

# NAUTILUS

**MANTA RAY GAMES**  
Fiction by Richard Powers

**THE MATH OF FIREFLIES**  
Illuminating the synchrony of nature

**DO ANIMALS UNDERSTAND DEATH?**  
What the humans think



The Animal Issue  
MEET YOUR NEIGHBORS



ISSUE 61

Science Connected

NAUTILUS



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# The Animal Issue

BY KATHERINE HARMON COURAGE

**T**HERE EXISTS AN ORGANISM known as the *Trichoplax adhaerens*. You might find one on the side of an aquarium—if you could spot it. It'd be only about 25 microns thick. A collection of simple cells so undifferentiated, if you break it apart into tiny pieces, *Trichoplax* can reform itself. Its structure and locomotion can best be described as bloblike. Nevertheless, just like us, it is an animal. It moves and eats, and occasionally even reproduces with sex. The curious *Trichoplax*—what many have called the simplest living animal—is a reminder of the vastness of the kingdom we too inhabit, Animalia.

And just how much we still have to learn about it. There are threads we're only starting to see connecting species—and challenging our own understanding of what it means to be an animal, to be alive.

In this issue, contributing editor Brandon Keim interrogates the complexity of animals' inner lives by asking: Can some animals understand death? It's a difficult concept—one many of us still grapple with. But not long ago, in northern Bengal, elephant calves were found interred in irrigation ditches. Their feet pointed heavenward. Locals said they'd heard elephant trumpeting at night. Had there been a burial, a ritual? Elephants have complex social lives, they call each other by name and seem to have long emotional memories. So what might keep them from pondering and marking a death? For this article, Keim spent months deep in the literature and in conversation with scholars and animal behavior experts learning the contours of the shifting field of comparative thanatology—the study of animals' behavioral, cognitive, and social responses to death. The resulting meditation enriches our understanding of other animals' capacities, while challenging our own.

Other animals have been helping us more deeply understand the unexpectedly rough-hewn line between biological life and death, raising plenty of philosophical questions in the meantime. More than 300 years ago, the first amateur microbiologist, Antonie van Leeuwenhoek, had a bit of a shock looking at dried rotifers under his homemade microscope.

The rotifers—small aquatic animals, which he called “Animacules”—had been dried out and showed no signs of life. But placed back in water, they quickly reanimated, carrying upon their business of swimming around and eating as if nothing had happened. Their sort of liminal state is far beyond a hibernation. Rotifers, and now we know some other small animals, can persist in and revive from this desiccated state—even after years. Some, like van Leeuwenhoek's rotifers, come back in even better shape than they entered in, a sort of Dorian Gray of the pond, posits science writer Phil Jaekl, who takes us along this improbable journey.

These are some of the ideas we explore, with the help of our fellow animals, in this issue, which also includes fiction by Pulitzer Prize winner Richard Powers, a test of AI to help search-and-rescue dogs find their humans, how firefly synchronization is pushing forward fields of mathematics and physics, and more. Into the wilds of the kingdom!





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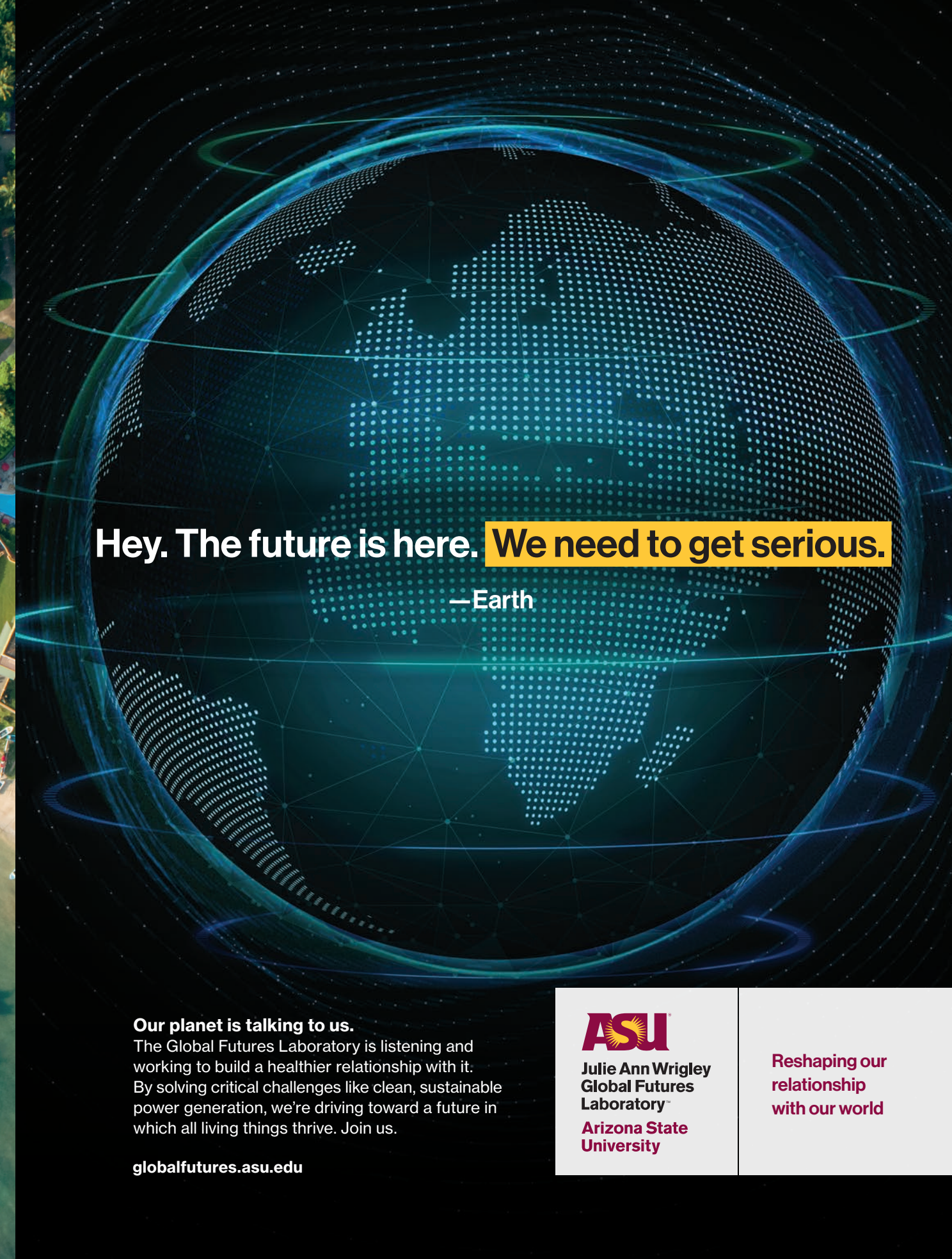
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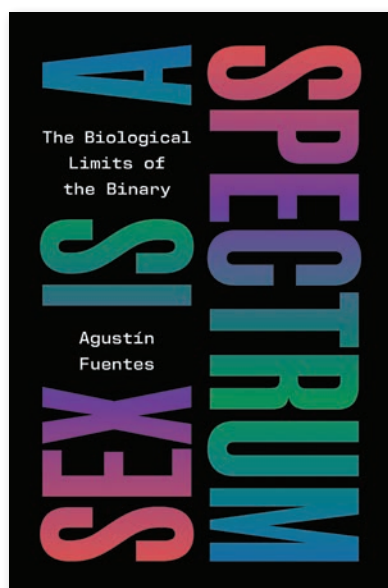
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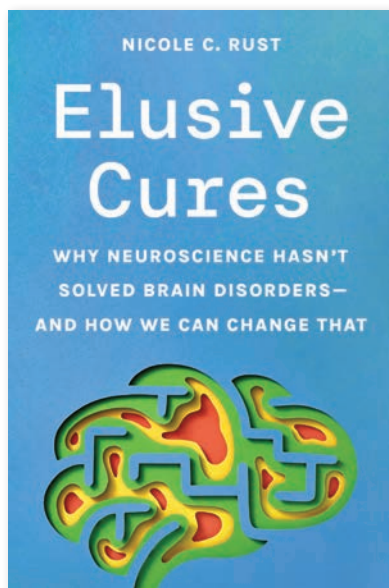




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# THE PORTHOLE

Short sharp looks at science

## EVOLUTION

### In Search of the First Animals

**N**EAR THE TOPS of some of the most remote peaks in the Canadian Rockies, well above the tree line, jagged limestone and shale rocks known as the Little Dal Group preserve the remains of 900-million-year-old reefs. Today the sun doesn't fully set over the fossil reefs on summer nights—they lie just south of the Arctic Circle. But millions of years ago, these reefs grew in a tropical sea not far from the equator. The movements of tectonic plates later transported them north, and then the plates collided to form these spectacular peaks.

Scientists have long believed the Little Dal reefs were built entirely by microbes—mats of cyanobacteria that grew upward into mounds. That's how reefs were built for almost 2 billion years, long before animals began to populate the planet. But in 2021, Laurentian University geologist Elizabeth Turner published a paper describing something unexpected she discovered while peering at Little Dal rocks through her microscope: small structures that could be the fossil remains of sponges, simple seafloor invertebrates that are thought to be among the first animals to evolve on Earth.

If Turner is correct, animals may have evolved some 300 million years earlier than we thought—before, instead of after, Snowball Earth, when the planet was repeatedly covered in ice, and possibly slush. Such a massive shift in timing could alter our understanding of the conditions necessary for complex animal life to evolve.

"Finding the first form of animal life is really important, because that gives us a timeline," says University



of Washington paleontologist Akshay Mehra. Based on Turner's discovery, Mehra and a team of other scientists traveled to the Little Dal region last summer for two weeks, to investigate whether the reef was in fact once home to simple sponges.

Precisely when sponges began to slink onto the scene was already a subject of much debate. Some fossil sponges have been identified in rocks in Iran and southern China that formed between 538 and 551 million years ago during the Ediacaran Period, a time when life diversified with many unusual soft-bodied forms that have since gone extinct. But scientists have also found fossils in older, 760-million-year-old rocks in Namibia that some believe may be sponges. Meanwhile, molecular clock calculations—which are based on rates of mutation in DNA and other biomolecules—point to a start date for the creatures of up to 800 million years ago. But without actual fossil evidence, molecular clock calculations are just estimates.





## Animals may have evolved some 300 million years earlier than we thought.

If sponges did evolve at this earlier date, then they not only weathered the wild climate swings of the Snowball Earth period. They also predated by hundreds of millions of years the so-called Cambrian Explosion—a time of rapid evolution starting 540 million years ago when many of the animal groups alive today arose, including the distant ancestors of snails, squids, worms, insects, spiders, and crabs. Like all animals, sponges develop multicellular bodies from a fertilized egg, but we still don't know exactly how life made this leap from simpler unicellular forms.

"It isn't crazy to think that animals may have a substantial pre-Ediacaran history as many, but not all, molecular clock estimates for animal antiquity suggest that the kingdom began to diversify 700 to 800 million years ago," says Harvard University paleontologist Andrew Knoll, who is not involved in the Little Dal research, in an email. Theoretically, sponges and other early animals could have survived Snowball Earth, says Knoll. After all, at least some bacteria and eukaryotes made it through the icy conditions, he says. But if sponges did arise 900 million years ago, then the molecular clock estimates for the oldest animals are off by at least 100 million years. He thinks it's "a stretch."

Mehra was joined at Little Dal last summer by Dartmouth College geologist Justin Strauss, Williams College micropaleontologist Phoebe Cohen, and five other collaborators. After months of planning and consultation with the local Sahtú Dene First Nations communities, helicopters shuttled them into a high alpine valley in late July where they set up camp. The fossil reefs towered about 2,000 feet above their cluster of colorful tents. To make sense of the reefs at a large scale, they flew drones up and around the outcrops, taking photos that would later be digitally stitched together to create a model.

Each day after breakfast, the scientists hiked up through short scrubby pine trees, sometimes following paths forged by wild sheep. They climbed above the tree line to the ancient reefs, toting rock hammers, sample bags, and backpacks that were heavy with rock

samples by the end of the day. "Everything you want to collect, you're carrying on your back," says Strauss. "We would divvy up the rocks as equitably as possible, sometimes according to whose knees hurt the most," says Cohen. In total, they collected about 400 pounds of rocks, enough to fill nine five-gallon buckets.

Over the next few years, Mehra, Cohen, Strauss, their students, and collaborators will analyze the rocks and fossils. They will use isotope analyses to determine the age of the rocks and investigate single-celled fossils under microscopes. The fossils in question were not made of mineral, and so cannot be dug out of the rocks, but are instead preserved as microscopic impressions. To analyze these impressions, Mehra will use a machine that grinds a few microns off a rock, take a photo of the surface, and then repeat the process again and again until the rock and ancient fossils are reduced entirely to dust. Mehra and his collaborators will then use the photos to create digital 3-D models of the fossils, which they will scour for the patterns of canals and chambers typical of sponges.

"If these are true mixed microbial-animal reef systems, it's a really interesting ecology to be studying, especially if these are the first ones," says Strauss. (Today, reefs are often built by coral invertebrates, in collaboration with algae and other microorganisms.) But even if the fossils they collected are not ultimately sponges, Cohen believes the Little Dal reefs could have set the stage for the evolution of animals. By 900 million years ago, life on Earth was becoming more complex—with a diversity of bacteria and eukaryotes, organisms whose cells have a nucleus inside a membrane. Many questions remain about how ecosystems populated only by microbes became hospitable to other forms of life, such as eukaryotes, she says. If the fossils are not, in fact, sponges, they could still offer some clues to the evolution of complex life. Says Cohen, "In some ways, it's almost more interesting if they were not made by animals."

—Lisa S. Gardiner

## ZOOLOGY

# Birds of a Feather Talk Together

**M**IGRATORY SONGBIRDS MAY TALK to one another more than we thought as they wing through the night. Each fall, hundreds of millions of birds from dozens of species co-migrate, some of them making dangerous journeys across continents. Come spring, they return home.

Scientists have long believed that these songbirds rely on instinct and experience alone to make the trek. But new research from a team of ornithologists at the University of Illinois suggests they may help one another out—even across species—through their nocturnal calls.

“They broadcast vocal pings into the sky, potentially sharing information about who they are and what lies ahead,” says ornithologist Benjamin Van Doren of the University of Illinois, Urbana-Champaign and a co-author of the study, published in *Current Biology*.

Using ground-based microphones across 26 sites in eastern North America, Van Doren and his team recorded over 18,300 hours of nocturnal flight calls from 27 different species of birds—brief, high-pitched vocalizations that some warblers, thrushes, and sparrows emit while flying. To process the enormous dataset of calls, they used machine-learning tools, including a customized version of Merlin, the Cornell Lab of Ornithology’s bird-call identification app.

The analysis revealed that birds of different species were flying in close proximity and calling to one another in repeated patterns that suggested a kind of code. Flight proximity was closest between migrating songbirds species that made similar calls in pitch and rhythm, traveled at similar speeds, and had similar wing shapes.

While the exact nature of their communication remains unclear, researchers speculate that the calls could relay details about landing sites, weather conditions, or individual traits like age or sex. Staying connected in this way might help the birds navigate more safely and effectively during the high-risk migration period to overcome challenges such as foggy conditions, inclement weather, or predator-rich landscapes.

“The function of these calls is still not quite fully understood,” Van Doren says. He does not deny that



instinct plays an important role in navigation, he says. “But it seems that’s not the whole picture. Our work suggests that songbirds may also use social connections with other species during migration.”

Sharing migratory intelligence may be especially important for younger songbirds, who are just getting the hang of migration, says Van Doren. “Many of the birds migrating in the fall are juveniles,” he says, “and are navigating this dangerous journey for the first time.”

Van Doren and his team are eager to use machine learning and audio sensors to learn more about what specific kind of information birds are sharing. “We’d love to follow individual birds through their journeys using wearable microphones. That would help us disentangle the functions of these vocalizations and social connections,” he says.

“This paper is very exciting, and a huge feat,” says Tessa Alise Rhinehart, a biologist at the University of Pittsburgh who was not involved in the study and who specializes in using artificial intelligence to identify and interpret animal vocalizations. “Nocturnal flight calls are somewhat of an enigma to biologists and bird enthusiasts because they’re so difficult to study,” she continues. Just observing free-flying animals at night is a formidable challenge, she says, nevermind collecting data and running experiments.

“This is a careful, quantitative demonstration of that old saying,” says Dan Mennill, another biologist who studies migratory songbirds and was not involved with the study: “Birds of a feather flock together.” Especially when they are on the move.

—Avery Schuyler Nunn





## ENVIRONMENT

## Sea Slug, Climate Change Warrior

**S** **COURING FOR SEA SLUGS** by combing through long seagrass blades is not easy, according to Richelle Tanner, a marine ecologist at Chapman University in Orange, California. She has to blindly but carefully run her hands along the entire plant, pressing lightly, to pick out the species she studies, Taylor's sea hare (*Phyllaplysia taylori*). "You're at the mercy of whether you can feel a tiny little lump in the grass," says Tanner.

The sea slugs, also called sea hares because of bunny-ear-like protrusions on their heads, blend into the seagrass they live on because of how they look—like little blobs of translucent green with white stripes.

