Brown University in Rhode Island are releasing the winged mammals, such as this Egyptian fruit bat, into a laboratory wind tunnel to study flight mechanics.

Doctoral student Brooke Quinn, at right, and her adviser, Sharon Swartz, work with a Seba's short-tailed bat in the lab tunnel at Brown. Bats have tiny sensory wing hairs that help them "feel" their way through the sky.

Not everyone falls in love with bats, but those who do fall hard.

AS A YOUNG SCIENTIST, Sharon Swartz studied gibbons. But she was intrigued by the fine skeletal structure of bat wings and by the evolutionary trade-offs necessary for mammals to take flight. So she took a detour from her primate research and traveled to Australia to study the large bats known as flying foxes.

She recalled one evening when she visited a suburban golf course where roosting bats filled the trees. First one, then a few more, then hundreds of the creatures lifted off as the sun set until, she said, there was "a river of bats in the sky." The next night Swartz, now a professor of biology and engineering at Brown University, and her colleague trapped bats in nets, and she held one for the first time. It was a flying fox with a wingspan of several feet. "My heart was racing. It felt like I had never seen anything so beautiful."

The more common reaction is probably an involuntary shudder. Bats have long been

National Geographic Explorer Paul Webala, a wildlife biologist at Maasai Mara University, and Erick Keter, a University of Eldoret biology student, catch bats at the Three Sisters Cave complex in southeast Kenya to record their vocalizations and collect genetic data.

associated with darkness and evil in Western culture, and unsettlingly hard to place in folk taxonomy—not birds but airborne, not rodents but small and furry. And, for some species, disturbing in close-up. The poet Theodore Roethke wrote, "something is amiss or out of place / When mice with wings can wear a human face."

Some people just find them creepy. Others worry about the diseases they may carry, including those similar to the virus that caused the COVID-19 pandemic. To be fair, dogs with rabies kill vastly more humans than bats do, and the flu virus passes through ducks and pigs, but none of these animals elicits the same dread. The writer D.H. Lawrence lapsed into a kind of know-nothing distaste when contemplating bats "hanging upside down like rows of disgusting old rags." One might have hoped that the author of the scandalous *Lady Chatterley's Lover* would be more open-minded, but no. "In China the bat is symbol

Webala captures a striped leaf-nosed bat as part of a project to build an acoustic library of Kenyan bats. Eventually, researchers may be able to identify and differentiate bat species using their calls.

for happiness," he wrote. "Not for me!"

For true bat appreciation, even evangelism, biologists like Swartz and her colleagues have no competition. Many have the zeal of converts who at some point turned from other mammals to find a wonderland of scientific mysteries, like bats' impossibly acrobatic flight, their remarkable longevity, or their enviable resistance to most cancers. Scientists worldwide are probing these secrets. Some hope to turn insights into these animals to human benefit. Others are simply captivated by their breathtaking diversity and evolutionary history. They would like you to know, queasy poets notwithstanding, that bats are so much more than flying mice.

BATS ARE ONE OF evolution's great success stories. Their ancestors were small mammals that scurried on all fours and probably lived on an insect diet, as many bats do now. How those ancestors came to fly is an unsolved mystery. The oldest known bat fossils—from the Green River geological formation in Wyoming, dating to more than 50 million years ago—already show the transformed forearm and fingers that form the scaffolding for the thin, muscular membrane of the bat's wing. Thus the Latin name for the order of bats, Chiroptera, meaning "hand wing."

Once bats had taken flight, they filled every ecological niche available to winged creatures and spread around the globe. One-fifth of all mammal species are bats. Only the order of rodents has more members. Bats eat everything: insects, fruit, nectar, blood, and fish. They range in size from the bumblebee bat, weighing in at less than an ounce, to the biggest flying fox, a fruit bat with a nearly six-foot wingspan and weighing up to three pounds. Some species are solitary, but many are social. They live in vast colonies and in small groups, roost in trees and caves and attics and behind house shutters. They are an integral part of just about every ecosystem. They consume mosquitoes and agricultural pests, and pollinate plants like bananas, mangoes, avocados, and durians,

On many nights, some five to 10 million straw-colored fruit bats leave their fig-tree roosts in Zambia's Kasanka National Park. They fly more than 30 miles in search of fruit. Kasanka is a stopover as they undertake one of the largest mammal migrations in the world.

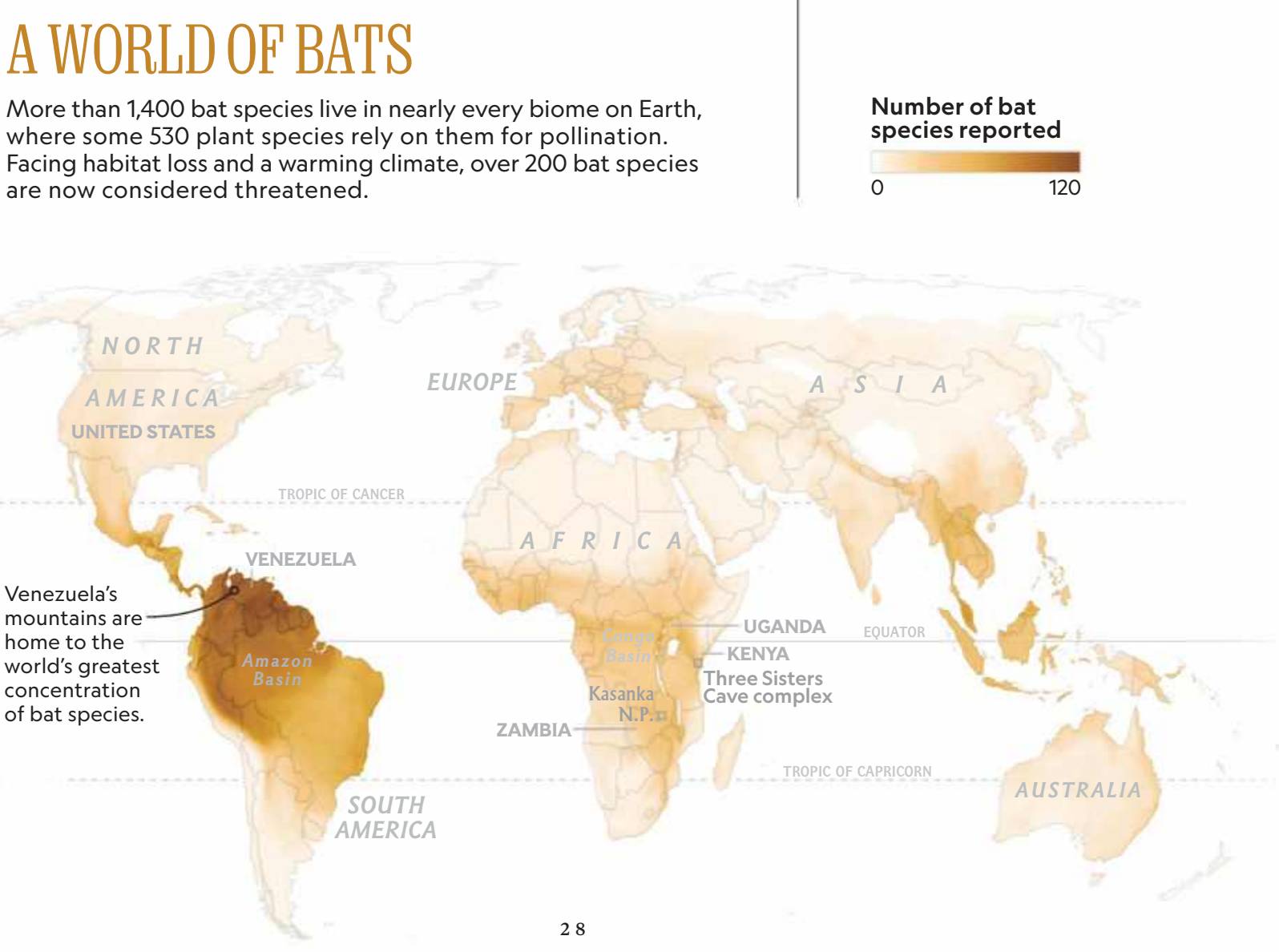
the notoriously odorous and economically important Asian fruit. Not to mention the prized agaves of the Sonoran Desert. In short: No bats, no tequila.

And they fly like no other creature, which is what first drew Swartz to that Australian golf course more than 30 years ago. At the time, she was studying the mechanics of movement in primates, looking at how skeletons evolved to balance the need for strength with the disadvantages of heavier bones. "It seemed obvious that weight is a problem for flying animals in a way that it isn't for anybody else," she said. "The structure of these limbs magnetized me in a way that no primate limb ever had."

Because bat wings are made of skin stretched on light bones with many joints, they interact with the air in ways that are not possible for less flexible bird and insect wings. Bird wings have three joints, roughly corresponding with the human shoulder, elbow, and wrist. "Bats have almost as many joints in the wing as we have in a human hand," Swartz said, "and they also have these crazy muscles that are embedded in the skin." Bat wings are covered with countless tiny hairs that sense shifts in airflow. They are in constant conversation with the air, changing shape, creating lift, responding with idiosyncratic invention to each puff and gust: In tests that Swartz and her team ran to present a challenge to normal flight patterns, they found that when they injected a saline solution into bats' abdomens to mimic the weight of a big meal, each animal responded in a different way. Dimitri Skandalis, who studies this extraordinary individual variation at Johns Hopkins University, compared the complexity of bat wing movement to human facial expressions. All smiles are recognizable as smiles, but no two are exactly the same.

A WORLD OF BATS

More than 1,400 bat species live in nearly every biome on Earth, where some 530 plant species rely on them for pollination. Facing habitat loss and a warming climate, over 200 bat species are now considered threatened.



Could this intricate, intuitive movement be replicated in a machine? Bat flight is "dancing in the air," said Alireza Ramezani, an assistant professor of engineering at Northeastern University. "For me, creating a drone that looked like that was exciting." Inspired by Swartz's experiments, he took on the challenge of creating bat robots. With the flexibility of hands and the stretchiness of skin, bat wings can cope with rapid and complex shifts in airflow, particularly those that exist inside confined spaces.

"There's so many challenges from an engineering design standpoint. How can you have all these components inside a system, a drone that weighs a hundred grams?" One of the keys to understanding and replicating bat flight, Ramezani said, is that bats do not consciously make every split-second decision. The soft tissue of bat wings deforms and reshapes in response to air pressure without needing direction from the brain's air traffic control center—an example of what engineers call passive dynamics. As bats move their major wing joints, the membrane of the wing transfers that movement to the smaller joints, and the stretchiness of the wing responds to the flow of air against it. "In bats," said Ramezani, "you have the locomotion characteristics of jellyfish and the locomotion characteristics of birds."

Although the beauty and complexity of bat flight first caught his attention, Ramezani said, the potential usefulness of a bat drone helped drive the project forward. Building on Swartz's findings, he and his team created a soft-bodied robot that can navigate in environments where quadcopter drones, now ubiquitous in peace and war, can't. In the United States alone, he said, there are more than a million miles of sewer lines that are difficult or dangerous for humans to inspect and monitor. And there are caves to explore, for mining and paleontological or archaeological research. What better place to send a bat robot than a small, dark cave, in search of ancient bones or artifacts?

EMMA TEELING, LIKE MANY of her colleagues, came to bats "completely, utterly, and totally by chance." Teeling is a co-founder of Bat1K, a project to sequence the genomes of all 1,400 or so species of bats, and one of the founding advisers of Paratus Sciences, a start-up devoted to mining bat biology for ways to fight human diseases. "We believe," its website states, "that bats hold the key to a safer and healthier world."

After initially working with foxes and deer, Teeling wanted to do a Ph.D. on mate choice in domestic cats and was trying without success to persuade various labs to take on her project. But, she said, there was a fully funded position in Belfast, Ireland, using genetic comparisons of living bat species to trace the evolution of echolocation. She applied, got the spot, and "literally, within six weeks, I got hooked." She quickly became fascinated by the weird biology of bats. Live small, die young is the general rule for mammals. But bats the size of mice can survive for decades. "They live for a ridiculously long time," for their size, she said. They rarely get cancers. "They can carry all these viruses without getting sick." Teeling, now a professor at University College Dublin, had to know why.

The answer she has become more and more convinced of over the years is one that at first blush seems hard to comprehend: They fly. Her hypothesis is that flight led bats to evolve unusual immune systems, which in turn led to longevity, even resistance to cancer.

Bats need to burn a lot of fuel to catch bugs on the wing, to dive and pitch and roll like a scarf in the wind. One study estimated the metabolic rates of flying bats to be three to five times those of similar size land mammals. Cellular engines called mitochondria have to work overtime to produce energy for flight. As a side effect, they also produce chemicals called free radicals that are known to harm DNA. "We should see this high level of damage" to DNA in bats, Teeling said. But in experiments, that is not what she and her

MAP: CHRISTINE FELLENZ, NGM STAFF. SOURCES: CLINTON JENKINS, *BIODIVERSITYMAPPING.ORG*; IUCN; BAT CONSERVATION INTERNATIONAL

BAT SUPERPOWERS

Over the course of 50 million years bats evolved from tree gliders to the only mammals that fly. The key to their success is a host of unique adaptations that have allowed them to thrive in an environment few animals exploit: the night sky.

ILLUSTRATIONS BY DENISE NESTOR

SMALLEST BAT

Kitti's hog-nosed bat (or bumblebee bat)
Craseonycteris thonglongyai
Weight: .07–.11 ounce
Wingspan: about 5 inches

MAMMALIAN FLIGH

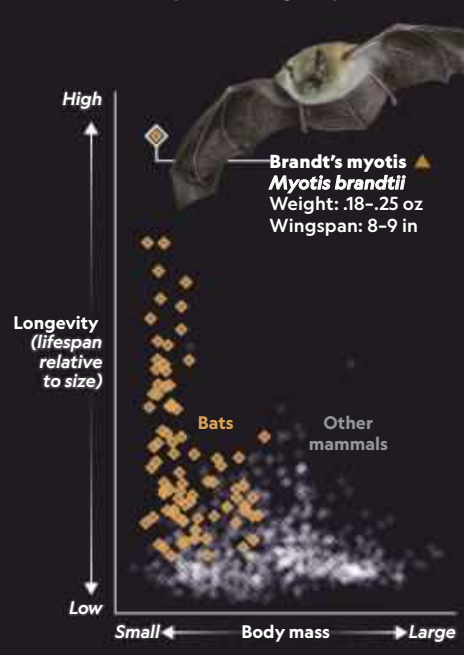
Since the age of dinosaurs, bat wings developed to fit myriad environment wings are good for hovering in forest wings, such as those of Brazilian free-t bats, enable these mammals to fly at of up to 99 miles an hour.

Brazilian free-tailed bat
Tadarida brasiliensis
Weight: .28–.53 oz
Wingspan: 12 in

Sensory across t ical trait insects– respond change

EXTREME LONGEVITY

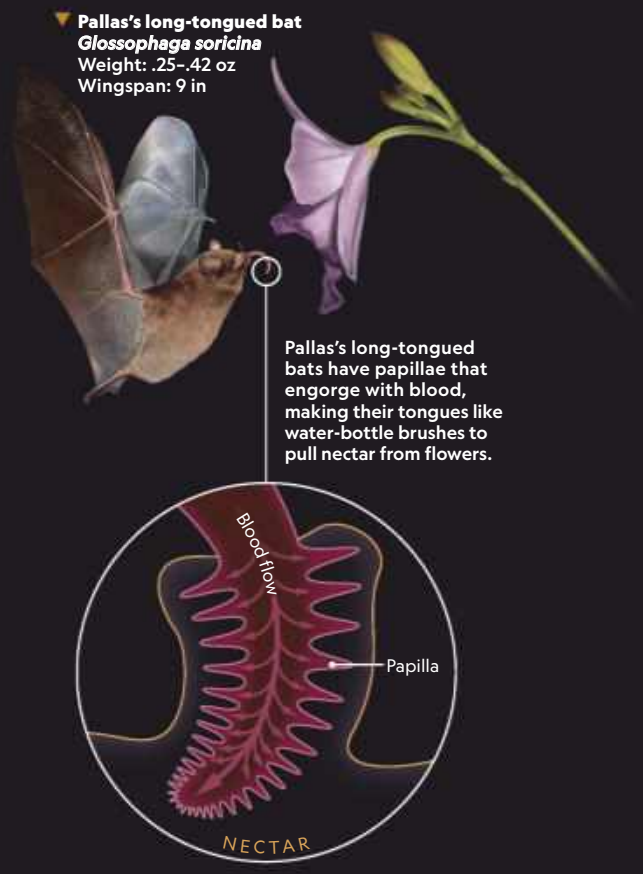
Although they're some of the smallest mammals, bats can live up to 10 times longer than expected for their body size. They also almost never get cancer. An ability to shut down their metabolism when at rest is one factor that may boost longevity.



