NATIONAL GEOGRAPHIC

THROUGH AN ASTRONAUT'S EYES

WHAT WE LEARN ABOUT EARTH FROM SPACE

Astronaut Peggy Whitson has spent 665 days in space — more than any other American

MARCH 2018

Colonial Tuco-tuco *(Ctenomys sociabilis)*
Size: Head and body length, 16.8 - 24.7 cm (6.6 - 9.7 inches) **Weight:** 180 - 234 g (6.3 - 8.3 oz)
Habitat: Prefers relatively arid steppe grasslands; also found in areas dominated by woody shrubs
Surviving number: Unknown; declining

Photographed by Anand Varma

WILDLIFE AS CANON SEES IT

The more the merrier. The colonial tuco-tuco is extremely social, living in burrows with as many as six individuals sharing a single nesting site. There is always just one male in each group, and males disperse every year to avoid mating with their own offspring. Nesting communally helps increase the survivability of young, as multiple adults pitch in to take care of the next generation together. But populations are still falling due to loss and degradation of their very limited habitat.

As Canon sees it, images have the power to raise awareness of the threats facing endangered species and the natural environment, helping us make the world a better place.

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MARCH 2018 • VOL. 233 • NO. 3 • OFFICIAL JOURNAL OF THE NATIONAL GEOGRAPHIC SOCIETY

FRONT

FEATURES

On the Cover Peggy Whitson has spent more days in space than any other U.S. astronaut: 665, accumulated over three flights. Raised in Iowa, Whitson is also the first woman to serve as NASA's chief astronaut and the first woman to command the International Space Station. "As I've traveled farther away from that farm in Iowa," she says, "my sense of what home is has expanded. Since being in space, home is actually planet Earth."
Photo by Dan Winters

Corrections and Clarifications
Go to *natgeo.com/corrections.*

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ELSEWHERE

TELEVISION

EXPLORING *ONE STRANGE ROCK*

Take a mind-bending tour of one of the universe's most peculiar and remarkable places: Earth. In the 10-part series *One Strange Rock,* award-winning filmmaker Darren Aronofsky tells the story of how our planet formed and generated so many natural wonders (among them ancient caves in the Bahamas that diver Becky Kagan Schott has explored, left). Actor Will Smith hosts the series, which airs on Mondays at 9/8c starting March 26 on National Geographic.

NAT GEO WILD

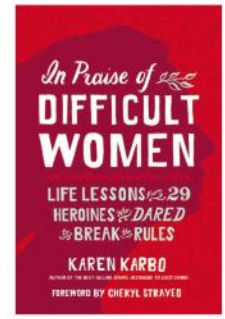
SAVOR *AMERICA'S WILD FRONTIER*

From the Appalachian woods to the Badlands of South Dakota and beyond, the five-part series *America's Wild Frontier* showcases the wild places and creatures that are national treasures. It airs Fridays at 8/7c starting March 2 on Nat Geo WILD.

BOOKS

SPEND QUALITY TIME WITH *DIFFICULT WOMEN*

What do Frida Kahlo, J. K. Rowling, and Angela Merkel have in common? They are among the "29 heroines who dared to break the rules" and are featured in the new National Geographic book *In Praise of Difficult Women.* It's available where books are sold and at *shopng.com/books.*



BOOKS

APPRECIATING *THE WISDOM OF WOLVES*

During six years observing an Idaho wolf pack, Jamie and Jim Dutcher saw traits such as curiosity, compassion, and kindness. Their reflections fill *The Wisdom of Wolves: Lessons From the Sawtooth Pack,* available where books are sold and at *shopng.com/books.*

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NATIONAL GEOGRAPHIC (ISSN 0027-9358) PUBLISHED MONTHLY BY NATIONAL GEOGRAPHIC PARTNERS, LLC, 1145 17TH ST. NW, WASHINGTON, DC 20036. $39 PER YEAR FOR U.S. DELIVERY, $44.00 TO CANADA, $51.00 TO INTERNATIONAL ADDRESSES. SINGLE ISSUE: $7.00 U.S. DELIVERY, $10.00 CANADA, $15.00 INTERNATIONAL. (ALL PRICES IN U.S. FUNDS; INCLUDES SHIPPING AND HANDLING.) PERIODICALS POSTAGE PAID AT WASHINGTON, DC, AND ADDITIONAL MAILING OFFICES. POSTMASTER: SEND ADDRESS CHANGES TO NATIONAL GEOGRAPHIC, P.O. BOX 62130, TAMPA, FL 33662. IN CANADA, AGREEMENT NUMBER 40063649, RETURN UNDELIVERABLE ADDRESSES TO NATIONAL GEOGRAPHIC, P.O. BOX 4412, STN. A, TORONTO, ONTARIO M5W 3W2. UNITED KINGDOM NEWSSTAND PRICE £5.99. REPR. EN FRANCE: EMD FRANCE SA, BP 1029, 59011 LILLE CEDEX; TEL. 320.300.302; CPPAP 0715U89037; DIRECTEUR PUBLICATION: D. TASSINARI. DIR. RESP. ITALY: RAPP IMD SRL, VIA G. DA VELATE 11, 20162 MILANO; AUT. TRIB. MI 258 26/5/84 POSTE ITALIANE SPA; SPED. ABB. POST. DL 353/2003 (CONV L.27/02/2004 N.46) ART 1 C. 1 DCB MILANO STAMPA. QUAD/GRAPHICS, MARTINSBURG, WV 25401. SUBSCRIBERS: IF THE POSTAL SERVICE ALERTS US THAT YOUR MAGAZINE IS UNDELIVERABLE, WE HAVE NO FURTHER OBLIGATION UNLESS WE RECEIVE A CORRECTED ADDRESS WITHIN TWO YEARS.

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FORGET 'EIGHT DAYS A WEEK'—PAUL McCARTNEY'S ASKING FOR JUST ONE

The singer-songwriter behind many of the Beatles' greatest hits, **Paul McCartney,** 75, is still selling out arena concerts. He's also leading the Meat Free Monday campaign, asking people to skip meat once a week to "help slow climate change, preserve precious natural resources, and improve their health." We met in London recently for an interview.

Susan Goldberg: Should I call you Paul or Sir Paul or ...?
Paul McCartney: Paul.

SG: OK. I wasn't sure. I'm American, so I don't know about these things.

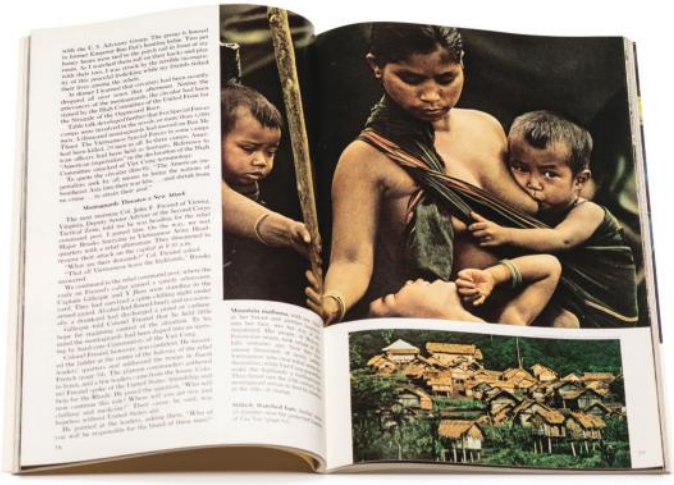
One thing I find so interesting about your Meat Free Monday campaign is that you're just asking for one day a week. Why did you decide to ask for only that?
PM: I think if you say to people, "I'm a vegetarian. I think it's great. I've been this way for 40 years. Now you should be a vegetarian," it's too much for them to take in. That means they've got to change their whole lifestyle. So what we find is, if you say to people, "Well, try one day," they can do that. And they're kind of willing to do that. And then some people go, "Oh. This is good." Or "Maybe I'll do two days." Things like that, I don't think you can approach with a sledgehammer. You've got to kind of just keep it gentle.

SG: Sometimes I see environmentalists with messages, and it sounds like moralistic scolding, and I don't know that it's terribly effective.

PM: That's what I mean. You know, you have to realize when you leave the room, they're going to talk about you, not necessarily in great terms. So I try and keep it something that I would've understood and I would've accepted before I was vegetarian.

SG: You've been vegetarian for a long time, right?
PM: Yeah. Years ago, Linda [his late wife] and I were on the farm, and the sheep had had lambs. It was the most beautiful time of the lambs' life, full of energy—and at one meal, we happened to be eating a leg of lamb. We weren't vegetarian then, so we made the connection. We said, "Should we try and not do this?" We did, and never looked back. It basically was compassion for these lambs that were in the first month of their lives and soon to have them ended. It didn't seem right.

SG: How has it changed your life?
PM: I feel very healthy, and I do shows three hours long and I don't feel knackered at the end of it. I still feel strong. So I think that's been one of the things. But then more recently, people have



McCartney says the inspiration for the song "Lady Madonna" came from this photograph, which he saw in the January 1965 issue of *National Geographic.*

"I love *National Geographic,* and I've loved it since I was a kid," he told me during our interview. "But one particular issue that I saw in the '60s had a woman ... and she looked very proud, and she had a baby ... And I saw that as a kind of Madonna thing, Mother and Child.

"Sometimes you see pictures of mothers, and you go, 'She's a good mother.' You could just tell there's a bond, and it affected me, that photo. So I was inspired to write 'Lady Madonna,' my song, from that photo."

PHOTO: MARY McCARTNEY, MPL COMMUNICATIONS

started to draw this comparison between greenhouse gases and basically too much livestock on Earth. It wouldn't be so bad if it was just one or two on a farm, but when there's billions, the way we now do it, it has a big effect on the atmosphere.

For me, the bottom line is we're on this incredible planet, and there doesn't appear to be another one in sight. And alongside us are these little dudes, these animals. We've all got the chance in life to survive, and I like the idea of giving them their best shot. I'm conscious of that now, whereas when I grew up, you never thought of it as meat. It was just some stuff that arrived from the supermarket, came all wrapped and packaged, and didn't look like an animal. I think that's how most people are.

SG: But you brought up your daughters very differently. Today your daughter Stella doesn't use any animal products in the clothes she designs.
PM: That's right. My kids are great, and they have always been vegetarian with the option that if they wanted to change, they could. But they never wanted to, and now they bring up their kids vegetarian. So the whole family is … and you know, nobody seems to be suffering.

SG: In a lot of parts of the world, though, there are people for whom raising livestock is their livelihood. Even having one pig or goat or cow is the road out of poverty.
PM: But I don't think that's the problem. I think the mass production is where the big problem starts to come in, where certain companies have billions of animals, often cramped in really cruel conditions.

I was brought up by my mom, who's a nurse, a midwife, and my dad was a cotton salesman. Just ordinary people in Liverpool, and we just had ordinary food, the same as everyone in our street. But when I reached a certain age, I made a change. I just thought, "You know what? Maybe this isn't what I want to do. I've got the free will to do something else."

So I encourage people. I say, it's actually quite fun when you look at what you do, what you eat, how you live, and think, "Is this what I'm going to do the rest of my life, or would it be interesting to try to make a change?" I think a lot of people do that these days.

We both wore blue suede shoes to the interview, as in the Carl Perkins song that the Beatles covered. But McCartney said his are "fake blue suede" shoes that daughter Stella's company makes with a non-leather material.

SG: You've been one of the most famous people in the world for a very long time. You could support so many causes and have your voice heard by a lot of people. Why this cause, and why now?
PM: Well, this is personal. I do support a lot of other causes too—but this particular one, this is how I live. And I like the idea of this particular campaign because I can then say to people, "Just try it." Nobody's forcing anyone to do anything; you just try one day meat free, because it's a good idea.

SG: So you think some of the main advantages here are personal health, health of the planet, and compassion for animals …
PM: Mm-hmm.

SG: What am I leaving out?
PM: Those are three pretty good ones. I'd go with those.

***

Thank you for reading *National Geographic*.

Susan Goldberg, *Editor in Chief*

PHOTO: NATIONAL GEOGRAPHIC
THIS INTERVIEW WAS EDITED FOR LENGTH AND CLARITY.

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VISIONS

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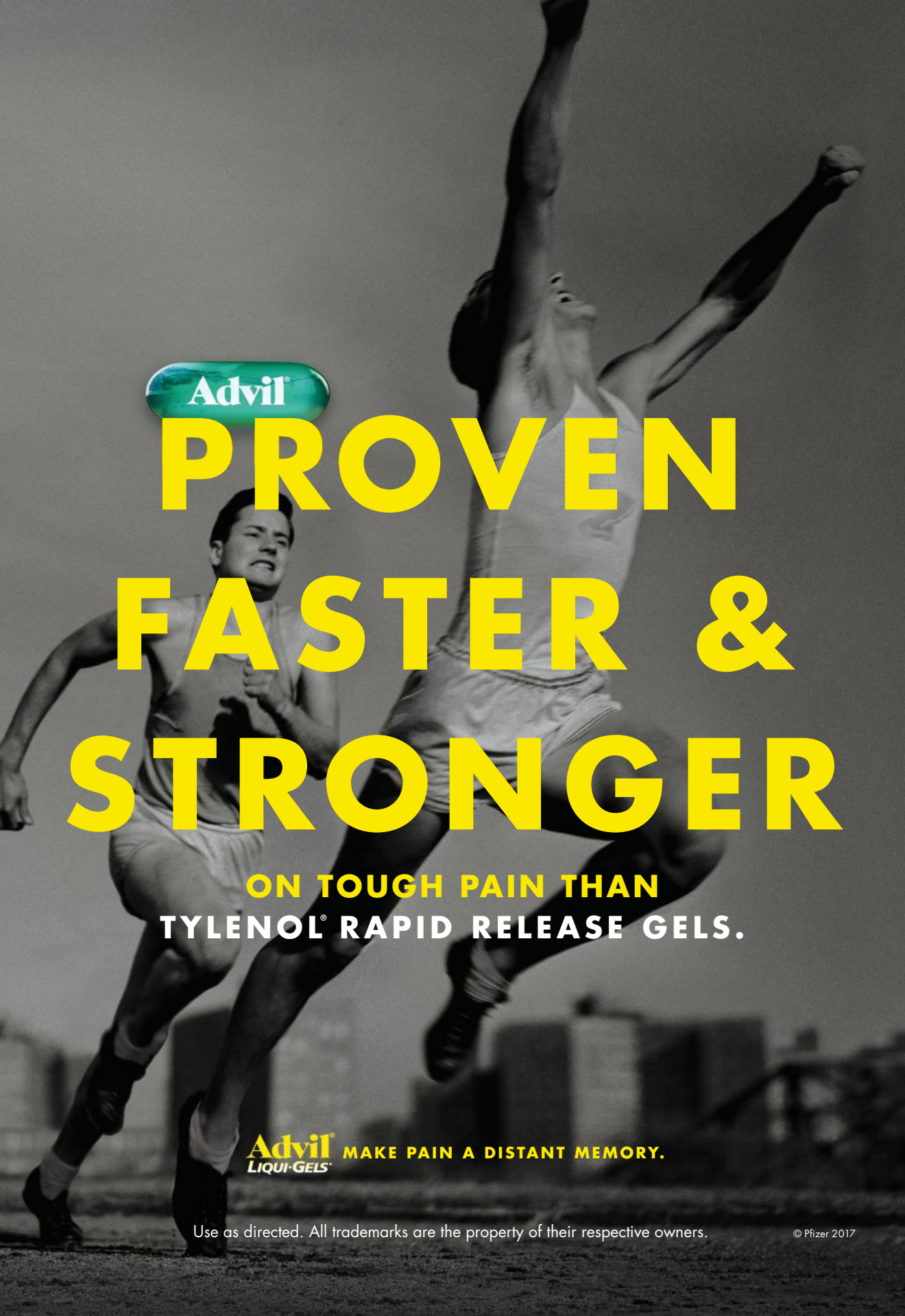
MICRONESIA
The Pacific Ocean atoll named Pingelap – pictured here in infrared – is also known as the Island of the Colorblind, because as many as 10 percent of the residents are believed to carry the achromatopsia gene that causes complete color-blindness. A typhoon wiped out most of the island's population in the 18th century, and a chief with the gene is said to have helped repopulate it.

PHOTO: SANNE DE WILDE, NOOR

Ottó Méhes
Calgary, Alberta

On a trip to Budapest, Méhes, an IT analyst, wandered the city with friends. Day's end found them at the Széchenyi thermal baths. As his friends waded into the water, Méhes, shaking with cold, took the shot he'd envisioned all day. "I would call this image," he says, "a calculated coincidence."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MUSHROOMING POPULARITY

By Daniel Stone

Mushrooms are everywhere—on forest floors, in gardens, in networks connecting below our feet. The largest organism on Earth is actually a honey mushroom, an underground web that covers more than 3.7 square miles in Oregon's Blue Mountains.

Yet mushrooms are poorly understood, and the field of medicinal mushrooms is still in its infancy. Fungi used to be overlooked as a low-calorie, low-nutrition food, but in fact many are full of nutrients. According to biochemist and herbalist Martin Powell, many produce compounds that show potential for improving treatment results for those suffering from ailments such as cancer and dementia.

"Fungi are far more mysterious than plants," says Robert Beelman, director of the Penn State Center for Plant and Mushroom Foods for Health. He led a recent study showing that two common antioxidants in some mushrooms—ergothioneine and glutathione—have the potential to help ward off diseases that come with aging, such as heart disease and Alzheimer's. Some species are famous for their hallucinogenic properties. Others, like the mushrooms on these pages, not only are appreciated by chefs but also show therapeutic value. Perhaps in the future, superfoods won't be just plants but also fungi.

CHAGA
Inonotus obliquus

Often consumed as a tea, the mushroom has been used to treat digestive disorders and psoriasis. A 1968 novel touted it as a cure for cancer.

BEAR'S HEAD TOOTH
Hericium americanum

Some research links this mushroom, as well as others in the *Hericium* genus, to boosts in cognitive health.

MAITAKE
Grifola frondosa

A culinary and clinical mushroom, it may help reduce blood sugar and boost immunity.

REISHI
Ganoderma lucidum

Known in China as the mushroom of immortality, it has traditionally been used to prolong life and is used to treat allergies and arthritis.

LION'S MANE
Hericium erinaceus

By helping the brain promote nerve growth, it could be a supplementary treatment for neurodegenerative disorders.

CHESTNUT
Pholiota adiposa

Consumption of chestnut-mushroom extract may offer protection from buildup of fat in blood, or high cholesterol.

PHOTO: REBECCA HALE, NGM STAFF
MUSHROOMS SOURCED FROM NORTH COVE MUSHROOMS AND SHARONDALE MUSHROOM FARM
THIS INFORMATION IS NOT INTENDED TO BE USED TO TREAT ANY MEDICAL CONDITION.

BLUE OYSTER
Pleurotus ostreatus

Studies have shown that oyster varieties help reduce cholesterol and boost levels of vitamins C and E.

INDIAN OYSTER
Pleurotus pulmonarius

This oyster variety is easy to cultivate, contains antioxidants, and may help treat inflammation.

POPLAR
Agrocybe aegerita

The poplar's antioxidant properties were shown in mice to increase skin collagen and reduce some effects of aging.

YELLOW OYSTER
Pleurotus citrinopileatus

Like other oyster mushrooms in the *Pleurotus* genus, yellow oysters are a known source of antioxidants.

SHIITAKE
Lentinula edodes

Injections of an extract of this mushroom may slow the growth of tumors and improve outcomes of chemotherapy.

PRINTING PARTS FOR A NEW YOU

By Erika Engelhaupt

What if you could press a button and a machine would make you a new nose or kidney? Scientists are exploring that futuristic vision by using special 3-D printers to make living body parts.

Called bioprinters, these machines use human cells as "ink." A standard 3-D printer layers plastic to create car parts, for example, or trinkets, but a bioprinter layers cells to form three-dimensional tissues and organs.

To create an ear, the printer lays down a pliable, porous scaffold made of hydrogel, a kind of polymer. The scaffold is covered with skin cells and cartilage cells, which grow and fill in the ear-shaped form. The hydrogel eventually biodegrades; after about six months the ear is composed entirely of human cells. "We use the patient's own cells," says Anthony Atala, director of Wake Forest University's Institute for Regenerative Medicine. That way the organs won't be rejected.

Before programming a machine to build a body part, Atala says, scientists need to figure out how to create it themselves. In their labs they have grown bladders, blood vessels, and many other anatomical parts that have been implanted into patients.

Now they're translating them for 3-D bioprinters and hope to soon be able to implant printed organs too. Already miniature kidneys and livers are used to test drugs, including chemotherapy agents.

Is there any area of anatomy that can't be made in this way? Printing at least parts of the human heart should be possible, Atala says. What about the brain? "Definitely not in my lifetime!"

To print an ear, a bioprinter simultaneously builds a polymer scaffold, like the one shown here, and covers it in cells that form cartilage.