But the camouflaged invertebrates are immensely important for seagrass survival. Warming waters and nutrient runoff can spur algae to overgrow and suffocate seagrasses. But the sea hares traverse plant leaves dining on these harmful algae. "The sea hare is my favorite animal, because they are like these little lawn mowers—they eat all the algae that are growing on seagrass, keeping it clean and allowing it to photosynthesize," says Brent Hughes, a marine ecologist at Sonoma State University.

And now, Tanner and her collaborators have found that the Taylor's sea hare may be able to withstand climate change, at least to a point.

In a recent study published in *Ecosphere*, Tanner and her colleagues discovered that the sea hares are remarkably resilient to changes in temperature, capable of tolerating maximum temperatures varying from 75 to 95 degrees Fahrenheit. Surface water temperatures off the Pacific Coast of the United States average around 52 to 57 degrees Fahrenheit, but climate models predict that ocean water temperatures will increase by about 2 to 5.8 degrees Fahrenheit by 2100.

The researchers also found that none of the 11 different Taylor's sea hare populations they sampled along the western U.S. coast were genetically distinct. Sea hares from near Washington State in the north to Morro Bay in central California all showed high levels of genetic diversity and seemed to be part of one big, well-mixed population. Both their ability to tolerate high temperatures and their inherent genetic diversity could make them key allies in seagrass restoration efforts, especially as ocean waters continue to warm.

RICHELLE TANNER

Human activities and climate change are shrinking once-lush seagrass meadows across the globe.

Seagrasses—tall, swaying, grass-like aquatic plants—are crucial marine environments. They store coastal carbon, provide a home for various sea creatures, reduce ocean acidification, and protect shorelines from destructive waves. Human activities and climate change are shrinking once-lush seagrass meadows across the globe, with algal overgrowth being one reason for the losses. Given their role in protecting seagrass from being overrun by algal blooms, Tanner says she wanted to see how a changing climate could potentially affect sea hares and their unique relationship with eelgrass—a type of seagrass.

To test the sea hares' tolerance to higher temperatures, Tanner and her team first exposed individuals from the 11 populations to three different temperatures in the lab—55 degrees Fahrenheit, 63 degrees Fahrenheit, and 70 degrees Fahrenheit—for two to three weeks. Animals held at higher temperatures were more capable of tolerating high temperature shocks, up to 95 degrees Fahrenheit.

But the temperatures of the waters they grew up in—their habitat temperatures—seemed to have no effect on the sea hares' ability to tolerate high temperatures shocks. Neither the location of their population off the U.S. West Coast nor their underlying genes seemed to affect the maximum temperatures they could tolerate in the lab. This means that the sea hares' brief laboratory conditioning was more important than adaptations they accrued over generations to modulating their impressive temperature tolerance.

"An animal could evolve to have responses up to a certain temperature, because that's the highest temperature they've ever seen in the last 100 generations," Tanner says. "This animal does not have that. We did not find an evolutionary basis for how it sets the highest temperature that it can withstand and maintain its function." Tanner suggests that the sea slugs have some sort of thermal tolerance plasticity, drawing a comparison to how humans acclimatize, to a lesser extent, to different seasons.

"During the winter you get a little bit more used to it being cold, and you might not have to wear as many sweaters as you would if you experienced that same cold temperature during the summer," Tanner explains. "If we acclimate [the sea hares] to different temperatures, they can raise the maximum temperature that they can withstand."

The high genetic diversity among the geographically distinct sea slug populations was also unexpected. Unlike many other marine invertebrates, these sea hares don't have a larval stage that can swim freely out into the ocean and intermingle with individuals from different populations. "A lot of my work has been looking at how organisms, at the physiological level, deal with the stress of a world that is changing. But it was really immediately the genetics that surprised me," says Scott Applebaum, a developmental physiologist at University of Southern California. "These things are supposed to just disperse a fairly short distance, but the mix of genetics up and down the coast says that there's a lot more exchange than we anticipated."

Tanner's hypothesis is that Taylor's sea hares hitch a ride on the seagrasses themselves, doing something called "rafting." Sometimes seagrasses can get physically uprooted because of storms or other disturbances, and they can travel with the ocean currents from one bay into another. The sea hares may go along for the ride and mate with individuals from distant populations in this way.

Hughes believes that learning how much heat the sea hares can withstand is an important step in managing seagrass ecosystems coping with a changing climate. "Moving forward, when doing restoration, we should consider how hot these organisms can get right before they die," says Hughes. "Because if the area gets too hot, then maybe it's not a good idea to plant seagrass [there]. If the organisms, not just the seagrass, can't tolerate those conditions."

—Rohini Subrahmanyam





## GENETICS

## Icelandic Horses Have Good Genes

**A** **SMALL DUSKY BROWN HORSE** high-steps through the snow. A dusting of powder accents his coat like sifted sugar. I crouch in the saddle in a thick snowsuit, gathering the reins as we trek into a blinding white wilderness about 30 minutes outside of Iceland's capital city Reykjavík. Though the temperature dips into the 20s Fahrenheit, he has broken a sweat from the ride.

The horse's name is Fjalar and he was born and raised to survive the seasons in Iceland. This land of fire and ice has shaped his genetics over 1,100 years. He stands just under 14 hands tall at his shoulders, at 55 inches. His fur is thick enough to obscure my fingers when I press my hand to his side. He can easily stomach grasses and hay poor in nutrients.

Fjalar also can do something most other horses in the world cannot. In addition to a traditional walk, trot, canter, and gallop, Fjalar can tölt and he can perform a flying pace, or skeið—two gaits unique to Icelandic horses.

Equestrians talk about gaits in rhythmic terms. A tölt is a four-beat movement in which the horse always has one foot on the ground in a specific sequence. A pace has two beats, in which the horse moves the front and back leg on one side simultaneously. During one phase, all four feet are off the ground. Pacing horses can reach up to 30 miles per hour. Both gaits can make it look as though the horse were ice skating, carrying a rider seamlessly across a plain, and some Icelanders race while carrying full beer steins.

In a recently defended dissertation, researcher Heiðrún Sigurðardóttir was able to identify for the first time two genes Icelandic horses have that affect these gaits, in addition to the one that had previously been identified, which could help shape future breeding decisions. Her genetic analyses also showed that centuries of inbreeding on the island have not harmed the genetic diversity in the breed and so continue to be sustainable.



The two new genes Sigurðardóttir identified that play a role in an Icelandic horse's special gaits are expressed in neural tissue: the *STAU2* gene, which was also shown to influence the quality of a horse's trotting and galloping, and the *RELN* gene, which impacts the quality of tölt, trot, canter, and gallop, and may influence the trainability and precocity of young horses. In addition, Sigurðardóttir showed that these two genes together with a previously identified *DMRT3* "gait keeper" mutation have additive and compensatory effects on an Icelandic horse's ability to pace. Previous research has shown that when Icelandic horses do not have a specific *DMRT3* mutation, these horses are unable to "pace," and she found this was so even when the horses had the other two genetic markers linked to strong pacing abilities.

"These are highly complex traits that we are looking at, which makes them interesting, but difficult," she says. "It's like looking for a needle in a haystack."

To identify the genes, Sigurðardóttir pulled pedigree data from Iceland's studbook, developed in 1923, which describes the lineages, gaits, and other characteristics



**GAIT KEEPER** Fjalar and the author on a ride.

Both gaits can make it look as though the horse were ice skating.

The only reliable forms of transportation on land were the horses brought by Norse and other settlers—including Mongolian and Norwegian Fjords, both stocky and hardy breeds.

After noticing certain horses moving in ways that made traveling smoother, they took the foals and started breeding for what became the pace and the tölt. Though other breeds in the world—such as the Paso Fino and Tennessee Walking Horse—are smooth movers, they cannot perform the tölt and some claim their pacing gaits are less graceful or quick than that of the Icelandic horse.

Since those early days, Icelandic horses have not incorporated new breeds into their lineage. Foreign horses are not allowed into Iceland, and once an Icelandic horse leaves the nation, they are not allowed to return. Icelandic horses are not vaccinated because of their isolation.

Fjalar seems to know he belongs to a special breed. He passes one horse, then another to take the lead. Snow flies from his hooves as he moves out across the snowy avenue. But he stays with his herd. It's easier to keep warm in a group, to break through the snow, to keep his bearings in this stunning monochromatic landscape where his ancestors once roamed.

—CD Davidson-Hiers

of individual Icelandic horses, and an international WorldFengur database that began tracking more than 560,000 individual Icelandic horses, dead and alive, in 2000. She then pulled hair and blood samples from individual living horses, applying genome wide association study analysis to genetic data and pace and gait “scores” of 380 of them and whole genome sequence analysis and pace and gait scores to 39 horses.

Early people in Iceland needed horses that could run for miles without tiring. More than 1,000 years ago, the newly discovered land was rugged and unforgiving, a world of volcanoes, rushing rivers, and winter storms with wind gusts that could knock over a grown adult.



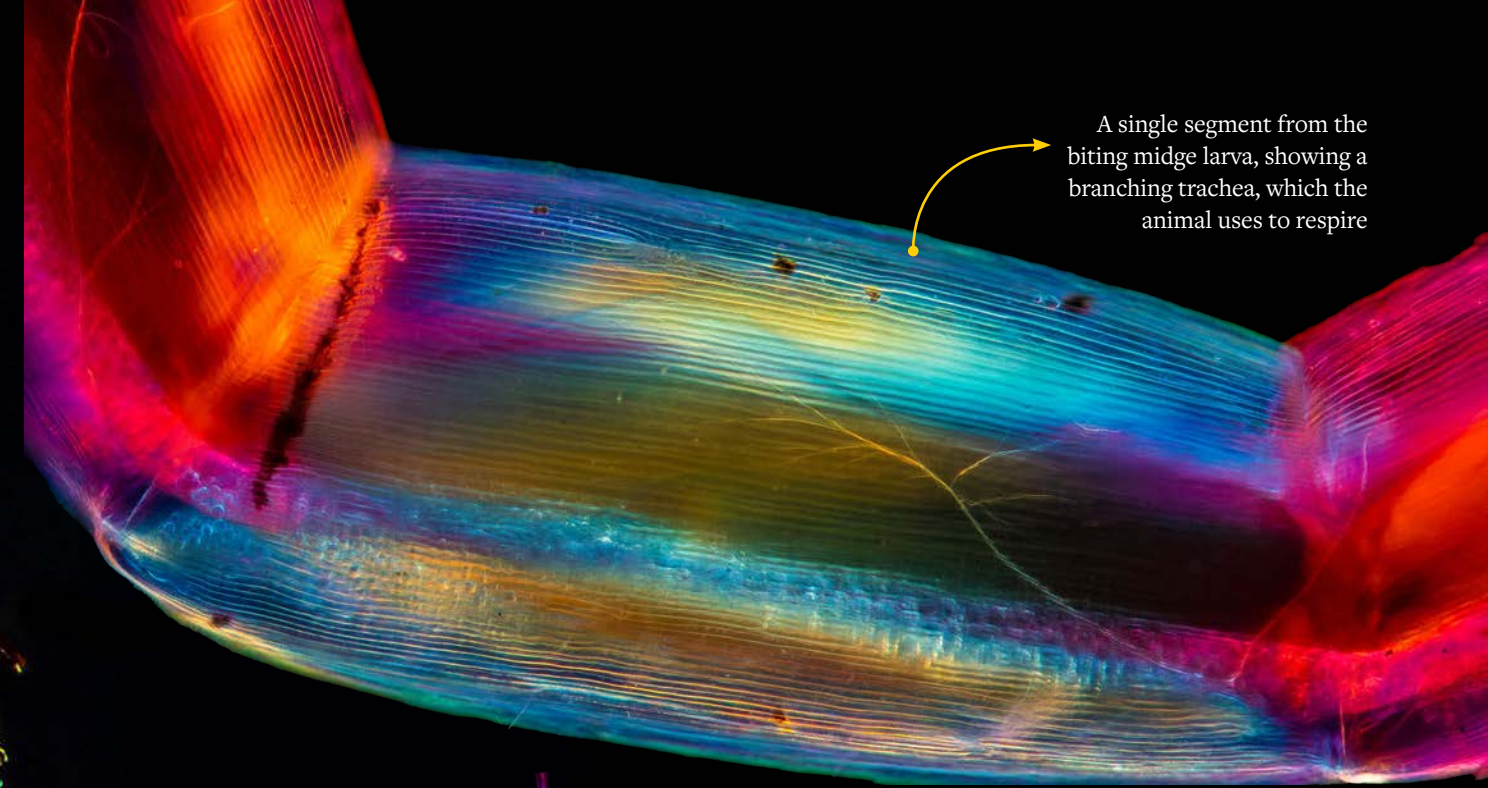


The larva of an insect from family Chironomidae, which are commonly called nonbiting midges, lake flies, or chironomids

A member of superorder Cladocera, which comprises several species of water flea, mostly freshwater crustaceans

A biting midge larva





A single segment from the biting midge larva, showing a branching trachea, which the animal uses to respire



Chironomid larva photographed with combined darkfield and Rheinberg illumination

#### MICROBIOLOGY

## Micro Kaleidoscope

**M**OSAIC-LIKE CHEMICAL CRYSTALS and microscopic worlds in a pond—Canadian nature photographer Robert Berdan captures life at its smallest in rainbows of color. These images record the animal life from puddles, ponds, and small lakes around Calgary, where Berdan lives and works. By using polarized light microscopy and Rheinberg lighting, a form of optical staining, the photographer renders muscles in astounding, colorful detail and highlights finer features, such as the branching trachea that insects use to breathe.

—Bob Grant

*Photos by Robert Berdan*



We  
make  
green  
sexy.

Imagine  
**5**





# We're All Wild Things

BY KATHERINE HARMON COURAGE

**D**O YOU REMEMBER the first time, as a kid, you stood beneath a looming dinosaur skeleton at a museum? The moment of awe, maybe a tingle of fear. Of realizing that you could have—but for a gap of 65 million years or so—been lunch. Or at least just another mammal squashed underfoot.

It's a weird thing, still, to be reminded that we're just another animal. *Nautilus* editor at large Kevin Berger was thinking about this. So he called renowned primatologist and neuroscientist Robert Sapolsky at Stanford University and asked him. "What does it mean to see ourselves as animals?"

Maybe it's a needed dose of humility. It's also a reminder, Sapolsky said, that we have so much running through us that's essentially the same as what runs through animals we might not fancy we have much in common with. Like the sea slug. "The biochemical pathway that a sea slug uses when it's learning condition-avoidance is the same one that we use in the hippocampus," Sapolsky said. "We use the same hormone, oxytocin ... that a narwhal mother would use." In short: "Evolution is amazing."

The further we go down, into DNA, the less we find that separates us. Some central genetic differences between us and chimpanzees seem to have more to do with how much hair we grow on our shoulders than those responsible for throwing signals in our newfangled brains. And as research out of neuroscientist Kenneth S. Kosik's lab, at the University of California, Santa Barbara, has suggested, the blueprints for our brains might well have started in some of the earliest simple animals anyway, sea sponges.

But we needn't always get down to neurons and base pairs and biochemicals to be reminded of our animalness. Sometimes it's as simple as a 4-year-old *Homo sapiens* standing in quiet stillness, mouth agape, gazing up at the towering Barosaurus and Allosaurus in the foyer of the American Museum of Natural History, momentarily unaware of the buzz of other humanity around them. Many of us have been this child (including Mick Ellison, now a senior artist in paleontology at this very museum, who tells us about his craft later in this issue). And now I get to watch my own children in that moment. Such points connect us not just to these other—sometimes seemingly unknowable—animals, but also to each other. Because if there's another thing we all have running through our DNA, it's that thread of wanting to know. 🌀

ILLUSTRATION BY MATHIAS BALL



# We Could Have Been Warthogs

*The peerless animal wisdom of Robert Sapolsky*

BY KEVIN BERGER









**LIKE NATURE SHOWS AS MUCH** as anyone. Who doesn't love watching the magnificent animals on our planet? But these shows seldom turn their cameras on the most dominant animal on Earth.

It's a pretty progressive attitude to see ourselves as just another animal crisscrossing the lands and seas. For centuries Western culture assigned humans to First Class, the rest of the animals to steerage. But we evolved like every other animal from a common microbial ancestor way, way back in the day. And like every other animal, the sands of time carved us into the creatures we are today. So, I've been wondering, what does it mean to see ourselves as animals? Does it change how we treat other life on Earth? How are we like our fellow animals? What makes us different?

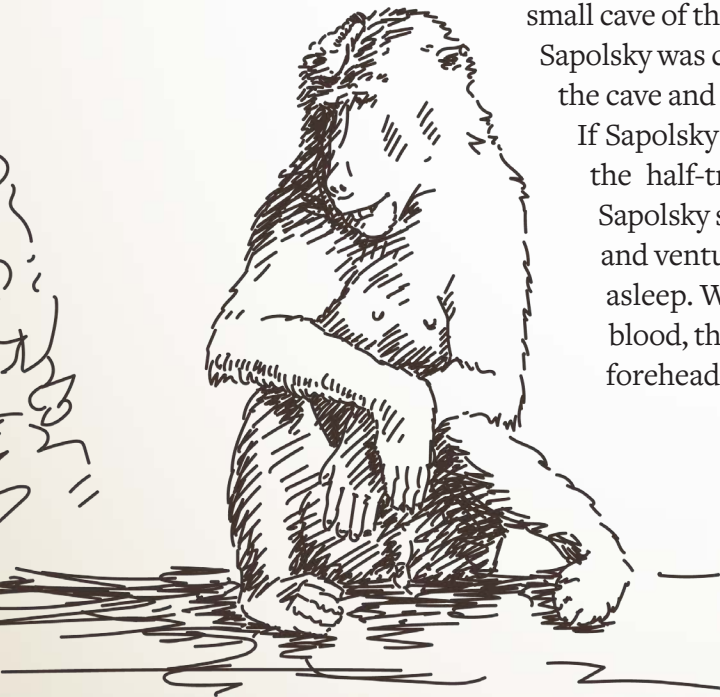
I didn't think twice about who I wanted to ask. I've probably learned more about humans as animals from Robert Sapolsky than any other scientist. And that's because the primatologist and neuroscientist, renowned Stanford University professor and lecturer, writes with a sense of humor that seals the science in your memory. In our recent conversation, I told Sapolsky about a scene I couldn't forget in his book, *A Primate's Memoir*, about the beginning of his career on the Serengeti, hanging out with baboons.