Data comparing bat longevity are sparse, but the Brandt's bat holds the record for the longest lived, at 41 years.

TURBOCHARGED METABOLISM

Different bat species have different appetites, ranging from insects, fruit, and blood to small animals, including other bats. Pallas's long-tongued bat has the fastest metabolism recorded in any mammal, burning through more than half its fat stores every day.



ECHOLOCATION

By sending out ultrasonic sounds and gulating the resulting echoes, many b their surroundings. These calls can be that some bats can temporarily immo their ear bones to keep from going de brown bats modulate their calls to he navigate cluttered acoustic environm

Big brown bat
Eptesicus fuscus
Weight: .39–.81 oz
Wingspan: 13–16 in

GRAPHIC: JASON TREAT AND EVE CONANT, NGM STAFF. BRANDON SHYPKOWSKI
SOURCES: DEEANN REEDER, BUCKNELL UNIVERSITY; SHARON SWARTZ, BROWN UNIVERSITY; NANCY SIMMONS, AMERICAN MUSEUM OF NATURAL HISTORY; EMMA TEELING, UNIVERSITY COLLEGE DUBLIN

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LARGEST BAT

Golden-capped fruit bat
Acerodon jubatus
Weight: 2-3 pounds
Wingspan: 5-6 feet

Bat wings are supported by the same bones humans have in their arms and hands. If a human had the same proportions as this giant bat, however, the middle finger would be about seven feet long.

Thumb

Finger

Egyptian rousette (or Egyptian fruit bat)
Rousettus aegyptiacus
Weight: 3–6 oz
Wingspan: 2 ft

DISEASE RESISTANCE

Many bats live in extremely dense populations, perhaps one reason they display immunity against a host of viruses. In many cases, they can tolerate infections without ever showing symptoms. The Egyptian rousette is a known carrier for the Marburg virus, a relative of Ebola.

WITH PERMISSION OF ROM (ROYAL ONTARIO MUSEUM), TORONTO, CANADA

The oldest fossilized skeleton of a bat—the minuscule 25-gram ***Icaronycteris gunnelli***—shows bats had already evolved the ability to fly 52 million years ago.

AN ACROBATIC AERIAL ATTACK

Split-second photos reveal a quick bat snack.

PHOTOGRAPHS BY MARK THIESSEN

When the first known bats appeared during the Eocene epoch, they probably had evolved echolocation to hunt insects in the air. Modern descendants such as this Townsend's big-eared bat have reached the apotheosis of aerial predation. The Townsend's echolocation calls are quieter than other bats' and their flight more acrobatic.

This series of photos shows one Townsend's hunt, captured by staff photographer Mark Thiessen in a field tent in Arizona.

In just half a second, the bat locates a moth (1), reaches to grab it with a wing (2), and transfers it from the wing to its tail pouch (3). Afterward, the bat will lower its head to retrieve the moth for a mid-flight meal. Aaron Corcoran, a University of Colorado, Colorado Springs researcher and National Geographic Explorer who studies the interaction between bats and their prey, said he had never seen a comparable photographic sequence. "You simply can't see what's going on with the naked eye."


1
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MARK THIESSEN

colleagues have found. In fact, they discovered that as the bats they studied aged, their ability to repair their DNA increased.

Another side effect of energy production in flight is that the mitochondria break down, and the results can look to the immune system like foreign invaders. So flight could produce a surging immune response—and inflammation. Bats would need to control that. Studies have shown that they not only respond to viruses that infect them, but they also tamp down that response, avoiding a damaging overreaction. That could also have evolved as a result of flight.

The connection is far from proven, and there are plenty of skeptics, Swartz among them. "I'd be more confident in that line of reasoning if we saw enhancements of immune function and longevity in other animals that have elevated metabolism, like birds or migratory mammals," said Swartz. Teeling said that, actually, many birds do live longer than might be expected given their size. She noted that in one survey of many

Researchers in Arizona take bat-wing temperatures before and after flight. One mystery is how bats' ability to regulate body temperature can vary widely, even moment to moment, depending on environmental conditions.

species, the single best predictor of long life was the ability to fly. She recognized, however, that this kind of correlation is far from proof and that more investigation is needed—the Bat1K project's genome sequencing, for instance. By comparing the genomes of many bat species, scientists can see what they have in common, pinpoint which genes are active in DNA repair and immune activity, and calculate when those abilities might have evolved. If they came with flight, that would be a strong indication that the two are linked.

WHATEVER LED BATS TO tolerate certain deadly viruses, a number of researchers are searching for genetic insights. Several immunity-related bat genes have been identified, and some have been experimentally transferred to other species, where they provide the same benefits. For instance, lab mice engineered with a bat gene showed resistance to bat influenza. Beyond bat flu, researchers wonder if there is an immunological advantage that all bats have, that works with viruses in general, or if disease resistance depends on the species and its history of exposure to specific viruses. Some species are reservoir hosts, meaning viruses live within the animal without causing disease. Presumably, a reservoir host would have a different reaction than a related species that is not usually exposed to the virus.

Ebola is a classic example. It is devastating to humans and some other mammals, and most scientists suspect that bats are the natural reservoir. Some bat species show evidence of exposure when their blood is sampled, while others do not. In Uganda, a team of U.S. and Ugandan scientists is using detailed tests of gene activity to find out precisely how different bats respond to Ebola (or, more specifically, to a noninfectious fragment of Ebola virus).

"Bats are extraordinary and amazing," said Bucknell University's DeeAnn Reeder, the team leader. "I want to understand how the heck they do all the things that they do, and their immune system is a piece of that. They're exceptionally good at managing those pathogens to avoid illness themselves." She and her Bucknell colleague Ken Field and Imran Ejotre at Muni University are trapping and

immunizing bats with Ebola proteins in hopes of seeing exactly how the immune systems of different species cope with a viruslike threat.

One species that Reeder and her colleagues are studying is the little epauletted fruit bat. Researchers have found signs of exposure to Ebola viruses in this species and its relatives, suggesting that they may have coevolved with these viruses. That could mean they have a greater ability to tolerate infection. Another species, the green house bat, shows no indication of living with Ebola. Researchers sample the blood and tissue of immunized bats, as well as control groups, to see which genes are active, and how active, after a first injection and a booster shot.

For the bats that seemed to have coevolved with some pathogens, Field said, "these viruses do not kill these bats. They don't even make them sick." Comparison with other bat species could pinpoint the immune strategies of resistant bats. Then the question with an enormous payoff is whether human biology could be manipulated to act in the same way. For instance, during the COVID pandemic, one of the things doctors noted in ill patients was a cytokine storm, a burst of proteins that caused such severe inflammation that patients died. What if scientists could find a way to mimic the immune systems of bats with a drug?

FOR THE SCIENTISTS who study and love them, bats are not only scientific treasures but also living beings that are at once so like us—with their hand wings, warm blood, and live birth—and yet irresistibly alien. Inevitably, students of bats become protectors of bats.

Tigga Kingston at Texas Tech University, who studies Southeast Asian bats and is deeply involved in bat conservation research, said that despite the great evolutionary successes of bats, they have many vulnerabilities. For instance, though they may seem like flying mice, rodents breed early and often, having multiple litters a year. Bats start reproducing

PROBING HOW BATS BEAT EBOLA

From the wild to the lab, scientists have developed a process for testing disease resistance.

1 BAGGING A BAT

Epauletted fruit bats hang in cheesecloth bags after being trapped near the village of Kanabu in northwestern Uganda. These bats seem to be able to survive Ebola virus infections, which can kill other mammals. Scientists want to find out how.

2 PREPPING FOR TRANSPORT

DeeAnn Reeder of Bucknell University works with her team to bag and label the bats. The bats spend a few nights in a screen tent flight cage before they are transferred to enclosures at Muni University in Arua, a two-hour drive away.

1

2

3 REST AND RECOVERY

Before leaving the field camp, the research team transfers the bats to large tents where they are free to fly. As part of the protocol, says Reeder, "we give them a little mango juice."

4

5

Researchers are working to identify how bat pathogens might spill over into human populations to spread disease. Key to curtailing the threat is preserving bat habitats and helping communities value bats as essential parts of the ecosystem. "You can't afford to do only science," says Imran Ejotre of Muni University.

4 TESTING IMMUNE RESPONSE

Members of the Muni University research team inject bats with noninfectious pieces of Ebola virus. The process is similar to vaccination. The team is experimenting with three bat species, each with distinct histories of exposure to Ebola, to observe differences in immune response.

5 TAKING TISSUE SAMPLES

For each bat in the study, Reeder and Adiga Kasim, a project technician, take more than 20 blood and tissue samples, along with other measurements. The many tests may reveal which genes allow some bats to tolerate deadly viruses, perhaps eventually aiding human medicine. The team is also trying to understand which bats are reservoir hosts for Ebola.

later than rodents, in their second or even third year, and have one offspring a year on average. Naturally, not all of those survive. "As a consequence," Kingston said, "anything that disturbs their populations is difficult for them to recover from." More than 200 species around the world are listed as threatened.

Bats are subject to all the problems of habitat loss and human encroachment that plague other species, along with some peculiar to them. White-nose disease has killed vast numbers of North American bats. Overharvesting of agave plants threatens nectar-feeding bats. And there is climate change. Some of the most at risk from a warming planet are large fruit bats, like those in Australia. They don't roost in caves but in the open, and extreme heat can kill them. "When it hits around 42° to 44°C [108° to 111°F], depending on the species, they just die of heatstroke," Kingston said. Mass die-offs have pushed some species that were doing well only 10 or 15 years ago to endangered status.

For defenders of bats, the first priority is to have good information on the populations themselves. Paul Webala, wildlife biologist at Maasai Mara University and a National Geographic Explorer, is building an acoustic library of the calls of Kenyan bats that he said could be a game changer in knowing the status, movements, and locations of different species. Bat Conservation International supports multiple efforts to monitor threatened species, but it is also working on projects of immediate benefit, such as reducing bat deaths from wind turbines.

In the U.S. hundreds of thousands of bats die each year from wind turbines, said Rodrigo Medellín, a senior professor at the National Autonomous University of Mexico's Institute of Ecology. A National Geographic Explorer at Large, Medellín co-chairs the Bat Specialist Group, part of the International Union for Conservation of Nature's Species Survival Commission, with Kingston. Over 60 percent of those deaths could be avoided, he said, if the industry would agree to start up the turbines at a wind speed of five or six

An Egyptian fruit bat flies in the Aeromechanics and Evolutionary Morphology Lab at Brown. Bats can control the three-dimensional shape of their wings, compensating for air turbulence mid-flight within a fraction of a second.

A bat-inspired robot called the Flapperoo is built to probe flight mechanics at Brown. Scientists can change the wings' flapping speed or skin stiffness to see how each variable alters flight—a level of experimental precision impossible with live animals.

Doctoral student Bibek Gupta demonstrates the Aerobat, a robot in development at Northeastern University in Boston. It is intended to maneuver in city sewers, caves, and other confined spaces where drones struggle to navigate.

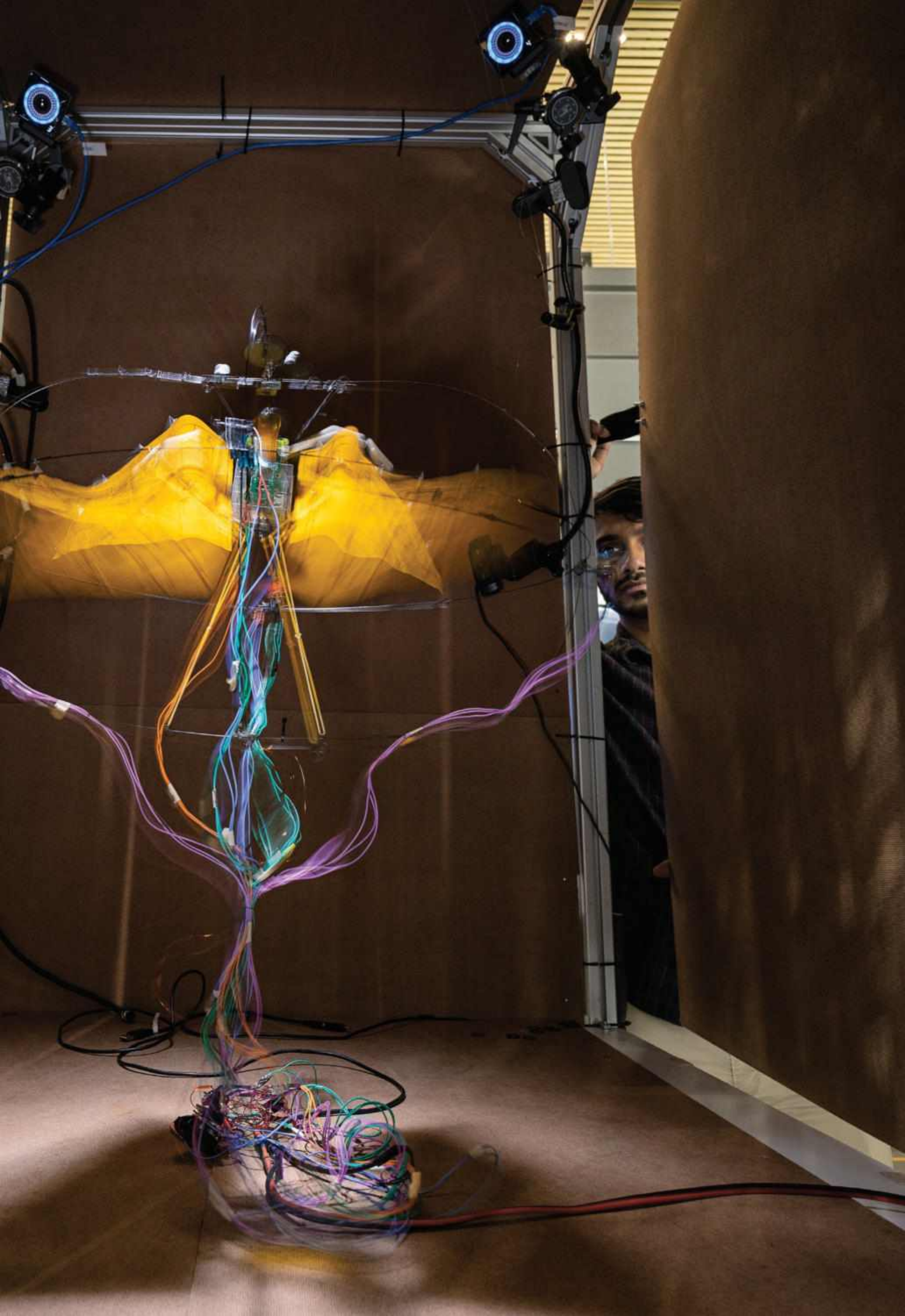
MARK THIESSEN

meters a second instead of three meters a second, resulting in a "tiny loss of efficiency."

Protecting roosts is also a top priority for Medellín. He recently lobbied to divert the path of the Maya Train, a $20 billion tourism project in the Yucatán, away from the famed Volcán de los Murciélagos. The "bats volcano" is the most populous roost from central Mexico to southern Argentina. About three million bats emerge from it each night to feed on insects.

It is just not fair, said Medellín, that such useful animals should have such a bad reputation. "We really owe it to bats to treat them right. And what do they ask?" he said. "Just leave them alone. That's all." In terms of convincing the public of the value of bats, scientists often mention their role in pollinating wild plants and crops and in eating insects, natural pest control worth billions of dollars a year in the U.S. But what about bats as bats, pure and simple? Kingston, who switched her focus from rodents to bats as an undergrad, is wary of placing too much emphasis on the practical value of wildlife. "What if there's a species that we can't pinpoint exactly what it's doing for the ecosystem?" she asked. Are we going to leave it off the list?

It is not a hypothetical question. So much about bats remains unknown. As much as we are learning about them, they are in some ways still undiscovered. And their mystery is as compelling as their usefulness. After 30 years, Swartz said, she still is moved when she steps into a space with the creatures and feels "the rustle of those wings and that breath of air as the animal is going by." One reason: "There are more unanswered questions than things that I understand." □



HISTORY *on* HORSEBACK

A photographer documents the female equestrians who saddle up and keep a Mexican tradition alive.