PHOTO: REBECCA HALE, NGM STAFF. EAR SCAFFOLD PROVIDED BY WAKE FOREST INSTITUTE FOR REGENERATIVE MEDICINE

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IN SEARCH OF A LONGER LIFE

By Nina Strochlic

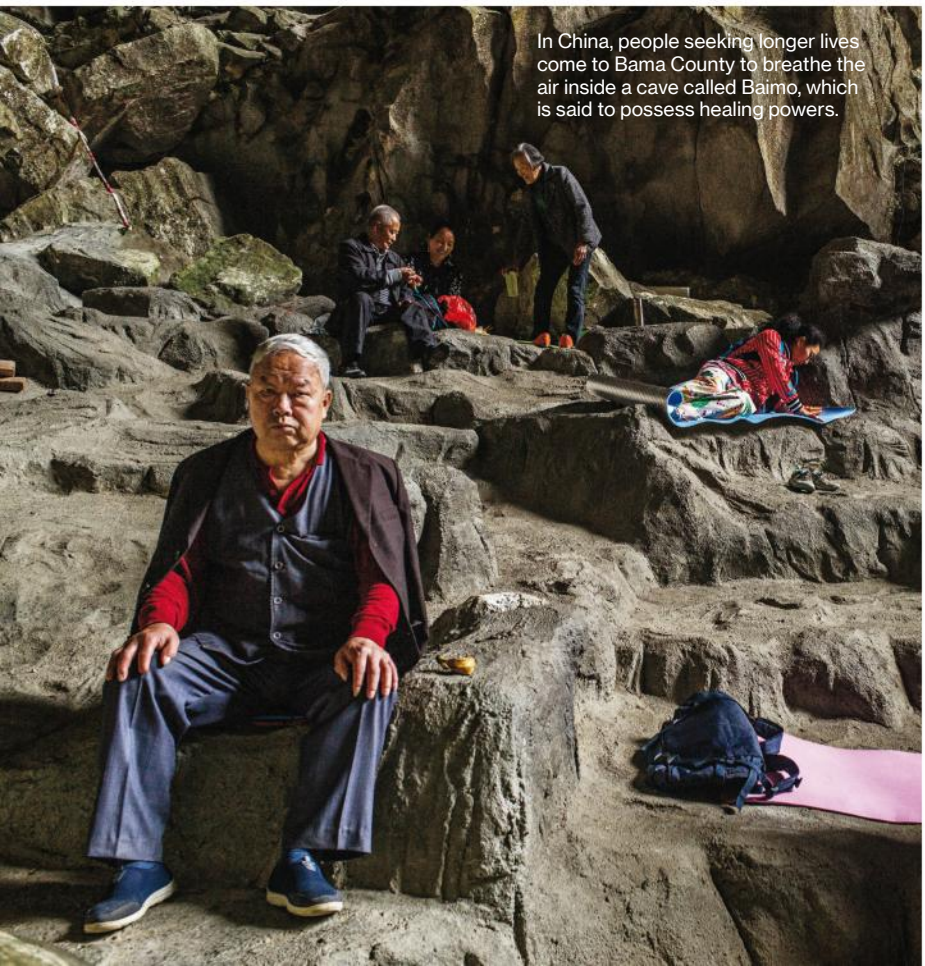
China is on the brink of a huge demographic shift. Over the next two decades, an unprecedented baby boom from the 1960s will age into "the largest number of elderly ever in the history of China," says Yu Xie, a Princeton University sociologist who studies the country.

While the government prepares for strains on the medical system, members of this older generation—more educated and mobile than those before—are taking health into their own hands. "They don't see how they can count on government for health care and services," says Xie, so "they turn to traditional methods."

Often this takes the form of widely accepted alternative medicine, such as acupuncture and herbal remedies. But sometimes, he warns, it leads people "to look for easy and quick solutions."

Increasingly, Chinese are leaving polluted cities and bringing their ailments to "longevity villages," where the relatively clean air and water are touted as miracle cures. Bama, an autonomous county renowned for its many centenarians, now reportedly receives at least two million visitors a year. Cancer patients and stroke victims travel there to undergo natural treatments but often find peddlers of shady remedies.

Rural China has embraced the financial potential of this type of ecotourism, says Stanford economist Karen Eggleston. Without regulation of treatments, though, an aging population is at risk. "There's a yearning to find the secret to longevity that people around the world search for," she says. "But that leaves people prey to those out for a fast buck."



In China, people seeking longer lives come to Bama County to breathe the air inside a cave called Baimo, which is said to possess healing powers.

PHOTO: LAM YIK FEI, NEW YORK TIMES/REDUX

TIPPING THE SCALES

Belts are loosening from Greece to China. A 2017 study in the medical journal the *Lancet* crunched the body mass index (BMI) trends of nearly 130 million people and calculated that the number of obese adults has increased nearly sevenfold since the 1970s, with the majority today in China and the United States. A similar study from 2016 found that adults have gained more than three pounds on average per decade over the same period.

The ranks of obese kids and teenagers grew from 11 million in 1975 to 124 million in 2016. The highest prevalence is in Polynesia and Micronesia, followed by Kuwait, the U.S., and Bermuda. At this rate, the world will have more obese children than underweight ones by 2022.

The culprit? "A rapid change in lifestyles over the past 10 years," says Juana Willumsen, a childhood obesity specialist at the World Health Organization. Cheap junk food, rural-to-urban migration, and screen-based entertainment all contribute to expanding waistlines.

Because obesity is linked to health problems like heart disease and diabetes, says Willumsen, "we're looking at a very heavy burden on health systems and society." *—NS*

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CLUES TO A DEADLY ILLNESS

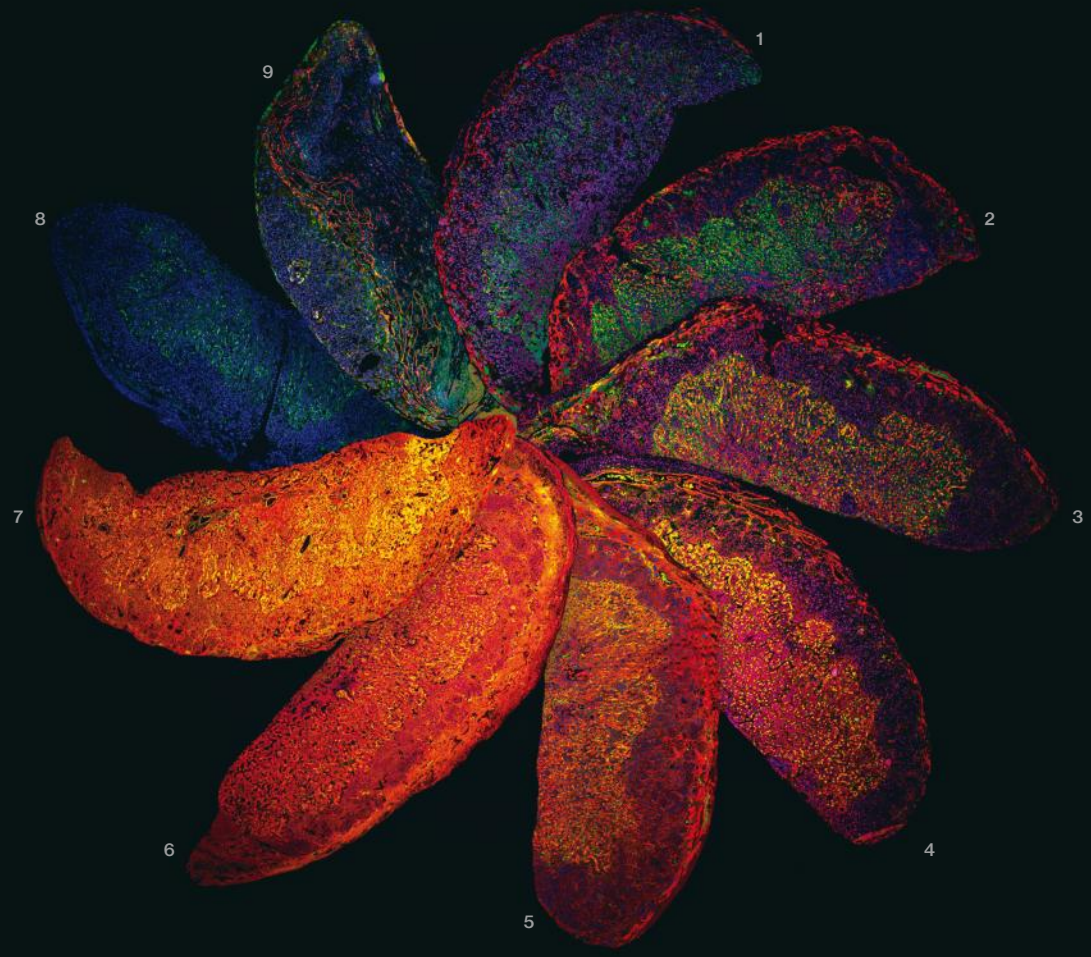
By Catherine Zuckerman

Every day hundreds of women die in pregnancy or childbirth. This statistic, which the World Health Organization deems "unacceptably high," reflects problems in all nations, however prosperous. In the U.S., pregnancy-related deaths have risen steeply in the last two decades.

A primary culprit is a cardiovascular complication called preeclampsia. Marked by high blood pressure, swelling, and elevated protein in the mother's urine, preeclampsia can be treated but still accounts for many maternal deaths each year—and usually results in premature birth. Worldwide it's a leading cause of mother and fetal mortality, says Suchita Nadkarni, an immunologist at Queen Mary University of London. Her research aims to find early markers for the illness, which to date is only identifiable in the second or third trimester.

To work toward earlier detection, Nadkarni studies the placenta. The organ grows in a gestating mammal's uterus to nourish a fetus—but can do that properly only if the immune system is working. When Nadkarni altered that system in mice, vital blood vessels (visible as red on the edges of slices one through five below) became abnormal (slices six through nine).

"Pregnancy is such a bizarre and wonderful thing," says Nadkarni. "If we can better understand how the immune system functions in that state, then we can ask why it doesn't work in preeclampsia."



Stained to show changes in their structure, slices of mouse placentas offer clues to preeclampsia, a serious maternal condition.

PHOTO (COMPOSITE OF MULTIPLE IMAGES): SUCHITA NADKARNI, WILLIAM HARVEY RESEARCH INSTITUTE, QUEEN MARY UNIVERSITY OF LONDON; NEIL DUFTON

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SIGNS OF HEALTH

By Natasha Daly

When the plague swept through England in the 1660s, it killed some 100,000 Londoners. To warn of disease, "plague crosses" marked victims' doors, along with the words "Lord have mercy upon us."

Public health warnings have evolved since then. In the book and exhibit "Can Graphic Design Save Your Life?" designers Lucienne Roberts and Rebecca Wright examine how public health messages are communicated. By the 19th century, Roberts says, mass media, medical science, and graphic design were adept at teaching people about health and disease. Tuberculosis inspired the United States' first big health-education campaign, with one poster discouraging "careless spitting, coughing, sneezing." The number of deaths fell steadily between 1900 and 1940.

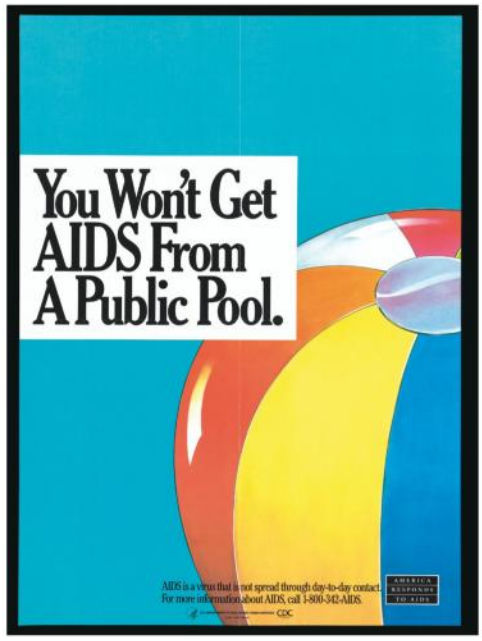
Both world wars sparked campaigns against sexually transmitted diseases. World War I–era posters warned soldiers against promiscuity while pointedly avoiding words such as "syphilis" and "gonorrhea." By World War II, language was more explicit: "You can't beat the Axis if you get VD," scolded one American poster. Starting in the 1980s, posters corrected misinformation about HIV/AIDS and urged condom use.

Roberts says that the link between design and public health extends beyond publicity campaigns. Some U.K. hospitals revamped emergency room signs to better inform people about wait times and triage. This helped drive a 50 percent decline in violent waiting room outbursts, she says: "The root thing that needed to change [was] information."

Graphic design's influence on public health can be lasting. A red cross once warned of plague's presence. Now a different take on the symbol is one of the world's most recognizable icons—and a reassuring beacon of health and safe haven.

IMAGES (FROM TOP): NATIONAL LIBRARY OF MEDICINE; U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES; ARIZONA DEPARTMENT OF HEALTH SERVICES

1940
World War II–era health posters framed women, especially promiscuous ones, as carriers of sexually transmitted diseases and moral decay. This image implores soldiers serving abroad to protect themselves.



1991
Many HIV and AIDS posters took a calm, measured approach. By teaching people how they *couldn't* catch the disease, the campaigns attempted to quell anxiety and stigma.

2017
A Google search for "Zika+honeymoon" turns up hundreds of thousands of results. This playful ad from the Arizona Department of Health Services directs would-be honeymooners to a website to find out more.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MONDAY MAR 26
NATIONAL GEOGRAPHIC

A new study says drinking a few cups of coffee a day may lower a person's risk of early death.

PHOTO: REBECCA HALE, NGM STAFF

DRINK COFFEE, LIVE LONGER?

By Catherine Zuckerman

Coffee lovers, rejoice. New research suggests that people who drink two to three cups of coffee a day—caffeinated or not—may have a lower chance of dying from certain illnesses than those who abstain.

The study, thought to be the largest of its kind, followed more than 500,000 people in 10 European countries over the course of 16 years. It found that compared with those who don't drink coffee, those who do show signs of having healthier livers and circulatory systems, as well as lower levels of inflammation, says epidemiologist and study leader Marc Gunter. The findings also indicated that "higher coffee consumption was associated with a reduced risk of death from any cause," including circulatory diseases and digestive diseases, says Gunter, who heads the nutrition and metabolism section of the International Agency for Research on Cancer in Lyon, France.

Previous, smaller scale studies have found a link between coffee drinking and increased resistance to certain ailments, but Gunter's findings provide the most substantial evidence to date. "This digestive disease relationship, which was strongest for liver disease deaths, is particularly striking," he says.

Gunter says the next step is to analyze coffee's chemical composition in hopes of understanding what makes the beverage beneficial. So he's going back to his research—and the rest of us, it appears, should be going back for refills.

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*Colgate Total® toothpaste reduces bacteria on teeth, tongue, cheeks, and gums; helps prevent plaque and gingivitis; fortifies enamel. Not intended for prevention or treatment of more serious oral conditions.

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LEGAL NOTICE

If you own or owned a home or other structure with Windsor Pinnacle or Legend Series windows, you may qualify for benefits from a class action settlement.

Go online at www.windowsettlements.com to learn how to file a claim.

A settlement has been reached with the Windsor Window Company ("Windsor") and Woodgrain Millwork, Inc. ("Woodgrain") about Pinnacle and Legend Series (including Legend Hybrid) windows manufactured by Windsor between January 1, 2000 and January 5, 2018. The settlement covers claims of wood rot to the windows themselves, additional damage caused by water leakage, and qualifying prior repairs. Windsor and Woodgrain (the "Defendants") deny the allegations. There has been no determination of wrongdoing by the Court.

Who Is Included?

The settlement includes all individuals and entities in the United States who are previous, current, or subsequent owners of a structure with Qualifying Windows (referred to as a "Qualifying Structure"). Examples of how to determine whether your windows are Qualifying Windows can be found at www.windowsettlements.com. The website has photographs and detailed instructions on how to identify if your windows are part of the Settlement.

What Does The Settlement Provide?

Those that file a valid claim can get replacement windows and window sashes, money for window frame damage, money for additional damage caused by a window leak, and reimbursement for qualifying prior repairs. Complete details on eligibility, claim options and the dollar amounts you could be eligible for can be found at www.windowsettlements.com.

How Do I Make A Claim?

You can file an online claim now at the website, or you can mail in a paper Claim Form. If you do not have a paper Claim Form, you can download one at the website or request one by calling the toll-free number below. Your paper Claim Form must be postmarked no later than **January 5, 2019**. If you file your Claim online, it must be submitted by **11:59 p.m. PST on January 5, 2019**.

Who Represents Me?

The Court has appointed lawyers to represent you: Daniel Bryson and Matthew Lee, Whitfield Bryson & Mason LLP, 900 W. Morgan St., Raleigh, North Carolina 27603. Inquiries to your attorneys should be made either at (919) 600-5000 or pat@wbmllp.com. If you want your own lawyer, you may hire one at your own expense.

Your Other Options.

If you do not want to be legally bound by the Settlement, you must exclude yourself from the Settlement Only Class by **April 16, 2018**, or you will not be able to sue the Defendants about the legal claims the Settlement resolves. If you exclude yourself, you cannot get money or other benefits from the Settlement. If you stay in the Settlement Only Class, you may object to it by **May 7, 2018**. The detailed notice available on the website explains how to exclude yourself or object.

The Court will hold a hearing on **July 6, 2018**, to consider whether to approve the Settlement, and a request by Settlement Class Counsel for attorneys' fees, costs, and expenses of no more than $1.3 million and incentive awards for the Class Representatives of $3,500. You or your own lawyer, if you have one, may ask to appear and speak at the hearing at your own cost, but you do not have to.

For more information, call or go to the website.

1-888-530-6598
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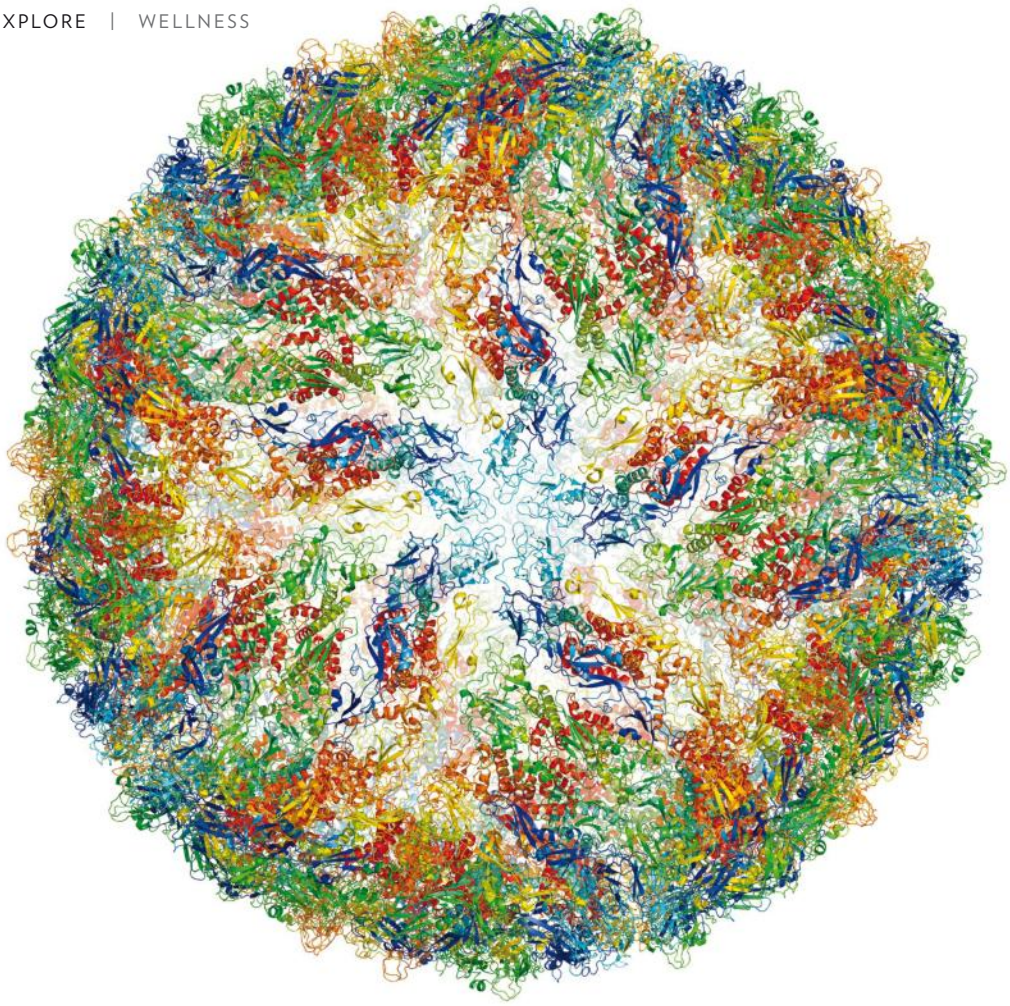


THE ULTIMATE FREEZE-FRAME

By Michael Greshko

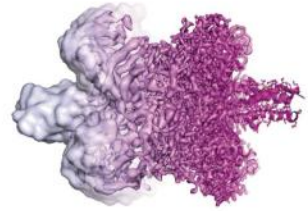
The kaleidoscopic ball above is more—and less—than meets the eye. This vivid terrain is actually a color-coded Zika virus, millions of which could fit in the period that ends this sentence.

We can see the virus here thanks to cryo-electron microscopy (cryo-EM), an extremely cool imaging technique that lets scientists visualize molecules, making it easier than ever to study life's cellular machinery.

Cryo-EM works by firing an electron beam at a flash-frozen film of water containing copies of a given molecule. This "exposure" yields many 2-D images of the molecules at different angles, which algorithms then merge into one 3-D model. At first cryo-EM rendered molecules as vague lumps, so some dismissed it as "blobology" compared with x-ray crystallography, a less versatile high-resolution imaging technique. But in 2013 cryo-EM achieved atomic resolution for the first time.

"It wasn't quite clear to me that we would get to atomic resolution; even 10 years ago I was sort of skeptical," says Columbia University biophysicist Joachim Frank, who shares the 2017 Nobel Prize in chemistry for helping develop cryo-EM. Now proteins' building blocks can be seen like beads on a string.

Cryo-EM allows us to see the proteins that stud our cells' membranes—or even "film" drug molecules as they bind to their targets. Who knows where this biochemistry revolution will go next? "I'm very excited," says Frank.



Cryo-electron microscopy once was mocked as "blobology," but its low-res days are over. In recent years cryo-EM images have gone from lumpy blobs – the left side of the purple figure above – to models that display individual atoms, as in the right side of the purple figure and in the Zika virus at the top of this page.

ILLUSTRATIONS (FROM TOP): ROYAL SWEDISH ACADEMY OF SCIENCES; MARTIN HÖGBOM, ROYAL SWEDISH ACADEMY OF SCIENCES

Epic Migrations

We're learning more about the incredible journeys that migratory birds endure—and how humans are making it tougher for them.

Panoramic images capture a single day in the life of these birds. Photographer Stephen Wilkes selected a vista, set up his camera, and photographed from day to night. Wilkes then edited the photos to select the best moments and digitally blended them to compress an entire day into a seamless composite image. "What you are seeing in these pictures is truly the story of what happened in that day," he says.

Northern gannets

BASS ROCK, SCOTLAND
(FIRST PAGE)

During breeding season, 150,000 gannets throng this island in the Firth of Forth. In winter the birds decamp south as far as West Africa. To make this image, Wilkes and an assistant lugged his gear 122 steps uphill and set up near the ruins of a church about six feet from the nesting birds. Standing on the rocky ground for 28 sleepless hours, he took 1,176 photos. "It's like a meditative state," he says. "I'm alert to everything. I'm seeing everything." He selected about 150 photos to make this image.