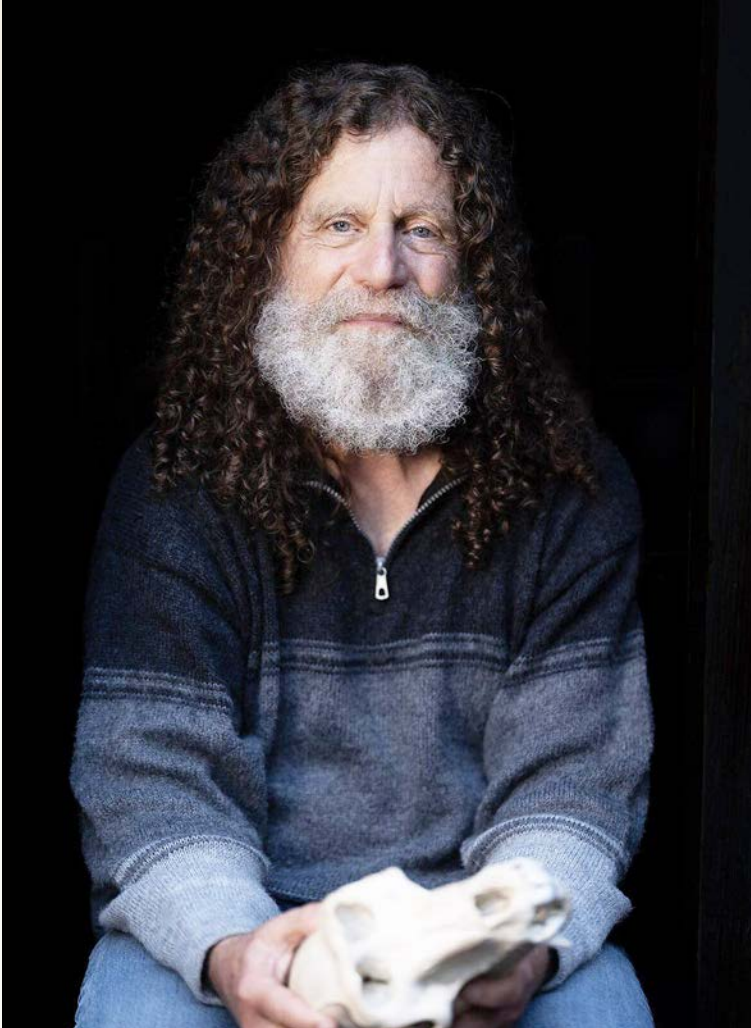
Sapolsky darted baboons with a tranquilizer so he could analyze their blood. He was keen on measuring the stress markers in their blood, particularly in the baboons who ranked low in their troop hierarchy, whose stress levels were off the charts, ravaging

their health. One day Sapolsky darted a baboon who ran into a small cave of thorn bushes with a small impala in its mouth.

Sapolsky was certain other baboons would soon cram into the cave and rip apart their drugged mate for the impala.

If Sapolsky went into the cave to get his blood sample the half-tranquilized baboon would rip him apart. Sapolsky scared away the other baboons by screaming and ventured into the thorny cave to find the baboon asleep. When he rolled the baboon aside to draw his blood, the impala sprang to life and kicked him in the forehead, opening a big gash.





COURTESY OF CHRISTINE JOHNSTON

“Here I am, figuring out a way to avoid all this craziness with these mad aggressive male baboons and I’m about to be killed by Bambi,” Sapolsky wrote.

Sapolsky smiled darkly when I reminded him, perhaps remembering when he almost bought the farm before his career took off. “Oh, god, that was ironic, wasn’t it?” he said dryly.

Thankfully Sapolsky continued to study baboons for the next three decades and write books that continue to light up the minds of readers. His studies of stress form the basis of one of his most influential books, *Why Zebras Don’t Get Ulcers*, whose takeaway is humans are killing themselves with stress, not from outrunning predators but worrying about imagined problems.

Sapolsky set the science world chattering with his conviction that humans don’t have free will in his most recent book, *Determined*. With his characteristic mix of neuroscience and examples of animal and people behavior from cultures around the world, Sapolsky

**BORN TO BE WILD** When he was a kid, Robert Sapolsky wanted to live inside the African dioramas at the Museum of Natural History in New York.

explains why “the biology over which you had no control, interacting with the environment over which you had no control, made you you.”

Sapolsky has written a host of articles for *Nature*, and I’ve been his editor. We had a great time recently talking about what makes us the animals we are, and as ever, Sapolsky took my questions into unpredictable directions, displaying his natural gift for perspicacity and humor.

**Let me get a little David Attenborough on us. Earth is home to such an amazing range of animals. What do you think about when you consider the panorama of animals on our planet?**

Besides being spectacular, it’s a pretty good indication that this Darwin guy was right. You want to grab a Creationist by the ear and say, “You’re going to tell me that every one of the lemurs got off Noah’s ark and happened to swim to Madagascar and leave no fossils along the way?”

**Do you remember when you first arrived on the Serengeti to study baboons?**

You always wish you could have that first day again. It was exhausting how hard you were looking at things, and listening to things, because everything was so sensorially vivid.

**In all your years of studying baboons in the wild, did you ever think about what the baboons could teach us about ourselves?**

Well, they could teach us that hierarchy exacts a toll on everyone, especially the ones stuck on the bottom. But their goals are not the same as ours. And their ability to effectively act out their goals is certainly



## *Humans are generalists. We're half-assed at an enormous number of things.*

not like ours. That's usually because they have no prefrontal cortex. Every time it would make sense to do something strategically, they invariably blow it by being impulsive.

And baboons don't do object-permanence. If the baboons are getting all crazed and agitated and threatening you because you just darted somebody, you cover the darted baboon with a burlap sack. Then he's gone, not there anymore to the other baboons. They instantly settle down.

So, yeah, early on, it was apparent we're not baboons, we're not chimps, we're not bonobos. But the ways in which we turned out to be different were subject to the same rules by which they turned out to be who they are.

**Which reminds us we are animals ourselves. Baboon, human, iguana, cricket—we're all shaped by evolution in our own ways, none more important than the other. Although, when I say that, I do wonder whether we really believe it.**

The pull of exceptionalism is pretty strong. But we are exceptional in one way: We're the only species who could say, "Be distrustful of intuitive exceptionalism."

### **Good point!**

But, yeah, it does take some detachment. It takes someone like Peter Singer building a whole movement around the fact that animals have emotions, too. But there's absolutely no clear-cut rules as to where a line should be drawn. We really don't think, and I assume Peter Singer doesn't think so either, that a fly has the same moral rights to have its needs considered as a human does. There's a line somewhere, but how the hell do you figure out the line? Subjectivity is pretty major at that point. We're just like other animals until we reach some critical realm where we're not just like them. And that seems to be a meaningful dichotomy.

### **Do you think there's a moral or social good of thinking of ourselves as just another animal?**

Insofar as we should be suspicious of framing anything as a moral good, treating other living organisms better is, yes, a good thing. The most fascinating aspect is the historical trend that shows when a society starts having animal protection laws, that's a good predictor that they're not far away from having laws that say you can't have 5-year-olds work themselves to death at textile factories. Logically, that should have been in the other direction. But prevention-of-cruelty animal organizations have been a good predictor that protection for other humans is going to expand as well.

### **Alas, we became the animal who dominates all the others. We've altered every animal ecosystem on the planet.**

And that could be a karma thing. It turns out that being a bacteria or virus can make you more adapted to life than humans. They've come up with evolutionary tricks that we don't have. They can evade our immune system. Just when you get antibodies that are going to recognize them, they switch their surface protein so they're invisible again. They're more adapted for doing us in than we're adapted for inventing antibiotics. Which is a great irony. For all the ways in which we evolved to have lots of neurons and be capable of creating all these incredible and destructive things, it turns out, oh, my god, it's a single-cell organism that eradicates us.

### **What do you think of E.O. Wilson's idea of "biophilia," that we have an inborn affinity for other forms of life?**

I think it's fair to say that there's something damaged about a person who sees a giraffe in front of them for the first time and doesn't feel compelled to stare at this thing for, like, forever. But we dole out empathy very unequally. There's a reason why pandas are much more likely to not go extinct than some disgusting lamprey.

I like mammals. Some reptiles don't do much for me. But there's people out there who obviously love their gigantic snake and give over half their apartment to keep it safe.

**Do you think biophilia is innate?**

I think it's innate in the ethological sense of prepared learning. We are not innately phobic about spiders or snakes. But it sure is easier to condition someone to be afraid of a snake than to a Basset Hound. It's easier for us to decide that mountains are more beautiful than public-housing projects. So, it's innate in that we have a lower mental threshold for making some associations. We have a lower threshold for deciding sunsets are amazing and parking meters are not.

**It's affecting to know we and other animals are made of the same biochemical stuff, don't you think?**

Absolutely. But it speaks to this weird, convenient thing that both sides of animal-rights debates do. If you're PETA, one of your strategic tools is to say that animals' physiology is different from ours and we can't learn from a lab rat or monkey. There's no continuity between us and animals. Look at what happened with things like thalidomide that appeared to be safe in animal studies and then wasn't for humans.

On the other hand, there is utter continuity with animals in the capacity for pain and emotional upset, to be frightened and lonely. But for the scientists who are indifferent to animal suffering, their argument is that there is complete continuity between us and animals, while there's no continuum for emotions or capacity for suffering. Each side is conveniently choosing which piece of the similarity argument they accept and which they don't.

**As you were saying about baboons and humans, we're different, but in light of evolution we originated from a similar blueprint.**

Right. And we're totally different in ways that are unprecedented. We get upset about what happens to characters in a movie. We do the same for

**GENES DON'T  
MAKE THE PERSON**

A species of lungfish has the same number of genes (20,000) we have.





# It's easier to condition someone to be afraid of a snake than a Basset Hound.

humans on the other side of the planet we're never going to see. But we use the same hormone, oxytocin, when we are feeling protective of those characters that a narwhal mother would use for its baby.

I mean, the biochemical pathway that a sea slug uses when it's learning condition-avoidance is the same one that we use in the hippocampus. You could trade out the genes that code for the avoidance pathway and they work the exact same in the sea slug and us. You could take human genes for programmed cell death and stick them in bacteria and the bacteria would die exactly the way they're supposed to.

So, Whoa! Evolution is amazing. Or, maybe, there for the grace of god, I could have wound up being a warthog.

**Very true! But knowing we share a blueprint with warthogs can maybe inspire compassion for them and other life on our planet.**

Humility, too. If you're like Ed Yong and delve into that literature, you learn, damn, there's a lot of organisms out there that run circles around us in very specialized ways. As animals, we're generalists. We're half-assed at an enormous number of things. But, oh, my god, some animals see in ultraviolet light. Mantis shrimp can punch out the glass on a fish tank or break your nose because of their musculature. Some animals see in 17 different wavelengths. Some humility has to

come out of that. And maybe that affective continuity can take us to feeling an imperative as to who should be protected from pain.

**I read recently about a species of lungfish in South America that has 30 times the amount of DNA that we do, and about the same number of genes (20,000), and, well, I know this might not come as a surprise to you, Robert, but we are nothing like lungfish. So, really, when it comes to being human, what do genes have to do with it?**

Not much. To appreciate that, unpack the cliché that we and chimps have 98.5 percent of the same DNA. And take that one step further and say, OK, where are the gene differences between us and chimps? Half of the genetic differences are about genes for olfactory receptors. In our evolution, we've turned them off and chimps still have them active. They have a better sense of smell than we do. The remaining half of different genes have to do with whether you grow hair on your shoulders, where you wind up being furry. But there's next-to-no brain genes that differ.

**Some human genes for cognition do differ from other primates, though, right?**

Right, but look at the ones that are different. They tend to be related to cell-cycle differences, how many rounds of division cells go through. What that tells



**WHAT A TROOP** Robert Sapolsky studied the fascinating ways of baboons in the wild for more than 30 years.

you is if you want to turn a chimp into a human, just let its brain go through two or three more rounds of cell division when it's making neurons, and it will invent theology, aesthetics, and social political theory. With enough quantity, you get quality. With a cell-cycle division that goes through enough rounds, you get enough neurons to do human stuff instead of regular old ape stuff.

In one of your *Nautilus* articles, “Metaphors Are Us,” you write that one trait that makes us uniquely human is we’re not very good at distinguishing between the metaphorical and the literal. Symbols and metaphors are “the product of clunky processes in our brains.” I

**love that. What makes us unique is a bunch of clunky brain processes.**

Evolution is not an inventor, it's a tinkerer. In the last couple years, a great example of the brain being clunky is Ozempic. Everybody on Earth is taking Ozempic to lose weight because, among other things, it makes you feel full. Satiated in terms of food. That's great. And we understand exactly what Ozempic is doing in the hypothalamus.

But it also makes compulsive gamblers less compulsive. It's being pioneered for treatments for substance abusers. You might say the comparison between an appetite for food and appetite for gambling is just a stupid metaphor. But our brain falls for it. Being hungry for



a big gambling payoff has some biological similarities to being hungry for high-fat, high-carb things when you're stressed. This drug turns out to be able to tap into all of that because that's the clunky way our brains work.

**One metaphor that seems woven into our brains regardless of our culture is blaming some cruel or violent act on our “animal nature.”**

Or flip it another way. Yes, we're the most violent species on the planet. But it's our animal nature that also makes us compassionate, altruistic, and cooperative. Not only that, but the same individual is capable of both extremes. Whether a behavior counts as extreme is in the eye of the beholder and culture. Someone commits a violent act, and half the people say they're a terrorist and the other half say they're a freedom fighter. That comes from the same building blocks in other animals. A baboon mother can be very altruistic to her kid and protect it if there's a lion around. At the same time, she could be a total jerk to the female who's lower ranking than her.

**It's nice to hear that being compassionate and cooperative is also ingrained in our nature.**

Do you know the studies by Peggy Mason and others at the University of Chicago? They've shown that rats

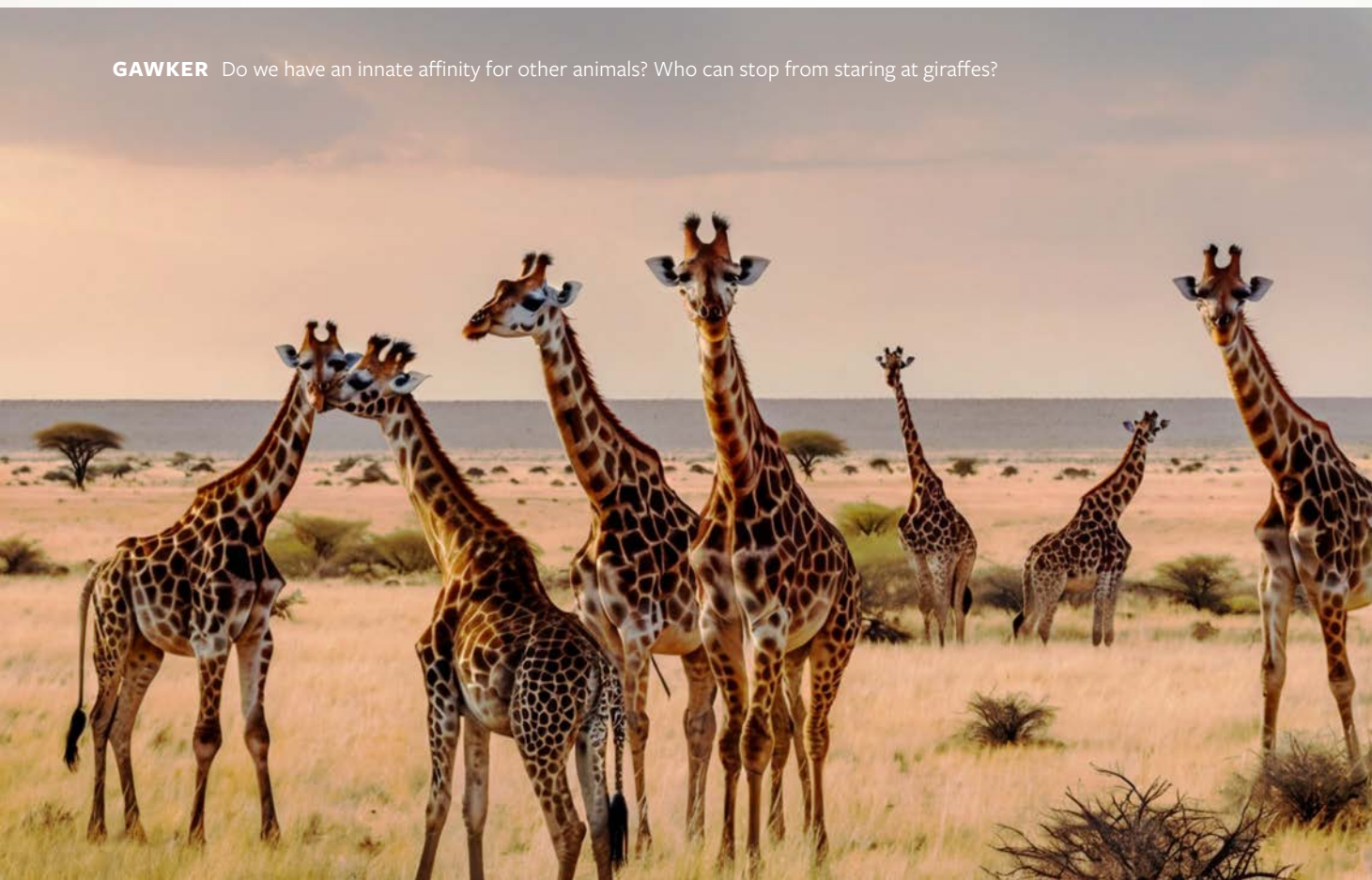
will press a lever to free their fellow rat from being restrained in a chamber. The trapped rat is emitting like stress vocalizations and stress pheromones. When given a choice to eat the greatest thing on Earth for a rat, a little piece of chocolate, or free the other rat, the rat presses the lever to free the other rat. That's amazing!