Photographs by
CONSTANCE JAEGGI

"IT'S ELEGANT and powerful—and also kind of dangerous," says photographer Constance Jaeggi, describing *escaramuza charra,* an all-female Mexican rodeo event popular in communities across North America. Riders known as escaramuzas sit sidesaddle in colorful dresses inspired by fighters of the Mexican Revolution. In teams of eight, they perform veritable ballets on horseback—frequently at a gallop. Growing up in Switzerland, Jaeggi adored horses and learned to ride at age 14. Nearly two decades later while living on a Texas ranch, she competed in equestrian contests and became fascinated with escaramuzas, seeing them as kindred cowgirls. After traveling the United States to interview and photograph them, she began to see how the sport offers Mexican American women a sense of connection to their heritage. **—ASHLEY HARRELL**

Constance Jaeggi photographed riders for Escaramuza Charra Azteca from Manor, Texas, and other teams at practices and competitions.

(Clockwise from above)

Interest in Mexican rodeo often runs in families. Laura Escobedo of Brownsville, Texas, learned about the sport from her parents.

Miranda Vargas's portrait is displayed at the National Cowgirl Museum and Hall of Fame in Fort Worth, Texas, along with some of Jaeggi's other works.

When competing, members of Escaramuza Charra Villa de Guadalupe, of Brownsville, wear sombreros, ruffled dresses, and *rebozos,* knotted shawls worn around the waist.

At a morning practice in Manor, Escaramuza Charra Azteca riders kick up dust, a move mimicking revolutionary battle tactics.

Rosary beads, religious cards, and cameos, such as these belonging to an escaramuza from Manhattan, Illinois, often adorn uniforms.

Part of Escaramuza Quetzalli from Des Moines, Iowa, Isabelle Marquez, 19, and cousins Candy Murillo Guzman, 15, and Wendy Murillo Camarena, 23, pose after a competition in Katy, Texas.

The

A CLEANUP OF OLYMPIC PROPORTIONS IS

Seine's

PLAYING OUT ON FRANCE'S MOST CELEBRATED RIVER

Renaissance

Words by **MARY WINSTON NICKLIN**
Photographs by **TOMAS VAN HOUTRYVE**

The Seine twists its way along a verdant landscape near Esclavolles-Lurey in north-eastern France.

Previous photo

River water passes through an aeration tank at the SIAAP Seine Aval plant, an instrumental player in making the Seine more swimmable.

PHOTOGRAPHED AT USINE SEINE AVAL DU SIAAP

Thousands of athletes competed in the 2023 Garmin Paris Triathlon, which included a swim in the Bassin de la Villette, an artificial lake that links two canals in the capital's 19th arrondissement.

A MAN CLIMBS OVER THE RAIL of the Pont des Arts in Paris. Below, the Nesquik-colored currents of the Seine, swollen from recent rain, sluice past the Louvre Museum. A crowd of spectators gathers and gawks. And then he jumps.

Thomas is one of the elite Paris firefighters stationed at the La Monnaie Rescue Center, a floating fire station in central Paris. (Official policy requires the omission of last names for security.) He bobs in the river for a matter of seconds before fellow firefighters fish him out of the 37-degree water and into a waiting rescue boat. Training exercises complete, the pilot speeds back to their base—a converted 1927 cargo boat that's kitted out with a gym, an aquarium, and an outdoor shower with the prettiest views in Paris. Under the boat lurks a giant, six-foot *silure* catfish they've nicknamed Roger.

Unique in France, the Paris Fire Brigade is a French Army unit thanks to an imperial decree by Napoleon in 1811. The "fluvial" force—as opposed to "terrestrial"—must undergo a rigorous training and selection process. They put out barge fires, rescue people from drowning, and on a fateful day in April 2019, helped extinguish the devastating Notre Dame inferno by pumping water directly from the Seine.

For years, these firefighters have been among the solitary few authorized to swim in the Seine in Paris. What was once a portal to pleasure—Parisians sunbathing and splashing in the river, modeling bikinis in the Seine-fed Deligny pool—has been banned for more than a century because of river traffic and pollution. But that's set to change. After an ambitious $1.5 billion

WILLIAM DANIELS

Riverboats offer a front-row seat to the sights along the Seine, its UNESCO-listed banks lined with monuments. Tourism is just one industry fueled by the waterway.

clean-up project, the river will play a leading role in the 2024 Summer Olympic and Paralympic Games. The Seine will serve as the stage for the Olympic opening ceremony and, if all goes to plan, as a venue for three swimming events.

"Our objective is an Olympic legacy that you and me or whoever happens to be in Paris can swim in the Seine," says Pierre Rabadan, the deputy mayor in charge of sport, the Olympic and Paralympic Games, and the Seine.

In length, the Seine is dwarfed by the Nile, Amazon, Danube, even the Loire. Yet this 483-mile river captures the global imagination, its meandering map a metaphor for France itself. "Over the past twenty centuries, many decisive moments in the history of France have taken place on the banks of the Seine," wrote historian Jean Favier in *Paris: Two Thousand Years of History*.

On the way to its sea outlet between Honfleur and Le Havre, the Seine's sinuous course offers a story at every bend: the Roman conquest of Gaul, Viking invasions, the fall of Richard the Lionheart's formidable Château Gaillard, Joan of Arc's ashes scattered in its currents, revolution, and the rise of the republic. Even after Napoleon's death in exile, he eventually returned as requested in his will a final time to Paris via the Seine—what in life he had called "Main Street."

The Seine has long been a conduit of civilization and national identity, inspiring centuries of French culture, from medieval folklore to Impressionist art. It also plays an outsize role in the lives of its citizens. Memories of my first childhood trip to France are hazy, but I still remember the shimmering reflections of Paris's illuminated monuments. Later, I would get engaged on a bridge, push my daughters' strollers on the quays, and celebrate milestone birthdays on the water. The Seine has always served as solace for sorrow, a willing accomplice to joy.

Since long before contemporary campaigns to grant personhood rights to rivers as a means of legal environmental protection, the French have personified the Seine. For author Victor Hugo, the waterway was both muse and murderer, after the drowning of his daughter Léopoldine in a boat accident. The Seine posed for plein air artists and murmured melodies to minstrels and musicians. And this aqueous character, for much of human history, was venerated as sacred. Especially at the source.

The Seine has long been a conduit of civilization and

Despite its setting in bucolic Burgundy, the river source is owned by the city of Paris. In this strikingly green milieu, springs trickle together into a stream. A small stone footbridge stands as the Seine's first crossing. The ancient Celts brought offerings here to the healing river goddess Sequana, followed by Gallo-Roman pilgrims, whose sanctuary was discovered in the 19th century and excavated by archaeologists. "It's famous for its wooden ex-votos, or sculptures offered to the Seine," says Sylvie Robin, head curator for archaeology at the Carnavalet Museum in Paris. "Either to ask for a wish or express thanks for a wish that had been granted."

Indeed, the source-to-sea archaeological record—Neolithic wood canoes, first-century

fish traps, good-luck talismans thrown into the river by Crusader knights—reveals the river's central role in France's story. It also shows how the Seine contains multitudes: from the sublime to a sewer.

LAUNDRY SUDS, human waste, animal parts tossed by medieval butchers: The Seine served as a dumping ground for centuries. As its water grew polluted, the river was also tamed as a commercial artery. Human engineering transformed the waterway—its banks lined with factories, its currents manipulated into locks and quay-lined channels, its depth assured by dredging, its islands it was inaugurated; Rouen's Pont Gustave-Flaubert in 2008, then the highest vertical-lift bridge in Europe, allowing its deck to be raised 180 feet for the passage of ships.

The Seine's bridges were a favorite subject of the Impressionist painters, who, fascinated by *la vie moderne,* often fused industry and nature in their work. Breaking with the allegorical focus of classical art, these avant-gardists painted everyday life. Claude Monet's 1872 "Impression, Sunrise," the very painting that launched the Impressionist art movement, portrays a salmon-smudged sky above the port smokestacks of Le Havre.

As glorious an invention as portable tubes of paint, the train allowed artists to escape

national identity, inspiring centuries of French culture.

eradicated as obstacles to river transport. Today the Seine's course appears chiseled, winding through a watershed home to nearly 30 percent of France's population.

Bridges were an early engineering feat. Around the fourth century A.D., the Romans succeeded in driving wood piles to create a bridge to what's now the Île de la Cité, a decisive moment in the construction of Paris-precursor Lutetia. Even more strategic for the Romans would be the river hub of Rotomagus, now known as Rouen. Later, the Vikings made it their capital, giving their name "Northmen" to Normandy. Centuries before the Pont Neuf in Paris, Empress Matilda ordered the building of a stone bridge in the mid-12th century. The age of the automobile prompted increasingly fine bridge construction: the Pont de Tancarville in 1959, the first to cross the estuary; the 1995 Pont de Normandie, the world's longest cable-stayed bridge when

to the countryside along the Seine to paint. In 1837, the first passenger train out of Paris brought revelers to Chatou, an island that's also known as Île des Impressionnistes. It quickly became a magnet for Sunday bons vivants to dance, drink, and mess about in boats—immortalized by Pierre-Auguste Renoir in his 1880-81 masterpiece "Luncheon of the Boating Party." (The river's reality was less rosy. In the 19th century, factory and human wastewater was often discharged directly into the Seine. A revolutionary new Paris sewer system, developed during city planner Baron Haussmann's seismic urban renewal project, was an engineering triumph for Paris, yet toxic for the Seine's health.)

Monet was also obsessed with the Rouen cathedral, graced by the tallest spire in France, which he painted 30 times. Rouen's medieval city center mostly escaped World War II bombing, but the river quays that served as a

BRIDGEMAN IMAGES

The Seine was an endless source of inspiration for Impressionist painters such as Claude Monet, whose 1879 work “Seine at Vétheuil” is housed in Rouen’s Fine Arts Museum.

Starting as a trickle on the Langres Plateau near Dijon, the Seine swells as it flows 483 miles, passing through Paris before ultimately meeting the sea between Honfleur and Le Havre.

Shaped by the Seine

Neither the longest nor strongest of France's five major rivers, the winding Seine has had a profound impact on the country's history and culture. Stretching from the hills of Burgundy to the English Channel, its watershed is home to nearly 30 percent of the French population. A stage for brutal battles and an evocative setting for some of the world's most famed artists, the Seine is now inspiring a new generation to follow its path to a cleaner, greener future.

A port for the centuries
Rouen, the farthest inland that oceangoing vessels can travel, has been a shipping hub since the age of the Romans. Proximity to agricultural fields makes it a key port for farmers.

Paris: city of abundance
Rome's Lutetia Parisiorum developed into the capital city in the middle of the Seine's drainage network, part of one of western Europe's most fertile regions.

The Seine and the sea
As the health of the river improves, a nature reserve at the estuary, in an area surrounded by industry, is welcoming seals and 350 species of birds.

Monet painted his famous water lilies at his home in Giverny.

Once a royal château, now a UNESCO World Heritage site

Land cover
- Cropland
- Forest
- Built-up area
- Seine River Basin
- Regional natural park

10 mi
10 km

MAP: ROSEMARY P. WARDLEY, NGM STAFF. SOURCES: ESA CCI LAND COVER TIME-SERIES V2.0.7; OPENSTREETMAP; INSTITUT NATIONAL DE L'INFORMATION GÉOGRAPHIQUE ET FORESTIÈRE

playground for the populace weren't so lucky. Postwar reconstruction prioritized the essential port, rebuilding all the destroyed bridges. Roads further severed the connection between the Rouennais and their river. "We erected a barrier between the city and the Seine," says Quentin Bicheux, a Rouen native who works for the tourism office.

Yet today there's a movement in the other direction. A years-long revitalization project has given new life to the quays, with industrial heritage repurposed as cultural venues. A polluted peninsula once used to store coal has been reborn as a park planted with trees chosen for their natural cleaning properties. "In about 50 years, the roots of the trees will have purified the earth," says Bicheux.

THE TIDE BEGAN to turn for the Seine's water quality in 1991, when the European Union passed legislation addressing a main source of water pollution: urban wastewater. The Greater Paris Sanitation Authority took significant strides to modernize sanitation networks, including major infrastructure investments at the Seine Aval treatment plant responsible for three-quarters of the area's wastewater. Later, in 2015, the city launched its *plan baignade,* or swimming plan, with concrete measures to clean the Seine and Marne, a tributary, and make the Seine swimmable by the 2024 Olympics—a centerpiece of its successful bid to host the games. The plan would connect more than 23,000 residences, as well as houseboats, to the municipal sewer systems, which previously had dumped untreated wastewater into

In the waters beneath the Pont de Bir-Hakeim, canoes and other people-powered boats are usually forbidden, but restrictions lift during La Traver-Seine, an event that attracted some 650 watercraft last year.

MARY EVANS/BRANDSTAETTER IMAGES

"Bathers at Asnières," an 1884 artwork by neo-Impressionist Georges Seurat, captures the Seine's multiple functions, from a leisure-lover's aquatic playground to an industrial powerhouse.

the rivers. "The Olympics acted as an accelerator," says Rabadan, the deputy mayor for sport. "Without the games, [the project] would probably have taken 10 more years."

THE EFFECTS OF THE CLEANUP are felt downstream in some of France's most urbanized watershed areas. Factories face forests at Normandy's Boucles de la Seine Regional Natural Park; recreational parks flank Gennevilliers, one of France's largest inland river ports; gigantic wind turbines are manufactured in Le Havre's port near the Seine Estuary Nature Reserve, which is an important stopover for vulnerable migrating birds like the aquatic warbler.

"We now have a population of seals that frequent the Seine estuary that we did not see 15 years ago," says Martin Blanpain, director of the Maison de l'Estuaire. Edged by dikes built to aid navigation, and surrounded by industry, this nature reserve is one of the most surprising in France. Its reedbeds welcome some 350 species of birds. "We're in a territory that has been heavily modified by

Between the Pont Alexandre III and Pont des Invalides, athletes stream into the Seine during the Women's 2023 World Triathlon Olympic Games test event.

man but which nevertheless harbors a very interesting biodiversity and natural heritage," says Blanpain.

Under moody skies, a boardwalk snakes across the wetlands. High grasses stretch toward the river in undulating waves. On the horizon, the Pont de Normandie has a celestial grace, seeming to hang by filaments over the Seine's mudflats.

It was under this bridge that a daring athlete-adventurer swam the last miles of a 49-day odyssey that ended on July 24, 2021. Arthur Germain, who also happens to be the son of Paris Mayor Anne Hidalgo, swam the entire length of the Seine. The administrative hurdles alone were a trial—permission to swim was required by each township along the way. Trailing a kayak filled with camping supplies, Germain traversed a tapestry of sometimes incongruous landscapes, from luxuriant vegetation to a nuclear power plant.

A big part of the experience, and preparation, was "understanding how the river lives, because the river is alive," says Germain. Some 40 miles from the Seine's source at a spring called La Douix, the river's temperature

Notre Dame Cathedral reigns over the city from its perch on the Île de la Cité. The Seine's water helped extinguish the 2019 fire and has been aiding in the restoration, including the rebuilt spire, by transporting building materials.


POTAIN
IMPERIO

plummeted about 10 degrees—a shock to the system. Sometimes when a tributary flowed into the Seine, he could see the river's color change. And after the last lock, Germain had to adapt his swimming schedule based on the tides. "Simply put, I had to respect nature. The river is stronger than me."

Germain took water samples roughly every three miles along the way, connecting in real time to a Paris lab. Only four readings passed the threshold for dangerous levels of *E. coli* and intestinal enterococci bacteria.

"There are a lot of people in Paris who don't know that the Seine is in good health right now. I'm not saying it's clean, but it's healthy for aquatic life," says Sandrine Armirail, director of the Maison de la Pêche et de la Nature, an environmental education center. "We look at water quality in terms of what's living in it. The more species you have, the healthier the environment." When she was a child growing up outside Paris, only four fish species, all pollution resistant, could survive. In fact, by the 1970s the Seine downstream of Paris was nearly biologically dead. Today there are 36 different fish species. "This means that water quality has improved quite significantly," Armirail says.

The *maison*'s aquariums show off many of the species that inhabit the Seine today, including the emblematic *brochet* (pike)—a predator with 700 teeth that Armirail calls the "shark of the river." At the water's edge, the maison is restoring the flooded prairies the fish needs as spawning habitat. Outside the building under the quay nests a pair of Eurasian kingfishers, just one example of the increasing numbers of nesting bird species lured back to the Seine.

Like so much else, the Seine's future is imperiled by climate

Paris's sanitation system is largely a legacy of 19th-century engineer Eugène Belgrand. Both rainwater and wastewater are channeled into a vast underground labyrinth of sewers and carried gravitationally to treatment plants outside Paris. But in times of heavy downpours, sewer valves were opened into the Seine to prevent an overflow into the streets.

Tanks like this one will help avoid that scenario. Developed by a team of 40 engineers, the Bassin d'Austerlitz is a technical marvel. Paris is an extremely well organized city, whose bowels are crisscrossed by layers of old quarries, Métro tunnels, sewers, gas pipes, and electricity cables. Within this densely urban milieu, a tunnel was bored underground and piped under the Seine, allowing a flow of stormwater. Eventually, the water held by the *bassin* releases slowly into the sewers, then funnels to water treatment plants, before returning to the river.