PHOTOGRAPHED WITH PERMISSION OF THE DALRYMPLE FAMILY AND THE SCOTTISH SEABIRD CENTRE

Lesser flamingos

LAKE BOGORIA, KENYA
(CENTER)

The lesser flamingos of Africa's Great Rift Valley thrive in the extreme environment of high-altitude soda lakes, feeding on algal blooms that are toxic to many other creatures. The birds are not migratory but nomadic, traveling from one lake to another, wherever food is plentiful. Wilkes shot 1,742 photos over 36 hours from a 30-foot scaffolding wrapped in camouflage, capturing the endless movements of the flamingos and the marabou storks stalking them. He chose about 30 for this image.

Sandhill cranes

ROWE SANCTUARY, NEBRASKA
(THIS PAGE)

From mid-February to mid-April, half a million sandhill cranes gather along the Platte River. Emaciated when they arrive from Mexico and the southern United States, they fatten up to migrate on to sub-Arctic and Arctic nesting grounds. From a blind 25 feet high, Wilkes shot 1,377 photos over 36 hours, using about 200 to create this image. During the day the cranes gorge on waste grain left in fields. In the evening they return to the river in wave upon wave. "It's one of the most magnificent things I have ever witnessed," he says.

PHOTOGRAPHED WITH PERMISSION OF AUDUBON'S ROWE SANCTUARY

Black-browed albatrosses and southern rockhopper penguins

STEEPLE JASON, FALKLAND ISLANDS

Albatrosses roost by the sea, sharing the grassy incline with penguins. While these albatrosses sit on their nests, warming and protecting their chicks, their partners soar above the ocean, swooping down to catch prey. The birds winter on the Patagonian Shelf and in estuaries in Argentina, and return to the same colony. To reach this remote location, Wilkes made his way through a phalanx of angry striated caracaras. Standing on a mound of tussac grass for a better vantage, he took 926 photos in 26 hours, using about 80 to make this image.

PHOTOGRAPHED WITH PERMISSION OF THE WILDLIFE CONSERVATION SOCIETY

BY YUDHIJIT BHATTACHARJEE
PHOTOGRAPHS BY STEPHEN WILKES

As the sun was setting over the Firth of Thames in New Zealand, dozens of bar-tailed godwits shuffled about lazily on the edge of the bay, the wind fluffing their feathers.

The tide was coming in, submerging the mudflats where the birds had been feeding, sticking their long bills into the soft earth to dig up worms and crabs. As the water advanced, they stopped foraging and waded ashore, inelegantly carrying their plump, butterball bodies on stilt-like legs. A bit homely and ungainly, with drab plumage, godwits appear quite ordinary. As the sky turned orange, they settled down to roost. Resting for hours on end, they can seem rather sedentary.

Nothing could be further from the truth. Six months earlier, these birds had made an epic journey to get here, flying all the way from Alaska. Astonishingly, they didn't stop along the way. For eight or nine days straight, they flew, beating their wings the entire way: about 7,000 miles, more than a quarter of the way around the world.

When the godwits arrived, they were bedraggled and emaciated. They had fattened up now for their migration back to Alaska, where they breed during the summer. They were going to fly about 6,000 miles, to the Yellow Sea. There they would spend about six weeks along a coastline split between China, North Korea, and South Korea, feeding and resting before flying 4,000 more miles.

Bar-tailed godwits have made this migration for thousands of years, but a clear picture of their travels has emerged only in the past few decades. Although migrations by birds have been a source of wonder for centuries, new scientific findings are helping to demystify them while adding to our appreciation of these incredible feats. At the same time, scientists are discovering how human activity and climate change are disrupting and possibly imperiling these ancient journeys.

The disappearance of godwits from New Zealand during the months when they breed led the Maori to view godwits—which they call *kuaka*—as birds of mystery. The sentiment is reflected in a Maori saying about the unobtainable: "Who has ever held the egg of the kuaka?" By the 1970s

Society Grant Your National Geographic Society membership helped fund this project.

Bar-tailed godwits look for food in the mud at the Heathcote and Avon Estuary in Christchurch, New Zealand. From their breeding grounds in Alaska, they fly to New Zealand without a break, but on their way back they stop over at the Yellow Sea.

bird-watchers and biologists suspected the godwits in New Zealand were the same ones that nested in Alaska. But it was only in 2007 that scientists were able to determine the migration routes.

Researchers Bob Gill and Lee Tibbitts, wildlife biologists with the U.S. Geological Survey, were part of a team that captured a small number of godwits and implanted satellite transmitters inside an air sac in their abdomens, leaving the antennas sticking out. Between March and May, they tracked a group on their northern migration. The batteries of the transmitters weren't expected to last beyond the summer, and sure enough, one by one, they stopped working. Except one. On August 30, 2007, a godwit known as E7 departed from Alaska, still transmitting its position.

With a rising sense of excitement, the researchers followed the bird's progress as it flew past Hawaii, past Fiji, and then, on September 7, past the northwestern tip of New Zealand. "It was a nail-biter because the battery was failing," recalls Tibbitts. That night E7 landed in the Firth of Thames. At eight days and eight nights, and 7,150 miles, it's still the longest nonstop migratory flight ever recorded. "It is a head-scratching, jaw-dropping feat," says Gill, now an emeritus scientist with USGS.

The tracking of E7 served to deepen the curiosity that bird migrations have long inspired. Where do they go? How can they fly as far as they do? How are they able to find their way to the same winter and summer sites year after year? Advances in satellite tracking and other technologies are enabling researchers to explore those questions in unprecedented detail.

TREKKING THROUGH the splendidly green boreal forest in Alberta, Canada, Michael Hallworth, an ecologist with the Smithsonian Migratory Bird

JONATHAN HARROD, MINDEN PICTURES

The Yellow Sea is a critical way station for millions of migrating waterbirds. But relentless development along the Chinese and South Korean coastlines is shrinking the habitats the birds need for feeding and resting. As tidewater stretches are filled in, shorebirds such as godwits, knots, and curlews are forced to compete for food on the dwindling mudflats.

GEORGE STEINMETZ

BAR-TAILED GODWIT
Breeds: May-August

NGM MAPS (ALL)
BIRD ILLUSTRATIONS: FERNANDO G. BAPTISTA (ALL)


有限公司

A pair of sandhill cranes performs a mating dance at the Bosque del Apache National Wildlife Refuge in New Mexico. The preserve was created in 1939 largely to protect critical habitat used by these sandhill cranes, which breed in the Rocky Mountains and winter in the southwestern United States and Mexico.

Center in Washington, D.C., listened for calls of the Connecticut warbler—a songbird with a yellow breast and striking white eye-rings. When Hallworth and his fellow researchers spotted a male they had tagged with an electronic device, they worked swiftly to drape a fine net between two trees. Hallworth placed a speaker behind the net, connecting it with a cable to his phone. Hiding behind a tree, he played a recording of a male warbler's song. It was a ruse to lure the warbler to see whether a competitor had entered its territory. Sure enough, the tagged male flew into the net.

Extricating the bird, Hallworth gently removed the tag on its back—a geolocating device weighing less than one gram that continuously records light levels. Because sunrise and sunset times change with location, scientists can analyze the data to trace the path a bird has taken. The study by Hallworth and his colleagues, still ongoing, will enable them to determine precisely where the songbird spends the winter months. "We know that the bird migrates to South America, but we have yet to find out where," he says.

Such efforts underscore how far we've come in our ability to track bird migrations. Until the early 19th century, theories to explain the disappearance of bird populations for part of the year were rather fanciful. Aristotle believed that some birds hibernated or transformed into other species. In medieval Europe the explanation for the appearance of barnacle geese in the winter was that they grew on trees. An English minister theorized in the 17th century that they flew to the moon. The most striking evidence that birds were migrating came in 1822, when a hunter in Germany shot

THE YEAR OF THE BIRD

National Geographic is partnering with the National Audubon Society, BirdLife International, and the Cornell Lab of Ornithology to celebrate the centennial of the Migratory Bird Treaty Act. Watch for more stories, books, and events throughout the year.

down a white stork with a curious appendage—an arrow impaled through its neck. The arrow was from central Africa, leading naturalists to conclude that the stork had traveled thousands of miles. In 1906 bird-watchers started putting rings on the legs of white storks and began learning where they wintered in sub-Saharan Africa.

In the two centuries since the shot that felled the impaled stork, scientists and bird-watchers have uncovered the migrations of thousands of avian species. Nearly half of known bird species are migratory, moving from one habitat to another with the change of seasons. Laysan albatrosses nest on tropical islands in the Pacific and spend almost half the year soaring thousands of miles, as far as the coasts of Japan and California, to look for food. Populations of bar-headed geese that breed in the highlands of Central Asia fly south over the Himalaya—honking their way through the rarefied, high-altitude air—to winter on lakes and estuaries on the Indian subcontinent. Having a large wingspan is not a prerequisite, as evidenced by the flight that tiny ruby-throated hummingbirds make. They travel solo from their breeding range in the United States and Canada to wintering grounds ranging from southern Mexico to Panama.

Whether they're going a few miles or a quarter of the way across the world, birds migrate to escape conditions that threaten their survival. When winter arrives in North America, the flowers that the ruby-throated hummingbird drinks nectar from and the insects it thrives on vanish. The bird has no choice but to travel to a place where food is plentiful. Upon the return of warmer weather in Canada and the United States, the northern home is attractive once again because its resources have been replenished.

Although many species migrate between cooler and warmer latitudes, some migrations are driven by flooding. That's the case with a subspecies of the black skimmer that nests on exposed sandbars

JACK DYKINGA, NATURE PICTURE LIBRARY

Snow geese fill the sky over New Mexico's Bosque del Apache refuge. Once nearly extinct, their numbers are now so high they're degrading their breeding areas and threatening other species. The birds arrive from northern Canada around November and spend about three months in the area. By the end of February, most have left for their breeding grounds.

DONALD JESKE, NATIONAL GEOGRAPHIC CREATIVE, YOUR SHOT

BAR-HEADED GOOSE
Breeds: March-May

in the Amazon Basin's Manú River, skimming the waters with its long bill to scoop up fish while flying. When heavy rains begin lashing the region starting in September, causing the river to flood, the birds depart for the continent's Pacific coast or migrate to higher ground, returning when the water level has subsided. Some bird populations migrate between high and low altitudes within the same area, nesting in mountains when streams are running but descending to valleys when the water is frozen.

"Migratory birds are both escaping and then coming back to these areas that are really harsh during part of the year, as well as really great for breeding and raising their young during the other part of the year," says Ben Winger, an ornithologist at the University of Michigan in Ann Arbor.

These migration routes have emerged over thousands of years of adaptation. Driven by competition for resources and nesting areas, some species are likely to have ventured farther and farther from their original habitats. Some researchers speculate that migrations arose when birds in the tropics expanded their ranges into temperate habitats. Another view is that many species originated in temperate zones and evolved to spend the colder part of the year in the tropics. "The reality is probably that both happened to some extent," Winger says.

Clues to adaptations that led to today's routes can be gleaned from certain unusual migrations. One example, according to Peter Berthold, former director of the Max Planck Institute for Ornithology in Radolfzell, Germany, is the sojourn of a population of marsh warblers that travels from northern Germany to East Africa and spends several weeks there before heading to South Africa. "In former times the birds could winter just south of the Sahara because the area remained green for a long time—it was a paradise," Berthold says. "Then it deteriorated, until the birds were forced to go farther and farther south."

Are these migratory behaviors written into the genes, steering birds like automatons to their destinations? Or do young birds learn from adults where to migrate and how? Scientists don't know yet, but as with most nature-versus-nurture questions, the answer is likely to be some combination of the two. "The field is in its infancy," says Jesse Conklin, a research scientist at the University of Groningen in the Netherlands.

THE ORDEAL OF FLYING NONSTOP from Alaska to New Zealand is hard for the human mind to comprehend, so when Gill talks to grade school kids about bar-tailed godwits, he uses a gimmick to get them to imagine the endurance needed to make that journey. "I say, 'All right, please stand up and extend your arms and start moving them in circles, and see how long you can do that.' " Then, just as their arms begin to tire, Gill tells them, "Now try and do that for eight days straight." The arm-flapping simulation may not be the perfect analogy—because flying is to birds what walking is to humans—but the kids get the point.

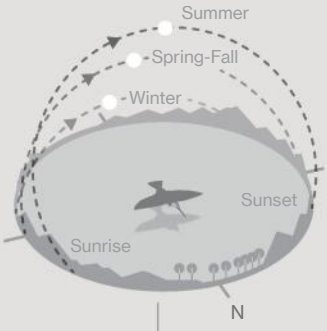
Like other long-haul migrants, godwits prepare by building enormous reserves of fat in the weeks leading up to their departure. The equivalent of gasoline, fat is what fuels the birds. When the godwits leave, more than half their body weight is fat. They look like feathered croquet balls, with a layer of fat under the skin up to an inch thick and more fat encasing their abdominal organs. "I call them lard asses," says Phil Battley, an ornithologist at Massey University in New Zealand.

As they fatten up, their pectoral and leg muscles also grow larger. Other long-distance migrants, such as red knots, shrink the gizzard and other organs in preparation for flight—the equivalent of jettisoning excess cargo.

Godwits, like other migratory species, don't rely just on their own power; they also take advantage of winds. The birds tend to depart from Alaska on the tail end of storms that produce winds blowing south. Their departure from New Zealand also coincides with favorable conditions for traveling. "You get pretty benign winds when

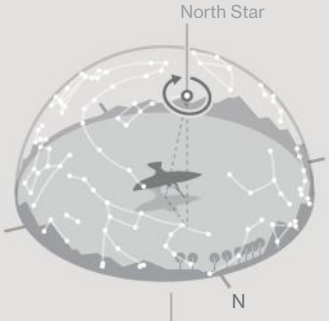
Sun, stars, and poles

Migrating birds use a variety of navigational cues – the sun, landmarks, stars, and even Earth's magnetic field – to make their journeys. Though some migrate only a short distance, extreme migrators can cross oceans and continents to reach nesting sites and seasonal food sources.

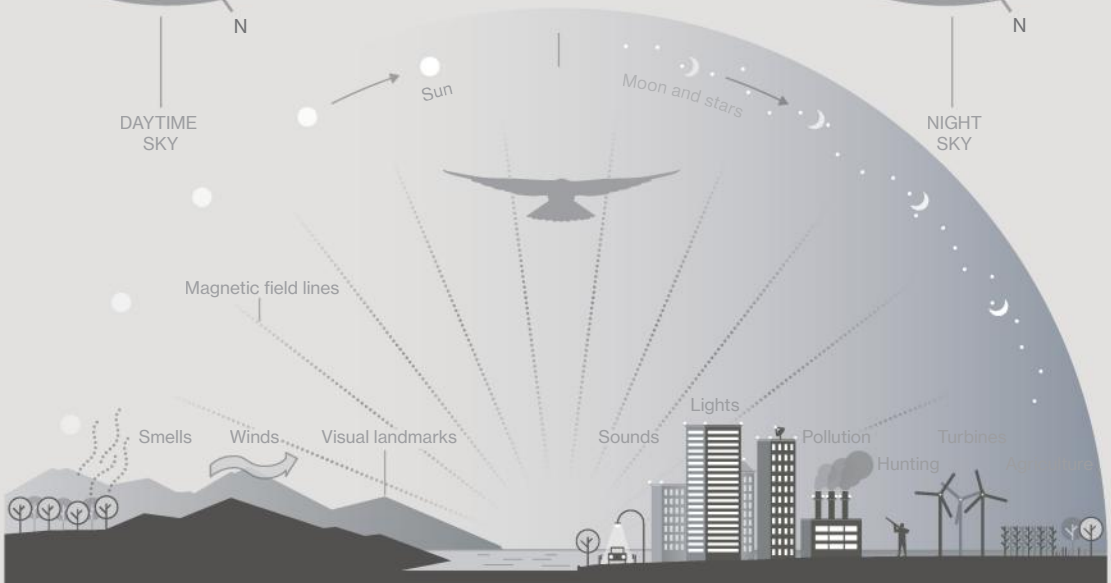


DAYTIME SKY

SKY MAPPING
Birds look to the sun and stars to point themselves in the right direction and time their annual migrations. When daylight hours wane, it may be time to migrate.



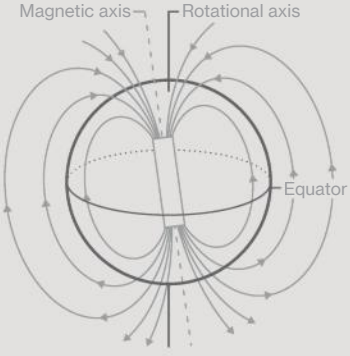
NIGHT SKY

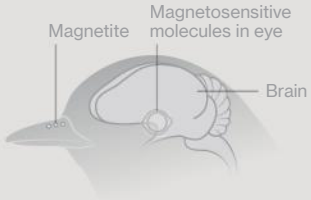


HELPFUL LANDMARKS
Birds that migrate during the day can use landmarks such as mountains, rivers, and coastlines to guide them. They often stick to familiar routes, returning to the same sites year after year.

CHALLENGING OBSTACLES
Human development can affect migrations in multiple ways. Wind turbines can kill birds and city lights confuse nocturnal fliers. Climate change can affect the timing – and thus the success – of birds' journeys.

MAGNETIC NAVIGATION
Earth's magnetic field lines are stronger and more detectable at the poles, where they converge. Birds flying closer to the Equator may have to rely on other cues to find their way.





Some birds have sensors in the eye that help them detect the magnetic field, and magnetite – a mineral that acts as a magnet – in their beaks to help them tell which direction to fly.

MATTHEW TWOMBLY; MESA SCHUMACHER
SOURCES: ANDREW FARNSWORTH, CORNELL LAB OF ORNITHOLOGY; IUCN; ANDREW IWANIUK, UNIVERSITY OF LETHBRIDGE

you leave New Zealand," Gill says, "but then they are able to hook into others as they go north." When they leave the Yellow Sea for Alaska, the winds once again have shifted to be with the birds.

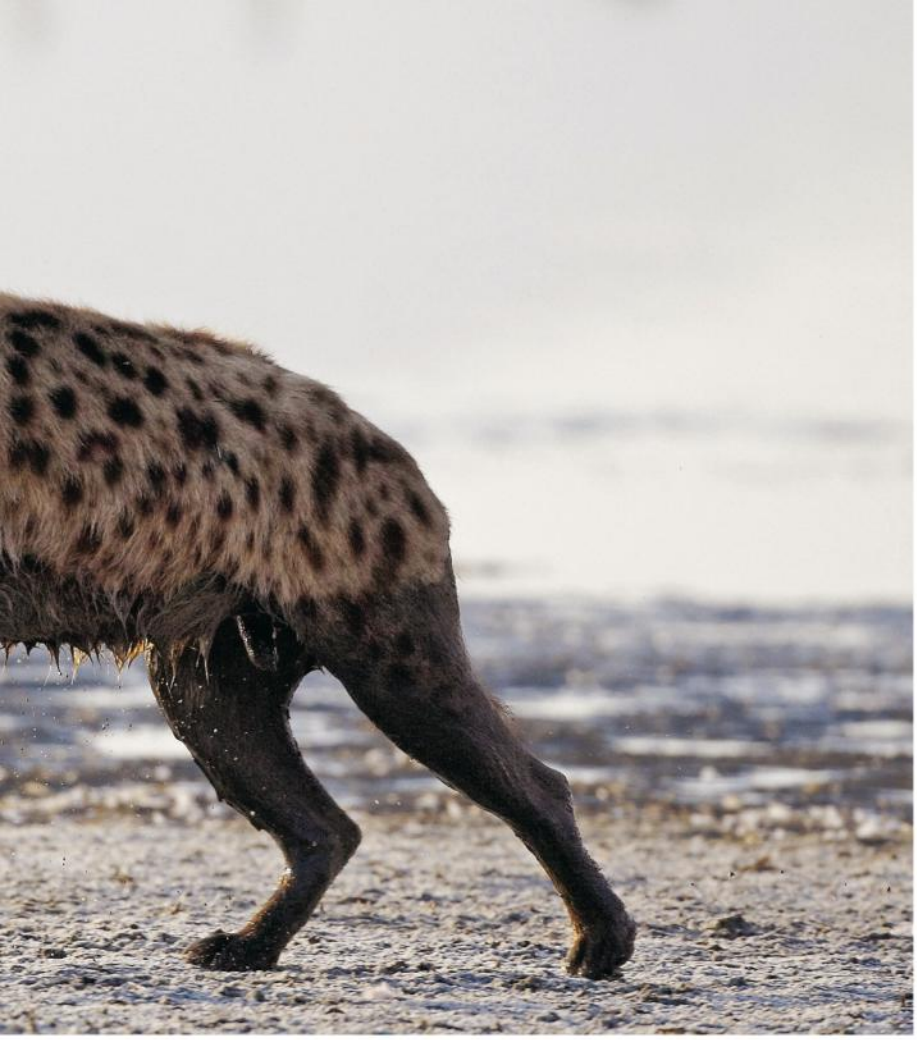
Researchers assume that godwits, which are not known to soar, flap their wings for most of their journey, even when riding winds, while other species, such as albatrosses, do soar.

Some species possess an astonishing flexibility in regulating their sleep. Niels Rattenborg at the Max Planck Institute and his colleagues went to the Galápagos Islands to study the sleeping habits of great frigatebirds, which have seven-foot wingspans and fly hundreds of miles over the Pacific Ocean looking for food. The researchers, capturing frigatebirds in their nests, implanted sensors to track brain electrical activity and glued data-recording devices on their heads before releasing them. Besides keeping track of location and altitude, the devices helped the researchers determine sleep patterns.

After spending up to 10 days over the Pacific, the frigatebirds returned to their nests and Rattenborg's group retrieved the devices. The data showed that the birds slept in short bursts lasting an average of 12 seconds, usually while soaring, that added up to an average of 42 minutes a day. That was a mere fraction of the 12 hours a day the birds slept when they were in their nests. For a substantial part of the time that they napped in the air, the birds only put half of their brain to sleep, while keeping the other half awake.