But then you look closely and the choice comes with the same fine print as it does with us. The trapped rat has got to be a rat it knows. It's got to be a rat that is a cage mate or who is of the same inbred strain so that they smell like a relative. And if it's some stranger rat, screw them, I'll take the chocolate. So, the capacity for empathy comes with all sorts of loopholes.

**Oh, boy, that does sound like humans.**

Let's say you suddenly find yourself in the middle of Zambia, and you run into a bunch of Americans, and you get to talk about football. Even if you hate football, you think, damn, that's grounds for feeling I'd give my life up for them. Organisms like organisms who are familiar to them. Faced with ones who are different, your first reflex is one of vigilance, not pro-social behavior. Oh my god, what an embarrassing thing to admit: You're a liberal and love diversity and all of

**GAWKER** Do we have an innate affinity for other animals? Who can stop from staring at giraffes?



# When it comes to being human, what do genes have to do with it?

that, but wow, it's kind of nice to go to a restaurant that serves food like my grandmother made. These are basic animal things.

## How do you define humanity?

Hmmm. We're the species with some of its most interesting behaviors occurring only in groups. Individuals are capable of being much better than their usual selves and much worse than their usual selves when they're in groups. Groups amplify emotional volumes. Large groups. Intellectually abstract groups. You will give your life up for a co-religionist from the other side of the planet if you have the right inculcation. Weird stuff happens when we come together in groups.

**Humanity to me means all the good things about being human: humility, compassion, having a conscience, being curious. But it's hard to deny that right now humanity seems in short supply. Wouldn't you agree?**

I had some reservations about Steven Pinker's *The Better Angels of Our Nature*, mainly because I thought he's much too much of a fan of European Enlightenment, and he needs to factor in how much of peace in Europe in the last half century has been because we figured out how to have proxy wars in the developing world.

But there's a whole lot more people now who say slavery is a bad thing than people would have said 400 years ago. We can send food to someone in Sudan and we couldn't do that 400 years ago. There's a sizable majority of people who say it's not good to beat your horse to death because it's not hauling your cart. That wasn't the mindset 400 years ago.

On the other hand, the thug in your village hamlet 400 years ago used a machete to kill someone. Now they have an automatic weapon and can kill 50 people. It's just that our ability to be both bad and good is so amplified now.

Whether humanity is doomed depends on tipping points. If the ice caps melt and we lose half the land mass on Earth, that may be a tipping point that swamps any ability to press a button and have charity delivered to someone on the other side of the planet.

**It sounds like our defining trait as humans is we're the species who amplifies.**

That's wonderful, yes, we're the species who amplifies. We don't have to be malicious. It's just that it's a whole lot easier to amplify destructive than constructive things. So, yes, things do get better. It's just whether it's going to get better fast enough to outweigh the stuff that goes bad.

## Care to cast your vote?

Because it's easier to make a mess of things than to put things together, that's probably a vote for amplified badness having a pretty good chance of swamping amplified goodness. ☺

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KEVIN BERGER is the editor at large of *Nautilus*.





# The Secret Lives of Moths

*The nocturnal insects with surprising pollination power*

BY CHRIS COSMA

PHOTOS BY THE AUTHOR

**IT'S AN HOUR PAST SUNSET**, and I'm alone atop a mountain in Southern California, surrounded by darkness. I'm fixated on a 5-gallon bucket, a halo of eerie blue light emanating from the top. A swarm of moths frantically pursues the light, completely entrancing me. This isn't some odd form of meditation—I'm an ecologist who studies pollinators. Many of these moths (around 60 percent of them, I will later discover) are carrying tiny pollen grains on their long, straw-like mouthparts. Although moths might not be the first creature most people think of when they hear the word "pollinators," they may be some of the most important on Earth, according to recent research. Globally, moths may even rank with the planet's most famous pollinators—bees.

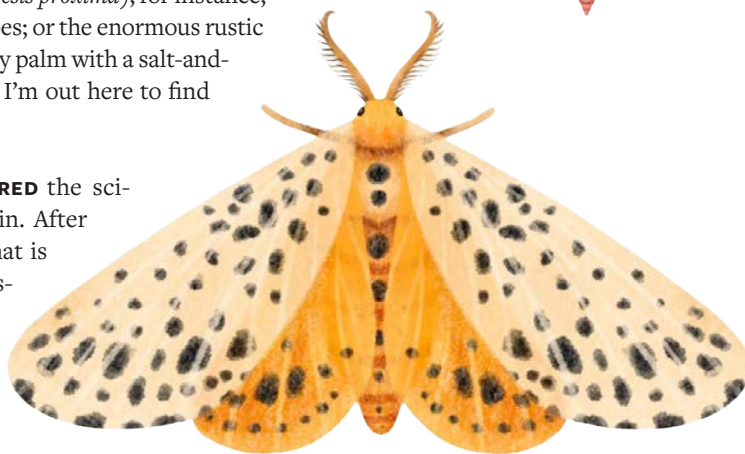
Pollinators enhance reproduction in 90 percent of the planet's flowering plant species, including 75 percent of our major food crops. The many different organisms that serve as pollinators—including insects, birds, even sometimes wolves and frogs—help sustain ecosystems and have a hand in producing a third of humans' food supply. Researchers long assumed that daytime or “diurnal” pollinators—butterflies, flies, hummingbirds, and especially bees—provide most of these essential ecological services. But recent research has steadily shifted that view. This includes a recent global meta-analysis which found that nocturnal pollinators—primarily moths, and to a lesser extent other night-loving insects and bats—contribute as much or even more to reproduction in many plant species, including several food crops.

For example, the authors of that analysis found no significant difference in pollination success between day and night for 90 percent of the 139 plant species they analyzed. In fact, nocturnal pollinators actually led to a significantly greater seed set, the proportion of plant ovules that become seeds, which is one metric of plant reproductive success. What's more, several studies included in the meta-analysis found no difference between day and night pollination for crop species that researchers had assumed to be primarily pollinated by bees during the day.

With my headlamp illuminating a narrow dirt path through the pines of the Santa Rosa Mountains, I find a good spot to set down the bucket of UV light, my homemade moth light-trap: It consists of a plastic funnel affixed to the top of a bucket. Above the funnel is a clear acrylic “vane,” on which a UV LED light is attached. Drawn toward the glow, the moths hit the clear vane, dropping into the funnel, which directs them into the bucket. Once inside, the moths sort themselves by size with a series of stacked metal filters with perforations of different diameters.

In this area, my bucket traps can collect dozens of species each night. They come in a dazzling array of shapes, sizes, and colors, and some would even rival butterflies, moths' dayflying, evolutionary cousins. The aptly-named Mexican tiger moth (*Apantesis proxima*), for instance, with its stunning orange-and-black stripes; or the enormous rustic sphinx (*Manduca rustica*), larger than my palm with a salt-and-pepper cloak. On this particular night, I'm out here to find out what they're pollinating.

**MOTH POLLINATION NOTABLY CAPTURED** the scientific curiosity of one Charles Darwin. After visiting the evolutionary laboratory that is Madagascar, he hypothesized the existence of a mystery moth with a 12-inch-long proboscis that would have co-evolved to pollinate an orchid (*Angraecum sesquipedale*, now known as Darwin's orchid). Its nectar lies





**COME TO THE LIGHT** Author Chris Cosma checks a “sheet trap” for moths at an outreach event in Spokane, Washington, he helped organize for National Moth Week.



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*It's time to embrace moths as important pollinators.*

hidden at the bottom of a nectar spur of the same length. In a now-famous validation of evolutionary theory, this long-tongued marvel—Morgan's sphinx moth (*Xanthopan morgani*)—was discovered in 1903, proving Darwin right 21 years after his death.

But like the nighttime visitor to Darwin's orchid, moths were largely thought to be minor pollinators, relevant only in specialized cases involving very specific types of flowers. Pollination research overwhelmingly focused instead on diurnal pollinators, leaving a significant diversity of potential pollinators underexplored. Indeed, in terms of species, moths are about eight times more diverse than bees, and 10 times more diverse than butterflies, which actually evolved from moth ancestors. In fact, we now know that moths are the single most diverse group of pollinators on Earth, with more than 123,000 species visiting flowers around the world.

It's time to embrace moths as important pollinators. Our appreciation for them has perhaps been delayed by the handful of moth species that eat our clothes, invade our pantries, and destroy our crops. These troublemakers have given moths a bad rap, even though most species are not pests.

But there's a simpler reason that moths have gone for so long with little credit for the ecosystem services they provide—one that exposes a fundamental bias in our understanding of nature as a whole: As daytime creatures, humans have focused more on the species that share our waking hours, such as bees and butterflies. Those charismatic denizens of the daylight have become the poster insects of pollination, the celebrated daytime heroes, while moths have remained obscured in the shadows, ignored, or even vilified.



#### **A MOTH IN THE HAND**

Cosma holds a Clio tiger moth (*Ectypia clio*) that he captured during fieldwork in 2022.





**BUCKET SCIENCE** One of the bucket traps that Cosma uses to capture moths, which he and his team then analyze to discover which plants they've been pollinating.

Leaning closer, I watch a drab gray moth, likely in the genus *Digrammia*, bury its head into a pale pink currant flower to sip nectar with its long proboscis. As it feeds, an electrostatic charge that the moth generates in flight—which is thought to occur due to friction between the air and their fluttering wings—causes its proboscis to pick up tiny pollen grains. Then, if fate allows, the moth will transfer some of this pollen to the next flower, fertilizing a future seedling.

This isn't just an academic issue. For instance, while it is often recommended to spray agricultural pesticides at night to protect honeybees and other diurnal pollinators, this practice may be harming an even greater number of beneficial nocturnal insect species, whose ecological roles have been largely overlooked.

**WITH ONE TRAP SET**, I weave between towering pines to place another. I'll place three traps on this part of the mountain, each separated by at least 300 feet. Along the path, I pause to discretely observe a wild currant bush with a red-light flashlight. Caught in the soft glow—invisible to them—dozens of moths flutter among the miniature, trumpet-shaped flowers. If I could illuminate the entire understory, I'd see it teeming with moths, flitting between many of the same blooms as those visited by diurnal pollinators.

My light traps will intercept moths as they forage on unknown numbers of plants in this way, their activities otherwise hidden under the cover of darkness. However, like cookie crumbs on a child's mouth, the pollen on their proboscides will betray them. Later, in our lab my collaborators and I will identify the plants they visited from the pollen grains' DNA, unraveling their web of surreptitious interactions.

Over the past decade, this genetic technique has helped overcome the logistical challenges of studying moth pollination—from the United Kingdom countryside to the islands of China's Bohai Strait—illuminating its global importance. Experimental studies have complemented this work, revealing that moths are more efficient than bees at pollinating some plants and that the insects meaningfully contribute to reproduction in food crops, including apples, avocados, berries, and gourds.

## *Moths are more efficient than bees at pollinating some plants.*

With my traps secured, I stand nearby to observe the first catches of the night. Dozens of moths filter in from the darkness around me, illuminated as they enter the blue light. Some, such as the Jalisco Petrophila (*Petrophila jaliscalis*), are smaller than my pinky nail.

The traps will collect moths throughout the night as I sleep nearby in my tent. In the morning, with dawn breaking on the horizon, I'll sort the catches for future analysis in the lab. Our study unfortunately requires euthanizing the moths. Ironically, it is sometimes necessary to kill insects at the small scale of a scientific study in order to better understand the dangers they face in their ecosystems.

Those threats—including habitat loss, pesticides, invasive species, and climate change—are together driving a 1 to 2 percent decline in global insect abundance *per year* and putting hundreds of thousands of species at risk of extinction. This anthropogenic onslaught has been termed “death by a thousand cuts.” As my traps also show, moths are further threatened by their often fatal attraction to artificial outdoor lights, which disrupts their feeding and mating and increases their risk of getting eaten by bats, spiders, and other predators.

**BACK IN THE LAB**, my collaborators and I discover that the moths I collected were transporting pollen not only from currant bushes, but from more than 100 other plant species. Among them are 18 crop plants, everything from soybeans to oranges—evidence that the fates of moths and humans are closely intertwined. In this study, part of my doctoral research at the University of California, Riverside, we also find that moths will likely become smaller, less diverse, and more sensitive to the loss of the plants that they rely on for nectar as climate change intensifies, jeopardizing their pollination services. This highlights the urgency with which we need to overcome our biases and include moths in conservation efforts, where they have long been neglected.

Fortunately, new technologies are making this easier. Along with better genetic sequencing techniques, automated monitoring approaches—such as camera traps coupled with computer vision—now allow the study of pollinators without the need to capture and euthanize them.

Together, these advances are generating critical data to guide conservation efforts, including ways individuals can support moths and other pollinators. For example, planting key native plants—even at the scale of backyard gardens or potted outdoor plants—supplies pollinators with resources they need to thrive. Native plants also support beneficial insects that prey on pests, in turn reducing the need for harmful pesticides that kill both pests and pollinators. Since many moths overwinter in leaf litter, it also helps to “leave the leaves,” even just in small patches. What’s more, using timers or motion sensors to keep outdoor lights off when not needed helps reduce the burden of light pollution.

By darkening our environments more, we may continue to help moths emerge from the shadows of pollination obscurity to challenge bees for the limelight.

So are moths more important than bees? A natural question to ask—but, I think, the wrong one. To understand why, consider biologist Paul Ehrlich’s rivet-popper hypothesis: If enough rivets were removed one by one from an airplane, it may eventually fall apart mid-flight. Likewise, as more species disappear, the risk of sudden ecosystem collapse increases. A resilient future—where ecosystems continue to provide food for humans and other animals—depends on a diversity of species, each playing a vital and complementary role.

If we are to reach that future, we must value and protect all pollinators—whether we are awake to see them or not. ☺

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CHRIS COSMA is a pollination ecologist at the Conservation Biology Institute.



# Last of Their Kind

*The rush to save the northern white rhino*

BY ELENA KAZAMIA





**UNDER THE BLAZING AFRICAN SUN**, I trained my binoculars on Najin and Fatu in Ol Pejeta, a wildlife reserve on the plains of northern Kenya. From a distance, the two rhinoceroses could be mistaken for boulders, propping up the sky. Alongside other travelers in 2021, I watched the pair graze peacefully in the field, their heads bowed down to the dry grass, munching in unison. Although we were far from the animals in a safari truck, everyone spoke in hushed tones.

A mother and daughter pair, Najin and Fatu are the last two northern white rhinos. The rest of their kin have been poached to extinction. When Fatu and Najin die, a thread of presence that connects generations of northern white rhinos to the African landscape, going back more than 10 million years, will be inexorably severed.

Najin and Fatu had two horns each—one large at the very front of the snout, and a smaller one behind it. But Fatu’s had been lightly trimmed, blunted, to prevent her from jabbing Najin, who is too elderly now to keep up with Fatu’s play. With two armed guards always by their side, the rhinos looked both inviolate and fragile.

But there is more to the lives of these two rhinos than meets the tourists’ eyes. Behind the scenes, veterinarians, cell biologists, and entrepreneurs are rushing to avert their imminent extinction through gene editing and in vitro fertilization. They believe it is still possible to restore the population of northern white rhinos to the African landscape by using surrogates of a closely related species (the southern white rhinoceroses) impregnated with lab-generated embryos from Fatu.

A partner in the rhino project is Colossal Biosciences, with a valuation of \$10 billion, which made headlines in April with its claim to have “resurrected” dire wolves, a species of wolf that went extinct some 10,000 years ago (and was the model for the wolves in *Game of Thrones*). The company sired three wolf pups from the DNA of ancient dire wolf fossils and modern

gray wolves. Embryos with the edited wolf DNA were implanted in dogs, mutts that are a mix of hounds. The company asserted it was the first time an extinct species has been revived by science, even though it’s not an exact clone of the ancient dire wolves.