HIDDEN UNDERGROUND near Paris's Austerlitz train station is a stormwater cistern that holds the equivalent of 20 Olympic-size swimming pools. Métro passengers witnessed the colossal construction project for three and a half years as their trains passed over it. Soon to be covered by green space, the concrete tank is supported by columns that reach 260 feet into the ground. The Bassin d'Austerlitz is a cornerstone of the plan to keep the Seine safe for swimming.

There is still work to be done. Officials were forced to cancel some of the swimming test events last August after rain spiked pollution levels—and a particularly severe storm could still disrupt Olympic events. But already last summer, scientific readings showed the Seine swimmable an average of seven days out of 10, and three additional collectors and stormwater tanks have opened since then. The ultimate result—as with the pedestrianized Parisian quays that used to be highways—is returning the river to the people.

Like so much else, the Seine's future is imperiled by climate change, a lurking threat greater than the fictional shark stalking swimmers in the Netflix movie *Under Paris*—and one that overflow tanks can't resolve. Flooding has always been a Parisian problem, evoked by the city's Latin motto (*Fluctuat nec mergitur,* "tossed by the waves but does not sink").

Imagine Paris underwater: The Seine cascades over the quays, water sloshes into Métro tunnels, Parisians paddle boats through the streets. And such a deluge is not fiction. The great flood of January 1910 is captured on vintage postcards and etched in stone with water markers on bridges and buildings. But a perfect storm of conditions—torrential rain, flooded tributaries, and early winter snowmelt—triggered that event.

"Today we could have worse," says filmmaker Mathieu Schwartz. His documentary *Quand la Seine Débordera (When the Seine Overflows)* investigates how events like January 1910, a so-called hundred-year flood, are predicted to happen more frequently with climate change. Extreme weather events caused by global warming are already happening, with storms unleashing more intense downpours.

Rising water could wipe out riverside villages and treasured wetlands like the Marais Vernier, home to one of France's largest concentrations of carbon-sequestering peat bogs. What's more, sea-level rise is affecting the Seine's tidal flows.

"At high tide, the water reaches the Poses Dam, which is upstream of Rouen, and then it goes down. At the moment, we're finding that the salt is rising higher and higher," says Laurence Dervaux, director of the Boucles de la Seine park in Normandy. Not only could this damage the factories that pump Seine water for cooling, but it also has consequences for the flora and fauna in the park's diverse ecosystems: marshes, forests, and the chalk cliffs now in danger of crumbling.

change, a lurking threat that overflow tanks can't resolve.

AN AGE-OLD PRACTICE on the Seine offers one response: the rise of river freight transport as a means of cutting carbon emissions. Inside the wheelhouse of his 328-foot cargo ship, the air redolent with tobacco, Captain Sébastien Neyt pilots 40 containers of dry goods for the Franprix grocery store chain. Entering a lock, he springs between the deck and the quay with the alacrity of a river eel. Neyt is a fourth-generation *batelier,* or professional boatman, from Conflans-Sainte-Honorine, the capital of French inland waterways.

Few figures have inspired popular culture like Joan of Arc, depicted in a 16th-century portrait. The French patron saint led troops to victory against the English. She was later tried for heresy and burned at the stake in Rouen in 1431. Her ashes were scattered in the Seine.

ARCHIVES CHARMET/BRIDGEMAN IMAGES

Unveiled in 2015, this statue by sculptor Eric de Laclos depicts Sequana, the ancient goddess of the Seine. The river's Burgundy headwaters were also the site of a Gallo-Roman sanctuary where offerings were made.

Neyt's vocation is more than a job. It is a centuries-old way of life, explains curator Laurent Roblin of the Inland Water Transport and Navigable Waterways Museum, a resplendent mansion on a bluff overlooking the confluence of the Seine and the Oise. One of the museum's highlights is a wall of jars containing examples of all the goods a waterman transported in his lifetime: wine, mustard seeds, even asbestos.

"Since time immemorial, we've used rivers," says Roblin. In antiquity, the *nautes,* a powerful guild of boatmen, held a monopoly on Seine commerce in Gallo-Roman Lutetia. A carved pillar they offered to Emperor Tiberius in the first century A.D. is prized today as a symbol of Paris. Rivercraft constantly evolved—from canoes to towed barges, from steamboats to cargo ships. Over time, highways spread across the country, and then the continent, and trucks became a quicker, cheaper way to move goods. But increasingly, fluvial transport offers an eco-conscious alternative.

"We avoid traffic jams, congestion, and accidents on the roads," says Antony Deniau,

Normandy's Boucles de la Seine Regional Natural Park is rich with what director Laurence Dervaux calls "exceptional heritage." Industry and nature meet there as horses graze in a flooded pasture near the Pont de Brotonne, a bridge inaugurated in 1977 to alleviate traffic pressure on the ferries.

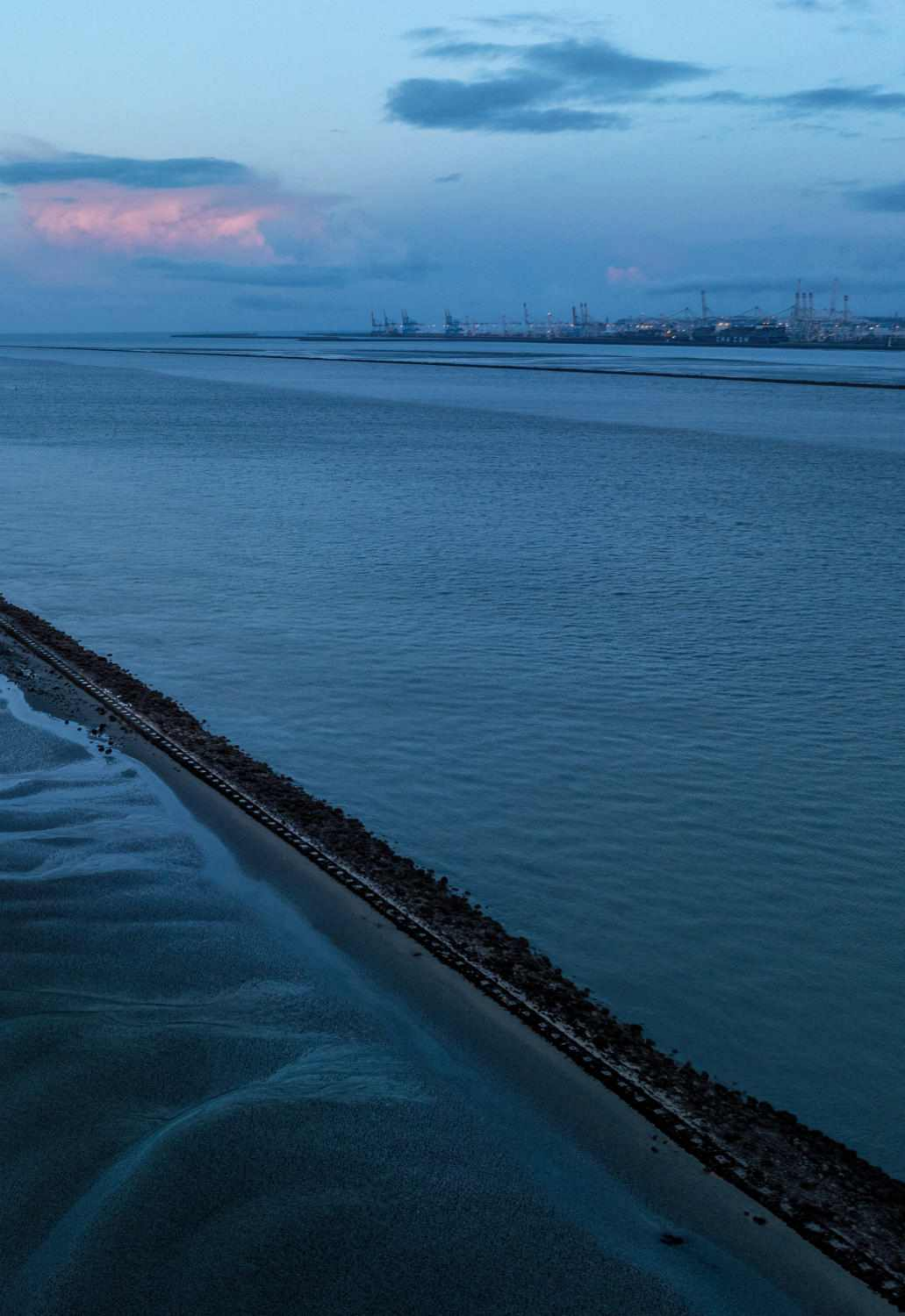
director of transport for Franprix. "And the environmental balance sheet is favorable, with 20 percent less carbon emissions." This translates to 3,615 fewer trucks on the road and 21,820 gallons of fuel saved each year. "It's more expensive than truck transport, but it's an eco-responsible choice we make."

Aided by the current, Neyt powers his barge downstream past the Marne's junction with the Seine. All of a sudden the lights of Paris appear in the darkness. Waves pound against the boat as the river funnels between the quays, the city's 37 bridges spawning whirlpools and eddies. The unmistakable silhouette of Notre Dame stands tall on an island in the middle of it all.

Neyt's vessel speeds toward the Pont Neuf. With the touch of a button, he lowers the wheelhouse to duck beneath the bridge's 400-year-old stone arches. The decorative *mascarons,* grotesque sculpted faces, seem to grimace. Voices crackle over the radio with increasing frequency—the river is a busy avenue for a parade of dinner cruises.

Soon this "Main Street" will welcome the pageantry of the Olympic opening ceremony, and starting in 2025, debut three designated swimming spots for Parisians to cool off—especially during summer heat waves, yet another result of climate change. Teens will loaf at the water's edge. Athletes will race in lap lanes. Kids will jump with abandon. Together they will follow in the rippling wake of the swimmers who competed in the first Paris Olympics, in 1900. And long before that, a tradition of 17th-century hedonists with a thing for skinny-dipping. And earlier still, even before a great city stood at this bend in the river, countless generations who lived their lives along, and with, and in the Seine's waters. □

After a serpentine journey through France, the Seine reaches the English Channel. Flanked by dikes to facilitate river navigation, the estuary now regularly shelters diverse wildlife, from gray seals to migratory birds.



TAKING OUT *the* TOXIN

With high tech and hard-earned data, a geologist aims to make gold mining in the Peruvian Amazon a mercury-free enterprise.

Words by
HICKS WOGAN

Photograph by
THOMAS PESCHAK

THE AMAZON IS a realm of contrasts, and Jennifer Angel-Amaya says she can hear them all around her. For more than two years, the Colombian geologist and National Geographic Explorer has been doing fieldwork in the Peruvian part of the rainforest, and she's noticed the sounds of gold miners getting closer and louder, as if competing with the calls of birds and monkeys.

Angel-Amaya focuses on Madre de Dios, the region of Peru most affected by illegal gold mining. As part of the National Geographic and Rolex Perpetual Planet Amazon Expedition—a series of research projects spanning the Amazon Basin—she studies the impacts of gold mining on waterways.

She's monitoring three sites: one where gold mining is sanctioned and conducted with heavy machinery, a second where illegal mining is extensive, and a third that's protected from mining and serves as the control in her experiment. For each, she collects soil, water, sediment, and plankton to determine the chemistry of the samples and the concentration of mercury. While the toxic metal is naturally occurring and gold

Jennifer Angel-Amaya holds a sediment core sample from a former gold mining site in Madre de Dios, Peru.

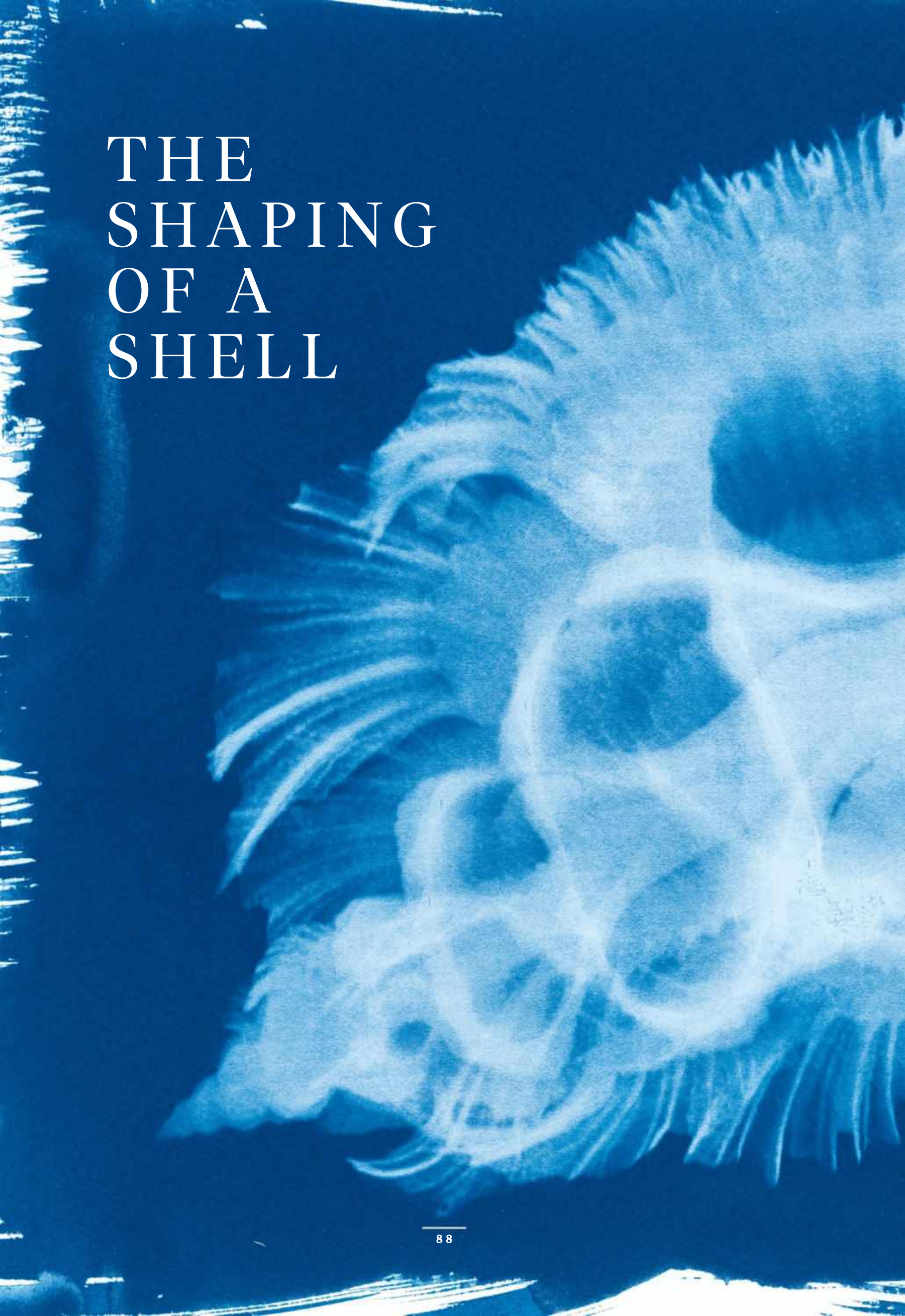
NGM MAPS

mining is not the sole source, Angel-Amaya expects that mercury levels will be higher downstream of the two mining sites—and potentially throughout the Amazon watershed. The mining in this region is artisanal and small-scale, and often uses liquid mercury to extract gold from alluvial sand. When the mercury-gold amalgam is heated, the toxin evaporates but stays in the environment. The process is fast and relatively cheap, and it remains legal in Peru despite mercury's harmful effects on human health.

Angel-Amaya would like to see mercury-free gold become a certified commodity, in the same way that conflict-free diamonds have found a market. So she's testing a new application for a handheld laser gun that would verify that a piece of gold was rendered without mercury. If the technology succeeds, it could help ensure that customers receive a better-sourced product—and incentivize artisanal miners to pursue certification and a premium price.

The challenges in Angel-Amaya's fieldwork are many. In addition to the science, there are long, hot days; mosquitoes; snakes; and questions from miners who are suspicious of her motives. And yet she loves being there. Someday her work may inform restoration efforts at polluted sites. "It's not going to be back as it was before," Angel-Amaya says, "but maybe it could become something else." At the abandoned mining ponds, nature's resilience amazes her. Not long ago, she spotted a caiman, and she's seen tapir and jaguar prints at the water's edge. It's enough to give her hope. ▯

THE SHAPING OF A SHELL



Math, physics, and evolution join forces to form some of our planet's most fascinating natural structures.