To learn whether godwits rely on similar sleep patterns in flight, researchers need considerably smaller batteries—a goal Rattenborg says is within reach. "It's possible that they get some sleep on the wing, perhaps even while flapping," he says.

AS A YOUNG BOY growing up in Denmark, Henrik Mouritsen occasionally saw birds that didn't belong there. He once photographed a desert wheatear, some populations of which divide their



A spotted hyena gets ready to savor a flamingo after a successful hunt at Lake Nakuru in Kenya. Vulnerable to predators such as hyenas and jackals, lesser flamingos seek safety in numbers. When they flock together, they have the best shot at protecting themselves.

time between breeding grounds across Central Asia and wintering habitats from North Africa to India. "I wondered what the hell had gone wrong in their heads for them to fly that far in the wrong direction," he says. That curiosity led Mouritsen, now a professor at the University of Oldenburg in Germany, to follow in the footsteps of generations of researchers who've sought to untangle the mystery of how birds orient themselves to return to the same breeding and wintering grounds. Scientists looking for the secret to this capability have found evidence of not one but several mechanisms birds appear to use.

In 1951 a German scientist named Gustav Kramer discovered that European starlings relied on the sun as a compass. Then, in the 1960s, Stephen Emlen, an ecologist at Cornell University, put indigo buntings in a planetarium and showed that, like ancient mariners, birds also look to the stars to navigate. Around the same time, laboratory studies of European robins by a German zoologist couple, Wolfgang and Roswitha Wiltschko, discovered that birds possess an internal magnetic compass.

Mouritsen, along with two colleagues—William Cochran and Martin Wikelski—conducted an experiment in 2003 to investigate navigation in thrushes migrating in the wild rather than hopping around in a lab. Initially, however, the researchers placed the birds in an outdoor cage at sunset, exposing them to a magnetic field that was turned between 70 and 90 degrees east relative to the Earth's. The birds, fitted with tiny radio transmitters, were set free at night, after no sunlight remained in the sky. Traveling in cars equipped with antennas to track the birds, the researchers followed them for up to 700 miles. As it turned out, the birds flew west instead of north on the first night of their travel. But on later nights, the same birds flew north, as they were supposed to. From this behavior, the researchers inferred that the birds were orienting themselves using

TONY CROCETTA, BIOSPHOTO

White storks build nests on high perches. In Extremadura, a region in western Spain, man-made nesting poles saved a colony living in an abandoned building when it was renovated. White stork migration is highly variable, with some wintering in Africa while others stay closer to home in Europe.

their magnetic compass, but calibrated it daily with twilight cues from the sun.

That migratory species would rely on multiple compasses is not surprising: Many travel at night, when the sun compass doesn't work. In cloudy conditions at night, the celestial compass can't be counted on either. Nor is the magnetic compass a reliable fallback everywhere.

The precise mechanics of the godwit's navigation strategy is not yet known. But Mouritsen speculates that, like the thrushes in his outdoor experiment, godwits rely on their magnetic compass and reset it every time the sun is visible.

A RED KNOT LOOKS a lot like a bar-tailed godwit, except that it's smaller and has a shorter bill. Like the godwit, it breeds in the extreme north and flies thousands of miles south for winter. It forages along the shore by sticking its slender bill in the mud to find mollusks. That's why Jan van Gils, a marine ecologist with the Royal Netherlands Institute for Sea Research who studies a subspecies that breeds in the Arctic and winters in Mauritania, was puzzled when he and his colleagues observed some of the birds eating sea grass. When had they become primarily vegetarian and why?

The researchers found that these red knots were juveniles, with shorter bills and smaller bodies than usual. They also discovered that the body size of juveniles varied considerably by year. Those born when the Arctic experienced the warmest temperatures had the smallest bodies and the shortest bills. The most plausible explanation was that these birds didn't have enough to eat as chicks because the snow had melted earlier than usual, which caused the insect population the birds feed on to peak too soon and robbed the newborns of nutrition.

When they migrated to Mauritania, the birds with short bills couldn't reach deep in the mud to find enough mollusks. "Sea grass is a poor source of nutrients," van Gils says. "We never expected

them to eat it, but now they're eating it because they have no choice." The researchers also found that red knots with short bills have shorter lives. "Food shortage in the Arctic eventually leads to dying from food shortage in the tropics," he says.

The red knot study is one of a few that offer concrete evidence of how climate change and environmental damage may be harming migratory species. Populations of many seabirds have shrunk drastically over the past half century, while shorebird populations in North America have crashed by 70 percent since 1973. Some of the sharpest declines have occurred in species that use the East Asian-Australasian Flyway—a group that includes knots, sandpipers, and godwits. A leading cause for this appears to be the ongoing destruction of stopover sites along the Yellow Sea, where the tidal mudflats that sustain the birds are being filled in at a frenetic pace to build ports, factories, and housing.

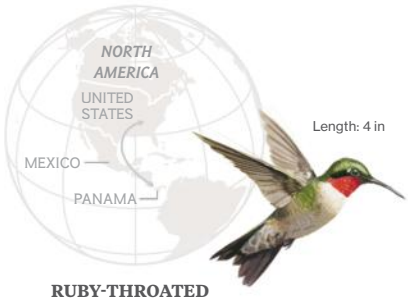
Similarly, illegal hunting and changes in land use have imperiled migrants that journey between Europe and Africa, and between North and South America. Conservationists estimate that from 11 million to 36 million birds are captured or killed in the Mediterranean region alone every year, threatening birds like the chaffinch and the blackcap. The winter habitats of many long-distance migrants in sub-Saharan Africa have become less hospitable, with more land being cleared of vegetation to make room for agriculture. The industrialization of farming at stopover sites has left migrating birds struggling to find food. In southern Europe, for instance, the countryside had clusters of small farms with wild spaces in between, which served as an abundant food source. Now the landscape has been homogenized into vast acreages planted with a single crop like corn and harvested more efficiently.

"Every single corn is used up, so there is nothing left over," says Hans-Günther Bauer, a research scientist at the Max Planck Institute. "If

JASPER DOEST

A flock of red knots wheels in front of an offshore wind farm in the Irish Sea. This subspecies breeds in the Canadian Arctic and Greenland and winters on the coasts of western Europe. Researchers in Europe are assessing whether offshore wind turbines pose a significant threat to bird populations.

GRAHAM EATON, NATURE PICTURE LIBRARY



RUBY-THROATED HUMMINGBIRD
Breeds: May-October

you are lucky, as a bird, you find someplace else. If you are unlucky, you don't, and that makes it very hard because you need to build up your reserves for the journey ahead."

Reversing these alarming trends would require a diversity of conservation efforts—from protecting forests and coastlines to enforcing laws to prohibit the capture and killing of migratory birds. The use of new tracking technologies, including ever smaller geolocating tags, could help target conservation efforts, says Pete Marra, head of the Smithsonian Migratory Bird Center. "Population size in a species like the wood thrush, a species that's declining by over 60 percent in the past 50 years, is influenced by what's happening in the breeding areas in the southeast United States, as well as habitat loss in the wintering grounds in Mexico and Colombia." Researchers found that although forests in the wintering habitat were being decimated more quickly, the birds suffered more from the loss of forest in their breeding range.

ON A BRIGHT AFTERNOON in Foxton Beach in New Zealand, Jesse Conklin, wearing rubber boots and a floppy sun hat, walked out toward the salt marsh in the Manawatu River estuary, splashing through puddles of ankle-deep water left behind by the receding tide. About 30 yards from a sand embankment, where a half dozen godwits were roosting, Conklin set up a telescope on a tripod.

The Netherlands-based scientist has visited the estuary every year for the past decade. Conklin has tracked about 160 godwits—identifiable through colored bands on their legs—that return year after year. He's found that individual godwits leave on almost the same day each year, as if guided by a precise clock, although they're flexible enough to shift their departure date to avoid unfavorable wind conditions.

Over an extended period, however, the birds have advanced their departure from the estuary. Conklin's godwits now leave an average of five days earlier than they did from 2008 to 2010. Many are spending the extra days bulking up at degraded foraging sites on the Yellow Sea, arriving in Alaska at about the same time. It's unclear if they set out early because they need extra time at the stopover sites or because they're trying to get to Alaska earlier to keep up with the advancing summers. In either case the godwits appear to be learning from experience, Conklin says, not just following a genetically programmed schedule.

For hours that afternoon, Conklin trained his telescope on the godwits. Some continued to roost; others foraged nearby, dipping their bills into the mud. When a few of them waded into the water to bathe and preen, Conklin felt a familiar heightening of anticipation. He knew that this behavior could be a precursor to a departure.

The sun mellowed as the afternoon progressed, the shimmer of the water growing softer. Then, one of the godwits began making a loud, high-pitched call. Other godwits responded with similar calls. The conversation went on for hours. A couple of godwits flew over to join the group. "I don't know if they are communicating real information—like, You like the wind now?—or if they keep this chatter going to collect all the birds that want to go," Conklin said.

Close to sunset the calling got louder, and then, all at once, the godwits took off. He adjusted his telescope to follow them—he counted 10 in all—as they made a rapid ascent over the estuary, flying out toward the ocean, first in a jumble and eventually sorting into a V-formation. Conklin watched them until they disappeared into the pale blue sky. ☐

Against a cloudy sky, three tundra swans beat their wings in harmony as they fly from the Arctic, where they breed, to the Pacific coast of the United States, where they will winter. They typically travel in family groups, which can number a hundred or more.

Yudhijit Bhattacharjee, a contributing writer for the magazine, flew to New Zealand to observe godwits but didn't burn even an ounce of fat getting there.

JIM BRANDENBURG, MINDEN PICTURES

Life Among the Ruins

Syria's civil war turned their neighborhoods into rubble. Now, as a fragile normalcy returns to Aleppo, the challenge is to rebuild what was lost.

A boy walks in front of a former school and mosque in the Sukkari neighborhood of south Aleppo. The mosque is being rebuilt while most of the surrounding buildings remain in ruins.

BY **CAELAINN HOGAN**
PHOTOGRAPHS BY **SEBASTIÁN LISTE**

On the third floor of a crumbling building, a pink sunset glowed through the clear plastic sheet covering a gaping hole in the wall. Sixty-year-old Amira Garman sat in a powder blue cardigan on a swinging bench beneath a gold-fringed yellow canopy. A broken chandelier with a single bulb doused the little room in shaky light. Through the makeshift window she looked down at Al Yarmouk school across the street, its playground now littered with bullet casings and an improvised cannon.

Garman's family had lived on the top floor, now a maze of caved-in walls and rubble. "I want to be in my home," she said. They took shelter in this room, one of only two occupied in the building. On their street, shops reopened among the debris; people bustled along with eyes to the ground. As fighting continued elsewhere, a fragile normalcy was returning to Aleppo. But the immense task of rebuilding loomed.

Their neighborhood of Kallaseh, in obliterated east Aleppo, had been surrounded by the Syrian Army after the government's months-long siege to reclaim the city from pro-democracy rebels and others opposed to President Bashar al Assad's regime. Once Syria's largest city, Aleppo had been home to nearly four million people, but hundreds of thousands fled. Across Syria millions more have done so during the brutal seven-year war. More than 400,000 have been killed, and the United Nations has accused Assad's forces of using chemical weapons to kill scores of people in several towns.

Garman and her family fled to the countryside about three years ago. "We were robbed by the armed group," her husband, Saleh, said, referring to anti-government fighters, many of whom were once his neighbors. Saleh was imprisoned for a year after opposition forces found a picture of the former president, Assad's father, in the family's home. In December 2016 the army reclaimed parts of the city. A year later about 300,000 residents had returned. Many men who return must complete military service.

A wedding at Riga Palace in Aleppo is the first celebration at the hotel in four years, a sign of normal life returning to the city. During the nearly four-year siege, the hotel's owner, Nawras Riga, and 45 employees lived at the hotel, near the front line of the fighting.

ON A FRIDAY AFTERNOON in Saadallah al Jabiri Square, families ate cotton candy and clambered over giant, multicolored letters spelling out "I ♥ ALEPPO," installed last year for World Tourism Day. Visitors from around the globe used to flock here. A ripped banner on a damaged building read: "Aleppo is your city and needs you to defend her." The square, desolate during the war, buzzed with life. A group of guys chatting about soccer had come from Damascus to study architecture and was traversing the city with maps, plotting its reconstruction. Rayyan Aloulou, 18, took photos with her mother, who had traveled 10 hours by bus from their home

NGM MAPS

in opposition-held Idlib, once a 45-minute trip.

At the public park nearby, photos of pro-government fighters, considered martyrs, were nailed to olive trees—a reminder of Assad's hold on the area. Young men practiced parkour on the grass, cheering on each daring flip. Women sat alone smoking on benches, eyes distant, while pimpled teenagers sipped espressos. In a fancy restaurant nearby, a family threw a lavish baptism celebration. At the Citadel of Aleppo—once occupied by the Syrian Army and now rumored to be used as a military base by Russian allies who have backed Assad's government—a 14-year-old in a pink jacket was visiting for the first time since the war began. "It's so beautiful, but the damaged part is so sad," Maryam said. She had a scar above her eye from shrapnel and was now learning Russian in school. "We hope that Syria will be better again."

Among half-collapsed buildings, shop shutters were freshly painted in the colors of Syria's flag—seemingly a mark of protection. A thin 12-year-old, Ahmad Samman cycled past the few intact balconies where laundry hung. His father disappeared during the war. Ahmad was back in school but worked in a barbershop to help his family. Those returning were tasked with rebuilding the area without electricity or water. At night the loneliness of the families there sank in.

On the city's outskirts, displaced families sheltered in warehouses. "Everything is so expensive now," said Ayasha Khalil, 16. "We have no home."

Back in Kallaseh, Garman's adult son worked to rebuild the family's home. Garman hoped more families would return, but the wounds are still fresh. □

Above: Girls sing during the first class of the day at Ibn al Nafees school in east Aleppo's Al Myassar neighborhood. The school had 15,000 students and six buildings when it closed five years ago. It reopened in October with 1,000 students. Prefabricated rooms replaced the badly damaged original buildings. Below: Another school, Al Yarmouk in the Kallaseh neighborhood, was a base of armed opposition forces during the conflict.

Above: Daily life returns to the Citadel of Aleppo, a medieval palace considered one of the oldest and largest castles in the world. The citadel was used as a base by the Syrian military. Below: Families and friends gather at Aleppo's public park. The 42-acre urban park near Gare de Baghdad, the main railway station, was struck by mortars during the conflict.

Near the international airport in east Aleppo's Karm al Jazmati neighborhood, workers build a road to replace one that was destroyed.

By
NADIA DRAKE
Photographs by
MARTIN SCHOELLER

BEYOND THE BLUE MARBLE

From space, the majesty of Earth can be difficult to describe. But these astronauts will try.

MIKE MASSIMINO

NEW YORK CITY

In 2009 the NASA astronaut visited the Hubble Space Telescope, some 350 miles above the planet, on a mission to fix the beloved eye in the sky for the last time. Hubble's gaze is perpetually turned toward outer space, but tethered next to the massive observatory, Massimino was entranced by Earth. With verdant South American rain forests, rugged African deserts, and sparkling city lights spread out below him, the planet looked like a paradise.

"I thought at one point, if you could be up in heaven, this is how you would see the planet. And then I dwelled on that and said, no, it's more beautiful than that. This is what heaven must look like. I think of our planet as a paradise. We are very lucky to be here."

WATCH ON NATIONAL GEOGRAPHIC

Take a thrilling tour of one of the universe's most peculiar places – Earth – in the 10-part event series *One Strange Rock*, airing Mondays at 9/8c starting March 26.

FOR THE BULK OF HUMAN HISTORY, IT'S BEEN IMPOSSIBLE TO PUT EARTH IN COSMIC PERSPECTIVE.

Bound by gravity and biology, we can't easily step outside it, above it, or away from it. For most of us, Earth is inescapably larger than life. Even now, after nearly six decades of human spaceflight, precious few people have rocketed into orbit and seen the sun peeking out from behind that curved horizon. Since 1961, a mere 556 people have had this rarefied experience. Fewer, just 24, have watched Earth shrink in the distance, growing smaller and smaller until it was no larger than the face of a wristwatch. And only six have been completely alone behind the far side of the moon, cut off from a view of our planet as they sailed in an endlessly deep, star-studded sea.

SAMANTHA CRISTOFORETTI

ITALIAN ALPS
(Previous spread)

The Italian astronaut holds the record for the second longest uninterrupted spaceflight by a woman, having spent 199 days on the International Space Station in 2015. (NASA's Peggy Whitson, on the cover, topped that record by almost a hundred days in 2017.) The longer she was in orbit, Cristoforetti says, the more her perception of humanity's time on Earth evolved. When the massive geologic forces that have sculpted the planet are visible at a glance, the eons in which we crafted pyramids and skyscrapers become nearly indistinguishable. It's as if, from her vantage point, all our constructed monuments arose overnight.

"You've got this planet beneath you, and a lot of what you see, especially during the day, does not necessarily point to a human presence. If you look at it on a geologic timescale, it's almost like we are this flimsy presence, and we really have to stick together as a human family to make sure we are a permanent presence on this planet and not just this blink of an eye."

PHOTO (ABOVE): NASA. ASTRONAUTS' QUOTES HAVE BEEN EDITED FOR LENGTH AND CLARITY.

It's an inherently unnatural thing, spaceflight. After all, our physiology evolved specifically to succeed on this planet, not above it. Perhaps that's why it can be difficult for astronauts to describe the experience of seeing Earth from space.

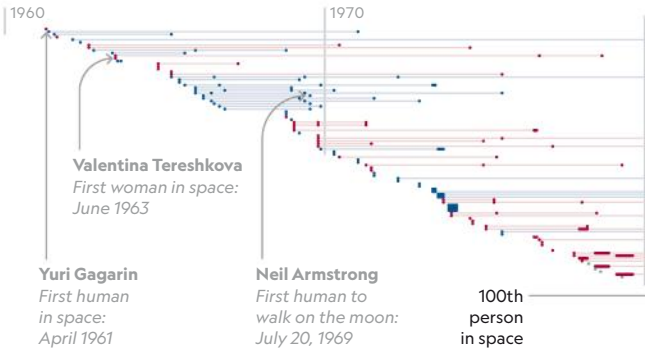
Italian space traveler Luca Parmitano says that we haven't yet developed the words to truly convey the realities of spaceflight. The building blocks of modern human communication, words are necessarily constrained by meaning and connotation, no matter which language you choose (Parmitano speaks five). And until the mid-20th century, there was no need to express what it means to see our planet in the fiercely primeval essence of space. "We just don't think in terms of spaceflight," he says.

Seeing Earth from space can change a person's worldview. U.S. astronaut Nicole Stott flew twice on the space shuttle *Discovery* and returned with a new drive for creating artwork depicting the view. Canadian spacefarer Chris Hadfield says that while orbiting Earth, he felt more connected to the people on the planet than ever before.

Kathy Sullivan, who in 1984 became the first American woman to perform a space walk, returned with an abiding awe for the intricate systems that come together to make Earth an improbable oasis. "The thing that grew in me over these flights was a real motivation and desire ... to not just enjoy these sights and take these pictures," she says, "but to make it matter."

After retiring from NASA, Sullivan led the National Oceanic and Atmospheric Administration for three years, using the robotic eyes of orbiting satellites to pursue her passion. She says Earth from above is so captivatingly beautiful, she never grew bored looking at it. "I'm not sure I'd want to be in the same room with someone who could get tired of that."

Even when words fail us, a single picture of home from above can change the perspectives



of millions of people. In 1968 the Apollo 8 crew became the first people to rocket far away from Earth and loop around the moon. On Christmas Eve, astronaut William Anders snapped what would become an unforgettable image: a lush world rising above the sterile, cratered lunar horizon. Now called "Earthrise," the photograph boosted awareness of our planet's beauty and fragility.

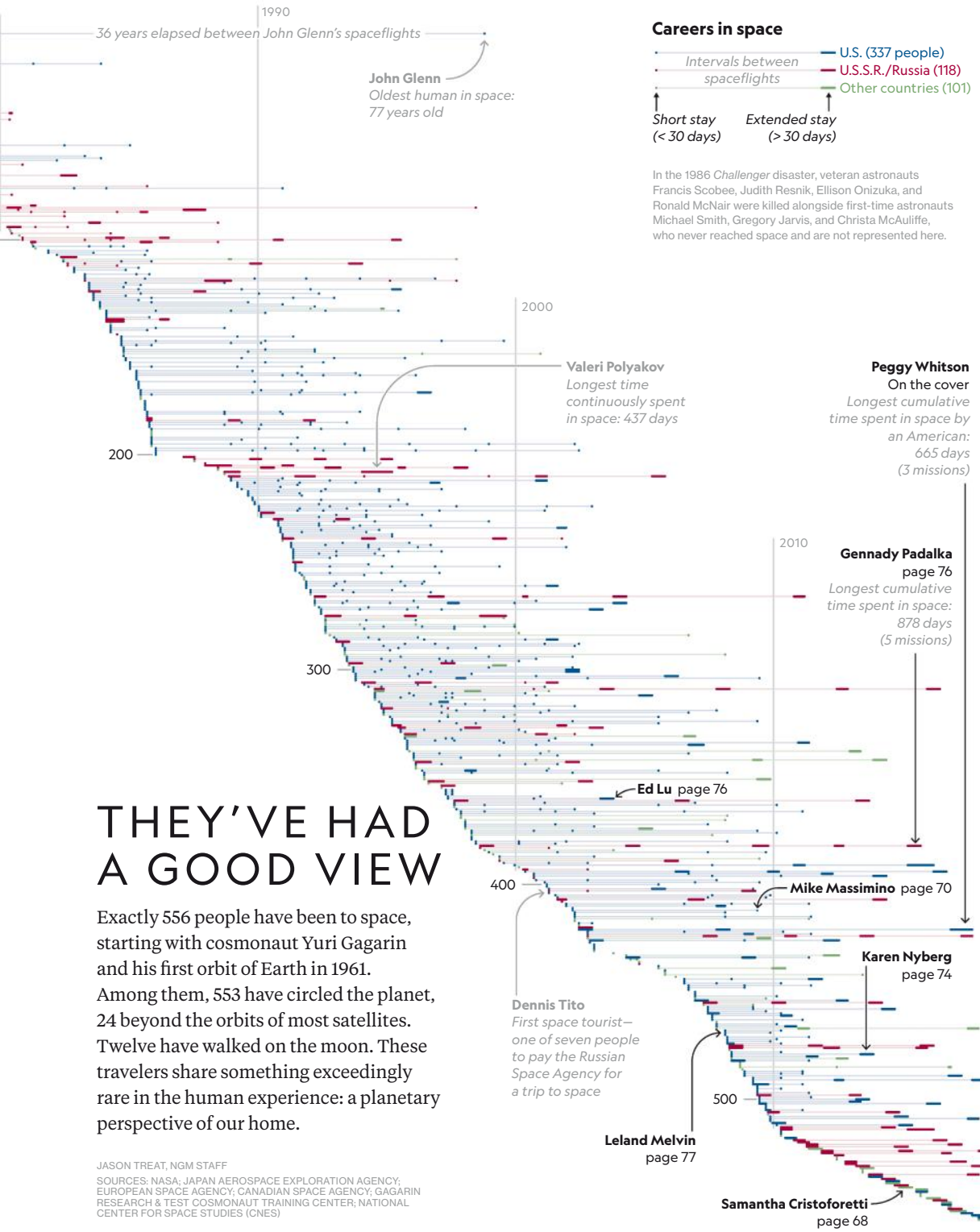
"Twenty eighteen is the 50-year anniversary of that iconic picture that helped define the environmental movement. What are the course corrections we need to do now that will help us get to the hundredth anniversary?" asks U.S. astronaut Leland Melvin. He's working with a coalition of fellow space travelers to rethink how we balance ecological health and human needs. The project will use astronauts' experiences to help others adopt more sustainable lifestyles.