The ambitious scientists aim for a similar approach with the northern white rhino. As with the dire wolf, the rhino experiment is being watched by skeptics. They question whether genetically engineering a northern white rhino is more of an exercise in technological hubris than genuine conservation. One thing is certain: No two rhinos in the name of conservation have been put through more of an ordeal than Najin and Fatu.

**THE STORY OF THE TWO RHINOS** begins as a familiar one for charismatic megafauna in the 21st century. Half a million northern white rhinos trod the African continent at the start of the 19th century. By the 1970s, the population was decimated to 70,000. Only a few hundred survived to the end of that decade.

Rhino horns are made of keratin, like hair or fingernails, and have been traded across illegal networks sprawling the globe for bogus medicinal properties and status. While some of the money helped alleviate local poverty, other proceeds have been channeled to fund armed conflicts.

Poaching of rhinos is particularly cruel. With no natural predators in the wild, rhinos are gullible and approach an illegal hunter out of curiosity, especially if





**HELLO, NAJIN** Thomas Hildebrandt, founder of BioRescue, offers a friendly pat on the shoulder to Najin, one of the two only remaining northern white rhinos.

lured by a call. They are killed at short range by guns or axe blows to the spine. Their skin may look thick to our eyes, but even a thorn can make the rhinos bleed.

The southern white rhinos, whose populations diverged from the northern white rhinos about 200,000 years ago, have also been decimated by poaching in the past century. Their populations have been narrowly restored by South African efforts and today number about 10,000.

In 1975, as the northern white rhinos appeared doomed, a bold and eccentric zoo director, Josef Vágner of the Dvůr Králové Zoo in what was then Czechoslovakia, set out to collect a menagerie of hundreds of African animals. His team captured six northern white rhinos in South Sudan and transported them to Europe. The animals first traveled to Uganda, then onward by train to the port city of Mombasa in Kenya. An ocean liner brought the animals to Hamburg and a river boat transported them along the Elbe River to Czechoslovakia. The journey took nine months.

AMI VITALE

“It’s phenomenal they survived,” Jan Stejskal, the director of communication and international projects at Safari Park Dvůr Králové (the zoo’s new name), told me recently.

From the beginning, the plan was to breed the rhinos. But the six individuals captured by Vágner refused to mate. A female rhino was brought to the Czech zoo on an animal exchange from the London Zoo—she had been captured in Uganda for a similar exhibition in the United Kingdom—and the dry spell was broken. Her third calf, Najin, was born in 1989. In the same year, three rhinos from the Czech zoo were shipped to San Diego Zoo in the United States.

Keeping multiple small populations of northern white rhinos in separate locations around the globe was a tactical strategy devised by the network of zoological societies. It prevented a single catastrophic event, such as a disease outbreak, from wiping out the entire captive community, Stejskal told me.

But after Najin was born, the success of all breeding efforts waned. Efforts to artificially inseminate the rhinos or stimulate a pregnancy failed for more than a decade at Dvůr Králové. Only when a bull was returned from San Diego to the Czech Republic did Najin conceive.

In the wild, male rhinos rule a specific territory, marked by dung and urine. When females are ready to mate, they move between the territories until they find their suitable mate. This courtship ritual is difficult to reproduce in a zoo, Stejskal told me. Nevertheless, Najin made her choice with the bull from San Diego.

Najin calved Fatu in the middle of a hot summer night in 2000. Jan Žďárek was the keeper on duty. He recalled the night with fondness. Hope was in the air, he said. “When she was little, Fatu was a terribly beautiful animal. She was this pale color, very bright.” Fatu was spirited and temperamental and has preserved her character to adulthood. Compared to wild rhinos, Žďárek said, the rhinos in his care were “calm, kind. They like touching, stroking, scratching.”



**THE GIRLS** After Najin and Fatu were brought from a zoo to the Ol Pejeta wildlife reserve in Kenya, they quickly earned the affectionate nickname “the girls.”

When Fatu turned nine in 2009, the zoo, with a push from Back to Africa, a nonprofit group based in South Africa dedicated to “giving back to Africa what it has lost,” moved the animals to the Ol Pejeta Conservancy, an established northern black rhino sanctuary. The animals were welcomed warmly. Najin and Fatu quickly got nicknamed “the girls.” They were joined by Sudan, a male who was Najin’s father and Fatu’s grandfather, and Suni, Fatu and Najin’s half-brother.

The move was based on the idea that the wildlife reserve might rekindle the rhinos’ urge to breed on land close to their ancient home range. Yet from 2009 to 2013, mating attempts both within the four northern white rhinos and with southern white rhino bulls failed. One male that mounted Najin was so heavy that he tore her Achilles tendon. Then Suni died, leaving only one northern white rhino male alive in the world, Sudan.









*No two rhinos have been put through more of an ordeal than Najin and Fatu.*

**THOMAS HILDEBRANDT, A PROFESSOR** of wildlife reproduction medicine at the University of Berlin, is a preeminent rhino veterinarian. He is charismatic with a tireless energy. For more than three decades he has made it his mission to save the northern white rhino. He worked with the Czech zoo for years on trying to breed them.

In 2014, Hildebrandt traveled to Kenya, collected sperm from Sudan, and examined the girls. Neither could carry a pregnancy. Najin had tumors on her ovaries, and Fatu's uterus looked "scorched," as if "someone had poured boiling hot water into it," Hildebrandt said. The rhinos were in a sorry state. In 2018, Sudan died of old age and the species was pronounced "functionally extinct."

This pushed Hildebrandt into overdrive. Time was ripe for something "radical," he said. By 2015, he had gathered funding for a nonprofit group, BioRescue, and a "very futuristic" intervention. Sperm had been cryopreserved from Suni and Sudan, and one other northern white bull, Angalifu, in the San Diego Zoo. Embryos could be generated on a petri dish using the sperm and eggs harvested from Fatu and Najin. A southern white rhino surrogate would carry the pregnancy.

To collect eggs from Fatu and Najin, Hildebrandt's team first sedated the rhinos using a potent cocktail of anesthetics. Since the rhino vaginal canal is long and winding, too tricky to navigate mechanically for a veterinarian, Fatu and Najin's ovaries are accessed through their rectums. Hildebrandt and colleagues

**GRAZING IN THE GRASS** Mother and daughter, Najin and Fatu, have been put through a lot by the scientists trying to save their species.



## *“A DNA sample is not equivalent to a species.”*

designed and patented a special needle angled to fit the anatomy of the rhino for the procedure. The animal is laid on her side and the needle is guided through the rectal wall, puncturing through the ovary to aspirate developing follicles. A course of hormonal stimulants is administered to the rhinos in the days prior to ovum pick up, to increase the egg count, much like in human IVF treatments.

Veterinarian Parker Pennington, an operations manager at the Cincinnati Zoo and Biological Garden who works with the American Institute for Rhinoceros Science, described the procedure to me as the safest method given the sheer bulk of the animal. “The ovary collapses onto the rectum wall, and now you’re not passing through body space,” Pennington said. There is a risk of infection, but the rectum is “cleaned very well,” and its thick skin “sterilizes” the needle along its passage. (Pennington was subsequently hired by Colossal Biosciences.)

The first egg collection was successful, and an embryo was generated in vitro. To date, Hildebrandt and his BioRescue colleagues have engineered 35 embryos using Fatu’s eggs and the sperm of her grandfather and half-brother. No eggs collected from Najin were fertilized in vitro. She was too old. In 2021, she was retired from further experiments because of their risk to her life.

In 2023, a southern white rhino carrying an embryo fertilized from Fatu’s eggs became pregnant. The pregnancy was hailed as proof that embryo transfers could succeed and “a cornerstone in the mission to save the northern white rhino from extinction.” Yet the pregnancy lasted only 70 days. The surrogate mother and fetus died from a toxic bacterial spore in the surrogate’s enclosure on the Ol Pejeta Conservancy. A photograph of Hildebrandt cradling the tiny dead fetus in his hand was selected by *National Geographic* as one of the most compelling images of the 21st century.

That same year, Hildebrandt and BioRescue partnered with the Texas-based Colossal Biosciences. “They are technology-drivers,” Hildebrandt said. That technology would help drive the next iteration of northern white rhino embryos. Fatu’s embryos, Hildebrandt explained, lack “a diverse genetic background.” Genetic diversity is key to a species’ long-term survival, as it overcomes inbreeding, fatal to animals’ health and ability to adapt to changing environments.

Colossal Biosciences, with its expertise in splicing ancient DNA into cells of living animals, would help engineer the new rhino embryos. They would be produced through “advanced gametogenesis,” the process which turns the rhinos’ pluripotent stem cells (which can self-renew) into reproductive cells. These cells would be edited with DNA from the old skulls of northern white rhinos preserved in museum collections. That way, Hildebrandt said, “We can bring back individuals who lived 200 years ago.”

**WHEN I WAS WATCHING** Fatu and Najin on the wildlife reserve in 2021, I spotted another rhino grazing nearby. This was Tauwo, a southern white rhino. Visibly, I couldn’t spot any real difference between the three rhinos.

I later learned from Hildebrandt about the differences between the two species. The northern white rhinos are larger, have bigger skulls and feet, and hair on their ears. “They are not the same because they are highly adapted to their special environment,” Hildebrandt said. If rhinos are to thrive again in northern parts of Africa, it must be the northern whites. This was their territory, one and true home.

Still, I thought in 2021, and even more now, why was so much time, money, and energy being poured into saving two northern white rhinos when the southern white rhinos, not to mention so many other animals in Africa, still needed protection from poaching and human encroachment on their native lands? I asked Barbara de Mori of the Ethics Laboratory for Veterinary Medicine, Conservation, and Animal Welfare at the University of Padua in Italy, who worked with BioRescue.

“Because the extinction of the northern white rhino is human made, not based on natural causes, we need to do whatever is possible to save them from extinction,”



## RHINO TECH

Thomas Hildebrandt and Susanne Holtze, a wildlife reproduction biologist, conduct a scan on a southern white rhino surrogate.

de Mori said. “We have to develop all the strategies in our possibilities. It’s our duty.”

An independent conservation ethicist, Thom van Dooren, a professor of environmental philosophy at the University of Sydney in Australia, whose research has pioneered the field of “extinction studies,” agreed. But he worried that the extensive focus on technology to turn back time for the northern white rhino was a distraction.

“I think a lot of the people involved are coming from a good place,” van Dooren told me. “But they’re also coming from a place of intellectual curiosity and trying to do cool things with science and technology. And too much of what’s going on in the de-extinction space is being driven by investment and financial imperatives. That creates a murkiness around motivations that prevents us from asking important questions about whether we ought to be doing this or whether we ought to be pursuing the very real conservation problems on the ground for all rhinos and poaching. Because there is a real conservation struggle today. And it’s not taking place in labs.”

The focus on genetics van Dooren continued, ignored the big picture of animals’ interdependence with their environments. “A DNA sample is not equivalent to a species,” he said. Rhinos learn from each other—where the best habitats to forage are, how to fend for themselves on the savannah, how to forge relationships with other species. The failed efforts in captivity showed how important social interactions are

to successful breeding. “The idea that we can continue business as usual and put them back in their native environment will not only not work, it allows the real causes of our biodiversity crisis to continue unchallenged,” van Dooren said.

I asked Hildebrandt for a response to the criticisms, and he assured me there would be “zero poaching” of the engineered northern white rhinos. The Kenyan government, he said, will take on responsibility for protecting “this precious element in their nature. They see it as a cultural heritage and a chance to develop ecotourism in a very intelligent way.”

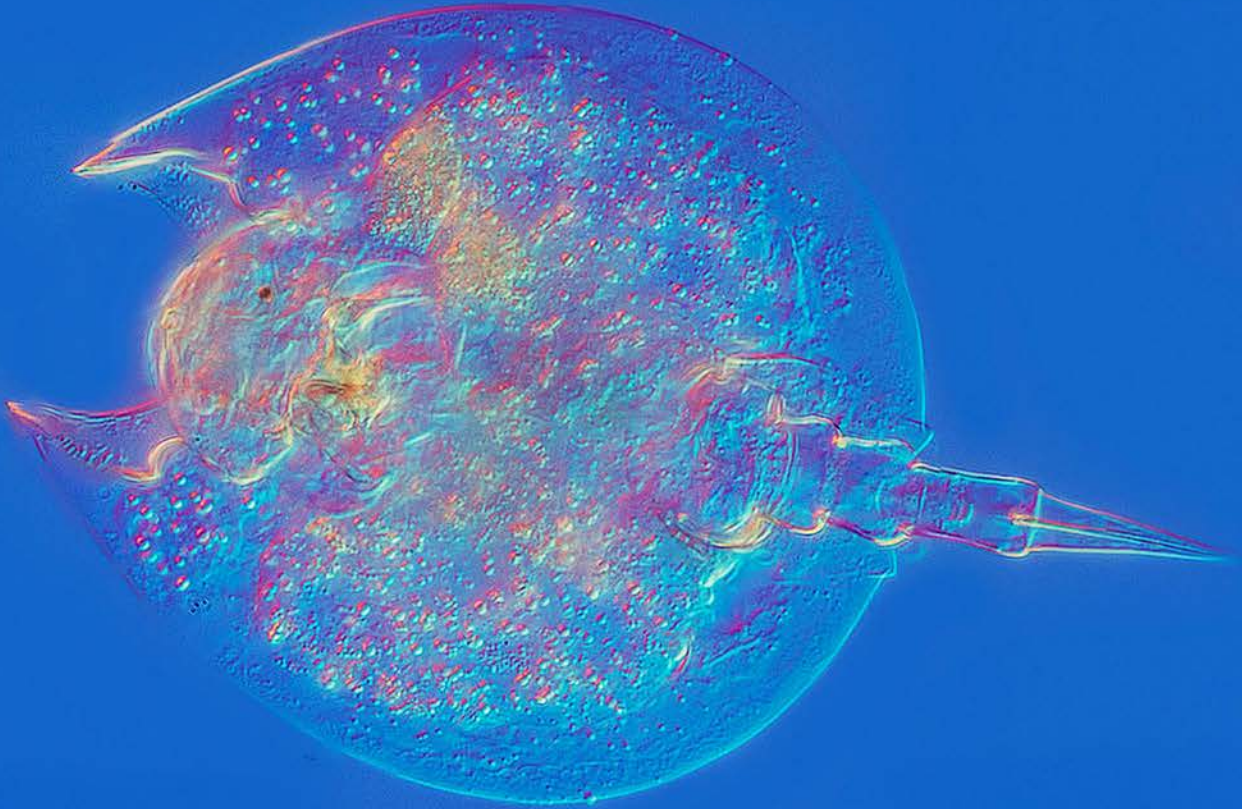
On the Ol Pejeta reserve, I felt melancholic knowing that when the girls died, northern white rhinos would be gone forever. But thinking about the ordeal they’ve been through, the *Jurassic Park*-like efforts to resurrect their species, and the kinds of lives their offspring might lead, I was left to reflect on something else van Dooren said to me. “It bears considering,” he said, “whether it is better to just let the animals go extinct.” ☹️

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Thanks to Pavel Kocian for his English translations of the Czech language.



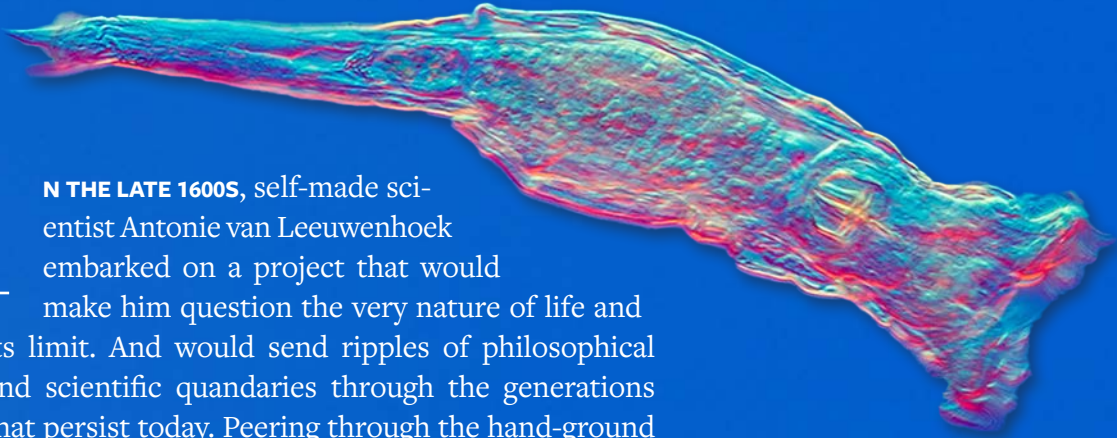


# The Animals That Exist Between Life and Death

*At the dawn of microbiology, scientists glimpsed unseen worlds and stumbled  
into a philosophical purgatory*

BY PHIL JAEKL

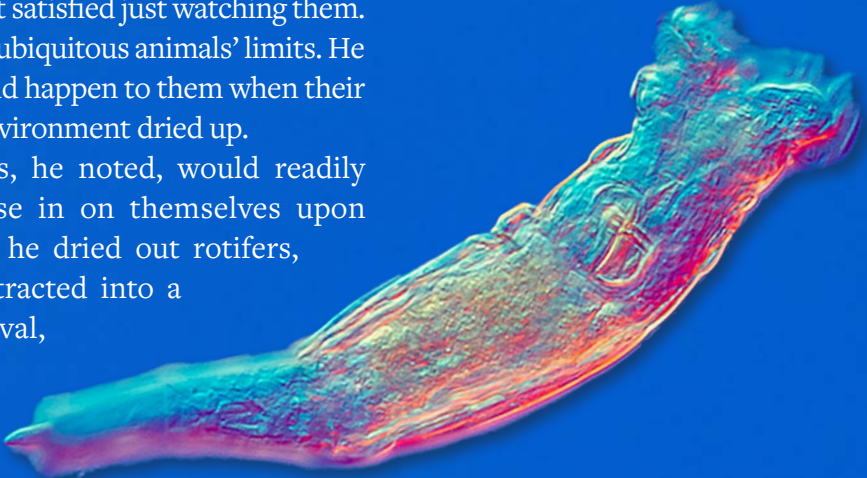
IMAGES BY ROBERT BERDAN



**I**N THE LATE 1600S, self-made scientist Antonie van Leeuwenhoek embarked on a project that would make him question the very nature of life and its limit. And would send ripples of philosophical and scientific quandaries through the generations that persist today. Peering through the hand-ground lenses he crafted, magnifying his subjects 275 times, the Dutch cloth merchant and naturalist was the first human to glimpse an otherworldly microcosmos where astonishing creatures seemed to defy the laws of nature and survival. He called them, adoringly, “animalcules.”