Words by **FERRIS JABR**
Photographs by **HUGH TURVEY**

Chicoreus miyokoae **(above) | See page 15 for details on x-ray and cyanotype processes in this story.**

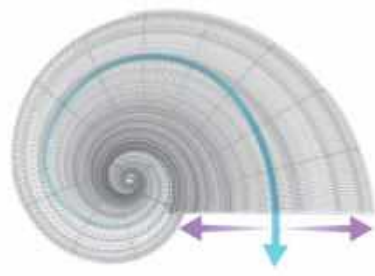
YOU CAN SEE IT IN THE logarithmic whorl of a nautilus. The milky iridescence of an abalone. The spiked turret of a queen conch. Precision, elegance, strength. The seashell is a consonance of form and function that both rivals and guides human creativity. From Botticelli's "Birth of Venus" to Frank Lloyd Wright's design for the Guggenheim Museum in New York, shells have inspired artists and architects throughout history. Our admiration for seashells even predates writing. Archaeologists in Israel recently unearthed the remains of a clamshell necklace made about 120,000 years ago.

As enduring as our fascination with seashells are the mysteries they hold. How did such complex and beautiful structures come into existence? Evolution by natural selection can help explain why shells became widespread among mollusks, but it cannot fully elucidate how an individual creature builds a skeleton as exquisite as, say, the exceptionally spiny shell of a Venus comb murex. To truly understand the seashell, we must peer beneath its biology to the underlying math and physics. In recent years, scientists undertaking such work have developed a considerably more sophisticated understanding of the physical forces that guide shell formation. Innovative studies by Derek Moulton, a professor of applied mathematics at the University of Oxford, and his colleagues have revealed that much of the astonishing variety of seashells can be explained by a few simple mathematical principles.

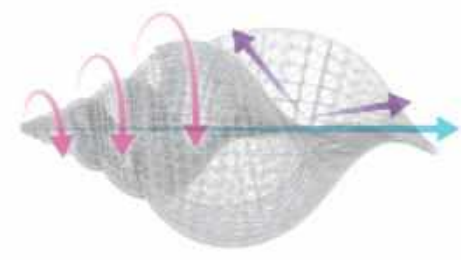
Every mollusk's body is surrounded by a mantle, a cloaklike organ that secretes calcium carbonate and mixes it with a scaffolding of protein to form a shell one layer at a time. As a mollusk expands its shell, it adds new material to only one area: the opening, or aperture. Envision this as a circle. If, with each new layer, a mollusk deposits a ring of material the same size as the aperture, its shell will lengthen into a cylinder. If, instead, the mollusk increases the circumference of each new ring, its shell will become a cone. By depositing more material on one side of the opening than the other, a mollusk can curve a cylindrical shell into a doughnut. Imagine gluing a stack of lopsided rings, one atop another—each thicker on its left side than

FORCES BEHIND THE FORMS

A shell of a mollusk is formed as the mantle secretes compounding layers of calcium carbonate and proteins. Shell shape is determined by physical processes, from the simple to the complex.



DILATING AND COILING
The nautilus's shell is an example of the most fundamental processes of growth. As with all mollusks, the shell coils, typically clockwise, around its middle, expanding outward.



TWISTING
The shell of this giant African land snail dilates and coils much like the nautilus's does. But it is also shaped by a third force, twisting around its central axis of rotation.

GRAPHIC: JASON TREAT AND BEN SCOTT, NGM STAFF
SOURCE: DEREK MOULTON, UNIVERSITY OF OXFORD

its right. Instead of forming a neat cylindrical tower as uniform rings would, they'd arc to one side—like the wedges in a stone archway—and eventually make a loop. By rotating the points where the mantle secretes more or less material, a mollusk can twist such a loop into a spiraling tube.

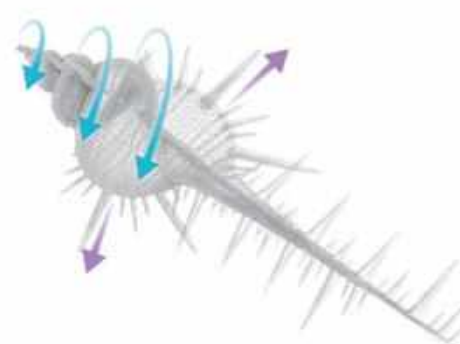
While these straightforward mathematical rules account for many of the fundamental forms of seashells, a more convoluted set of interactions generates their most ostentatious features. Spines, knobs, and other ornaments arise from a mismatch between the growth rates of the soft-bodied mollusk's mantle and its rigid shell. This mismatch creates bulges that are exaggerated with each new layer. The mantle's relative growth rate and stiffness determine the length, thickness, and curvature of these projections. Such embellishments may initially form because of a combination of chance mutations and inescapable outcomes of the mechanical forces involved in shell growth. If they prove advantageous to a creature's survival and reproduction, however, they may be perpetuated by natural selection, eventually becoming a prevalent trait.

Although we primarily prize shells for their aesthetic attributes, the animals they house value them for a more pragmatic reason: protection. About 540 million years ago, during a burst of evolutionary innovation known as the Cambrian explosion, predatory animals became much more numerous and proficient. Soft-bodied, slow-moving organisms found themselves in constant jeopardy. Around this time, marine mollusks evolved simple but robust shells to protect their vulnerable exposed tissues. In response, crustaceans, fish, and other predators developed more sophisticated weaponry and hunting techniques.

Eventually, the coevolution of predator and prey contributed to a dramatic increase in the diversity of mollusk shells. Some evolved particularly large and thick shells that only the strongest or craftiest animals could crack. Narrow openings, sometimes reinforced with doors called opercula, made it more difficult for predators to reach their prey. Tall spires allowed some mollusks to retreat even further from danger. Spikes, spines, and knobs thwarted pincers and jaws, as did smooth and slippery surfaces.

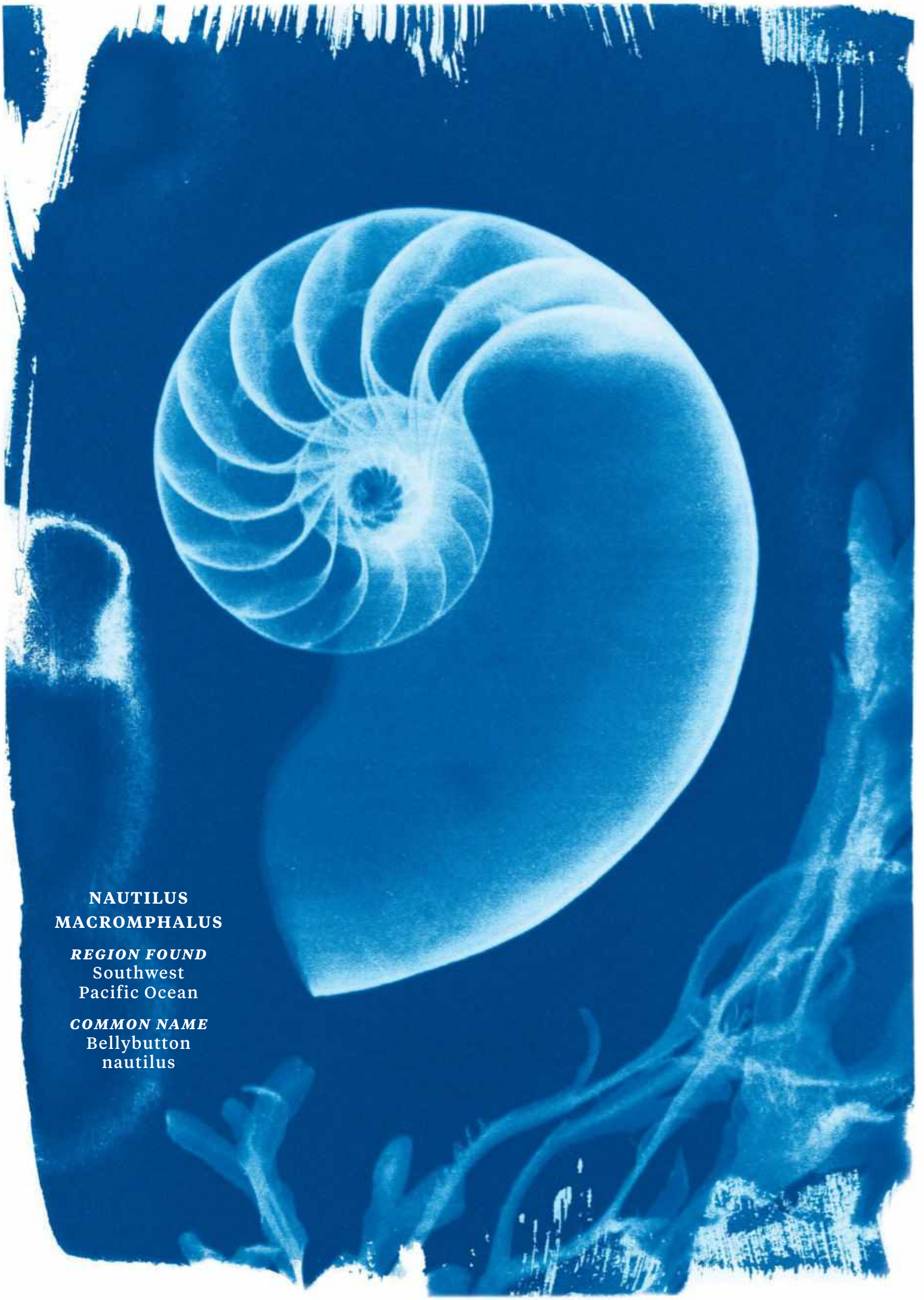
Seashells, then, are not purely constructs of either biology or physics, nor can they be adequately described by either mathematical modeling or Darwinian theory alone. The exacting, sculptural beauty of shells that we find so enchanting emerges from a confluence of geometry, mechanics, ecology, evolution, and luck. Every shell you've ever scooped out of the sand or marveled at in a museum is a palimpsest layered with secrets that science is still untangling—a physical manifestation of our planet's complexity and splendor. □

COMPRESSION
If a mantle and hardened shell mismatch, the resulting force can cause ridges. Mantle properties and degree of mismatch determine the number of ridges.



GROWTH SPURT
A sudden burst of mantle secretion can amplify a pattern of ridges, creating spines. The faster the growth spurt, the taller and pointier the spines.

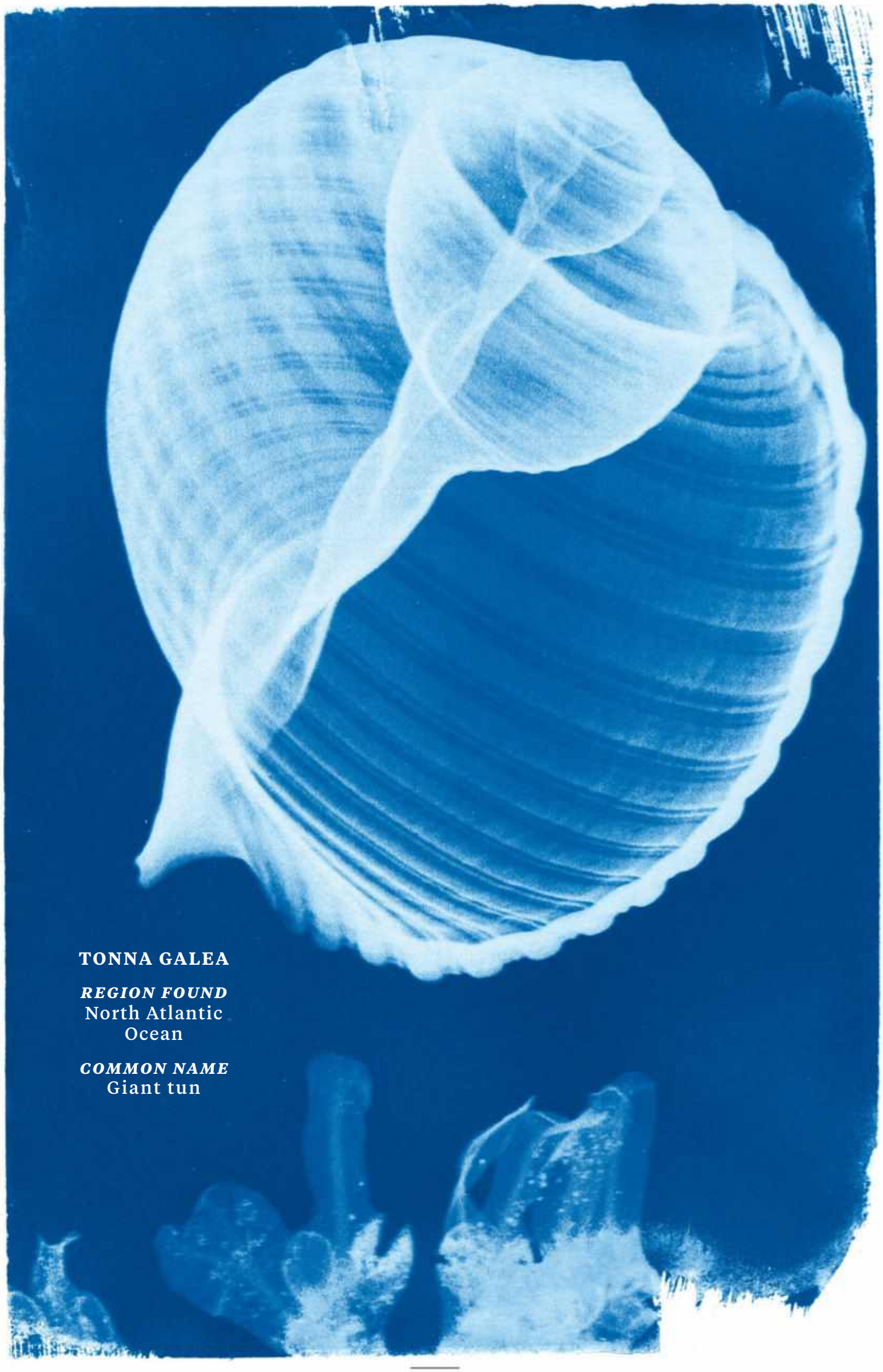
ANTISYMMETRY
The processes that create ridges and spines can also lead to antisymmetric forms, such as those of the fluted giant clam, perfectly opposite and interlocking.