Clearly, a desire to protect the planet is common among those who have left it. Russian cosmonaut Gennady Padalka has logged more cumulative days in space than anyone else. The allure of spaceflight kept him on the job for 28 years, but something even more powerful than gravity kept bringing him home.

"We are genetically connected to this planet," he says. And to the best of our knowledge, Earth is unique in its ability to support life as we know it. The past decade of astronomy has shown us that we are one among billions of worlds in the Milky Way galaxy, but our tangled web of geology, ecology, and biology makes this strange rock the only one in reach that's just right for humans.

There really is no place like home. □

Contributing writer **Nadia Drake** once applied to be an astronaut and now feeds her curiosity by covering the cosmos. Photographer **Martin Schoeller**'s cover story on the Amazon's Kayapo people appeared in the January 2014 issue of *National Geographic*.



THEY'VE HAD A GOOD VIEW

Exactly 556 people have been to space, starting with cosmonaut Yuri Gagarin and his first orbit of Earth in 1961. Among them, 553 have circled the planet, 24 beyond the orbits of most satellites. Twelve have walked on the moon. These travelers share something exceedingly rare in the human experience: a planetary perspective of our home.

JASON TREAT, NGM STAFF

SOURCES: NASA; JAPAN AEROSPACE EXPLORATION AGENCY; EUROPEAN SPACE AGENCY; CANADIAN SPACE AGENCY; GAGARIN RESEARCH & TEST COSMONAUT TRAINING CENTER; NATIONAL CENTER FOR SPACE STUDIES (CNES)

KAREN NYBERG

CADDO LAKE, TEXAS

In September 2013, during her second visit to the International Space Station, Nyberg made a stuffed dinosaur for her three-year-old son. It was, perhaps, the first toy sewn in space, constructed from spare material the mechanical engineer found aboard the orbiting outpost. Making the stuffed animal helped her feel more in touch with her loved ones far below. But the creative project was also a manifestation of the deep connection Nyberg felt to ecosystems past and present while she was in orbit.

"In the future, I would like to be more of an advocate for animal conservation. Every single part of the Earth reacts with every other part. It's one thing. Every little animal is important in that ecosystem. [Seeing the planet from above] makes you realize that, and makes you want to be a little more proactive in keeping it that way. If I could get every Earthling to do one circle of the Earth, I think things would run a little differently."


KAREN NYBERG

GENNADY PADALKA

LOSINY OSTROV NATIONAL PARK, RUSSIA

The Russian cosmonaut holds the record for time spent in space, with 878 cumulative days logged from 1998 to 2015. For him, the experience was a lesson in the virtues of teamwork, which become amplified in the lethal environment of spaceflight. There's no doubt in his mind that the planet will endure, even if it is significantly altered by humanity. But he wonders if we as a species will survive our more selfish actions.

"The overriding impression I got of life on Earth is how robust it is. Life has managed to essentially completely cover this planet in all sorts of different places—it finds a way." —ED LU

ED LU

METEOR CRATER, ARIZONA

A veteran of three NASA spaceflights from 1997 to 2003, Lu looked back at the planet and was struck by the massive craters pressed into its crust by past bombardments. In 2002 he co-founded the B612 Foundation, a nonprofit that works on what he calls "engineering on the largest scale imaginable." The group's goal: to prevent any devastating asteroid impacts on Earth.

LELAND MELVIN

LONG ISLAND, THE BAHAMAS

Drafted into the National Football League in 1986, Melvin played briefly with the Detroit Lions. But when an injury cut short his athletic career, his life took a dramatic turn—into orbit. During his two flights as a NASA astronaut, in 2008 and 2009, Melvin was gobsmacked by the sight of Earth's oceans from above. The colors were so varied, he found himself searching for new ways to describe all the shades of blue. His thirst for knowledge continues to distinguish his efforts to inspire people, especially kids, to preserve the planet and chase their dreams.

ONE STRANGE ROCK

13 THINGS THAT MAKE LIFE ON EARTH POSSIBLE

Earth is well equipped as a planet and ideally placed in our solar system and galaxy to support life as we know it. The product of some 4.6 billion years of cosmic construction, our planet is flush with life thanks to a fortuitous set of conditions, from the optimal chemical makeup of our planetary core to our safe distance from the hidden black hole at the heart of our galaxy.

BY MANUEL CANALES, MATTHEW W. CHWASTYK, AND EVE CONANT

1 Our planet recycles life-friendly carbon over time

Carbon dioxide is one of many greenhouse gases that trap heat and keep Earth's surface warm enough to support life. The static surfaces of Venus and Mars keep carbon locked in the air and rocks. But over millions of years, Earth dynamically cycles this vital element through its air, land, and sea due to the constant action of plate tectonics.

A: CARBON IS DEPOSITED

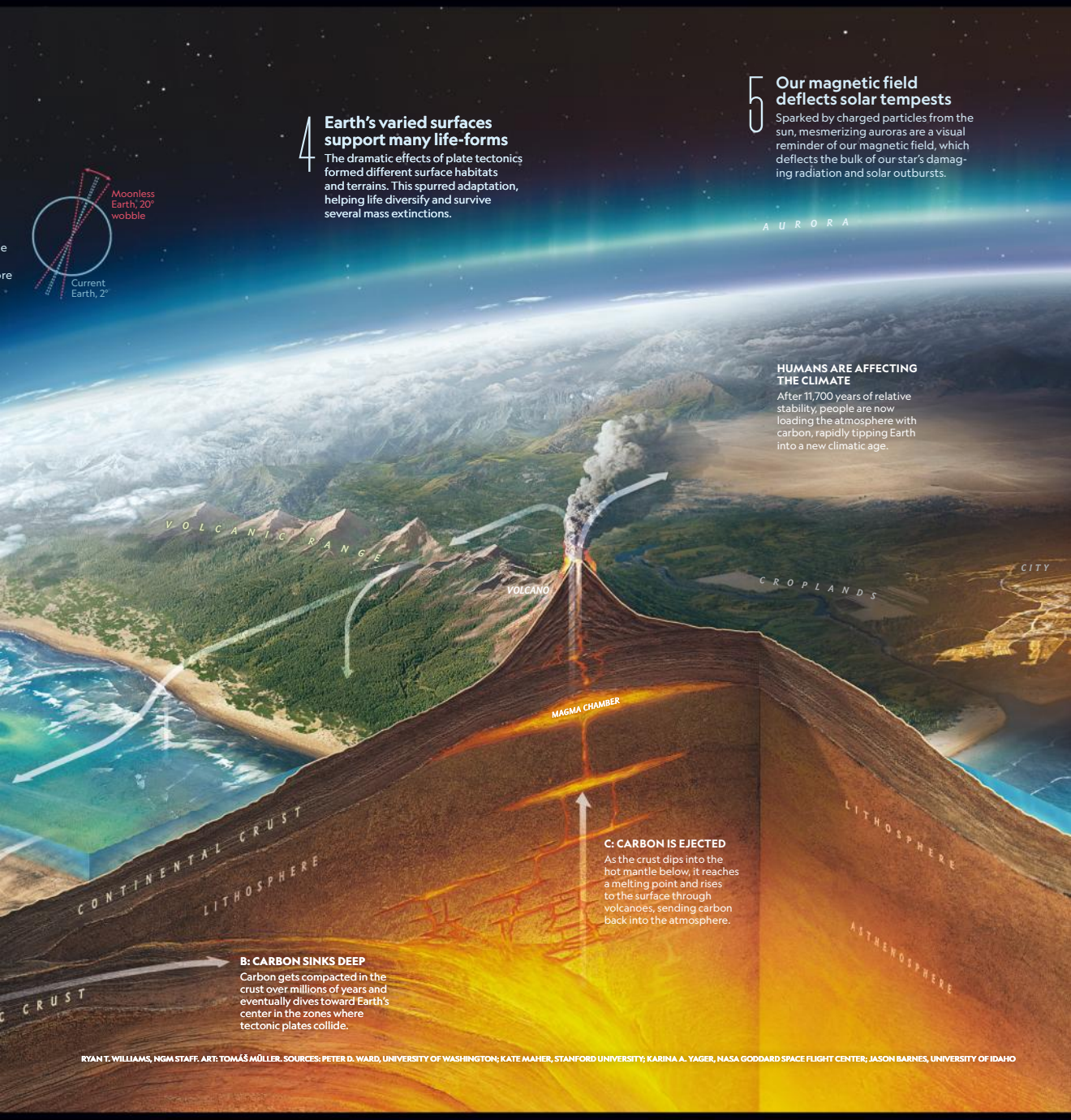
Chemical processes that dissolve minerals in rocks draw carbon out of the atmosphere and eventually incorporate it into Earth's crust.

2 We have an ozone layer to block harmful rays

Ancient plantlike organisms in the oceans added oxygen to the atmosphere and created a high-altitude layer of ozone that shielded early land species from lethal radiation.

3 We have a big moon to stabilize our axial wobble

Earth is tilted with respect to the sun, and teeters as it spins. This tiny wobbl can shift the climate from hot to icy every 41,000 years—and might vary mo without the moon's stabilizing pull.

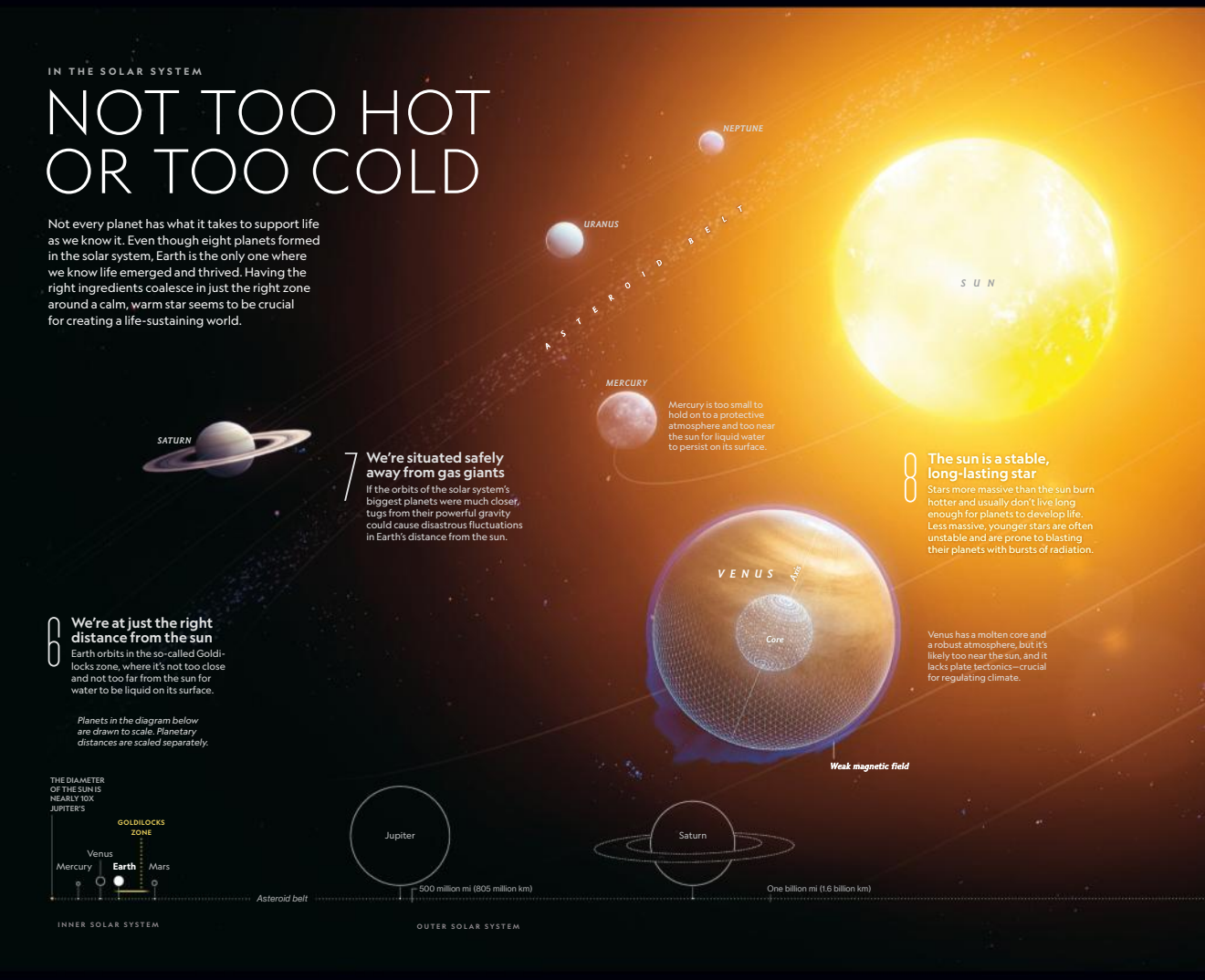


RYAN T. WILLIAMS, NGM STAFF. ART: TOMÁŠ MÜLLER. SOURCES: PETER D. WARD, UNIVERSITY OF WASHINGTON; KATE MAHER, STANFORD UNIVERSITY; KARINA A. YAGER, NASA GODDARD SPACE FLIGHT CENTER; JASON BARNES, UNIVERSITY OF IDAHO

IN THE SOLAR SYSTEM

NOT TOO HOT OR TOO COLD

Not every planet has what it takes to support life as we know it. Even though eight planets formed in the solar system, Earth is the only one where we know life emerged and thrived. Having the right ingredients coalesce in just the right zone around a calm, warm star seems to be crucial for creating a life-sustaining world.



Mercury is too small to hold on to a protective atmosphere and too near the sun for liquid water to persist on its surface.

6 We're at just the right distance from the sun

Earth orbits in the so-called Goldilocks zone, where it's not too close and not too far from the sun for water to be liquid on its surface.

Planets in the diagram below are drawn to scale. Planetary distances are scaled separately.

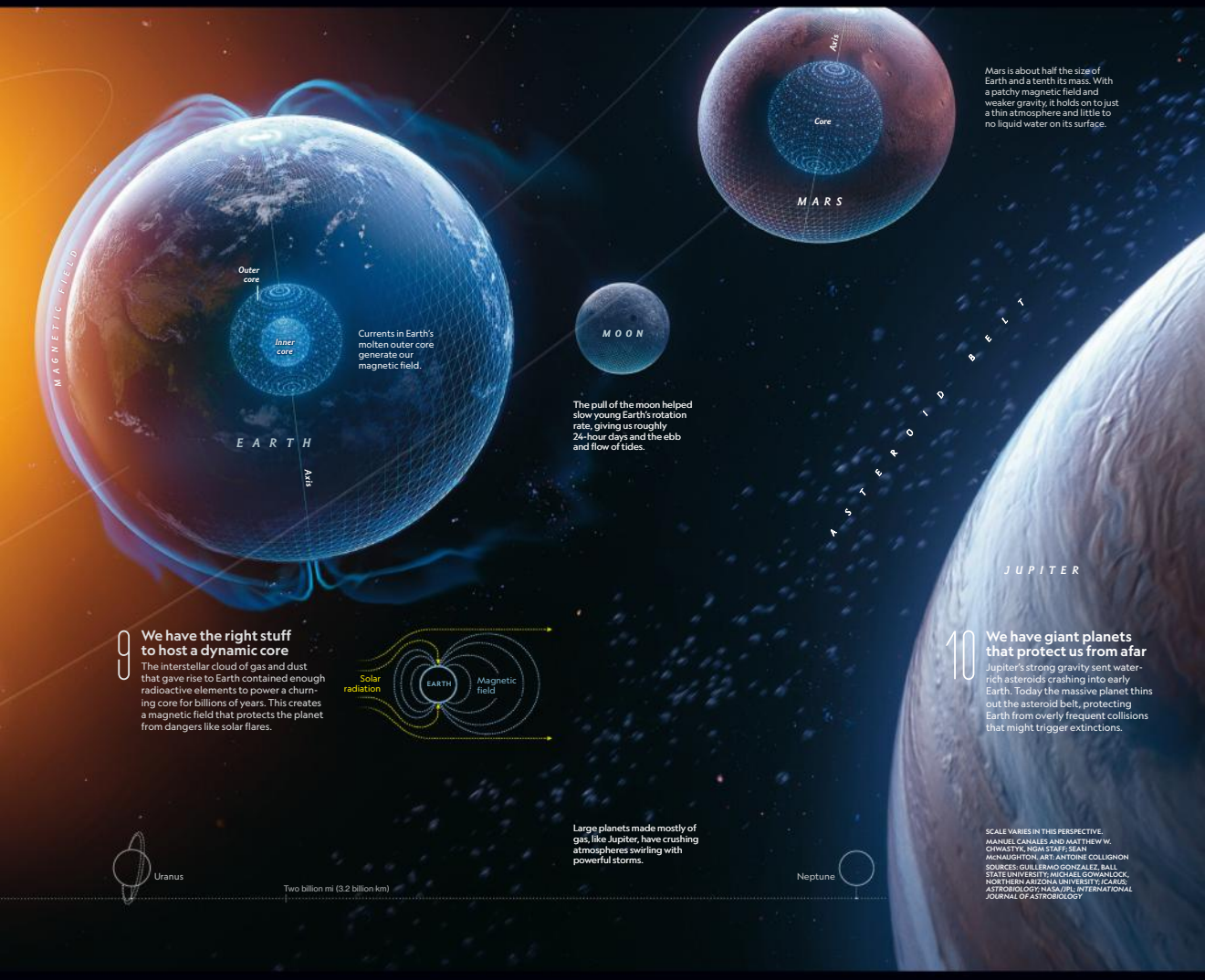
7 We're situated safely away from gas giants

If the orbits of the solar system's biggest planets were much closer, tugs from their powerful gravity could cause disastrous fluctuations in Earth's distance from the sun.

8 The sun is a stable, long-lasting star

Stars more massive than the sun burn hotter and usually don't live long enough for planets to develop life. Less massive, younger stars are often unstable and are prone to blasting their planets with bursts of radiation.

Venus has a molten core and a robust atmosphere, but it's likely too near the sun, and it lacks plate tectonics—crucial for regulating climate.



9 We have the right stuff to host a dynamic core

The interstellar cloud of gas and dust that gave rise to Earth contained enough radioactive elements to power a churning core for billions of years. This creates a magnetic field that protects the planet from dangers like solar flares.

10 We have giant planets that protect us from afar

Jupiter's strong gravity sent water-rich asteroids crashing into early Earth. Today the massive planet thins out the asteroid belt, protecting Earth from overly frequent collisions that might trigger extinctions.

SCALE VARIES IN THIS PERSPECTIVE.

MANUEL CANALES AND MATTHEW W. CHWASTYK, NGM STAFF; SEAN McNAUGHTON, ART: ANTOINE COLLIGNON

SOURCES: GUILLERMO GONZALEZ, BALL STATE UNIVERSITY; MICHAEL GOWANLOCK, NORTHERN ARIZONA UNIVERSITY; *ICARUS; ASTROBIOLOGY*; NASA/JPL; *INTERNATIONAL JOURNAL OF ASTROBIOLOGY*

IN THE MILKY WAY

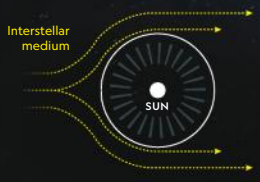
A SAFE LOCATION

The Milky Way is a spiral galaxy with gracefully curving arms and a bright, central bar of stars passing through its core. To sustain life, planets embedded within the galaxy must avoid catastrophic threats such as close supernovae, gamma-ray bursts, and active black holes. They also can't be crowded in star clusters that would jostle them around too much. Luckily, Earth is in an ideal place for its inhabitants to thrive.