In 1687, he discovered some animalcules so peculiar in form and function that he would spend decades observing them. We now know these tiny animals, which had wheel-like appendages that van Leeuwenhoek correctly surmised were for feeding, as rotifers. They live in watery environments throughout the globe, from the tropics to Antarctica, in oceans, temporary puddles, and even in moisture within moss. But van Leeuwenhoek wasn't satisfied just watching them. He decided to test these ubiquitous animals' limits. He wanted to see what would happen to them when their surrounding aqueous environment dried up.

Other animalcules, he noted, would readily break apart or collapse in on themselves upon desiccation. But when he dried out rotifers, they each instead contracted into a shrunken, wrinkled oval, now called a “tun” or “xerosome.”





*Philosophers are still grappling with the idea that life and death may not be the only states of being.*

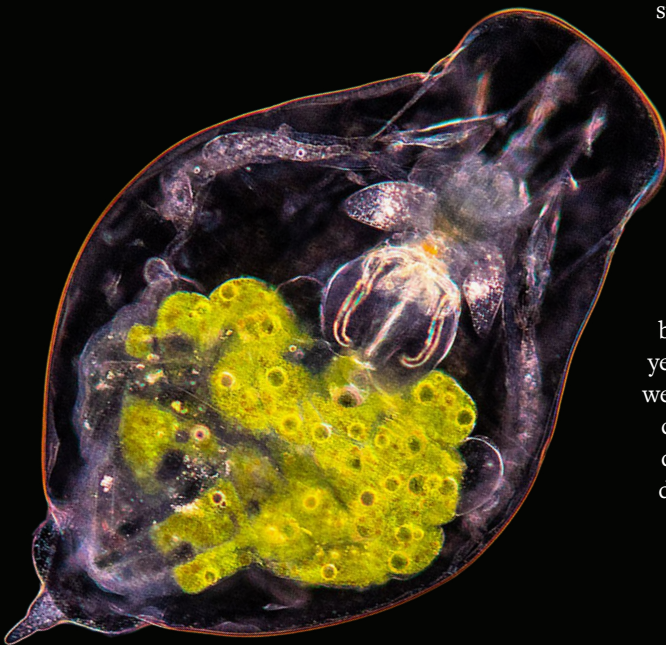
What van Leeuwenhoek discovered next went beyond anything he could have imagined: After adding water to a glass tube that contained dried sediment and rotifer tuns he'd collected from a rain gutter, van Leeuwenhoek watched in wonder through his homemade microscope as rotifers came back to life. "I examined it, and perceived some of the Animalcules lying closely heaped together," he wrote in a letter to the British Royal Society. "In a short time afterwards they began to extend their bodies, and in half an hour at least a hundred of them were swimming about the glass ..." As a good experimentalist, he repeated the process by drying out other rotifers and witnessing the same phenomenon numerous times—even after samples were desiccated for a month.

"These little animals, which had appeared to be completely dried and lifeless, were restored to motion upon the addition of water, as if they had never suffered any harm," van Leeuwenhoek wrote. Microbiologists would later find that some species of rotifers are able to reanimate after up to nine years of desiccation.

According to University of California, Davis philosophy professor Cody Gilmore, van Leeuwenhoek's observations presented a philosophical paradox beyond the biological questions they raised concerning desiccation and survival. Consider those newly identified rotifers in van Leeuwenhoek's dried gutter sediment that apparently came back to life. The tuns, as far as the progenitor of microbiology could tell, showed no signs of living—no movement or activity or perceptible change for days, potentially weeks. Were the animals technically dead? Were they, in tun form, actually still alive but dormant, like a mammal in hibernation? Or were they in some kind of liminal, in-between state? An underlying assumption held by most people, including biologists and philosophers today, is that organisms are either alive or dead. Gilmore notes that the paradox lies in maintaining the possibility of such a binary proposition in the face of rotifers and other extremophiles that seem to occupy such a third state as they await reanimation.

Van Leeuwenhoek wrote that his rotifers "came back to life," but he never hinted at whether he thought they were resurrected or if they had remained alive, apparently failing to fully realize—or being unwilling to confront—the philosophical quandary raised by his discovery.

Despite acceptance from the Royal Society, his observations also failed to gain notice by his contemporaries and were shelved for years. Without a powerful enough "van Leeuwenhoek microscope" or accurate scales to precisely measure desiccation, naturalists of the day could neither replicate his observations nor dive into their implications. In fact, many of





**TUN OF FUN** Rotifers and other extremophiles can survive years of desiccation by entering into a state of diapause, transforming into a “tun” or “xerosome” such as this one, which likely formed from the rotifer *Macrotrachela quadricornifera*.

van Leeuwenhoek’s early observations were often met with skepticism. Forget about tiny, resurrecting bugs. A microcosmos of bizarre lifeforms, unseeable with the naked eye, sounded to most of his contemporaries more like fiction than reality.

Even as microbiologists have been working for centuries now to piece together how rotifers and several other animal species survive desiccation and other extreme conditions, philosophers are still grappling with the idea that life and death may not be the only states of being in which organisms can exist.

**SINCE VAN LEEUWENHOEK’S** seminal observations, subsequent biologists have found other microscopic beings that could similarly survive desiccation. One of these is the microscopic “eelworm” (now known as the larval stage of the pathogenic roundworm, *Anguillulina tritici*), which live in diseased grain. They can be dehydrated to the point where they crumble into powder.

But, when left intact, these thoroughly dried animals can revive and squirm around upon rehydration.

After confirming this mysterious eelworm resurrection and observing rotifers reanimate, British naturalist Henry Baker alighted upon their seemingly supernatural quality, writing, in his 1764 guide, *Employment for the Microscope*, “What Life really is, seems as much too subtle for our Understanding to conceive or define, as for our senses to discern and examine.”

In the 1770s, Italian biologist Lazzaro Spallanzani burrowed even deeper into the philosophical ramifications of this physiological phenomenon, which by then scientists had learned also included tardigrades, microscopic “water bears” (tiny animals that researchers have since discovered can survive not only desiccation but also radiation, extreme temperatures, and even the vacuum of outer space). Spallanzani wrote, in his “Observations and Experiments Upon Some Singular Animals which may be Killed and Revived,” “an animal, which revives



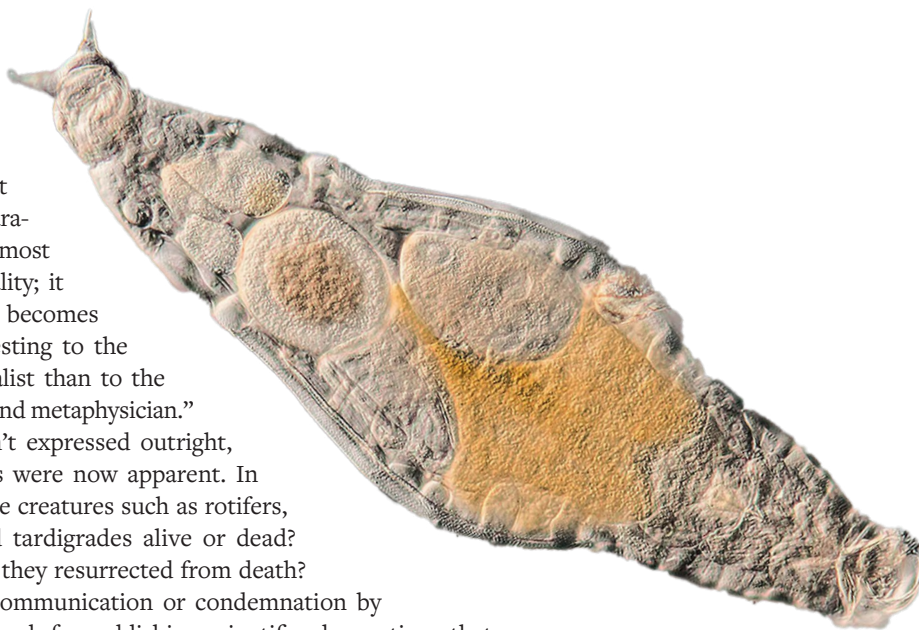
after death, and which within certain limits, revives as often as we please, is a phenomenon, as incredible as it seems improbable and paradoxical. It confounds the most accepted ideas of animality; it creates new ideas, and becomes an object no less interesting to the researches of the naturalist than to the speculation of the profound metaphysician.”

Although they weren't expressed outright, the tricky, big questions were now apparent. In their dormant state, were creatures such as rotifers, some worm larvae, and tardigrades alive or dead? When reanimated, were they resurrected from death? At the time, fear of excommunication or condemnation by the Roman Catholic Church for publishing scientific observations that challenged Church doctrine impacted communication about new scientific findings.

But science marched on. In the 19th century, the French zoologist Louis Doyère, who was among the first to study tardigrades, developed and improved desiccation methods by bringing precise temperature measurements and vacuum chambers that eliminated moisture into the experimental mix. Still, leading naturalists remained skeptical as to whether rotifers, eelworms, and tardigrades were fully desiccated and whether or not they ceased physiological activities entirely. At that time metabolism was only an emerging concept, so life was defined more by visible criteria like reproduction, self-initiated movement, and growth.

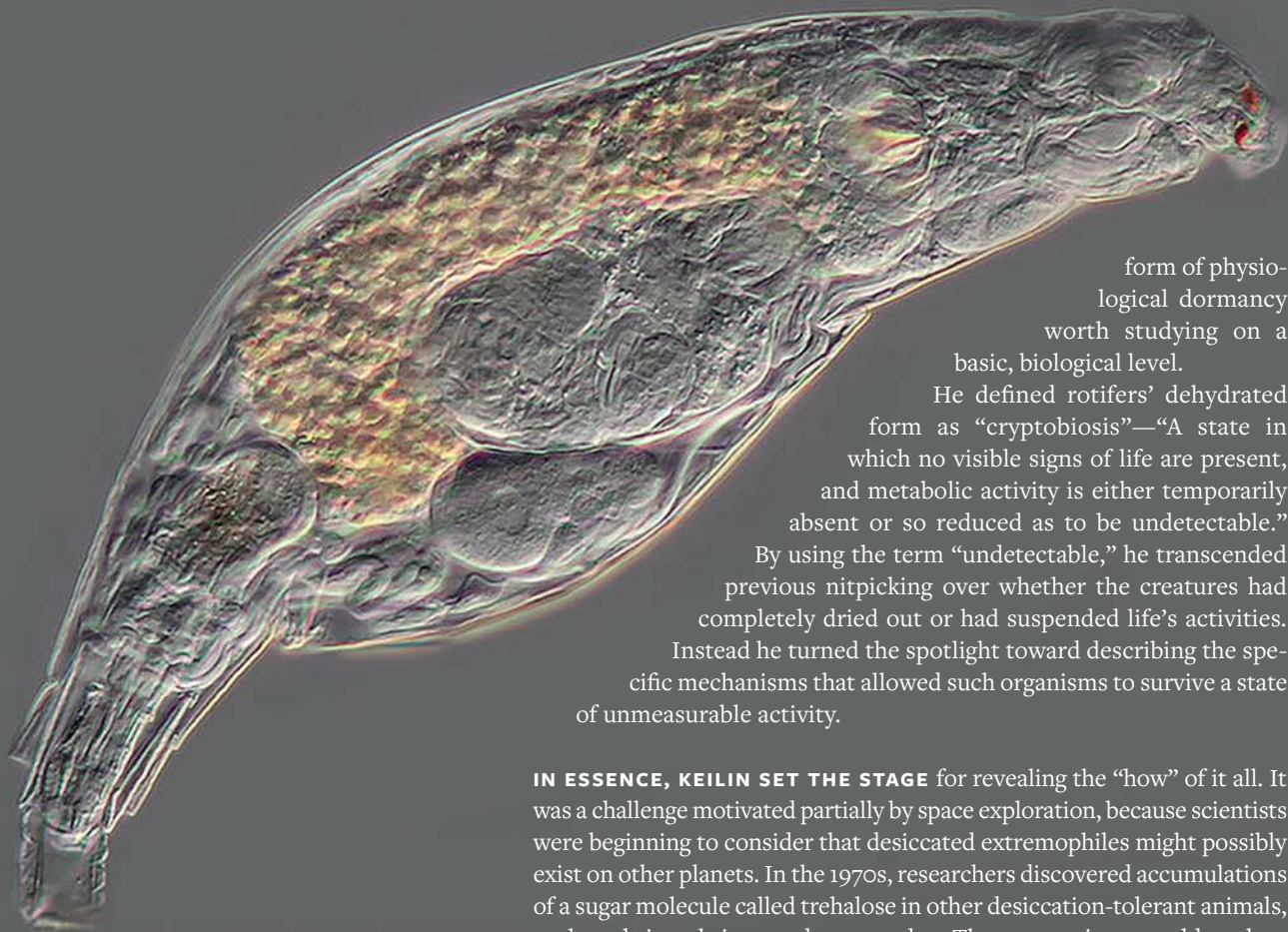
With a few exceptions, further investigation into the life-and-death question raised by van Leeuwenhoek's rotifers stagnated like a tun for about the next century. It wasn't until the mid 20th century that David Keilin, a Russian-born, British biologist, set the stage for contemporary research into extremophiles by articulating the need for scientifically understanding their ability to survive desiccation.

Keilin himself suffered from asthma and was intrigued by the mechanisms that enable respiration. His greatest scientific contribution was his discovery of cytochromes, enzymes crucial for cellular respiration. He was fascinated by animals with the ability to suspend respiratory processes. In 1959 he wrote, in painstaking detail, the entire scientific history of rotifer desiccation survival, from van Leeuwenhoek's initial experiments with gutter sediment onward. Although the paper did not include new data or observations, Keilin revolutionized understanding of the enigmatic process in this single work. Rather than viewing desiccation survival as a philosophical curiosity, he showed that, death or life aside, it's an extreme




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*In their dormant state, are creatures such as rotifers, some worm larvae, and tardigrades alive or dead?*



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*About 10 percent  
of rotifers'  
genome isn't  
even animal.*

form of physiological dormancy worth studying on a basic, biological level.

He defined rotifers' dehydrated form as "cryptobiosis"—"A state in which no visible signs of life are present, and metabolic activity is either temporarily absent or so reduced as to be undetectable."

By using the term "undetectable," he transcended previous nitpicking over whether the creatures had completely dried out or had suspended life's activities.

Instead he turned the spotlight toward describing the specific mechanisms that allowed such organisms to survive a state of unmeasurable activity.

**IN ESSENCE, KEILIN SET THE STAGE** for revealing the "how" of it all. It was a challenge motivated partially by space exploration, because scientists were beginning to consider that desiccated extremophiles might possibly exist on other planets. In the 1970s, researchers discovered accumulations of a sugar molecule called trehalose in other desiccation-tolerant animals, such as brine shrimp and nematodes. These organisms could replace water molecules in cells with this compound and prevent their membrane from breaking or collapsing upon desiccation. Trehalose forms a glass-like matrix that fortifies cellular structure, maintaining it during dehydration. Upon the return of water, the sugar molecules simply dissolve and cellular activity returns.

But there was a wrinkle: Rotifers didn't seem to use the trehalose trick. Researchers working in the mid-2000s discovered that instead of relying on sugars to form a protective matrix in their cells, these animals produce proteins to replace the water in their cells. The molecules, known as late embryogenesis abundant (LEA) proteins, were originally discovered in plants, which use them to protect seeds from drying out. Essentially, LEA proteins create stability in cell membranes which might otherwise break down during desiccation. The proteins, which are scattered throughout the membranes of rotifer cells, act as a shield. As the cells dry out and their contents physically shrink and fold over, LEA proteins assure that the membranes don't break. When water returns, everything expands and unfolds back into its original form.

This doesn't mean that rehydrated rotifers rejoin the living unscathed. During desiccation they undergo considerable chromosomal breakage.



Some regions of their DNA are shattered. But when water returns, potentially after years, the organisms are still able to begin moving again within about five to 10 minutes. Within about half an hour, they will have restructured their DNA as it was. To achieve their apparent resurrection, rotifers rely heavily on advanced DNA repair mechanisms.