NAUTILUS MACROMPHALUS

REGION FOUND
Southwest
Pacific Ocean

COMMON NAME
Bellybutton
nautilus



TONNA GALEA

REGION FOUND
North Atlantic Ocean

COMMON NAME
Giant tun

LISSACHATINA FULICA

REGION FOUND
East Africa

COMMON NAME
Giant African land snail

MUREX PECTEN

REGION FOUND
Indian Ocean

COMMON NAME
Venus comb
murex

CHICOREUS RAMOSUS

REGION FOUND
Indo-Pacific waters

COMMON NAME
Branched murex

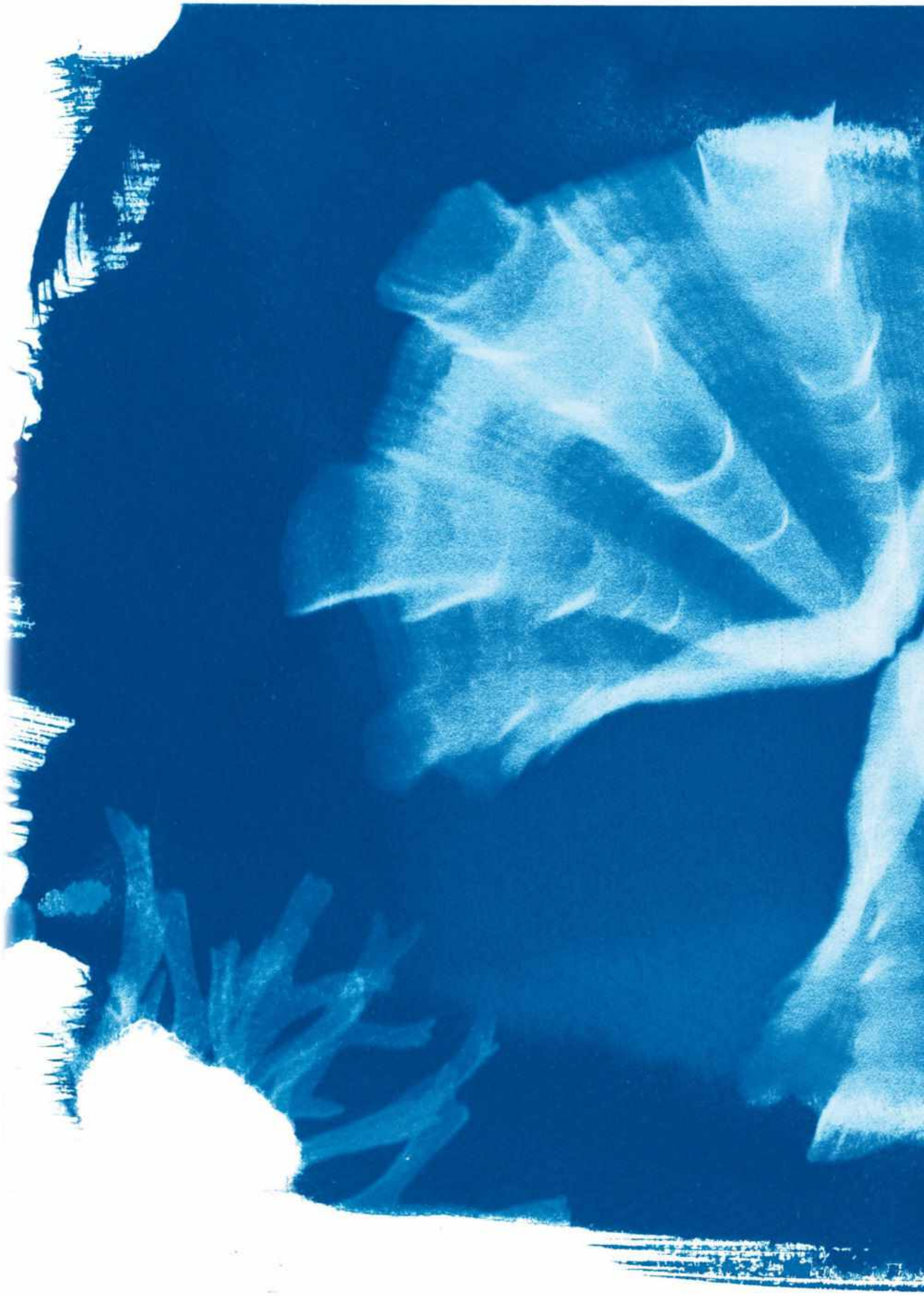
TRIDACNA SQUAMOSA

REGION FOUND
Indo-Pacific waters

COMMON NAME
Fluted giant clam

Shells courtesy
SIMON TAYLOR, BRITISH SHELL COLLECTORS' CLUB

Technical collaborator
NADIA RADJABI, MIDDLESEX UNIVERSITY



A NEW KIND *of* FELINE

Scientists have confirmed a third species of tiger cat that lives in Latin America.

Photograph by JOEL SARTORE

EVERYONE KNOWS THE lions, tigers, and other big cats of the world. But tiger cats, small solitary felines that range from Costa Rica to Argentina, have long been shrouded in mystery. Researchers recently discovered the clouded tiger cat, using a combination of genetics, museum skins, and thousands of camera trap photos that set it apart from the two other known tiger cat species: savanna and Atlantic forest. All three spotted predators are now in danger as a result of habitat loss and disease spillover from domestic animals. "They've lost more than 50 percent of their original area," says Tadeu de Oliveira, a wildlife conservationist at Brazil's State University of Maranhão. He founded the Tiger Cats Conservation Initiative, which works with local people to vaccinate their pets. "The red alert has been turned on," he says. **—JASON BITTEL**

NATIONAL GEOGRAPHIC
PHOTO ARK
JOEL SARTORE

The National Geographic Society funds Explorer Joel Sartore's Photo Ark project, which aims to document every species living in the world's zoos, aquariums, and wildlife sanctuaries.

SENSITIVE WHISKERS
These long hairs help the predator navigate dense vegetation in its mountain home.

HAZY SPOTS
The clouded tiger cat gets its name from its cloudy rosettes and cloud forest habitat.

FLUFFY TAIL
Thick and long, the tiger cat's tail looks similar to that of another diminutive cat of the Americas, the margay.

SCIENTIFIC NAME
Leopardus pardinoides

TYPE
Mammal

DIET
Carnivore

AVERAGE LIFESPAN
Less than 10 years in the wild

SIZE
5 pounds; 2.5 feet long (including 1-foot tail)

TIGER CAT RANGES

MAP: MATTHEW W. CHWASTYK, NGM STAFF
SOURCE: TADEU GOMES DE OLIVEIRA, STATE UNIVERSITY OF MARANHÃO (UEMA)
PHOTOGRAPHED AT TOUCAN RESCUE RANCH, SAN JOSECITO, HEREDIA, COSTA RICA

COURTESY MINISTRY OF CULTURE, ARCHAEOLOGICAL PARK OF POMPEII

More

SECRETS

TO SHARE

Archaeological projects in Pompeii have moved from excavation to preservation. But there's still much we can learn from already unearthed finds.

Words by CHRISTINA STERBENZ

IN RECENT YEARS, excavations in the ancient Roman city of Pompeii have uncovered a 2,000-year-old laundromat, a bedroom used by slaves, and a fresco depicting an early iteration of pizza (minus the tomatoes—those wouldn't come to Europe for at least another 10 centuries).

None of those discoveries, however, stemmed from new digs into the roughly 20-foot layer of ash that encased the city after Mount Vesuvius's eruption in A.D. 79. For decades, the Italian government had a moratorium on any additional excavations in Pompeii. That means most of the finds are by-products of efforts to preserve and restore what's already been unearthed, according to Steven Ellis, a professor of Roman archaeology at the University of Cincinnati who worked on excavating Pompeii's Porta Stabia neighborhood.

"When they dug [the city] out, they created a kind of cliff edge of that volcanic debris," Ellis says, adding that landslides and cave-ins have occurred along previously excavated areas, causing international outcry. "So they're restoring those and shoring those up, and to do that, they've had to excavate a bit of the edge."

Pompeii, of course, still has more secrets to reveal. Estimates vary, but anywhere between 15 and 25 percent of the city remains covered. For many archaeologists, though, the question isn't so much what they have left to find but if

This recently discovered fresco in Pompeii's House of Leda and the Swan depicts mythological siblings Phrixus and Helle escaping on a golden ram.

While parts of Pompeii were excavated long ago, archaeologists estimate that up to a quarter of the ancient city awaits exploration.

digging should continue at all. Or at least when and how would it make the most sense to keep exploring, given serious concerns over how the historic site has aged.

"We have enough of [excavated] Pompeii for the general public. We have enough of Pompeii for the scholarly community to learn from," Ellis says. "What we really need to be doing is keeping it as well-preserved for the future as we possibly can."

EXPLORING WITH TECHNOLOGY

Zoning didn't exist in the ancient Roman city, and most of the businesses and retail areas were clustered around the large streets, many of which have already been explored, according to Eric Poehler, a professor of classics at the University of Massachusetts Amherst who has also worked in Pompeii. Eastward, however, population density and land use decreased, and swaths of land there, especially the southeastern portion of the city, remain relatively untouched. Rather than backyards with large gardens featuring topiary, statues, and columns, as seen in more populated and wealthy areas of the city, Poehler suspects eastern Pompeii may resemble farmland. "We should expect something more like big backyards that might even be planted with agriculture for profit rather than just for leisure," he says.

But Poehler also notes that archaeologists have overlooked a lot of information in previously excavated areas, including pedestrian artifacts, paintings, and graffiti. Going back over those places with improved technology could yield just as exciting discoveries as new excavations without putting the city—and future generations' ability to see it—at risk, Ellis adds.

In the past, for example, broken or incomplete frescoes or pottery were sometimes

COURTESY MINISTRY OF CULTURE, ARCHAEOLOGICAL PARK OF POMPEII, PAOLO METELLI

thrown away. Now AI robots are helping archaeologists piece them back together, and lidar (a type of laser scanning) can record spaces in three dimensions. "We'd have photographs, but we'd never have enough," says Ellis. "Now we have these 3D models where we basically can return to almost any time of our excavation and see that space."

Poehler, who helped create the Pompeii Bibliography and Mapping Project, also points to technologies that allow people to better visualize the city. He's currently working on the Pompeii Artistic Landscape Project, which will enable internet users to search for any of 87,075 terms painted on a Pompeian wall—from a "protopizza" to a cupid. These new projects are "giving us a chance to revisit, now, 200 years' worth of excavation history," Ellis says.

Some of the excavated city, however, has already been lost. In 2014, for example, heavy rain caused three collapses in just three days: a tomb, an arch in the Temple of Venus, and the wall of a workshop. In 2010, the House of the Gladiators fell, likely as a result of problematic restoration work in the 1940s and '50s. The destruction of the gladiator school, one of the most celebrated structures in Pompeii, prompted UNESCO to threaten to take the city off its coveted World Heritage list. (Years later, the group decided to keep Pompeii's status after significant restoration steps.)

Excavations that may have contributed to those issues weren't necessarily done improperly. Processes and technology just evolve as time passes, which contributes to the idea that archaeologists may want to decelerate their efforts a bit. "There's an opportunity cost to digging a lot today, because tomorrow we might have better skills, tools, information, technologies, and just physical abilities," Poehler says. "And if we do it today, we rob ourselves of the opportunity in the future."

NGM MAPS

'WONDERMENT AND SURPRISE'

Italy has launched several initiatives to preserve and restore what's already been unearthed in the city. The Great Pompeii Project, a joint effort with the European Union between 2012 and 2019, spent 105 million euros ($113 million) to secure embankments and restore walls, among other goals. How to attract tourists with new discoveries while also protecting the existing remains of the city, however, continues to be a point of friction in Italian politics.

Discoveries made during the Great Pompeii restoration project, however, proved just as attention-grabbing as previous finds. Work to improve the stability of Region V (Pompeii has nine regions) in 2018 revealed frescoes, including one featuring a pair of dolphins found near the House of the Silver Wedding, a majestic example of how the aristocracy lived. Later that year, archaeologists uncovered what they dubbed the Enchanted Garden, a lavishly decorated part of a house set aside as a shrine. It depicted a man with a dog's head, potentially a nod to the Egyptian god Anubis.

"One of the things that we can look forward to every time that we think about excavating Pompeii or just peering below its ground level is wonderment and surprise," Poehler says. "We will find absolutely gorgeous pieces and glimpses of the past." □

Words by **EMILY SOHN**

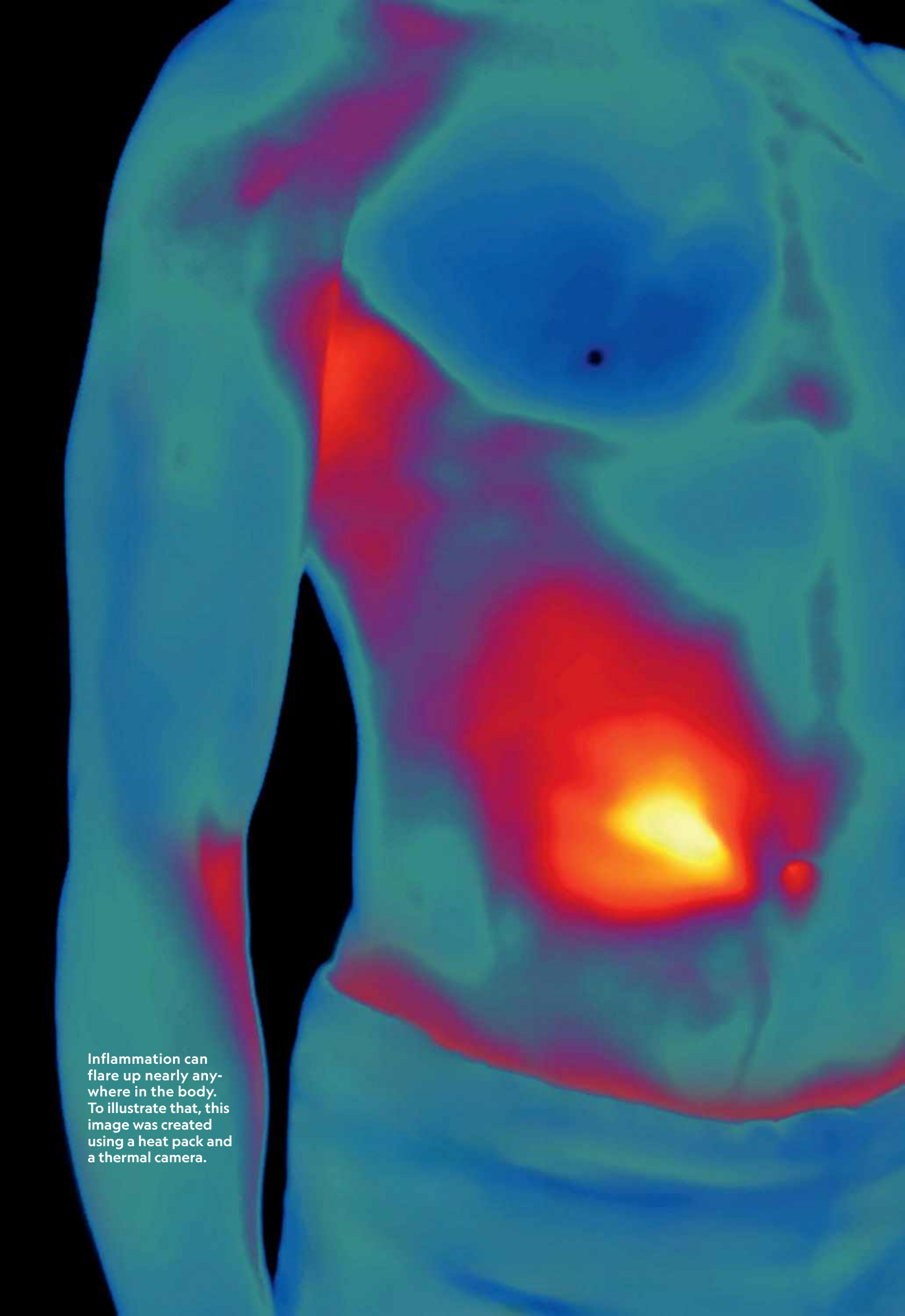
Illustrations by **BRIAN CRONIN**

THE INFLAM

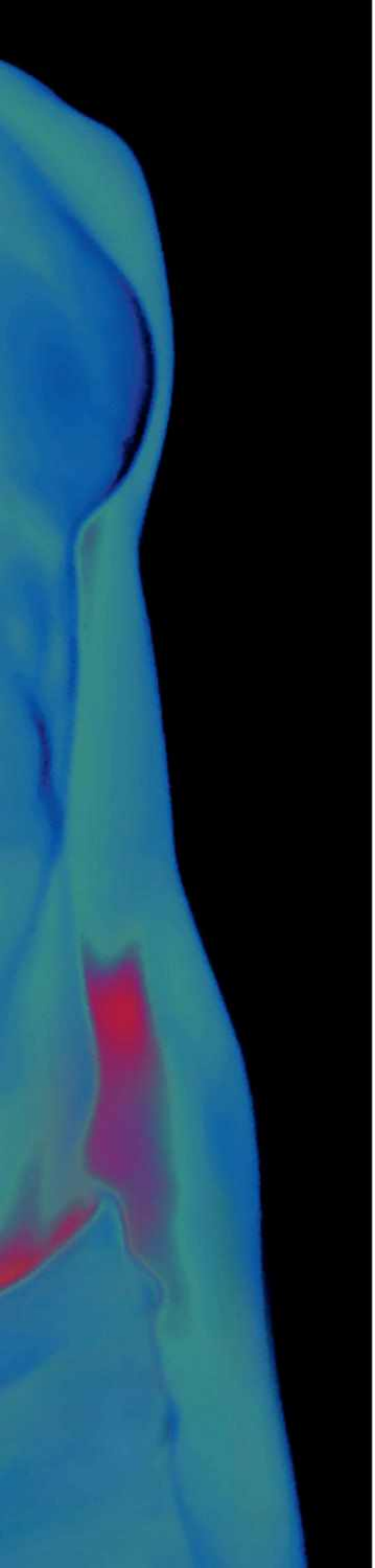
WE KNOW MORE THAN EVER ABOUT INFLAMMATION'S CAUSES AND

MATION AGE

TREATMENTS. BUT EXPERTS SAY OUR BODIES NEED IT—JUST NOT TOO MUCH.



Inflammation can flare up nearly anywhere in the body. To illustrate that, this image was created using a heat pack and a thermal camera.



GILES PRICE

INTRODUCTION

Inflammation gets a bad rap. Consider the various anti-inflammatory diets, supplements, medications, and lifestyle tips aimed at providing some degree of relief from uncomfortable symptoms like redness, pain, heat, or swelling from an injury or infection.

"People definitely associate [inflammation] with something that's negative," says Wolfgang Marx, a senior research fellow and expert in nutritional psychiatry at Deakin University in Melbourne, Australia.