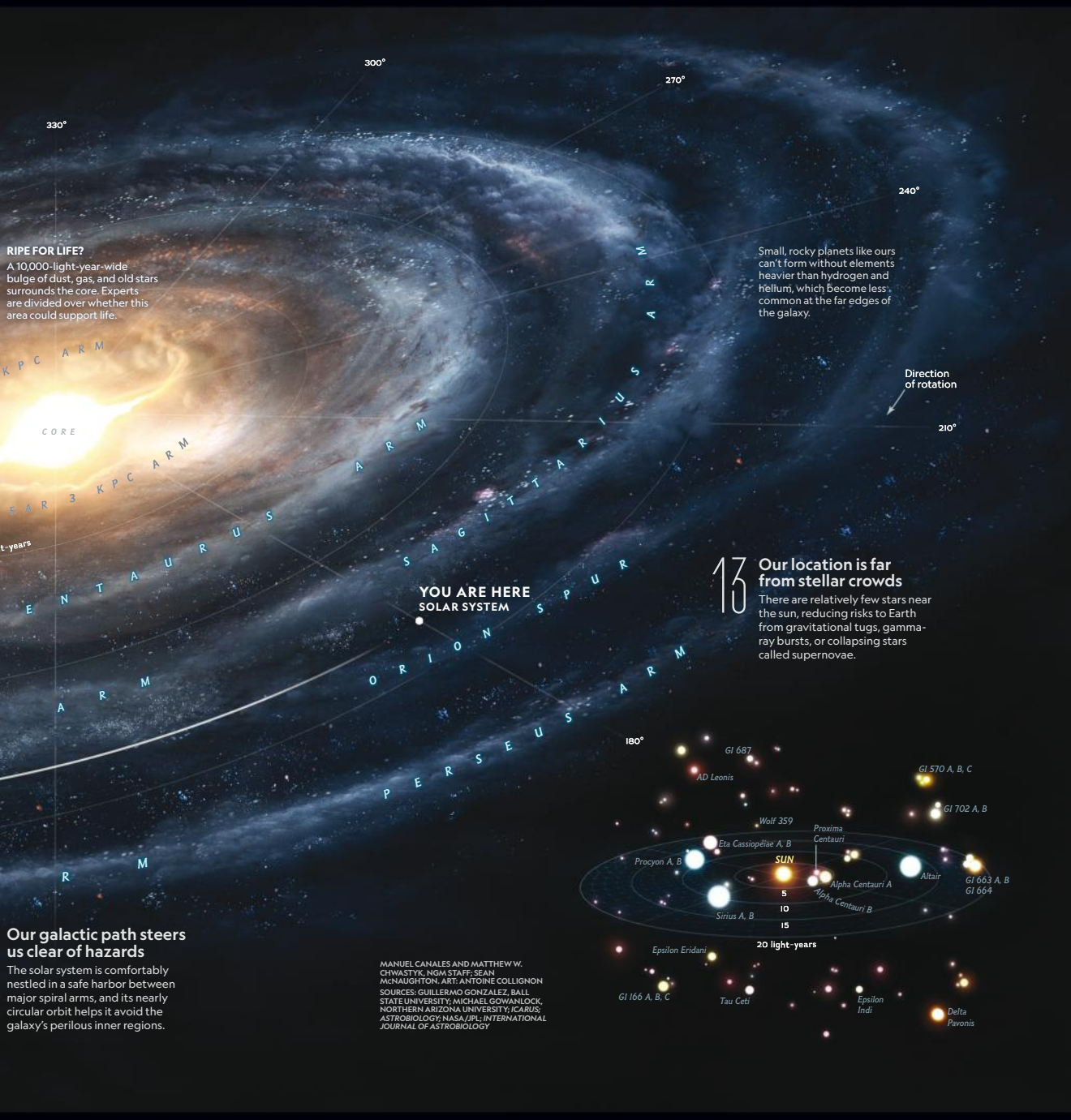
GALAXY HALO
Loose stars and some 150 dense stellar clusters orbit within the Milky Way's halo. Life-sustaining planets are unlikely here, because heavy elements are too sparse to build Earthlike worlds.

CHAOTIC CORE
A hidden black hole four million times the mass of the sun makes the galaxy's heart a dangerous place, with intense bursts of radiation hostile to life.

The Milky Way's arms are filled with hazards to habitability, including radioactive clouds, areas of active star formation, and sterilizing blasts from dying stars.



11 **Our sun offers protection from galactic debris**
The sun engulfs its planets in a bubble of charged particles that repel dangerous radiation and harmful materials coming from interstellar space.



13

Our location is far from stellar crowds

There are relatively few stars near the sun, reducing risks to Earth from gravitational tugs, gamma-ray bursts, or collapsing stars called supernovae.

Our galactic path steers us clear of hazards

The solar system is comfortably nestled in a safe harbor between major spiral arms, and its nearly circular orbit helps it avoid the galaxy's perilous inner regions.

MANUEL CANALES AND MATTHEW W. CHWASTYK, NGM STAFF; SEAN McNAUGHTON, ART; ANTOINE COLLIGNON

SOURCES: GUILLERMO GONZALEZ, BALL STATE UNIVERSITY; MICHAEL GOWANLOCK, NORTHERN ARIZONA UNIVERSITY; *ICARUS; ASTROBIOLOGY*; NASA/JPL; *INTERNATIONAL JOURNAL OF ASTROBIOLOGY*

FROM 508 MILLION YEARS AGO Preserved in the Burgess Shale of British Columbia, the worm *Canadia spinosa* was part of an explosion in biodiversity during the Cambrian period that gave birth to most of the major animal groups alive today.

ROYAL ONTARIO MUSEUM INVERTEBRATE PALAEONTOLOGY (ROMIP) SPECIMEN 41145
ALL FOSSILS PHOTOGRAPHED AT THE ROYAL ONTARIO MUSEUM

TO TODAY The striking similarity between this modern bristle worm and its Cambrian relative speaks to a lifestyle that hasn't changed much in 500 million years.

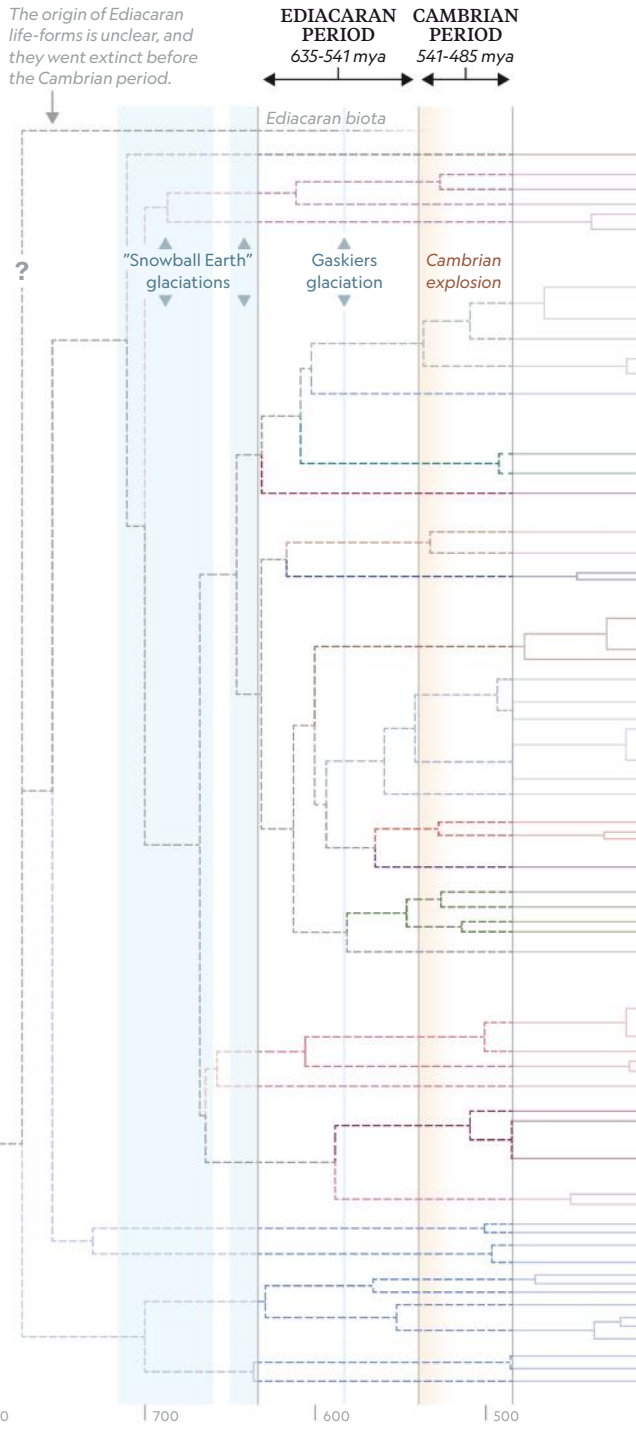
WHEN LIFE GOT COMPLICATED

How did life on Earth explode from simple microbes to large, complex creatures—not once but twice? Scientists see clues in fossils from as far back as 570 million years ago.

PHOTOGRAPHED AT THE ELIZABETH MOORE INTERNATIONAL CENTER FOR CORAL REEF RESEARCH & RESTORATION

GROWING IN COMPLEXITY

Single-celled and simple multicellular organisms reigned on Earth for more than three billion years. Then, starting 635 million years ago—after a long series of glaciations called "snowball Earth"—ice melted and oxygen reached a critical threshold that allowed more complex multicellular life to flourish. In the Cambrian period, animal life as we know it exploded into its myriad forms.



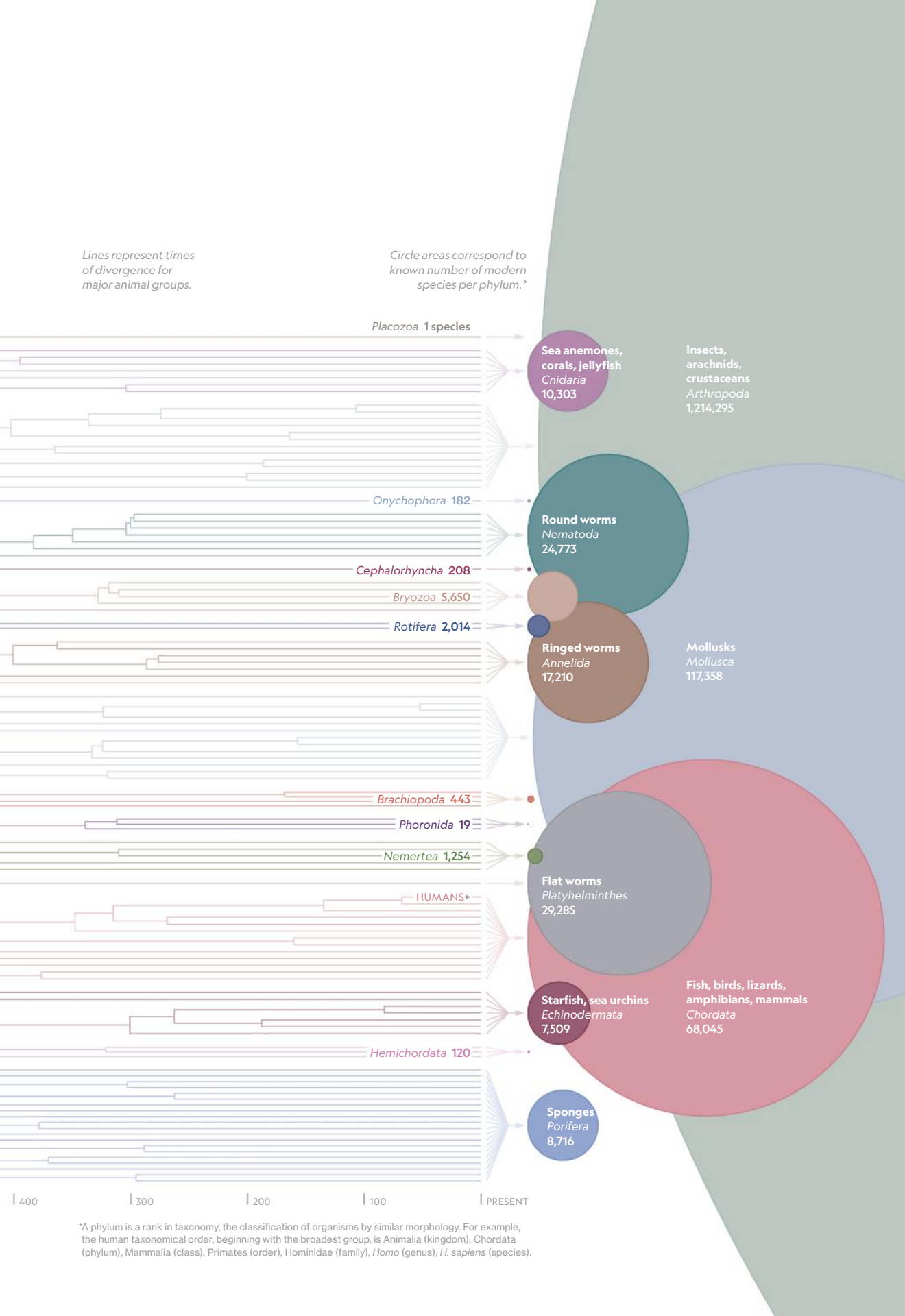
JASON TREAT, NGM STAFF; MEG ROOSEVELT

SOURCES: DOUGLAS H. ERWIN, SMITHSONIAN NATIONAL MUSEUM OF NATURAL HISTORY; SPECIES 2000 AND ITIS CATALOGUE OF LIFE: 2016 ANNUAL CHECKLIST; MARC LAFLAMME, UNIVERSITY OF TORONTO MISSISSAUGA

By David Quammen
Photographs by David Liittschwager

On the southeast coast of Newfoundland, near North America's farthest eastward reach, lies a promontory of rocky cliffs called Mistaken Point. The place got its name from the shipwrecks it helped cause in foggy weather, when sea captains mistook it for somewhere else. Today it represents something quite different: a set of extraordinary clues, recently reinterpreted, to one of the deepest and most puzzling mysteries of life on Earth. After burbling along for more than three billion years as tiny, mostly single-celled things, why did life suddenly erupt into a profusion of complex creatures—multicellular, big, and astonishing? Although these new life-forms spread worldwide, beginning at least 570 million years ago, the earliest evidence of them has been found in one place: Mistaken Point. Paleontologists have been going there for decades. But what the experts think they see now, in small nuances with large implications, is radical and new.

On a cool autumn day I made the journey to Mistaken Point myself, driving south from St. John's, Newfoundland's capital, in a rented Jeep, along a black ribbon of highway through forests



*A phylum is a rank in taxonomy, the classification of organisms by similar morphology. For example, the human taxonomical order, beginning with the broadest group, is Animalia (kingdom), Chordata (phylum), Mammalia (class), Primates (order), Hominidae (family), *Homo* (genus), *H. sapiens* (species).

of spruce and fir. With me were Marc Laflamme of the University of Toronto Mississauga and his longtime colleague Simon Darroch, an Englishman based at Vanderbilt University in Nashville.

We reached Mistaken Point beneath a blue sky and a blazing sun—rare weather, Laflamme told me, but the strong angled light, especially in late afternoon, helped highlight the subtle fossils we had come to see.

At the Mistaken Point Ecological Reserve, established by the provincial government to protect the fossil beds, we took a gravel road to a broken sea bank and climbed down. Laflamme pointed to a single slab of smooth, purplish gray rock, tilted at about 30 degrees. An image in the stone, like an intricate shadow, suggested the skeleton of a snake, a repeating pattern of ribs and spine, about three feet long. But there was no skeleton here, indeed no bone at all—only the imprint of a soft-bodied creature, dead and buried on the sea bottom a very, very long time ago. It didn't swim; it didn't crawl. It couldn't have lived like any organism alive today. It belonged to a more obscure period, inhabited by cryptic, otherworldly creatures that most people don't realize ever existed. "This is the first time that life got big," Laflamme told me as we knelt on the rock.

'THIS IS THE FIRST TIME THAT LIFE GOT BIG,' LAFLAMME TOLD ME AS WE KNELT ON THE ROCK.

THE MYSTERY OF THESE LIFE-FORMS, known as Ediacarans (Ee-dee-AK-arans), begins in the remote Flinders Ranges of South Australia, where a young geologist named Reginald Sprigg, on an assignment to reassess the derelict Ediacara Mines in 1946, noticed some peculiar impressions in exposed sandstone beds. They seemed to him "suggestive of jellyfish." They weren't jellyfish. There were other shapes too, some of them bearing no clear resemblance to any known creature, living or extinct. One figure looked like a fingerprint pressed into the sand.

Sprigg didn't realize (nor did those who had found similar figures in stone before, unsure what to make of them) that the fossils were about 550 million years old—dating to at least 10 million years before a better known evolutionary drama, the famous Cambrian explosion. Scientists until then had believed that the Cambrian explosion was *the* point when life on Earth opened out, *kaboom,* like a starburst of wondrous beasts—elaborate and sizable beings (we call them animals), many of whose descendants are still around. Sprigg's discovery proved important as a first signal that the period now called Ediacaran, not the Cambrian just following it, was where the saga of bigness and complexity began.

Then in 1967 a graduate student named S. B. Misra noticed a fossil-rich slab of mudstone at Newfoundland's Mistaken Point. Some of its ancient forms seemed to match the "jellyfish" things from South Australia, others looked like fronds, but several resembled nothing known to science. Other beds nearby, sitting one upon another like layers of Precambrian cake, also proved to contain abundant and various fossils, preserved together as whole communities. Many were still covered with thin crusts of fallen volcanic ash, like icing between each layer of cake. The ash, with its traces of radioactive uranium and the lead into which that decays, allowed for precise radiometric dating of the beds. The Mistaken Point fossils, going back 570 million years, are the earliest evidence on Earth of large, biologically complex beings.

There are now more than 50 different Ediacaran forms known, from nearly 40 localities, on every continent except Antarctica. So what was it, after billions of years of only microbes populating the globe, that allowed the Ediacarans to get big and cover the Earth? And what does their bigness suggest about their internal anatomies, their means of feeding, their ways of living?

Before Ediacaran forms flourished on the planet, evolution worked on a mostly microscopic scale, kept in check by a shortage of oxygen, the

element that fuels animal metabolism. Thanks to marine bacteria that generated oxygen as a product of photosynthesis, levels of the gas rose about two billion years ago but stayed relatively low for another billion years. Then, between 717 million and 635 million years ago, a series of glaciations took place, so widespread and severe that they may have frozen over the entire planet, a situation some scientists call a "snowball Earth." During that time oxygen levels bumped up again, for reasons that are still poorly understood.

EDIACARAN

The first large, biologically complex organisms appear in the fossil record some 570 million years ago, even before the Cambrian explosion, during a mysterious period called the Ediacaran. Known only from impressions their soft bodies left in mud or ash they were buried in, Ediacaran organisms like this *Fractofusus misrai* from Newfoundland are unrelated to and unlike any animal alive today. *Fractofusus's* body plan, composed of ever smaller repeating branches, dramatically increased its body surface area, the better to feed by absorbing nutrients directly from seawater.

The great freeze ended as volcanic eruptions spewed carbon dioxide into the atmosphere, creating an early greenhouse effect that warmed the planet and thawed the oceans. Another brief glaciation around 580 million years ago, known as the Gaskiers, may not have been global, but it put Newfoundland, among other places, in a deep freeze. These changes all preceded the earliest appearance of Ediacarans in the fossil record. Were they the *causes* of what happened next? Did the end of the glaciers, an increase in available oxygen, and the evolution of more complex cells allow the Ediacarans to blossom, like the first crocuses of springtime? Maybe.

Equally enigmatic is their relationship to life today. One eminent German paleontologist, Adolf Seilacher, assigned them to a kingdom all their own, distinct from the animal kingdom, because of what he called their "unique, quilted type of biological construction," so different from most multicellular animals. The "quilted" effect seemed to offer structural stability that might have compensated for the absence of a skeleton. Maybe the quilting, and the frondy shapes, also helped maximize surface area, so they could better absorb nutrients through their skin.

Nutrition would have been problematic for the Ediacarans because, so far as fossil evidence reveals, almost none of them had a mouth. They had no gut, no anus. No head, no eyes, no tail. In some cases there was a sort of anchoring knob or disk at one end, now known as a holdfast, which gripped the sea bottom and allowed the frond to waft upward in the water. Many sea-bottom areas at that time were coated with thick microbial mats, which helped stabilize the sediments like a layer of crusty soil. But the frond wasn't a plant—photosynthesis couldn't have nourished it—because many Ediacarans lived in the depths, thousands of feet underwater, where light didn't penetrate.

If they couldn't eat and they couldn't photosynthesize, how did they nourish themselves? One form, a sluglike thing called *Kimberella,* may have scratched up and swallowed (this one did have a mouth, major advantage!) sustenance from the microbial mats beneath it. But the leading hypothesis for most Ediacarans is osmotrophy, a fancy word for a very basic process: the uptake of dissolved nutrients by osmosis, or absorption through their outer membrane. It was good enough, maybe, in a simpler world at a simpler time, but it would have been meager sustenance. Some scientists have focused on another fascinating aspect of many Ediacarans: their finer architecture. At a glance they look quilted, but close inspection reveals that their structure is fractal. That is, similar patterns repeat

ROMIP SPECIMEN 36502

PHYLUM CHORDATA

FROM SO SIMPLE A BEGINNING

Like the rest of the vast diversity of fish, reptiles, birds, mammals, and other vertebrates alive today, the splendid betta fish owes its body construction to early chordates in the Cambrian such as *Pikaia gracilens* (below). Fishy yet not a fish, *Pikaia* possessed a flexible rod of cartilage, called a notochord, which in vertebrates develops into a spine. "All vertebrates have probably evolved from something like this," says Royal Ontario Museum paleontologist Jean-Bernard Caron.

ROMIP SPECIMEN 61233

PHYLUM CHORDATA

DISTANT COUSINS

It would be hard to find two animals as dissimilar as the giraffe and an invertebrate sea squirt such as *Ciona savignyi,* at right. And yet they share a common Cambrian chordate ancestor. While the giraffe extends the notion of spinal column to the ultimate extreme, a sea squirt possesses a central notochord only fleetingly, in its larval stage. With its muscular tail, the larva swims about for a few days until it finds a suitable surface to attach to. Then it dissolves and absorbs its own tail, and morphs into a spineless, immobile adult.

GIRAFFE PHOTOGRAPHED AT SAFARI WEST

themselves at progressively smaller scales. A big frond was composed of smaller fronds, and those smaller fronds composed of still smaller fronds, all similar except for size. The basic shape echoes itself at three or four scales. Possibly that fractal structuring helps explain how they were able to grow large. It provided some rigidity, it maximized surface area, and perhaps it reflected a genetic shortcut. A simple formula in the genome might have specified: Build a small frondy unit, then repeat that operation over and over, adding one upon another, to make me big.