The process of desiccation and repair keeps their DNA in a relatively fragile, yet flexible state. Such resilience in turn sets the stage for a number of mysterious genetic anomalies that are likely connected to their extremophilic capabilities.

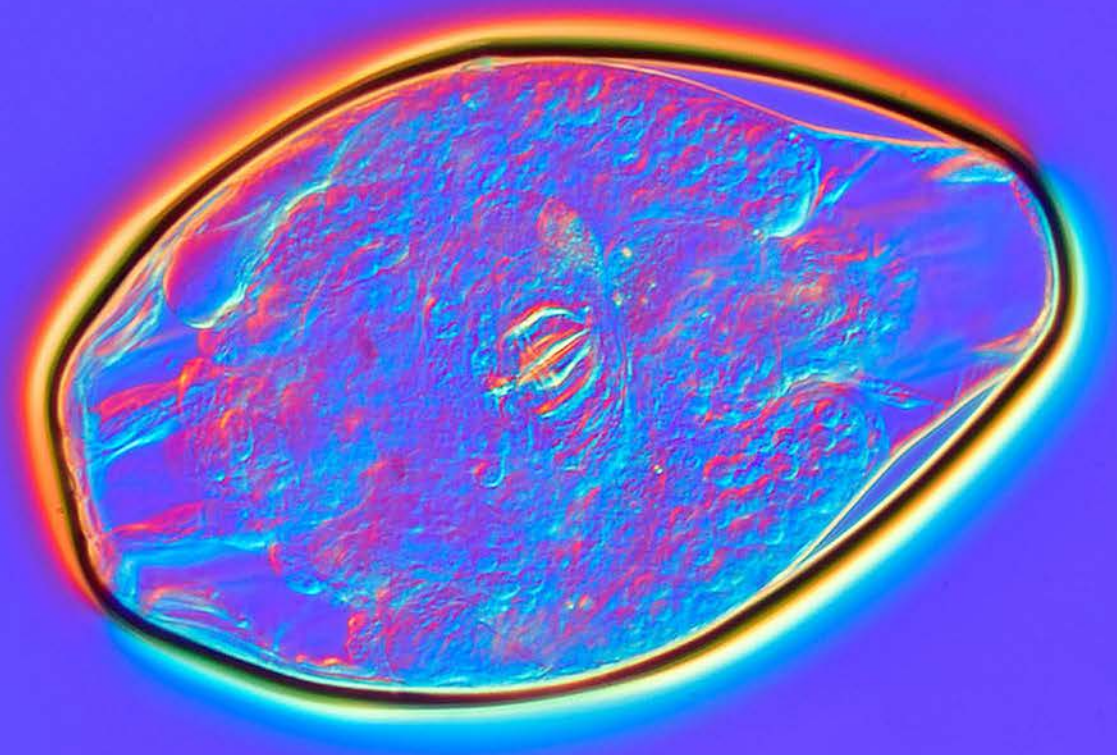
Rotifers are known as “evolutionary scandals.” About 10 percent of their genome isn’t even animal. They appear to have taken on DNA from yeast, fungi, and plants and incorporated it as their own. Genetically, their ability to survive desiccation derives largely from these other organisms. Researchers have identified the non-animal genes rotifers have co-opted as the very genes that enable desiccation survival.

Their advanced DNA repair mechanisms and their ability to incorporate foreign DNA are both extraordinary and seem unlikely to be coincidental. But which came first? Diego Fontaneto, a biologist at the Water Research Institute in Verbania, Italy, explains that rotifers could have originally adopted foreign DNA through

the process of desiccation and recovery. “If this is true, how could they use the bacterial DNA for surviving desiccation?” he asks. “It becomes an issue of what came first—the chicken or the egg.”

One thing we do know however, is that when the rotifers are dried out, their physiological activity indeed comes to a halt. There is no detectable trace of life in a tun, whatsoever. Fontaneto offers two literary analogies to which researchers have turned to over the years to try to understand rotifers’ strange feats. Are they more like Oscar Wilde’s Dorian Gray, whose portrait ages while he appears to remain young, only to have his true, older form revealed upon the destruction of the painting? That is, do rotifers age while they are dehydrated, revealing a degraded form upon reanimating? Or are they more like “sleeping beauties” whose aging pauses during stasis?

It might be neither. Upon rehydration, rotifers can actually appear even younger than they were before they entered stasis, Fontaneto explains. Reanimated rotifers tend to live longer while active and to produce more offspring than rotifers that have not desiccated, despite having lived the same amount of time in water. “It seems they really need to desiccate,” Fontaneto suggests. “For them it’s not a stress. It’s so beneficial, they really can’t live without desiccation.”



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*The simple dichotomy of  
alive or dead doesn't  
make sense.*

**ALTHOUGH BIOLOGISTS** now understand some of the mechanics underlying rotifer desiccation and survival, the philosophical debate over whether or not they die remains unsettled. Despite Keilin's clever workaround that motivated researchers to stick to the science of their survival, we appear to be back where we started.

For Gilmore, the presence of metabolic activity is not completely synonymous with life. "So there's a pretty strong case that there's no metabolism" in a tun, he says. "Then the question is still not answered as to the status of the organism. Is it alive? Is it dead? The answer to the question about metabolism doesn't provide a direct answer about biological status."

According to Gilmore, even though there's a solid argument rotifer tuns show no detectable sign of living—metabolism, respiration, digestion, etc.—there's an equally strong argument that they are not dead because as soon as water returns, they become active. There must, he suggests, instead be fault in the model that all things are either alive or dead. He calls this "exhaustivism," simply because it exhausts other possibilities.

Gilmore explains that the simple dichotomy of alive or dead doesn't make sense. "It's just that to be dead is partly a historical property and it requires having died and having died requires having been alive—or at least cryptobiotic," he says. "So there are lots of things that are not alive and not dead, and they're not dead because they were never alive—a toothbrush, a rock, a toaster." Rather, Gilmore and others posit that cryptobiosis is a unique state of being.

Thomas Lemke, a professor of sociology at Goethe University Frankfurt in Germany, has a slightly different framework for what state van Leeuwenhoek's dried rotifers were in. Lemke suggests moving past the

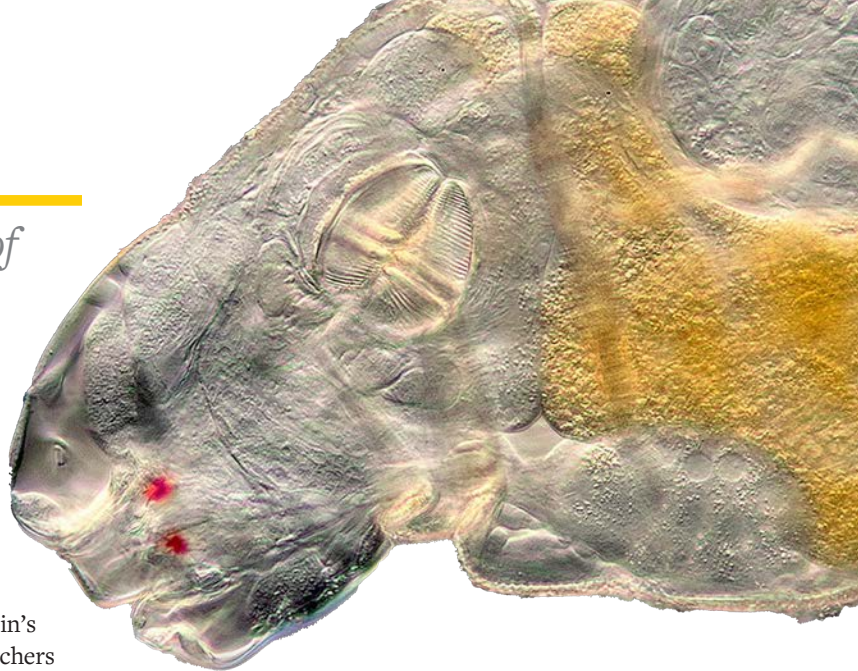
term cryptobiosis because, in strict Greek translation, it implies the existence of some hidden, or latent form of life. Rotifers and other animals that enter cryptobiosis don't have any kind of hidden capacity, he argues.

Lemke prefers the concept of suspended life, what he terms "limbosis," derived from the Latin *limbus*, meaning edge or border. It offers connections to other elements. He explains that if you are suspended, you are suspended between other things. A suspension bridge for example suspends one between shores. Such a state might hinge on, "What is *going on* not what *might go on in the future*—the potential," he says.

Rotifers will continue to make the case for a fully fledged third state of being, even if it maintains a connection between the two main states of alive and dead. Van Leeuwenhoek's original observations of their strange microscopic world sounded like fantasy to other naturalists at the time, influencing his staunch empirical approach to science and his advocacy of visible evidence for phenomena over philosophical reasoning. What surprise he might have had if he found out that his strange observations of reviving animacules had laid the groundwork for a philosophical debate enduring for centuries. ☺

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# Living with Lab Mice

*A philosopher reflects on their  
unexpected roommates*

BY EVA MEIJER

PHOTOS BY THE AUTHOR

**B**ULLIE WAS THE MOST CARING person in the group. Whenever someone else was ill, she would sit with her and comfort her. Bram and Wezel had the strongest friendship. There was just the two of them after their friends had died, and they did everything together: eating, sleeping, pottering about like an old married couple. They also took up nest-building and created beautiful flower-shaped nests for sleeping in.

Bullie, Bram, and Wezel were three of the 25 ex-laboratory mice with whom I lived between 2020 and 2023. These mice were part of a pilot project for the adoption of small laboratory animals—mice and rats—set up by a coalition of Dutch animal advocacy organizations and Utrecht University, in the Netherlands.

I am a philosopher who writes about the languages and political agency of nonhuman animals. When I adopted these mice, I looked forward to interacting with them and perhaps becoming friends. The mice soon made clear that they were not interested in that. Whenever I put my hand in their house, they looked at it with disgust and tried to bury it. I decided to play music for them, because they did like my voice. When I played songs for them on the guitar and ukulele, I watched them. Through spending time with them, I learned that mice are not the kind of beings that most humans think they are.







**MOUSE FRIEND** Spokie, the longest-lived of Eva Meijer's adopted lab mice. Though she didn't much socialize with other mice, Spokie enjoyed Meijer's company.



# I learned that mice are not the kind of beings that most humans think they are.

Mice are used in experiments because they are small and cheap, because they make lots of babies quickly, and because humans see them as simplistic, mechanistic, and replaceable. In the Netherlands, where I am based, around 200,000 mice are used in experiments every year, and about as many are bred but not used. Nearly all are killed. In the United States, an estimated 10 to 111 million mice are used each year; rodents are not covered by the federal Animal Welfare Act, so exact counts are not made. Yet even though humans use so many mice, we know surprisingly little about them.

This is because the experiments are focused on humans. Laboratory mice are rarely studied to learn about mouse cognition, emotions, or social life for their own sake. Instead they are used to create knowledge about human bodies, minds, and disease. Apart from the many problems of extrapolating from mice to humans, those findings don't always give us a clear picture of mice. For example, mice are frequently scared of male scientists, which may confound observations. The conditions under which mice live also distort insights. Apart from their captivity and boredom, they are often cold.

In order to understand these mice who came to live with me better, I looked for studies about the social lives of laboratory mice: about their characters, friendships, communities, the ways in which they play. I did not find any. There are plenty of studies on capacities like "emotional contagion," or behaviors like "affiliative grooming"—but those studies paint an incomplete picture because they only focus on one aspect of mouse life, and set out to map species characteristics instead of looking at individuals and social relations. Of course, lab mice generally don't live long enough to build a community, and scientists usually view them as objects of a study instead of subjects with a life that matters most to them.

I then looked for studies about the social lives of mice more generally. Again I did not find what I was looking for. There are studies about mouse communication, sex lives, and social structure, but no long-term studies of their communities as there are for, say, chimpanzees or corvids. I decided to write about mice myself.

I am not a biologist or ethologist, and as a philosopher I am quite critical of human-centered ways of getting to know other animals. I turned to the work of ethologists like Barbara Smuts, who lived with a troop of baboons, and Len Howard, who opened her English countryside home to the birds living outside because she wanted to get to know them. They learned to see other animals by attending to them over long periods of time and on their own terms, approaching them as beings who had their own perspectives on life. I decided I would try to do the same with laboratory mice.



**IN ORDER TO FIND OUT** more about the relationships between the mice and to understand their practices I first needed to learn who was who. The first group I adopted consisted of 10 female mice. Each had brown hair. After a few days I began to recognize the differences between them. I made a list of their names and physical characteristics. Some were bigger, like Grote Muis (Big Mouse) and Kleinoor (Small Ear). Other mice were smaller, like Kleine Muis (Little Mouse) and Kraaloog (Beady Eye). Witoog (White Eye) had a white ring around one of her eyes, and through describing them in this way I learned to see who was who. After a while I also began to see differences in their characters. Flankie was always the first to try out new foods and houses. Vachtje was a bit of a loner. Kleinoor and Grote Muis were calm, Kraaloog was feisty and fast.

Slowly I began to understand their forms of expression. They made a *chk-chk* sound when they explored, which expressed a kind of content curiosity. They squeaked loudly while being groomed. When they wanted to be groomed, they had a special movement—holding half of their face flat to the floor—that they used as invitation. Holding their tails straight up meant excitement. Mice who liked each other often sat with the tips of

#### MOUSE HOUSE

Bram and Wezel built an elegant nest.





### EVERY MOUSE IS SOMEONE

Kleinoor was among the first mice adopted by Meijer. Each had their own unique personality; Kleinoor was notably calm.

their tails wrapped together. The mice also had many greetings, like kissing one another on the mouth, intertwining their tails' tips, and aligning their posture with that of another.

Over time I also began to see how meaningful some of their habits and practices were. The first time I clearly saw this was when Vachtje could not run in the exercise wheel anymore because of her tumor. (Many of the mice developed tumors, and not much health care was available for them. This is ironic, given how much we know about their bodies and how much cancer drug research involves mice.) The mice liked running in the wheel; when someone else was already running, they sat next to the wheel and gauged its speed with their hands before jumping in. When Vachtje could not make the jump anymore, she still sat beside the wheel and moved it with her hands.

The mice also changed over time. A simple example is grooming. In the first days after a new group arrived, I only saw them groom themselves, but never one another. They usually began mutual grooming after a week or so—quite long in mouse time—in the shoeboxes in which they slept. As time went on, they became more comfortable grooming out in the open, and they especially liked to use the roof of the sleeping shoebox for this.

# Vachtje was a bit of a loner. Kleinoor and Grote Muis were calm, Kraaloog was feisty and fast.

When they got older, they further developed their practices of care. The first year with each group was easiest: all mice were healthy and happy. But after about a year, they began to develop illnesses—mostly tumors, but they also had strokes. Whenever a mouse was ill, others took care of her. They would sit next to her to support her with their body while eating; healthy mice slept next to mice who were unwell, perhaps to keep them warm. I twice witnessed the mice form a circle around a mouse who was ill. A scientist might write about this as their acquiring potentially useful information about their environment. To me it looked like a circle of care.

They also began taking care of their dead companions. Whenever a mouse died, I left her body in the mouse house, so that the others could understand she was dead and say goodbye. I saw the same response in all three groups. With the first dead mouse, they ignored the body and went on with their business. When the second and third of their companions died, it frightened them. They were shy and stayed in their sleeping houses more than usual. With the fourth death, they began taking care of the body. They first greeted the dead mouse; then groomed her in the same way they groomed their living companions; and then dragged the body to a corner, where they buried the mouse with nesting material and hay. One New Year's Eve I missed Wolkje (Little Cloud) and had to take all the boxes and wheels out of their house before I found her body, completely sealed in with pieces of paper in one of the small play houses.

Of course, I did not just look at the mice. They also looked back and tried to figure out what kind of being I was. Over time we formed habits, like the music ritual, and I shared my food with them. When they were old, they could roam freely in the room where their house was located and were not scared of me, so our contact grew. But they were still mostly interested in one another and I did not form strong relationships with them. This changed with Spokie.





**KNOWING THEM** Lab mice are studied almost entirely for the benefit of humans. How might we understand mice if we observed them for their own sake?

Spokie was the last mouse of the last group. After her friends died, she was too old to match to new mice. She had never been very social and I was glad that it was her who remained, and not someone who was more attached to the other mice and would miss them. Still, I worried she felt alone, and I often sang or spoke to her. She'd then come out of her house to greet me. We also went on trips through my house: I brought her to different rooms and she enjoyed exploring new spaces. She was not fast anymore, and this was in summer, so we also went into the garden, where she could roam through the grass while I sat next to her. At first she seemed indifferent to my presence, but as time passed she stayed close and sat with me. One day she invited me to groom her. She held one side of her face down to the floor and looked at me with the other eye. I recognized this posture from when the mice invited other mice to groom them. So I began to stroke her head and ears, very softly, because that was what she wanted.

# Mice who liked each other often sat with the tips of their tails wrapped together.

**IN ONE OF HER BOOKS** about living with songbirds, Len Howard writes that she cannot make general statements about what kind of animal a great tit is. They all have their own personalities, similar to humans. Howard does not mean that birds do not have common characteristics; rather, she wants to draw attention to the fact that they are individuals, and that defining them in species-general ways risks obscuring their individuality.