But the truth is far more complicated—and potentially beneficial. After centuries of debate and research, scientists now know that inflammation is as much a hero as it is an enemy. Ideally, the physiological process conquers infections, prevents cancer from taking hold, allows injuries to heal, turns vaccines into long-lasting disease protection,

and more. In fact, we could not survive without the many roles that inflammation plays in the daily functioning of our bodies.

"Every facet of human health impinges on inflammation," says Bali Pulendran, an immunologist at Stanford University. "Without the appropriate type and level of inflammation, the immune system would not be capable of launching effective immunity against pathogens."

As with many biological reactions, though, the danger lies in how much. When inflammation persists at chronically elevated levels after an initial infection or injury has passed, it can shift functions, leading to long-term illnesses such as heart disease, cancer, type 2 diabetes, depression, and Alzheimer's. Many of these conditions become more common with aging, which is also linked to rising levels of inflammation. The immune system is capable of attacking the body's own tissues, resulting in autoimmune conditions such as rheumatoid arthritis, multiple sclerosis, and Crohn's disease. Some researchers are also exploring whether there's a connection between excessive inflammation and long COVID.

Over the past two decades, such major yet often contradictory health impacts have galvanized scientists to dig deeper into understanding this process. When geriatrician and epidemiologist Luigi Ferrucci started looking into the links between inflammation and aging in 1999, there were five or six known molecules, called markers or mediators, that were used as measures of inflammation in the body. Today there are thousands.

A BRIEF HISTORY OF INFLAMMATION

The condition has been under investigation for thousands of years. The better we understand it, the more we see just how much there is to learn.

In the beginning, there was swelling, pain, heat, and redness. These cardinal signs of inflammation were described by Aulus Cornelius Celsus, a Roman encyclopedist, more than 2,000 years ago. Eventually, a fifth major sign emerged: loss of function.

Today the reaction Celsus described is called the acute inflammatory response, and it is known to involve hundreds of molecules and pathways that lead to healing when things go right and to infection or disease when they don't. Scientists working in increments and leaps over centuries pieced together a detailed story of what inflammation is and how it works on the level of cells, proteins, and other molecules.

It all started in earnest with the microscope, which gave scientists their first window into this response at a molecular level, says Klaus Ley, an immunologist at the Medical College of Georgia at Augusta University. In 1839 German scientists first described seeing leukocytes, or white blood cells, respond to an injury in experiments with frogs. In 1882 Russian scientist Ilya Mechnikov described the way leukocytes consumed bacteria and dead cells, a discovery that earned him a Nobel Prize in 1908.

Scientists now know there are many types of leukocytes, but the key observation at

"Now we can measure 10,000 proteins in a drop of blood, and so we start understanding that there are many subsets of inflammation, and those are driven by different inflammatory mediators," says Ferrucci, who is scientific director of the National Institute on Aging. "By studying how they are organized and connected, we understand more about the inflammatory response than we did before."

This deepened knowledge suggests that "inflammation," as a single word, is relatively meaningless, because it has so many expressions. Rheumatologists, immunologists, orthopedic surgeons, vaccinologists: For each type of specialist, the word describes a distinct but often overlapping set of molecules, molecular interactions, symptoms, and outcomes. "The word 'inflammation' is a word of convenience. It's something that we all bandy about haphazardly, but it clouds clarity, and it clouds thinking," Pulendran says.

As researchers learn more about the inflammatory process, they are getting better at tinkering with it to harness the good that it can do. On the horizon are new medications and more refined diet and lifestyle recommendations to address the many forms of inflammation and help prevent and treat more diseases. Figuring out how to make these innovations accessible and affordable to everyone is an urgent task.

The emerging consensus among scientists is that inflammation isn't inherently bad or good; we need just the right amount of it depending on the situation. It is not something we want to eliminate. It is something we want to learn how to control.

the time was that these cells migrated out of blood vessels into tissues, where they did the work of cleaning up messes. "Their understanding was essentially, OK, there are these components of blood, the white blood cells, that do the repair," Ley says, "and we can see them in this state of what we consider inflammation."

Incremental advances came over the next few decades. In 1927, for one, Welsh cardiovascular specialist Sir Thomas Lewis discovered that chemicals called histamines played an important role in the response of blood vessels during bodily harm. It took nearly 60 more years until this basic understanding exploded into something infinitely more intricate: the discovery of the first cytokine, an inflammatory marker called interleukin-1. There are now about 200 known cytokines—small proteins released by cells that tell the immune system to do its job. Some are better understood than others.

As research has progressed, so too have treatment strategies, moving on from the dried myrtle the ancient Chinese used for rheumatic pain and the opium poppies used by the Greeks. One modern breakthrough came with the discovery in 1928 of penicillin, which could kill the bacteria that caused life-threatening inflammation. And the cytokine revolution has provided yet another window into which treatments actually work.

Today there are numerous anti-inflammatory medications, but in some cases it may not make sense to use them, says Karim Khan, a sports medicine specialist at the University of British Columbia. "I've got hip arthritis, and I'm not taking anti-inflammatory drugs," Khan says. "I don't want to damage and block the other processes I want."

After nearly two millennia, we know that sometimes getting in the way of inflammation can be a bad idea.

01

Beating the Heat

COLD DUNKS, PLASMA INJECTIONS, AND SAUNAS ARE POPULAR WAYS TO BATTLE INFLAMMATION. BUT DO THEY WORK?

AS AN ATHLETIC teenager in Ireland, Joseph Costello often followed hard Gaelic football sessions with ice baths. By the time he was a graduate student, he had found a more extreme method to chill the sore muscles and joints that come with exercise-induced inflammation: standing in a chamber cooled to minus 110°C (-166°F) for a few minutes at a time.

The experience was equal parts excruciating and invigorating, says Costello, now an exercise and environmental physiologist at the University of Portsmouth in the United Kingdom. "It was literally out of this world," he says. "The coldest temperature ever recorded on Earth was about 20 degrees Celsius warmer than this."

Ice plunges and cold showers are trendier than ever as strategies for battling inflammation, but they are not the only ways people are trying to hack their health. The options range from a set of specialized injections that require assistance from a health-care provider to heat-exposure sessions that essentially fight fire with fire.

But do any of these techniques accelerate healing? Evidence is both promising and murky, with some studies showing benefits, some showing no effects, and others showing that inflammation-control tactics can backfire.

MOST OF US ARE DESTINED for some very specific aches and pains. As we get older, our odds of developing a musculoskeletal injury increase, and our body heals more slowly. By the age of 55, an estimated 80 percent of people suffer from osteoarthritis (the degeneration of cartilage around the joints), leading to more stiffness and soreness. Inflammation is a major driver of these types of pain, according to some studies. But preventing or controlling the discomfort is tricky, in part because inflammation is an essential process that our bodies need to repair damage.

Here's how it works: When someone strains or tears a ligament or tendon, the injury triggers the release of inflammatory molecules and cytokines, starting a sequence of events known as acute inflammation. Immediately blood vessels dilate to allow more fluid to flow into the injured area. Swelling and clotting ensue while more inflammatory cells arrive to clear out the damage and mobilize other cells to rebuild tissue.

The idea of tinkering with inflammation is tantalizing because, in some ways, you could augment this process. For those less excited about full-body refrigeration, the most direct way to do that right now is with a simple shot.

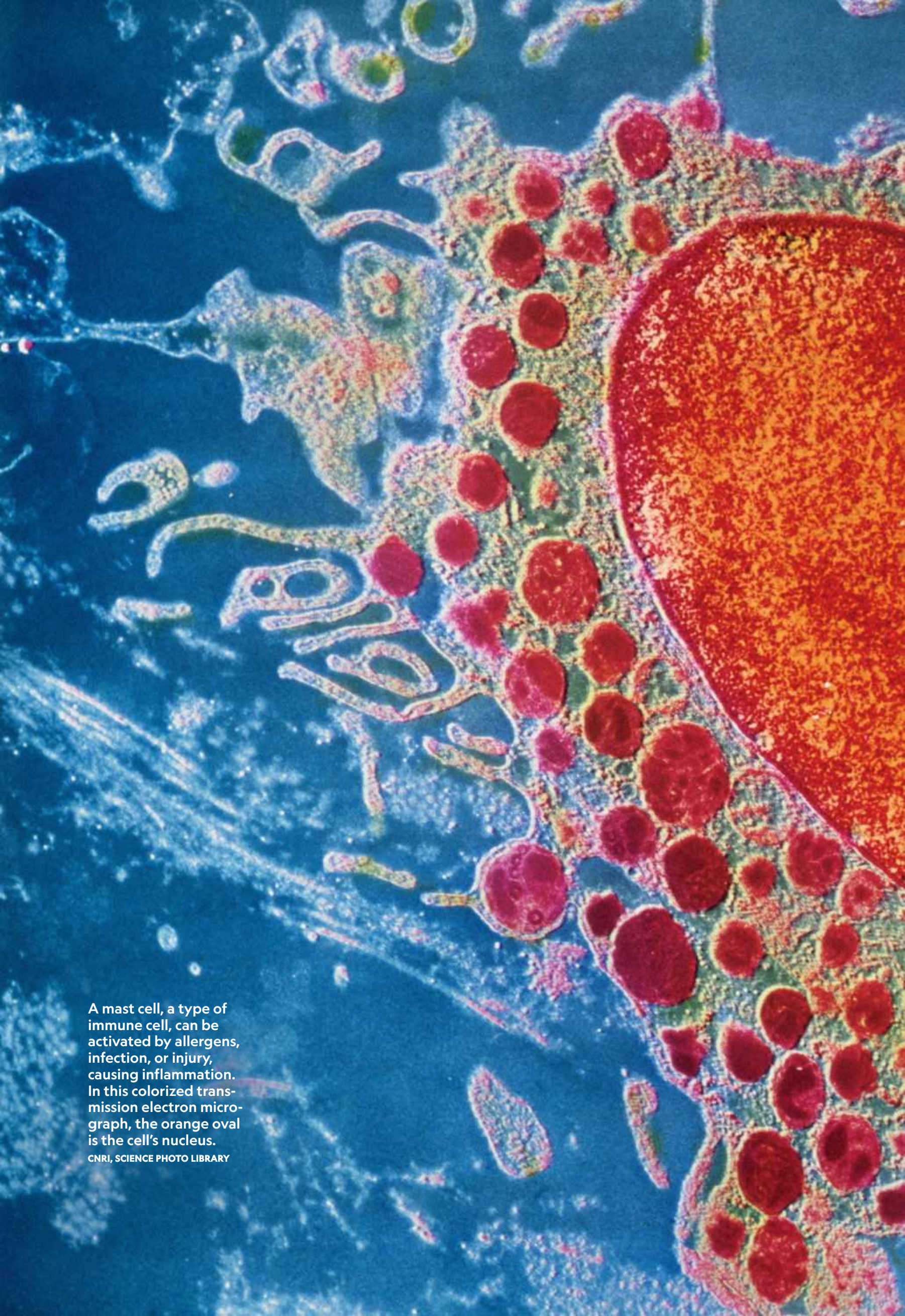
This increasingly popular medical approach, called platelet-rich plasma (PRP), is aimed at treating more chronic types of pain from tendinitis, arthritis, and other problems. Injections of PRP are made from a person's own blood, which is first spun rapidly to filter out red blood cells and isolate platelets, essential for clotting and full of anti-inflammatory growth factors.

PRP shots can contain various concentrations of white blood cells and other ingredients that dial inflammation up or down as needed, says Dean Wang, an orthopedic surgeon and chief of the sports medicine division at the University of California, Irvine. For his arthritis patients, he uses an anti-inflammatory PRP. For people with chronic tendon injuries such as tennis elbow, he makes pro-inflammatory formulations.

Evaluating the effectiveness of PRP remains a work in progress, in part because it's being used in many ways. In a 2021 analysis of existing research, Wang and colleagues reviewed 132 studies on the use of PRP for 28 conditions in eight specialties, including musculoskeletal issues, cosmetic uses, and neurology. Overall, 61 percent of the studies supported the use of PRP, though only a third detailed their formulas. Different studies varied in how they measured outcomes, making them hard to compare.

SCOTT CAMAZINE, SCIENCE SOURCE

A color-enhanced x-ray shows a knee replacement for degenerative joint disease in a 79-year-old woman. Inflammation may contribute to joint pain, especially in older people, but this bodily response is also part of the healing process.



A mast cell, a type of immune cell, can be activated by allergens, infection, or injury, causing inflammation. In this colorized transmission electron micrograph, the orange oval is the cell's nucleus.

CNRI, SCIENCE PHOTO LIBRARY

"The practice of it is far outpacing the science," Wang says. "But our science is good enough to show that there's some promise with these treatments."

FOR PEOPLE WILLING to endure extremes, the sort of cold exposure that Costello embraced has become a leading contender, attracting devotees who rave about its ability to ward off pain, anxiety, depression, and more. But scientists are still working on making that direct connection.

While many studies show that cold helps with pain—probably by lowering skin temperature, which reduces how fast nerves can deliver pain messages—Costello says that trying to assess the effects of cold exposure on both acute and chronic inflammation has been a challenge. For instance, scientists in Japan and Germany have found that infusing cold saline can reduce inflammation in rats, but the effects of animal studies are not directly comparable to humans. In one 2013 study of 20 men who ran downhill at a 10 percent grade for 40 minutes, a team of New Hampshire-based researchers tracked a slight reduction in inflammatory molecules among the 10 participants who sat in a 4°C (40°F) ice bath for 20 minutes afterward. Still, those results aren't statistically significant, and the ice bath made no difference in muscle soreness.

Researchers have also learned that cold therapy may counteract the muscle gains that come with exercise, possibly by interfering with the inflammatory process. In some cases, cold interventions might even increase inflammation, Costello says.

"There's more evidence coming out on an annual basis," he says. "But there are still only a handful of research studies that are supporting the effectiveness of cold therapy for reducing the inflammatory response."

PERHAPS THE MOST SURPRISING recent finding is that heat therapy could be another way to address inflammation and improve health. Regular sauna users have a lower risk of cardiovascular disease, according to research on more than 1,600 men in Finland. And physician-supervised procedures using tools such as targeted lasers, ultrasounds, fluid infusions, or heat chambers to raise body temperature have shown promise for treating depression and cancer.

In a 2021 review of research on repeated sauna and hot tub use, University of Oregon environmental physiologist Chris Minson and colleagues found evidence that heat can suppress pro-inflammatory pathways and enhance anti-inflammatory ones in both animals and people.

Minson recently put a sauna in his backyard. Most days, he spends about half an hour in it, punctuated by a cold shower. His research has convinced him that by adhering to a new regimen against inflammation, he's making a healthy choice. All evidence aside, he can feel it. "When I take care of my body by doing these kinds of things, I sleep better," he says. "I'm happier. I feel healthier." To Minson, that feels like a pain-free step in the right direction.

BY THE AGE OF 55, AN ESTIMATED 80 PERCENT OF PEOPLE SUFFER FROM OSTEOARTHRITIS, LEADING TO MORE STIFFNESS AND SORENESS.

INFLAMMATION TO THE RESCUE

When bacteria or a virus invade your body, the immune system reacts with both immediate and long-term protections. The body's first line of defense: a phalanx of white blood cells.

Illustration by
MATTHEW TWOMBLY

HOW THE BODY FIGHTS INFECTION

1 First responders
Trillions of white blood cells circulating in the bloodstream are mustered to the infected area in 15 to 20 minutes.