This sort of fractal structure showed in the snakelike creature Marc Laflamme and I saw in the purplish gray rock at Mistaken Point. It shows too in a number of other Ediacarans, collectively called rangeomorphs, named for a Namibian exemplar of the form, known as *Rangea*. During our day on the Newfoundland rocks, Laflamme steered my eyes onto many more rangeomorphs, inconspicuous from 10 feet away but spooky when viewed closely. Here was *Beothukis mistakensis,* a paddle-shaped frond, named for its locale of discovery. Over there was *Fractofusus,* a spindle-shaped form, tapered at both ends. It lived flat on the sea bottom. When death came to a community of Ediacarans, as when a blizzard of volcanic ash settled through the seawater to smother them or an avalanche of sediment came off a steep slope to bury them, the vertical frondy things sometimes got smashed over (as the fossil evidence shows), but the *Fractofusus* spindles seem to have died gently where they lay.

Although these rangeomorphs dominated the deep-sea ecosystem at Mistaken Point for millions of years and flourished elsewhere in somewhat shallower water, they all disappeared, leaving no known descendants. By the start of the Cambrian period 541 million years ago, or soon after, they had almost entirely vanished from the fossil record as we know it. That's why some scientists have suggested that the Ediacarans represent "failed experiments" in the early evolution of multicellular life.

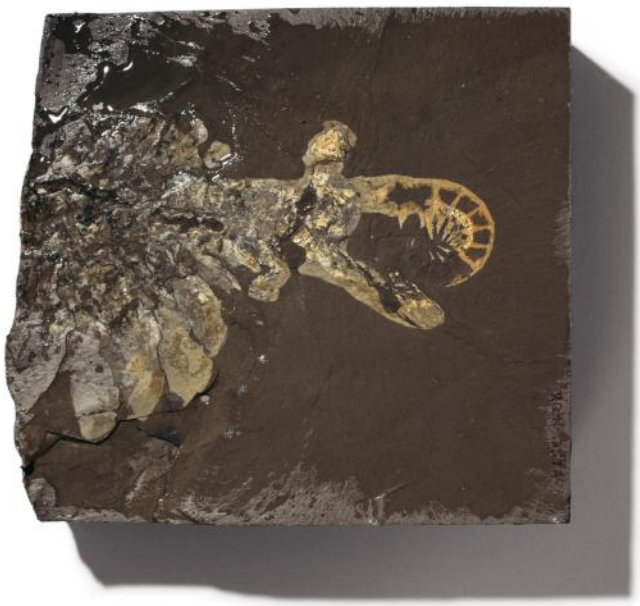
WHY DID THE EDIACARANS suddenly disappear? Was the extinction absolute, or were there

PHYLUM ARTHROPODA

THE RULING CLASS

Judging by number of species and sheer abundance, arthropods are hands down the planet's most dominant phylum, or principal division, in the animal kingdom. Defined by shared features such as tough exoskeletons and segmented bodies, the phylum includes well over a million named species, among them (clockwise from upper left) a snapping shrimp, a jungle nymph, an eastern lubber grasshopper, an Australian walking stick, a mantis shrimp, and a gaudy clown crab. Millions more species are believed to be still unknown to science. Arthropods were the most diverse animal group in the Cambrian period and the Ordovician period that followed. The 452-million-year-old limestone slab at left captures an Ordovician menagerie, including various echinoderms and trilobites, such as *Ceraurus,* the turtle-like form on the left edge.

LIMESTONE SLAB: ROMIP SPECIMEN 64530; LEFT COLUMN, ABOVE: PHOTOGRAPHED AT THE ELIZABETH MOORE INTERNATIONAL CENTER FOR CORAL REEF RESEARCH & RESTORATION; RIGHT COLUMN: SPECIMENS FROM INSECT DISCOVERY LAB, SAVENATURE.ORG



PHYLUM ARTHROPODA

THE RACE IS ON

The astonishing proliferation of new animal species in the Cambrian period was driven in part by a radical new way of fueling life's engines: eating other animals. As predators evolved claws to grasp and mouths to munch, their prey in turn developed armor and new means of escape, triggering further innovations in the predators to catch up with them. Among the first top predators in this arms race was *Anomalocaris,* which may have preyed on trilobites. Three of its weapons are visible above: claws, propulsive swimming flaps, and at the base of the claws, eyes on eyestalks. The emergence of vision in the Cambrian helped both predator and prey. One of *Anomalocaris*'s living relatives, the giant whip scorpion at left, boasts two eyes on the front of its body and three more on either side.

LEFT: SPECIMEN FROM INSECT DISCOVERY LAB, SAVENATURE.ORG;
ABOVE: ROMIP SPECIMEN 51212

PHYLUM MOLLUSCA

LIFE IN THE DEEP

Like arthropods, mollusks gained a foothold during the Cambrian period and eventually branched out into a profusion of divergent forms, including (clockwise from left) a modern lettuce sea slug, chiton, tusk shell, keyhole limpet, and spotted sea hare. *Nectocaris pteryx,* the 508-million-year-old fossil preserved in the Burgess Shale at right, sports several features seen today in squid, octopuses, and other creatures in the cephalopod class of mollusks. The shared traits include tentacles, eyes, and below them, a funnel used for propulsion. Most early mollusks lived on the ocean bottom, but *Nectocaris* had specialized to wander throughout the water column.

ALL EXCEPT FOSSIL (ROMIP SPECIMEN 59668) PHOTOGRAPHED AT THE ELIZABETH MOORE INTERNATIONAL CENTER FOR CORAL REEF RESEARCH & RESTORATION. SEA SLUG AND SEA HARE: SPECIMENS FROM FLORIDA KEYS MARINE LIFE

PHYLUM MOLLUSCA

SHROUDED BEAUTY

A defining feature uniting all mollusks ancient and modern is the possession of an outer layer of flesh called a mantle, which in this flame scallop is mottled in scarlet and decked with sticky tentacles. The mantle plays different roles in various species, depending on the creature's needs. In shelled mollusks like snails, clams, and scallops, it secretes a substance used to make the shell. Squid, octopuses, and cuttlefish propel themselves by filling the cavity beneath their mantle with water and shooting it out through a siphon.

PHOTOGRAPHED AT THE ELIZABETH MOORE INTERNATIONAL CENTER FOR CORAL REEF RESEARCH & RESTORATION

descendants in different forms? And if the end wasn't so abrupt and complete, what finished the Ediacarans as Ediacarans, dying off species by species in obscurity?

Laflamme's colleague Simon Darroch has offered one possible answer. On the afternoon of our visit to Mistaken Point, Darroch reached into his day pack and produced a surprise: small pieces of flat brown stone from the late Ediacaran beds he studies in Namibia. He had brought them from his lab at Vanderbilt to show me some trace fossils. A trace fossil, as distinct from a body fossil, records traces of animal activity—moving, chewing, defecating—as preserved in rock. It's a record of behavior, not of bodily shape. Any such traces are notable in the Ediacaran period, because most Ediacarans couldn't do those things: move, chew, or defecate.

"This is a very static, sessile ecosystem," Darroch said, referring to a famously rich early Ediacaran fossil bed on which we stood.

a recent paper, Darroch and his co-authors (led by James Schiffbauer, and including Laflamme) have called this early Cambrian time the "Wormworld." It was no place for Ediacarans.

Worminess wasn't the only factor that brought oblivion to the Ediacarans and triggered the Cambrian explosion—there also were changes in ocean chemistry that allowed animals to acquire hard parts (calcium-rich skeletons, teeth, and shells), a generalized increase in modes of mobility (not just burrowing), and the rise of predatory habits, among other things. But the worminess of that transitional time, in the late Ediacaran period, may have played a crucial role. A few weeks after our Mistaken Point outing, I talked with James Gehling, a leading Ediacaran researcher. Go up to the Flinders Ranges in South Australia, near the Ediacara Hills, he told me by phone from his office in Adelaide, and look at the first formation of Cambrian sedimentary layers. "It's just Swiss cheese." Burrowed all through by

THE RISE OF 'WORMWORLD' CREATURES WAS BAD NEWS FOR THE EDIACARANS.

The later Ediacaran, as revealed in Namibian rocks, was much different. One big difference, he said, was that "for the first time we have complex burrowing." Experts disagree about just when the intricate patterns of burrowing creatures first appeared, but by any judgment those traces signaled a big change from the Ediacaran to the Cambrian. Wormy creatures had long been wriggling along on the sea bottom; now they were tunneling down into it as well. Darroch showed me a little slab marked with dotted-line traces. "They're on the surface, and they disappear, then they come to the surface again." That was evidence of an organism with complicated musculature, allowing it to move about in three dimensions. If it moved that way, it had a front and a rear end. On its front end, probably a mouth. In the mouth, maybe teeth. These were extraordinary new tools and capacities at the time. The worms crawled in, the worms crawled out, disrupting the microbial mats, possibly munching directly on Ediacarans. In wormy creatures that had churned the sand and "recycled" the soft-bodied Ediacarans. "That's where the Cambrian begins," Gehling said. "The advent of the musculature to burrow."

Guy Narbonne, at Queen's University in Ontario, largely agrees with the importance of burrowing. But together with his graduate student Calla Carbone, he has taken Wormworld a step further. Based on careful analysis of trace fossils from the late Ediacaran and the early Cambrian, Narbonne and Carbone noticed a significant difference in how those wormy creatures turned. By the early Cambrian, burrowing animals became more systematic in their searches for food, as well as more muscled. They ranged more efficiently, tracking the resources better and crossing their own tracks less. "It reflects the evolution of braininess," Narbonne told me. "Our interpretation," he added, "is that the Cambrian explosion is when behavior became coded on the genome." They titled that paper, "When Life Got Smart."

PHYLUM ECHINODERMATA

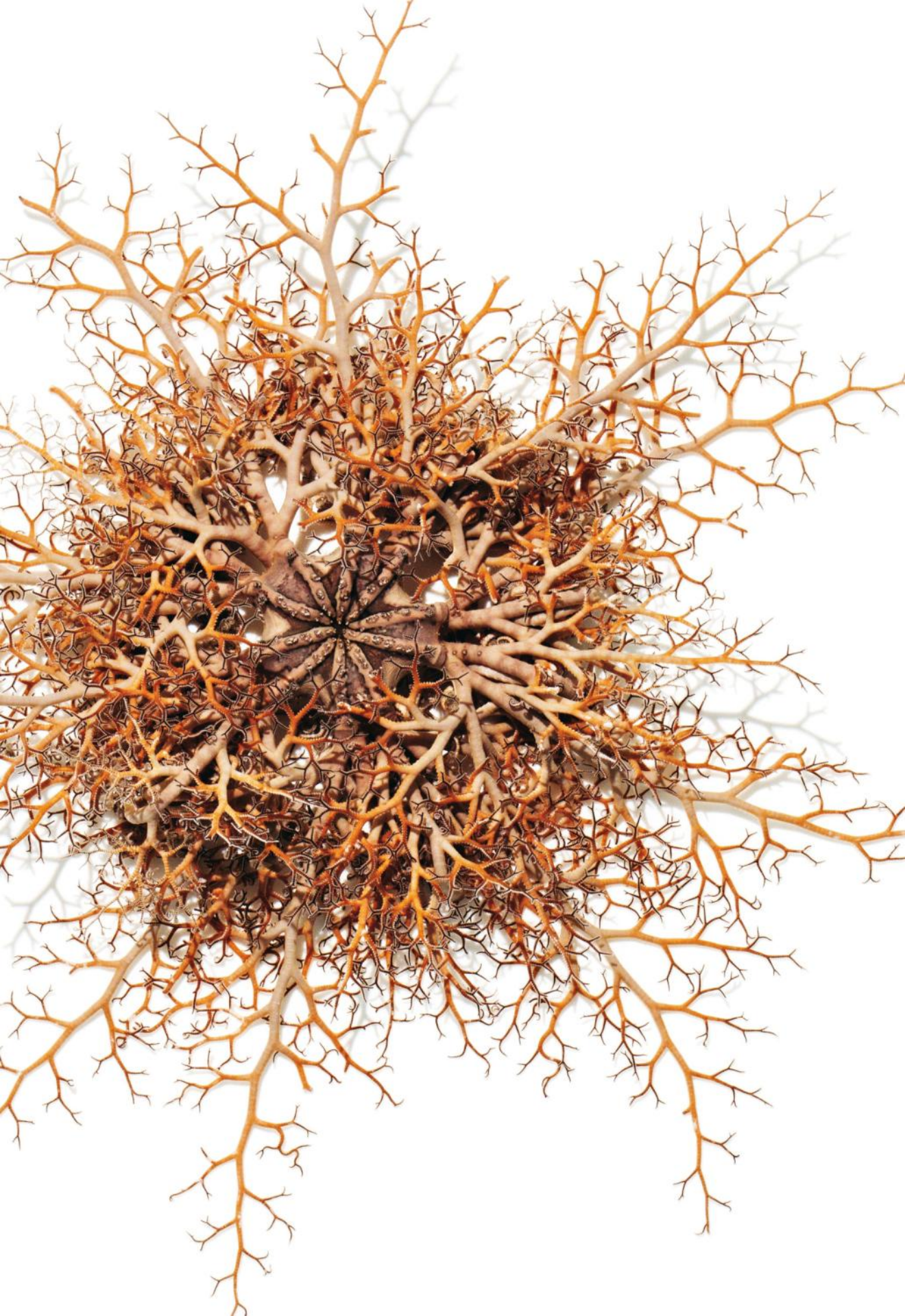
AN ENDURING DESIGN

Like more familiar echinoderms such as sea stars and sea urchins, the Ordovician sea lily above and modern basket star at right have a body plan arranged symmetrically around a central mouth. Fixed to the bottom by a stalk, the sea lily fed by gathering particles from the water with its arms and bringing them to its mouth. Four hundred fifty million years later, the basket star employs much the same strategy, spreading its profusion of armlets to filter as much water as possible.

Most experts would agree that smartness, even on a level expressed by a primitive worm, wasn't a wrench in the Ediacaran tool kit. Those creatures' genomes may have been coded for fractal repetition—at least in the rangeomorphs, where it yielded a simple sort of complexity—but not for responsiveness to circumstances, or efficiency. Still, it's a mistaken point to dismiss the Ediacarans as doomed. People made that error with the dodo, when they branded it an emblem of ill-fated stupidity. But the real dodo, *Raphus cucullatus,* a large, flightless, fruit-eating bird endemic to the island of Mauritius, had thrived in its peaceable home for many thousands of years—until *Homo sapiens* and other predators arrived. Likewise the Ediacarans, with their own new threats. You can call them "failed experiments" in evolution if you want, but they succeeded and flourished, within their preferred but challenging environments, for more than 30 million years. We humans should be so steadfast and lucky. □

Contributing writer **David Quammen**'s next book, *The Tangled Tree,* will be published by Simon & Schuster in September. Photographer **David Liittschwager** has been illuminating the elegance and beauty of the natural world for *National Geographic* since 2005.

FROM LEFT: ROMIP SPECIMEN 64529; SPECIMEN FROM FLORIDA KEYS MARINE LIFE



DRYING

Warming climates, drought, and overuse are draining some of the world's biggest lakes, threatening habitats and cultures.

LAKE POOPÓ
The dry, salt-crusted Bolivian lake bed unfurls into the distance. Boats are stranded; the fish and waterfowl are gone. Fishermen who depended on the lake are moving elsewhere. It's a diaspora born of drought.

L A K E S

BY **KENNETH R. WEISS**

TIRE TRACKS STRETCHED ACROSS THE FLAT LAKE BED TO THE HORIZON.

We followed them in a Suzuki 4x4, looking for clues about what's happened to Poopó, once Bolivia's second largest lake, which has vanished into the thin air of the Andean highlands.

We were driving on the lake bottom, yet we were more than 12,000 feet above sea level. The spring air was lip-chapping dry. Many of the fishing villages that have relied on Lake Poopó for thousands of years have emptied too, and we drove past clusters of abandoned adobe homes. Dust devils danced around them, spinning in warm winds. In the distance we spotted several small aluminum boats that seemed to be floating on water. As we drove closer, the mirage receded, and we found the boats sitting abandoned in the silt. I stepped out of the vehicle. My shoes cracked the salty crust that had formed jagged lumps, like ice cream in a freezer that has melted and recrystallized.

My guide, Ramiro Pillco Zolá, crunched across the salt pan to reach one of the dilapidated, half-buried boats. Boyhood memories of paddling across the lake flooded back to him from long before he left his village of San Pedro de Condo to study hydrology and eventually earn a Ph.D. in hydrology and climate change at Lund University in Sweden. "We're not talking about a small

LAKE POOPÓ A woman washes clothes outside her home in Llapallapani, which is next to the village school where she teaches. With many wells turning salty, freshwater for washing is scarce. Many of the men have left the village to work at urban construction sites or in metal and salt mines.

LAKE POOPÓ, BOLIVIA

PHOTOGRAPHS BY MAURICIO LIMA

Children in Llapallapani learn how to weave straw so they can make money as adults by selling hats, key chains, earrings, and other handicrafts. The Uru people remaining in small fishing villages are struggling to survive while hoping for the return of their dried-up lake. NGM MAPS (ALL)

thing," Pillco Zolá told me. "Three decades ago this lake covered 3,000 square kilometers. It's going to be hard to recover."

Water that once spread across an expanse about the size of Rhode Island was gone. A pair of black rubber boots lay discarded near the boat. A fish skull bleached brilliant white flashed under the blinding sun. The wind suddenly stopped, cloaking the post-apocalyptic scene in silence. If water is life, this was the absence of both.

AROUND THE GLOBE, climate change is warming many lakes faster than it's warming the oceans and the air. This heat accelerates evaporation, conspiring with human mismanagement to intensify water shortages, pollution, and loss of habitat for birds and fish. But while "the fingerprints of climate change are everywhere, they don't look the same in every lake," says Catherine O'Reilly, an aquatic ecologist at Illinois State University and co-leader of a worldwide lake survey by 64 scientists.

In eastern China's Lake Tai, for example, farm runoff and sewage stimulate cyanobacterial blooms, and warm water encourages growth. The organisms threaten drinking-water supplies for two million people. East Africa's Lake Tanganyika has warmed so much that fish catches that feed millions of poor people in four surrounding countries are at risk. The water behind Venezuela's massive Guri hydroelectric dam has reached such critically low levels in recent years that the government has had to cancel classes for schoolchildren in an effort to ration electricity. Even the Panama Canal, with its locks recently widened and deepened to accommodate supersize cargo vessels, is troubled by El Niño–related rainfall shortages affecting man-made Gatun Lake, which supplies not only water to run the locks but also fresh drinking water for much of the country. Low water levels have also forced limits on the draft of ships so the ships don't run aground in the lake.

Of all the challenges lakes face in a warming world, the starkest examples are in closed drainage basins where waters flow into lakes but don't exit into rivers or a sea. These terminal, or endorheic, lakes tend to be shallow, salty, and hypersensitive to disturbance. The vanishing act of the Aral Sea in Central Asia is a disastrous example of what can happen to such inland waters. In its case the main culprits were ambitious Soviet irrigation projects that diverted its nourishing rivers.

Similar scenarios are playing out in terminal lakes on nearly every continent, a combination of overuse and worsening drought. Side-by-side satellite images reveal the shocking toll. Lake Chad in Africa has shrunk to a sliver of its former self since the 1960s, heightening shortages of fish and irrigation water. Displaced people and refugees who now depend on the lake put an additional strain on resources. Shortages as well as tensions in the hot, dry Sahel are driving conflict and mass migration. Utah's Great Salt Lake and California's Salton Sea and Mono Lake have undergone periods of recession too, diminishing critical breeding and nesting areas for birds as well as playgrounds for recreational boaters.

After the Caspian Sea, Iran's Lake Urmia was once the largest saltwater lake in the Middle East. But it has shrunk by some 80 percent over the past 30 years. The flamingos that feasted on brine shrimp are mostly gone. So are the pelicans, egrets, and ducks. What remain are piers that lead nowhere, the rusting carcasses of ships settled into the silt, and white, barren salt flats. Winds that whip across the lake bed blow salt dust to farm fields, slowly rendering the soil infertile. Noxious, salt-tinged dust storms inflame the eyes, skin, and lungs of people 60 miles away in Tabriz, a city of more than 1.5 million. And in recent years Urmia's alluring turquoise waters have been stained blood-red from bacteria and algae that flourish and change color when salinity increases and sunlight penetrates the shallows. Many of the tourists who once flocked here for therapeutic baths are staying away.

Although climate change has intensified droughts and elevated hot summer temperatures around Urmia, speeding up evaporation, that's only part of the story. Urmia has thousands of illegal wells and a proliferation of dams and

AFRICA'S LAKE CHAD IS A SLIVER OF ITS FORMER SELF. IRAN'S LAKE URMIA HAS **SHRUNK BY 80 PERCENT IN 30 YEARS.** WHAT REMAIN ARE THE CARCASSES OF SHIPS SETTLED INTO THE SILT.

irrigation projects that divert water from tributary rivers to grow apples, wheat, and sunflowers. Experts worry that Urmia could fall victim to the same overexploitation of water as the Aral Sea. Their voices seem to have reached Tehran. Iranian President Hassan Rouhani has pledged five billion dollars to revive Urmia by releasing more water from dams, improving the efficiency of irrigation systems, and switching to less thirsty crops. And although United States–Iran relations have been strained for decades, the two countries have permitted scientists to brainstorm about ideas to replenish both Urmia and Great Salt Lake. Neither nation wants to see its salt lake go the way of Poopó.

BOLIVIA'S HIGH PLAIN, the Altiplano, unfurls like a leaf-shaped plateau wedged into an unusual place where South America's Andes cleave into two separate ranges. The windswept landscape remains brown much of the year. Grasses and shrubs grow sturdy and low to the ground. The people who eke out a living in this inhospitable landscape are just as hardy. Toward the north end of the plateau sits Lake Titicaca, at 12,500 feet, straddling the border between Peru and Bolivia. At the southern end is blindingly white Salar de Uyuni, at 11,995 feet. Poopó rests between them, the transition zone between the world's highest commercially navigable lake and the world's largest salt flat.

Scientists have long suspected that Poopó would someday be choked with sediment, desiccate, and transition into another salt flat like Salar de Uyuni. Yet its demise wasn't projected to come for at least another thousand years, says Milton Pérez Lovera, a natural sciences professor at Oruro Technical University and a member of a team monitoring bodies of water in the Bolivian highlands. A combination of factors, including climate change, drought, upstream water diversions for agriculture, and mining, have accelerated the process, he says, leaving the lake increasingly dry and barren. Pérez Lovera expects Poopó may partly refill, perhaps as soon as this year, if La Niña conditions bring more rain to the Andes. But he and other scientists are less sure the lake will regain its ecological function as a prime wintering habitat for waterfowl, including three species of flamingos, one classified as vulnerable to extinction. Nor are they certain whether or when its fertile fishing grounds—which for millennia provided food for indigenous people—might recover.

The fate of Lake Poopó is intertwined with that of the Urus, an indigenous group known as "people of the water." The lake's size and depth have been diminishing for years, forcing Uru fishermen to travel farther onto the lake to catch fish. In 2014 and 2015 the ever shallower lake suffered fish die-offs as water temperatures soared beyond the usual 60s and 70s Fahrenheit. Millions of carcasses floated belly-up at the surface. When Franz Ascui Zuna, assigned by Bolivia's Ministry of Health to monitor the largest Uru village, Llapallapani, recorded a water temperature of 100.4°F, he pronounced a diagnosis: The lake was "running a fever."

Soon the ducks, herons, flamingos, and other birds that typically inhabit the lake were starving, either dying or flying away. In a flash of evaporation in 2015, the remaining lake vanished as its overheated waters were fanned by the Altiplano's winds. The government declared Poopó a disaster area. It sent each family in surrounding villages some pasta, rice, cooking oil, and sugar. Then rains refilled a portion of the lake, prompting federal officials, in early 2017, to celebrate and release pictures taken from a helicopter. But soon after, Bolivian President Evo Morales toured the

LAKE URMIA, IRAN

PHOTOGRAPHS BY NEWSHA TAVAKOLIAN

Summertime bathers wade into waters colored red by salt-loving bacteria and algae. Tourists from across Iran have come here for generations, but the number of visitors has fallen as the lake has shrunk some 80 percent since the 1980s, raising fears that this will be the last generation to play in its waters.

LAKE URMIA Reza Manafzadeh works on a fruit-tree farm at the edge of the salt lake, where crops are irrigated by a new method—recycled factory water brought by tanker truck. "I'm so worried about my son's future," he says. "If there will be no water in Iran, our children will lose interest in their country."

lake and confirmed what locals already knew: The shallow layer of water was receding fast. Satellite images in October 2017 showed the lake was once again nearly dry.

Morales has sought to deflect any government culpability in the crisis, pointing to natural cycles of drying and recovery. His father once told him about bicycling across the lake bed from a nearby village where he grew up. Indeed, the lake has dried and recovered, most recently in the mid-1990s. Yet scientists point out that things have worsened since then. And now the watershed and the poor people who live here are teetering on something more tenuous.

On the road into the village of Puñaca Tinta María, we watched an old man in rubber boots and a floppy straw hat stoop over, using a short-handled hoe to stir together clay with salty water he had hauled out of a hand-dug well. Every day since the lake dried up, Féliz Mauricio has toiled in mud-splattered clothes to make adobe bricks. "We have no lake," he says. "We have no fish. We have nothing." Mauricio, 77, comes from a long line of indigenous fishermen. A respected elder of the Urus, he's known for his craftsmanship in lashing together reeds into small balsa fishing boats using giant bulrushes called *totora* and for preparing a table of offerings in traditional ceremonies to usher in bountiful rain and fishing seasons.

By his reckoning, Mauricio, his wife, and their daughter are one of the few families left in adobe and thatch-roofed homes on the banks of what was once Lake Poopó. One son moved away to herd sheep and cattle; another took a low-skilled construction job in the city of Cochabamba. His neighbors in Puñaca Tinta María and other villages have scattered too, like chaff in the wind. Some have gone to work in textile and garment factories in Chile and Argentina; others have moved to cities and taken jobs as day laborers or work underground as miners extracting tin, lead, silver, and other metals. A few dozen have headed off to what may be the future of their beloved Poopó—working in the salt mines of Salar de Uyuni.

LAKE URMIA

Empty buildings and abandoned boats are all that remain at Rahmanlu Port. When the lake was full, cars queued up on the pier to load onto a ferry that cut hours off the drive time around the lake from the city of Tabriz to Urmia on the other side.

GREAT SALT LAKE, UNITED STATES

PHOTOGRAPHS BY CAROLYN DRAKE

Benjamin Anderson floats on the north arm of the lake. In the hypersaline water, he found it hard to sit up and hit the bottom in water only a foot deep. The lake's salinity has increased as its volume has dropped nearly 50 percent since the mid-1800s. The water in the north arm is eight times as salty as the ocean.

GREAT SALT LAKE This young hunter (and any under 18) can get a day's jump on duck season—with some adult help—at this important stopover for millions of migrating birds. But as humans shrink the lake, diverting water for agricultural and municipal needs, animals are losing nesting grounds and food sources.

In the global scheme of things, the fate of the Urus may seem trivial. An estimated 5,000 Urus remain today, and fewer than a thousand lived around Poopó before it went dry. Yet those who are forced to relocate join a procession of people around the world who have been uprooted from their homes by climate-related environmental disruptions. The United Nations warned a decade ago that indigenous people would be among the first to be ravaged by climate change because so many rely on nature's bounty as subsistence hunters and fishermen. An estimated 23.5 million people fled their homes in 2016 because of storms, floods, wildfires, extreme temperatures, and other weather-related disasters, according to the Norwegian Refugee Council's Internal Displacement Monitoring Centre. That exceeded the 6.9 million newly displaced by conflict and violence that year.

In sheer numbers those fleeing "natural" calamities have outnumbered those fleeing war and conflict for decades. Still, these figures do not include people forced to abandon their homelands because of drought or gradual environmental degradation; almost two and a half billion people live in areas where human demand for water exceeds the supply. Globally the likelihood of being uprooted from one's home has increased 60 percent compared with 40 years ago because of the combination of rapid climate change and growing populations moving into more vulnerable areas.

Most of these displaced people stay within their home countries. If they cross a border, they do not qualify for UN protections as refugees because they cannot claim they are fleeing violence or persecution. "We live in an era of the most forced migration since the Second World War," says William Lacy Swing, director general of the United Nations' International Organization for Migration. "This time, though, in addition to war, climate is looming as a major driver. We are going to need to support those who are ravaged by climate change so they can migrate with dignity."

"STOP!" PILLCO ZOLÁ YELLED inside our wind-buffeted SUV. "Go back." We were racing across a flat, sandy expanse of highlands above Poopó. Without realizing it, we had crossed a

LAKE TANGANYIKA, TANZANIA

PHOTOGRAPHS BY MICHAEL CHRISTOPHER BROWN

The morning haul in Kibirizi village brings sardines. Catches are declining as too many boats chase too few fish in this African lake bordered by Tanzania, the Democratic Republic of the Congo, Burundi, and Zambia. A warming lake results in less algae and thus less food for fish, amplifying the problem.


T.KGM.
MV. PRINC

LAKE TANGANYIKA

This cargo boat plies the waters of the world's second largest freshwater lake by volume (after Siberia's Lake Baikal). Millions of people rely on the lake, which is threatened by climate change, for water, transportation, and fish.

small bridge over an irrigation canal. The canal was empty, as was the adjoining Desaguadero River, with the exception of a small pool we found as we walked around the bend. More than 65 percent of Poopó's water comes from the Desaguadero River, which meanders 185 miles through the Bolivian highlands from its primary source, Lake Titicaca. Hundreds of irrigation canals and other water-diversion schemes have been built along the river for mining and for growing crops. Farms and cities also siphon water out of the Mauri River, a major tributary in Bolivia and Peru.

Another 22 smaller, seasonal streams and rivers also flow into Poopó from surrounding mountains. Virtually all of them are tapped for agriculture or mining operations, such as a state-owned tin mine in the dirt-poor town of Huanuni. When I visited, a chute emerging from the hillside mill was plopping ash gray tailings directly into the river in a conical mound as big as a house. Such tailings contribute to the lead, cadmium, arsenic, and other heavy metals that pollute the lake and fill it with sediment.

An hour's drive away, a dam built in 1961 on the Tacahua River holds a thick layer of sediment with only a veneer of water. "We've got five dams like this one," Pillco Zolá told me as we walked across the dry spillway, looking at the reservoir bed far below. "It doesn't make sense to build dams in a semiarid area. We are just stopping water upstream, causing it to evaporate."

In an average year the Lake Poopó region collects about 15 inches of rain from November to March, followed by seven dry months. Yet the rainy season keeps shrinking, when it comes at all. The Altiplano has suffered repeated El Niño–related droughts, which scientists project will come more often in a warmer climate. The 2015-16 El Niño brought the most dramatic drought and the hottest temperatures ever recorded in the Bolivian highlands, Pérez Lovera says. The Altiplano tends to trap heat between the mountain ranges, he said, and mean temperatures increased 1.6 degrees Fahrenheit over a single decade, accelerating water loss due to evaporation.

Rising atmospheric temperatures in the Andes over the past 40 years also have triggered the rapid retreat of its glaciers, melting half the ice that rings the Titicaca-Poopó basin.

When glaciers first begin to melt, they provide an extra flush of water, explains Dirk Hoffmann, a German researcher based in La Paz who co-authored the book *Bolivia in a 4-Degree Warmer World*. "But we've probably reached peak water in most glacial watersheds," he says, meaning that meltwater from glaciers will now diminish in the region until it is gone.

Meanwhile, demand for water has surged along with Bolivia's population, which has grown by 42 percent since the mid-1990s. Last year the government dug a canal in one branch of the sediment-laden Desaguadero River to speed water to Poopó. It also provided wheelbarrows, pickaxes, and some food to support desperate Uru workers as they built a one-and-a-half-foot-high earthen berm on the lake bed in hopes of concentrating water in one small section so it might last longer. To hydrologists like Pillco Zolá, such efforts seem all but futile. More realistic solutions would mean tearing down dams, switching to more efficient irrigation, and reducing the volumes of water diverted from the rivers. Yet there's little political will to cut off upstream farmers and even less funding for water projects in Bolivia, one of the poorest nations in Latin America.

A Peruvian-Bolivian commission that co-governs Titicaca has built floodgates designed to release more water into the Desaguadero River during dry years. But as demand for water increases upstream in Peru, these floodgates may be rendered useless in the not too distant future. Mark Bush, a paleoecologist at the Florida Institute of Technology, notes that it doesn't take much of a drop in the water level at Lake Titicaca for the river to stop flowing altogether. That has happened three times before, tucked in the deep recesses of time.

"The Altiplano is exquisitely sensitive to evaporation," Bush says. Although he cautions that climate models don't capture the Andes particularly well, he predicts that the region soon may reach a tipping point. "The prognosis for cities like La Paz and villages around Lake Poopó is really dire, given what we think is going to happen

'WE LIVE IN AN ERA OF THE MOST **FORCED MIGRATION** SINCE THE SECOND WORLD WAR. WE ARE GOING TO NEED TO SUPPORT THOSE WHO ARE **RAVAGED BY CLIMATE CHANGE** SO THEY CAN MIGRATE WITH DIGNITY.'

William Lacy Swing, director general of the United Nations' International Organization for Migration

in the future," Bush says. "By mid-century we might see at least two degrees [Fahrenheit] of warming, and we would be flirting with the threshold that would cause Lake Titicaca to evaporate away or greatly reduce its volume."

SOUTH OF POOPÓ, in the highlands, the lakeshore gives way to an even more arid landscape, with wind-sculpted rocks and herds of llamas, alpacas, sheep, and a few wild vicuñas—often clustered near no-hunting signs posted on the highway. In early spring much of the land remains bare, with soil left exposed after the harvest of quinoa that feeds an insatiable appetite for the high-protein grain in Europe and the U.S.

The timing is unfortunate. Before the year's crops are planted, the winds off the Atacama Desert in Chile scour the empty fields, carrying twice as many tons of sediment into the lake as they did before native grasses and shrubs were cleared for quinoa production. The result: The lake, which used to be 12 feet deep, is filling with sand and dust faster than had been projected.

Beyond the highlands the surface of Salar de Uyuni—crusted with polygons the size of card tables—is broken only by roads and mounds of salt chipped out of the ground to be shipped to nearby salt factories.

Is this the future of Poopó? Paulino Flores, a former Uru community leader, hopes not—but he's preparing, just in case. Flores, 57, and his family moved to the neighboring town of Colchani to work in the salt factories. Flores says he has mastered every aspect of production: chipping the salt out of the hard ground with a pickax and shovel, hauling it to the factory, removing impurities, grinding it, bagging it. He rubs his callused, salt-stained hands as he talks, squinting into the sun under his knitted Andean chullo hat.

Flores has considered establishing a salt factory on the shores of Poopó, working with the nongovernmental group Center of Ecology and the Andean People. The group's executive director, Gilberto Pauwels, says his colleagues are exploring every angle to help the Urus develop other livelihoods, preserve their communities, and keep their culture alive. Puñaca Tinta María is just one of the half-deserted villages on one desiccated lake that has left subsistence fishermen and hunters scrambling to figure out how to feed their families. It's a pattern that's being repeated around the world.

Flores dreams about the lake's recovery, the return of its fish and fowl. He talks wistfully about his former life, growing up hunting and fishing with his father and relatives—a life that revolved around Lake Poopó. The Urus believe they are descendants of people who first settled on the Altiplano 3,700 years ago. A 2013 genetic study suggests they may be right, revealing distinctive ancestry likely derived from ancient Andean lineages. These self-reliant people, who once lived on floating reed islands, outlasted the Inca Empire and survived the brutal conquest by the Spaniards. But now the Urus around Poopó face a diaspora with the disappearance of their cherished lake. "If there is no lake, there is no Uru people," Flores says. "It gives us food and gives us a future." □

Kenneth R. Weiss, a freelance writer based in Carpinteria, California, earned a degree in folklore from the University of California, Berkeley and was awarded a Pulitzer Prize for explanatory reporting in 2007.

LAKE TANGANYIKA

Off the coast of the village of Kazinga, men cast nets to catch sardines. Even a one- or two-degree Fahrenheit rise in water temperature here could affect fish yields and spell catastrophe for the millions who rely on them.

Siberian Solitude

A young Russian explores her ancestral ties to an isolated settlement.

BY EVE CONANT
PHOTOGRAPHS BY ELENA ANOSOVA

In the cold of March, villagers provide food and warmth to semi-feral horses like this pregnant mare. Later in the year, hunters load horses with elk, reindeer, and sable. The photographer's family has named this mare Tuchka—Small Cloud in Russian.

Elk lips are a holiday delicacy, and five-year-old Dasha waits, candy in hand, for an elk's upper jaw to defrost. In a few hours her mother will skin it and then boil it with spices as part of their New Year's feast.

Fairy tales can come true, but sometimes it takes a few decades.

As a city kid, Elena Anosova heard seemingly tall tales of a village visited by elk and wolves, of a vast forest, impassable roads, and an environment both bitter and beloved. As an adult, the visual artist, now 34, finally visited the settlement founded more than 300 years ago by her ancestors. They were hunters, swept up in the waves of Russians who ventured east to Siberia in search of fur and never left. Anosova's father was born there, and most of the 120 or so people who call the place home—and don't want outsiders to know its name or location—fall comfortably into the category of family.

In the native Tungus (or Evenki) language, the settlement's name translates roughly to "Island." That's a physical representation of what lies at the heart of Anosova's work: the exploration of isolation and boundaries. To reach this dreamy, landlocked "island" by jeep, there is the winter road that for a time freezes over the swampy, subarctic taiga. The fastest approach is by helicopter, which flies twice a month from the town of Kirensk, 200 miles away. If the chopper is full, it means two more weeks waiting to get in, or out.

Once in, Anosova has discovered much to do and little rush to leave. There are wild horses to wrangle when it's too warm to hunt on snowmobiles. There are crops to grow in oven-warmed greenhouses and preserve for winter. Cash is rarely necessary, except for trips to the city financed by the sale of sable fur. After visits to the village, city life feels different. "It's difficult," says Anosova, "because you need silence."

Even the cold becomes something to long for. Temperatures in June can dip below freezing. Anosova keeps an image on her iPhone of the reading one recent January morning: minus 53°C (-63°F).

One photograph included in this story shows a man with his face awash in snow. To Anosova, it speaks of how those in the village "are at once overwhelmed and at one with the elements." □

Like Madonna and Child (above), the photographer's cousin Valentina holds her youngest child, 10-month-old Varvara, as the baby plays with a fox fur. Dogs in the village (top right) have found cold comfort outside on a discarded couch. The villagers keep genealogical track of each dog; there's a waiting list for those expected to become strong hunters. The village doesn't lack freshwater, but an elderly hunter, Valery (bottom right), prefers to wash his face with snow each morning because the cold is considered a source of vitality.

FURTHER

A GLIMPSE OF WHAT'S NEW AND NEXT

REVVING UP CANCER FIGHTERS

By Erika Engelhaupt

Today's high-tech cancer killers are based on a century-old idea: turning the body's immune system against tumors. In 1891 a New York City surgeon named William Coley noticed that some cancers seemed to disappear after patients suffered an infection. Acting on a hunch, Coley injected bacteria into a patient with a deadly neck cancer, and the man's tumor began to shrink.

Now immunotherapy is the hottest field in cancer research. Scientists have learned that an infection can rev up the immune system, dispatching T cells that hunt and kill foreign invaders, including cancer cells.

Research is yielding new ways to boost such immune attacks, including drugs that strip cancer cells of the camouflage they use to hide from T cells. Some approaches take the brakes off the immune system, while others accelerate it or remove molecular and cellular roadblocks in its way, says Elfriede Noessner, a cancer researcher at Munich's German Research Center for Environmental Health. She has equipped T cells with an extra molecule that strengthens their response to cancer cells and is armed to trigger once it's inside tumors.

Though not all cancers respond to immunotherapy, researchers are beginning to untangle the genetics that make some tumors vulnerable to immune attack. Eventually, Noessner says, doctors will be able to target more types of cancer with combination treatments, including antibodies that remove immunological barriers. "I think they will be like bacon," she says. "Bacon is good on everything."

New kinds of cancer treatments help the immune system's T cells (pink) find and attack cancer cells (yellow).

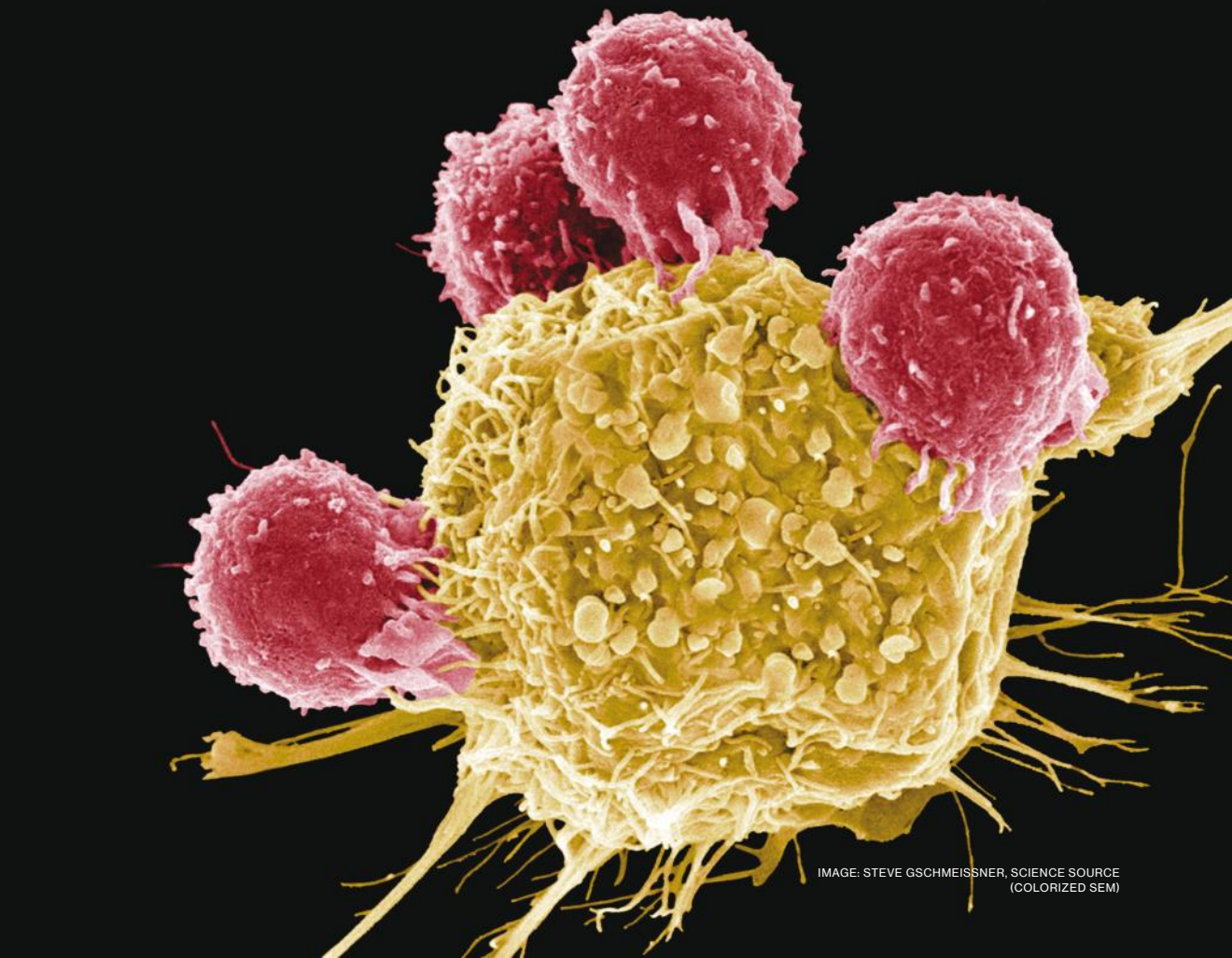


IMAGE: STEVE GSCHMEISSNER, SCIENCE SOURCE (COLORIZED SEM)

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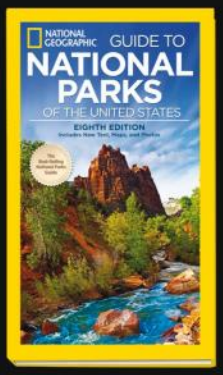

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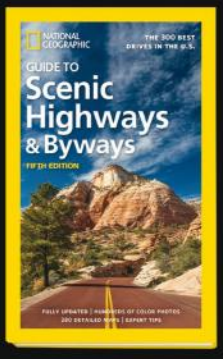

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