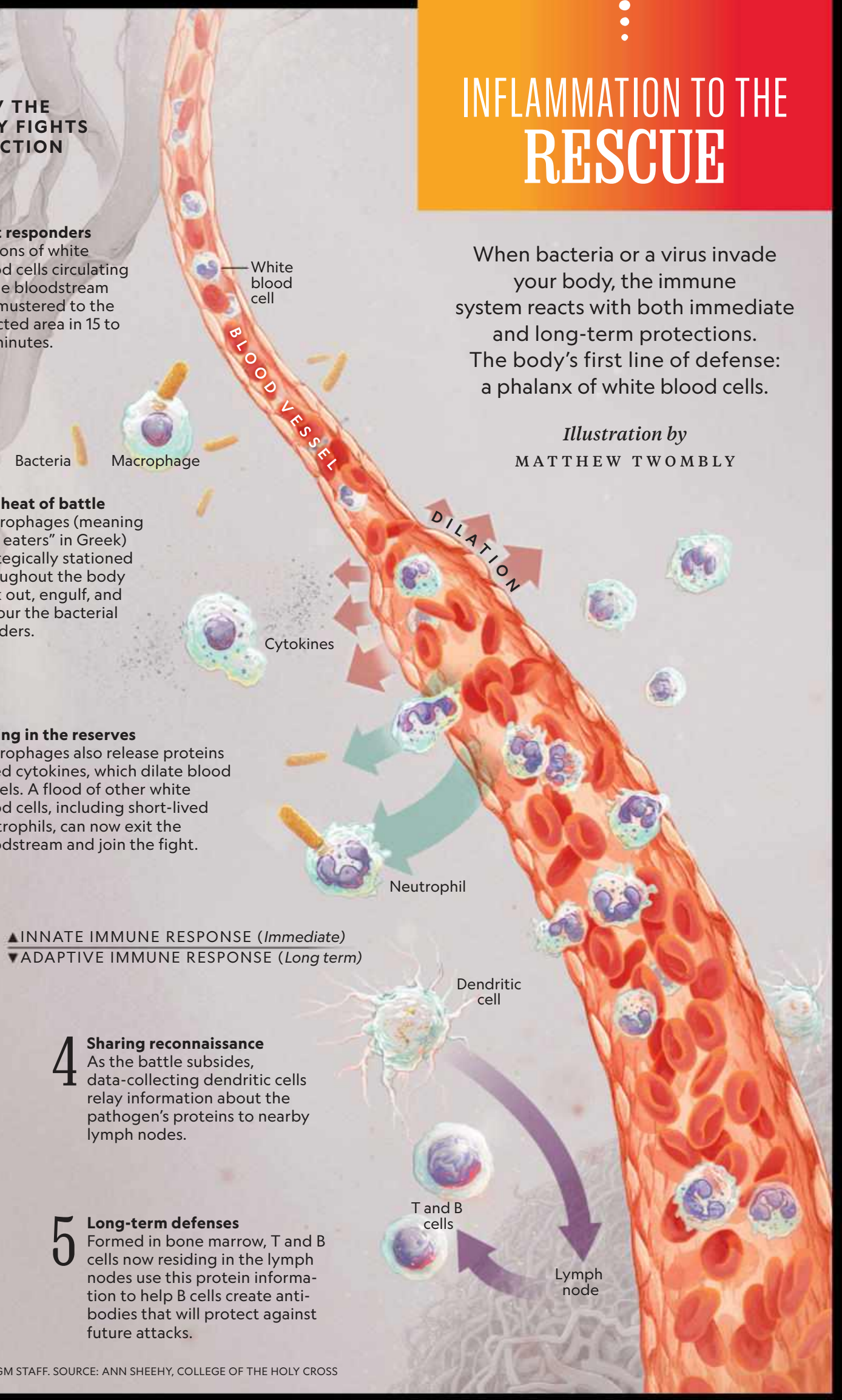
2 The heat of battle
Macrophages (meaning "big eaters" in Greek) strategically stationed throughout the body seek out, engulf, and devour the bacterial invaders.

3 Calling in the reserves
Macrophages also release proteins called cytokines, which dilate blood vessels. A flood of other white blood cells, including short-lived neutrophils, can now exit the bloodstream and join the fight.

▲INNATE IMMUNE RESPONSE (*Immediate*)
▼ADAPTIVE IMMUNE RESPONSE (*Long term*)

4 Sharing reconnaissance
As the battle subsides, data-collecting dendritic cells relay information about the pathogen's proteins to nearby lymph nodes.

5 Long-term defenses
Formed in bone marrow, T and B cells now residing in the lymph nodes use this protein information to help B cells create antibodies that will protect against future attacks.



GRAPHIC: NGM STAFF. SOURCE: ANN SHEEHY, COLLEGE OF THE HOLY CROSS

02

Slowing the March of Time

AS WE GET OLDER,
MORE INFLAMMATION DRIVES
ACHES AND PAINS.
BUT EXPERTS SAY IT DOESN'T
HAVE TO, AND SOLUTIONS
ARE ON THE WAY.

Inflamed blood vessels, blocked by blood clots, in the lung of a COVID-19 patient appear yellow in this 3D image.

IT HAPPENS to everyone. With age come achy joints and a rising risk for cancer, heart disease, dementia, arthritis, and other illnesses. Those changes follow an uptick in inflammatory molecules over the course of a lifetime so common it has a scientific name: inflammaging.

Now researchers are racing to unravel how the inflammatory process changes over our lifespan, what instigates the shift, and how it might be possible to interfere with it.

As people age, increasing amounts of pro-inflammatory cytokines and other inflammation-related molecules circulate in the blood. When the shift occurs depends on the person, says Ron DePinho, a cancer biology and aging researcher at the University of Texas MD Anderson Cancer Center in Houston. But 50 is generally when inflammation starts to increase, with a dramatic shift after 60.

The uptick tracks closely with disease trends. Starting at 65, the number of people with Alzheimer's doubles every five years. In the United States, 80 percent of adults over 65 also have at least one chronic condition. By 85, a third of people may have Alzheimer's, while a third of men and a quarter of women have had cancer.

ON THE MOST BASIC LEVEL, anti-inflammatory medications and healthy habits like exercise can slow some aspects of the inflammaging process, says DePinho. But to find more targeted solutions, researchers are working to understand the problem better.

A dozen biological changes corresponding with age have been identified so far. All those hallmarks of aging are associated with inflammation, says Ferrucci of the National Institute on Aging. As people age, their immune cells lose their protective functions and stop fighting off invaders, turning into what scientists call senescent cells. Other kinds of cells can also become senescent in response to stress. They cease replicating, stop working, and start secreting powerful inflammatory molecules that cause yet more cells to become senescent.

Meanwhile, DNA damage inside cells accumulates over time, especially at the tips of chromosomes in protective regions called telomeres, which are long stretches of bunched-up DNA. Each time a cell divides, its telomeres become shorter until they reach a critical length that is perceived by the cell as DNA damage or instability, which may spark deterioration.

As telomeres become damaged, they initiate a signaling process through proteins that turn certain genes on and off. Some of those genes support the function of mitochondria (the cell components that produce energy). As a result of the gene disruption, mitochondria become defective and leak their DNA into cells, causing inflammation.

Scientists used to consider telomere shortening, mitochondrial damage, inflammation, and other processes separate theories of aging that could contribute to diseases like cancer, DePinho says. Now it is clear that all these changes are connected and that inflammation acts as a co-conspirator in the aging process.

As chronic inflammation sets in, it becomes harder for the immune system to perform routine tasks such as detecting and eliminating cancer cells and pathogens, which could make diseases more likely. But this burgeoning understanding of inflammaging as a relentless circuit of steps that all exacerbate inflammation is revealing new ways to break the cycle.

DEVELOPING ANTIAGING interventions that target inflammation remains a challenge because they need to be specific enough to avoid causing more harm than good, Ferrucci says. Trying to tackle chronic inflammation with general anti-inflammatory drugs, for example, could make us more susceptible to disease by impairing the inflammation we need to stay healthy.

"When you have an infection, if you don't have inflammation, you're going to die," Ferrucci says. "Shutting

ESRF, HUMAN ORGAN ATLAS

This colorized x-ray shows the hands of a patient with rheumatoid arthritis, which causes chronic inflammation and bone erosion (orangish patches) near the finger joints.

ZEPHYR, SCIENCE SOURCE

CAN YOU EAT TO COMBAT INFLAMMATION?

The global obesity epidemic has been fueled by a diet that's high in calories, fat, and sugar, all of which can lead to weight gain and have an inflammatory effect on the immune system. But plenty of cultures eat for longevity instead.

In 2021 researchers from the University of Valencia and the German Institute of Human Nutrition compared several well-known healthy diets—the Nordic, Mediterranean, Washoku, and Jiangnan—to find the most common foods associated with anti-inflammatory effects.

This sample menu includes recommendations from the study, emphasizing unprocessed foods, nuts, fruits, and vegetables for a more filling, healthier meal plan.

BREAKFAST
Start with two slices of whole wheat bread with mashed avocado and a fresh fruit salad. Sip on some soy milk.

SNACK
Grab a handful of almonds, and pour a glass of pomegranate juice.

LUNCH
Mix a green salad with carrots, olives, cucumbers, shallots, sweet potatoes, white beans, tomatoes, and chicken. Add olive oil and a squeeze of lemon.

SNACK
Blend together kale, avocado, pineapple, blueberries, and banana to make a smoothie.

DINNER
Grill salmon with olive oil, eggplant, artichoke, and rosemary. Serve with brown rice or lentils.

This is a magnified cross section of a blueberry, which has antioxidant and anti-inflammatory properties that may help brain function.

COMPOSITE OF 210 IMAGES BY NATHAN MYHRVOLD, *MODERNIST CUISINE*

down inflammation with a bomb like a corticosteroid or some monoclonal antibodies works. It's also quite dangerous."

One of the most promising new strategies for dealing with inflammaging is attacking senescent cells. In mice, a low-dose combination of two substances, dasatinib (a drug) and quercetin (a plant pigment), appears to be particularly effective at getting rid of deadbeat cells in the intestines. Clinical trials are now under way to see if these so-called senolytics work in people.

Scientists are hopeful that they'll soon understand which interventions will help most. "Tissues retain a remarkable capacity to renew themselves if you remove the underlying instigators of the aging process," DePinho says.

For now, exercise really is one of the best medicines, enhancing DNA repair and improving mitochondrial function. Studies show it can reduce the risk of serious disease. As little as 15 minutes a day can make a difference, DePinho says.

Dietary choices too can improve inflammaging, according to a raft of international studies that support eating a Mediterranean-style diet with an emphasis on whole grains, fresh produce, nuts, and fish. Consuming a wide variety of vegetables may also support the gut microbiome.

When Ferrucci shops, he buys 10 kinds of vegetables. "That is something that has been suggested in the literature," he says. "And I think that's a simple way of following that advice."

●●●● 03 ●●●●

Linking Depression and Inflammation

INFLAMMATION IN THE BODY CAN AFFECT THE BRAIN AND ALTER MOOD, FINDINGS THAT COULD LEAD TO NEW SOLUTIONS FOR HARD-TO-TREAT ISSUES.

The brain's limbic system (directly below) includes the hippocampus and amygdala. Inflammation there can impair memory and affect behavior.

SUFFERING FROM a chronic illness can obviously alter your mental health. Not surprisingly, depression affects over 40 percent of cancer and rheumatoid arthritis patients, and nearly 30 percent of those with diabetes, according to the Centers for Disease Control and Prevention. But there is another factor that these and other severe diseases have in common: inflammation.

Scientists now believe that in many cases, inflammation may exacerbate mental health conditions. Their work is leading to new medications and insights for treatment. "All along the pathway of that clinical course of depression, inflammation seems to play at least some sort of role," says Marx of Deakin University.

For a long time, researchers considered depression to be a simple story of neurotransmitters gone wrong, Marx says. Serotonin and dopamine are two particularly important neurotransmitters, messenger molecules in the brain that help regulate mood, motivation, and emotion. When those molecules got out of whack, the thinking went, mental health problems followed.

In the past few decades, however, multiple lines of evidence have converged to suggest that while neurotransmitters matter, the immune system is linked to mental health, and inflammation can alter mood. As knowledge of the number of molecules involved in the inflammatory process has exploded, so too have studies linking a variety of inflammatory cytokines with major depressive disorder, as well as bipolar disorder and schizophrenia.

Some of the strongest evidence that inflammation can wreak havoc in the brain comes from research on a drug called interferon alpha. An inflammatory cytokine secreted by infected cells, interferon alpha works as a powerful antiviral. Synthetic versions are used to treat hepatitis C, malignant melanomas, and other conditions. But side effects include psychosis and depression: A quarter of people who take interferon alpha for hepatitis C develop major depression.

There could be several ways inflammation might damage mental health. Among them, Marx says, chronic inflammation may impair the production of serotonin and other neurotransmitters, inhibit the creation of new brain cells, or damage brain cells' ability to form new connections. The hippocampus, responsible for memory, emotional regulation, and mood, seems to take the biggest hit.

ON A GRANULAR LEVEL, specific molecules involved in inflammation are under study, as are ways they might alter brain processes. For example, certain kinds of T cells and cytokines cross the blood-brain barrier and affect microglia, the central nervous system's resident immune cells. Normally, microglia repair damage and eliminate injured cells, but when stimulated by excessive inflammation, they appear to damage neurons instead, essentially eating up parts required for neuronal functioning, says Eléonore Beurel, a biochemist at the University of Miami Miller School of Medicine. "We are still trying to put the puzzle together," she says.

To understand how inflammation-related depression develops, some researchers are looking to key risk factors in the earliest stages of life. Scientists have known for decades that trauma in childhood raises the risk for adult depression, the treatment-resistant type in particular. Inflammation could explain the association and might help mitigate it, says Andrea Danese, a child and adolescent psychiatrist at King's College London.

Danese has found that kids under 10 who experience abuse and neglect show elevated levels of several inflammatory molecules by the time they are in their early 30s, putting them at heightened risk for cardiovascular disease, type 2 diabetes, and other physical health conditions.

"Individuals who have a history of childhood maltreatment tend to have more chronic and more persistent types of depression, and they

K.H. FUNG, SCIENCE SOURCE

also tend to respond more poorly to conventional treatment," he says. "Inflammation may be one of the biological reasons for why this happens."

AS SCIENTISTS DISCOVER more about inflammation's role in mental health, they hope to find more ways to combat depression. The opportunity appears most promising for the estimated 30 percent of people who don't respond to standard treatments like antidepressants. This group, studies show, tends to have the most inflammation.

Many mood stabilizers and other mental health drugs already have anti-inflammatory effects. And a wide variety of anti-inflammatory medications also appear to ease depression, according to a 2019 analysis by Chinese scientists of existing research, which included 26 studies that involved more than 1,600 people. Compared with people who took a placebo, the analysis found, those who took anti-inflammatory medications or supplements—including NSAIDs, statins, omega-3 fatty acids, and antibiotics—reported reduced depressive symptoms, especially when they combined the anti-inflammatories with antidepressants.

Working with a doctor to try multiple interventions at once is important, Marx says, because mental health issues are complex. Your risk for depression may be tied to genetics, environmental factors, and life experience—and your mood is also influenced by many processes. Traditional medications aren't always necessary either; solutions that have worked to curb other kinds of inflammation may have an impact here too.

Mediterranean-style eating in particular has been linked to a reduction in depression symptoms, Marx and his colleagues found in a 2020 review of related research. That may be because the diet's key ingredients—produce, legumes, fish rich in omega-3, raw nuts, and whole grains—all have anti-inflammatory properties.

Evidence also supports sufficient sleep, time outside, and meditation as ways to lower inflammation and, in turn, boost mood.

This holistic approach shows promise. "By exercising, by engaging with nature, by eating healthily, we can actually make a pretty substantial difference," Marx says. "Not only in physical outcomes but also our mental health." □

MARTIN OEGGERLI

HAPPY GUT, HAPPY BRAIN?

Science is increasingly finding a relationship between gut health and mental health. In 2017 U.S. researchers discovered that a healthy gut microbiome is extremely important for people suffering from depression and anxiety. Diet is just one component that influences the microbiome, but because our digestive process takes about a day, changing the foods we eat can affect our brain and mental health within 24 hours.

One increasingly popular way of eating—the Mediterranean diet—may cut the risk of depression by a third. This approach focuses on plants, moderate amounts of animal protein, and less saturated fat. It also incorporates fiber, which keeps gut microbiomes in balance.

Nutritionists recommend eating about 30 grams of fiber a day. Here are some of the top fiber-filled foods.

FIBER SOURCE	GRAMS OF FIBER PER CUP
Legumes	12-18 g
Beans	12-15 g
Berries	8 g
Whole grains	5-7 g

A colorized, microscopic close-up depicts gut microbes, the health of which is shaped by our dietary choices. Anti-inflammatory foods are key to overall wellness.

In the Bahamas, a camera team films the tight turns of a hammerhead shark in search of prey.

TELEVISION

DIVE INTO National Geographic's 12th annual SharkFest, which features surprising shark behavior around the world, some of it quite close to people. In *Baby Sharks in the City,* biologists reveal a nursery of Atlantic great whites just off the coast of New York and deploy a camera tag to show the life of a pup. In *Shark Beach With Anthony Mackie,* the Marvel star investigates the increase in shark sightings near his hometown of New Orleans, which may be related to environmental issues across the greater Gulf of Mexico. These shows—as well as *Attack of the Red Sea Sharks, Man vs. Shark With Ross Edgley* (pictured above), *Sharks Gone Viral, Supersized Sharks,* and *Shark Attack 360*—are streaming now on Disney+.

MAGAZINE

The July/August issue of *National Geographic History* shares a potential new answer to an age-old mystery: What happened to the two young princes who were famously imprisoned in the Tower of London by their uncle, King Richard III, never to be seen again? Philippa Langley, who led the successful effort to find Richard III's buried remains, argues that the notorious king may not have been responsible for their murders after all. To learn more, find the issue at Barnes & Noble or subscribe at *nghistory.com/subscribe*.

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