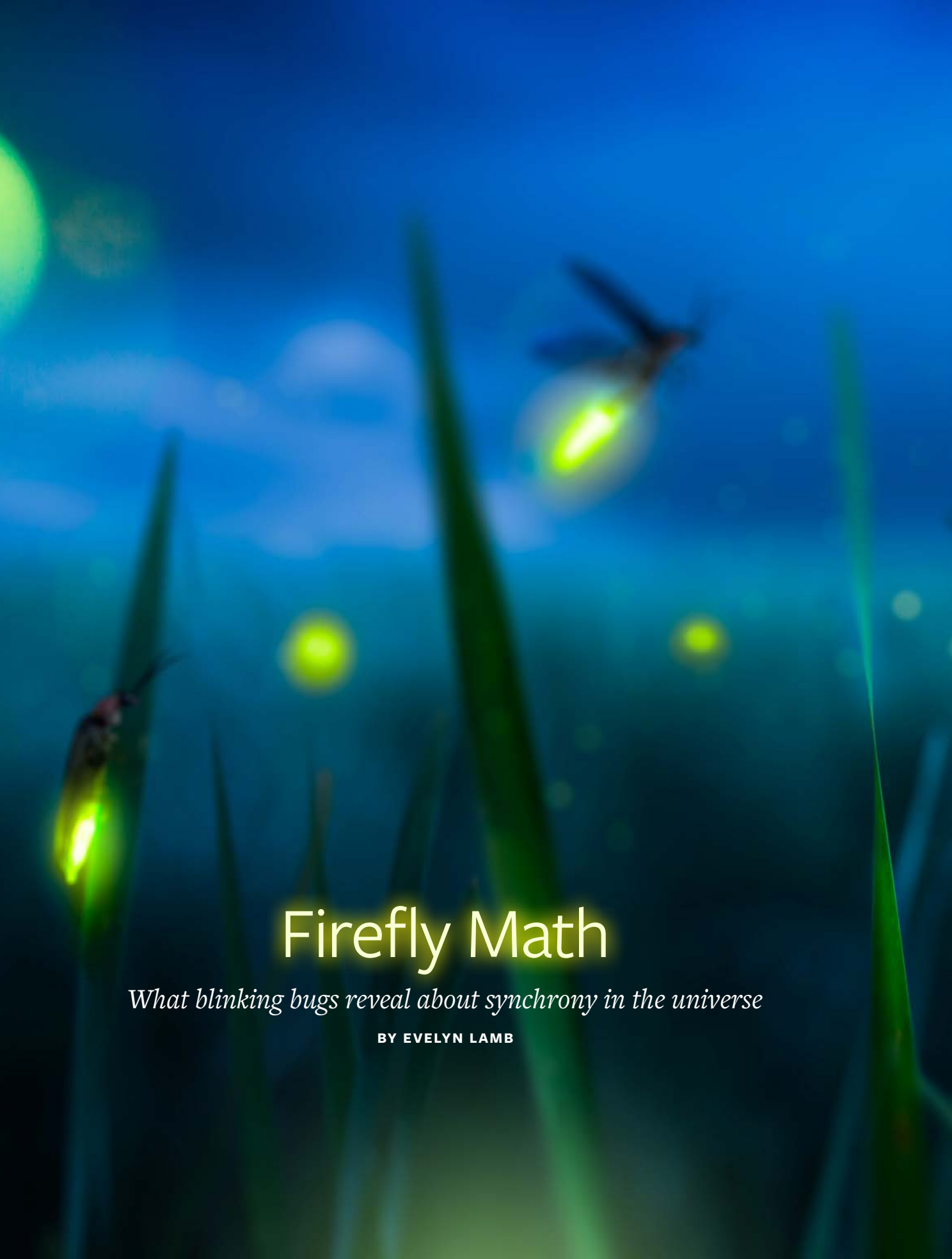
The same can be said of mice. Flankie, Bullie, Spokie, and the others all had their own characters and personalities. At the same time, it is clear that the existing image of mice in human societies and science, as simple, mechanistic, replaceable beings, is entirely wrong—so I do want to make general statements to counter this. The mice who lived with me were deeply social beings, and care was central to their lives. They continued learning throughout life, and kept developing their projects and relationships with others.

All animals, I think, know more or less the same about what matters in life: community, love, care, death. Seeing how the mice lived their lives—not as a biologist or neuroscientist, but as a philosopher and fellow creature to the mice—taught me about life itself. Because their lives are so short, I also witnessed the cycle of life 25 times. First you are young and look for your place in life; then you are strong and work on your projects; then you slow down; and finally you become part of all there is before you were born. The mice showed me how life and death are always entwined, and how thin the thread is that separates them. In the end, we are all vulnerable beings who are here only briefly. The best thing we can do is take good care of one another. ☺

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# Firefly Math

*What blinking bugs reveal about synchrony in the universe*

BY EVELYN LAMB



**O**N A STICKY, late-spring night in parts of the eastern United States, you might witness one of the wonders of the animal kingdom: a constellation of hundreds of fireflies blinking in unison. Only three of the 130 or so species of fireflies in the U.S. are known to exhibit this synchrony, and they do so for only a few weeks a year.

The displays have gotten so popular that the Great Smoky Mountains and Congaree National Parks hold lotteries for the privilege of watching the fireflies in the parks during their peak. If you are lucky enough to win that lottery, you might run into Orit Peleg, a computer scientist and biophysicist from the University of Colorado Boulder, setting up cameras to record the display with some of her research collaborators.

The data she and her colleagues have collected over the past seven years has shed new light not only on how and why fireflies synchronize, but also on the mathematical properties of synchrony across biological and humanmade systems, in the contraction of heart tissue, audience applause at the end of a concert, even the electrons of a superconductor. “It’s like seeing all of these mathematical models come to life,” says Peleg.





“Once all of these experiments are running, there’s downtime where we just have to wait and watch the fireflies.”



Peleg first learned about firefly synchrony as an undergrad physics major, when she was introduced to the work of Steven Strogatz, an applied mathematician renowned for models of synchronization in nature. In his writing, he drew parallels between the synchronous displays of fireflies and the alignment of electrons in a superconductor, a material that allows electricity to flow through it indefinitely without energy loss. Later, as a postdoctoral researcher, Peleg used physics to explore the complex dynamics of living systems, including honeybee swarms and protein folding patterns. When she started her own lab, she recalled Strogatz’s example of the fireflies and was surprised at how little empirical data she could find about the phenomenon, so familiar to children around the world in spring and summertime.

Peleg and her collaborators were soon trekking into the forest with tents, cameras, nets, and other equipment to capture the glittering displays of the fireflies. “It’s both the best time of the year, and at the same time the most stressful time of the year,” Peleg says of her time in the field. They only have a week or two to collect data, and if something goes wrong, they have to wait until the next year to try again. Fireflies don’t observe the Gregorian calendar. Their emergence each year varies based on weather conditions and other unpredictable events. The researchers rely on park entomologists and amateur scientists to help them decide when to make the trip out, but they don’t always get a lot of advance notice.

**WESTERN SCIENTISTS WERE SKEPTICAL** when they first heard reports of synchronous firefly displays from Southeast Asia in the early 1900s. They dismissed these displays as an illusion or a statistical coincidence. Then in the 1960s, American biologists John Buck and his wife and collaborator Elisabeth conducted some of the first scientific studies of firefly synchrony.<sup>1</sup> The pair captured fireflies while traveling in Thailand and took them back to their hotel room to observe them. Once the fireflies settled down, they began blinking, first separately and then gradually together in groups of two or three, until eventually the whole group blinked in unison. These first, informal observations paved the way for decades of more rigorous investigations into firefly behavior by the Bucks and other researchers.

Since then, firefly synchrony has become a popular topic of study not just in biology but also in mathematics. Blinking fireflies proved a compelling case study for various mathematical models of so-called coupled oscillators. An oscillator is any object that cycles between states in some way, like the tick of a metronome or the blink of a light. Oscillators are said to be coupled if their oscillations influence one another. For instance, metronomes that are sitting on a platform suspended in the air will often lock into the same rhythm.

In 1975, Kyoto University physicist Yoshiki Kuramoto developed the Kuramoto model for coupled oscillation, which explained how a large number of individual actors with their own natural frequencies could spontaneously synchronize. In his model, oscillators



**LIGHTNING BUG** The fireflies pictured here belong to a species known as *Photinus carolinus*, which computer scientist and biophysicist Orit Peleg has studied. When certain population densities are reached, the males of the species will blink in unison to better attract females in their vicinity to mate. But the flashes aren't actually 100 percent synchronous, Peleg has found. They propagate like a "wave" you might see at a crowded sports stadium.

that were out of sync with each other would adjust their timing slightly based on how close they were to being in sync. Two oscillators that were only slightly out of rhythm would lock in together quickly, while it would take longer for oscillators whose rhythms were more distinct.

Kuramoto's paper was purely theoretical: He was trying to streamline the mathematical approach that another researcher, theoretical biologist Art Winfree, had taken to describing synchrony in biological systems. "At the time, I had no idea that my model could realistically describe synchronization in natural or manmade systems," Kuramoto wrote in an email.

But in the 1990s, other researchers started publishing papers that showed that the Kuramoto model for coupled oscillators could describe real-world situations such as the motion of electrons in superconductors and, yes, swarms of synchronous fireflies.

Even hidden motions in our own bodies. "Having a new model system where you can really study synchrony in quite granular detail is a good thing," says Bard Ermentrout, a mathematical biologist at the University of Pittsburgh who has worked on the mathematics of several different examples of coupled oscillators in nature, from fireflies to neurons to the intestinal pulsing that pushes material through the gut. "It turns out there's this really cool intrinsic pacemaker system in the colon," Ermentrout says. It may not be the most glamorous example of biological synchrony, but "if that's broken, then you die," he says.

When Peleg started studying fireflies, two mathematical models already existed for firefly synchrony—not just the Kuramoto model, but also another known as integrate-and-fire, which is based on neuron firing and takes into account the length of a firefly's light burst and the gap of darkness between bursts. Peleg felt that





# Among the thousands of firefly species in the world, only a handful blink in sync.



researchers needed better experimental data to verify that the models fit and to help refine the way they work. Previous researchers had made still and video recordings of firefly swarms, but three-dimensional information about firefly movements was lacking, so they could not accurately determine the distances between individual fireflies in a swarm. Using multiple cameras to record the firefly displays, Peleg and her colleagues were able to create more accurate reconstructions of the flickering swarms of insects, which allowed them to get a clearer view of how and when synchrony was happening.

**PELEG AND HER TEAM** usually spend the first night of their trip staking out likely firefly haunts so they can set up their equipment where the fireflies will be, no matter how out of the way those places are. The insects don't necessarily choose to hang out in the spots where researchers can observe them most easily. "A few times, we were optimistic and put the cameras in places that were convenient for us, Peleg says, "and the fireflies just didn't show up." Still, she relishes the chance to sit in the parks and take in the light show. "Once all of these experiments are running, there is kind of a downtime where we just have to wait and watch the fireflies," she says. "No complaints there."

Synchronization is a relatively rare behavior for fireflies. "It's weird," says Sara Lewis, a firefly researcher at

Tufts University and author of the book *Silent Sparks: The Wondrous World of Fireflies*. "The behavior has evolved many times, independently, in different lineages of fireflies that are not related." Among the thousands of firefly species in the world, only a handful blink in sync. A family of fireflies with dozens of species generally only has one or two synchronous species. Scientists still do not understand why synchrony has evolved only in these isolated cases. "Why these species and not other species?" Lewis asks. Does it confer an advantage on species with particular physiological characteristics or habitats? Some researchers have conjectured that it helps the insects mate en masse in places where visibility may otherwise be low, such as tropical swamps.

While both male and female fireflies flash, only the males synchronize. In one species Peleg has studied, *Photinus carolinus*, males generally flash on the wing to attract the attention of females, who perch in the vegetation. The females occasionally flash back in response, a gesture meant to entice the males to come mate with them. *Photinus carolinus* females are most likely to respond when males are synchronized.

In a 2021 paper, Peleg and her coauthors Raphaël Sarfati and Julie C. Hayes used their reconstructions to measure how the density of fireflies in a particular area would affect their synchrony.<sup>2</sup> If a few fireflies are spread out over a large area, they probably won't end

up synchronizing. As more fireflies congregate in the same space, it becomes more likely that they will start to flash in sync. Peleg, Sarfati, and Hayes came up with a critical density threshold fireflies need to attain to start synchronizing. Their study also addressed one of the most pressing scientific questions about firefly synchrony: *How* do they do it?

The group found that “synchronous” firefly flashes aren’t actually 100 percent synchronous. They propagate a little like “the wave” in a crowded sports stadium and sometimes run into physical obstructions such as trees that break up the synchrony, supporting one theory that fireflies use visual cues to start synchronizing with each other. Ermentrout hopes the work will help clarify the radius of influence each individual firefly has on a group. “How close does another firefly have to be to influence the rhythm?” he asks.

In 2002, Kuramoto and his coauthor Dorjsuren Battogtokh discovered that under certain conditions, the coupled oscillators in the Kuramoto model could exhibit strange behavior, which has since been dubbed a “chimera state.” In a chimera state, some of the oscillators are locked in phase with each other, while the rest are either out of phase or completely asynchronous. Even more than two decades after the phenomenon was given a name, the way chimera states function remains mysterious. The biological significance of such states is not clear yet, either, although some researchers have found evidence that epileptic seizures display aspects of chimera states, so a deeper understanding of them could inform treatments for epilepsy and potentially other diseases.

Peleg and Sarfati published a 2022 paper describing these chimera states in swarms of fireflies in Congaree National Park, an old growth river swamp forest in South Carolina.<sup>3</sup> Observing a chimera state in a natural system is alluring because, despite the Kuramoto model’s prediction that they will occur, it has been hard to find tangible evidence of such behavior in nature. “If we know that fireflies do something weird,” Peleg says, “we can try to check whether all of these other systems are doing that as well.”

Other researchers are skeptical. There’s a fine line between a chimera state and a few odd fireflies that are out of step with a larger group. “We really don’t see it,” Ermentrout says. “It’s hard to define a chimera state

unless you’ve got really a lot of oscillations.” He doesn’t think the number of fireflies that have been observed out of sync with the group is sufficient to truly call the phenomenon a chimera state.

But Peleg believes that even though the numbers they observed are small, the persistence of the behavior over time makes it a good example. “These two groups coexist for a duration that is much longer than the interval of the individual flashes,” she says, around half an hour. One of Peleg’s students is currently working on experiments to further probe the conditions and mechanisms that might produce chimera states in firefly groups, using LEDs to influence their rhythms.

For decades, global firefly populations have been declining, due to habitat loss, light pollution, and pesticide use. If it turns out that synchrony confers a mating advantage on males of synchronizing species, population declines may have a vicious cycle effect: Fewer fireflies could lead to lower population densities, which would decrease synchrony and therefore mating success.

Peleg is interested not only in how her work can help us understand the mysterious rhythms and mathematical models that govern some natural systems, but also how we can protect these glowing bugs. 🦋

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## REFERENCES

1. Buck, J. & Buck, E. Biology of synchronous flashing of fireflies. *Nature* **211**, 562–564 (1966).
2. Sarfati, R., Hayes, J.C., & Peleg, O. Self-organization in natural swarms of *Photinus carolinus* synchronous fireflies. *Science Advances* **7**, eabg9259 (2021)
3. Sarfati, R. & Peleg, O. Chimera states among synchronous fireflies. *Science Advances* **8**, eadd6690 (2022)





# Manta Rays at Play

*Underwater, the mantas circled Evie, ready for a game.*

*A work of fiction.*

BY RICHARD POWERS



**IN A CRYSTALLINE AFTERNOON** in a calm patch of the South Pacific with the sun coming hard across the sky and nothing on any horizon but endless saline blue, a gangly 92-year-old woman pitched backward over the gunwale of a 5-meter dive boat and sank wakeless into the sea.

Curled up like a fetus from the plunge, she relaxed, unfolded, and surrendered to sinking. She dropped face-upward through the bright top layers of the photic zone. The weight around her waist pulled her down. Pressure built against her frail frame, and the surrounding water darkened. She looked upward through that undulating membrane between two worlds as it receded 10, then 20 feet above her.

For decades, Evie Beaulieu had nursed a secret wish to die diving. But not today. Today, she had one last task to finish. She was on this island for a single reason: To compile another book before she died. To try one more time to make the land dwellers love the wild, unfathomable God of waters. To give the smallest hint of creatures so varied and inventive and otherworldly that they might compel humility and stop human progress in its tracks with awe.

One of those creatures had brought her to this reef, a massive-brained, flattened torpedo with a skeleton half the density of bone, a fish who achieved stunning speeds with one beat of its huge wings, who put its truck-sized body through graceful loop-de-loops, grazed in geometric formations, lofted its thousands of pounds into the air, and played in curiosity with the world around it as with a toy. A creature born swimming, and swimming ceaselessly every moment of its life, even as it slept. If she could tell someone, evoke even one reader's wonder and love ...

Eight years shy of a century, the last person ever to have used the earliest aqualungs sank faceup through the sunlight zone. The girl was trapped now in a failing body, hammered thin by use, her muscles wasted, her bones ready to snap at the slightest impact. But here, in water, she was strong and well. Here, in the warm seas of the Tuamotus just out of sight of land, all she had to do was breathe.

She did just that, sinking down toward the edges of the submerged seamount. Below her, an active cleaning station she called Makatea Spa teemed with more workers and clients than most successful urban businesses. Cleaner shrimp and wrasses removed the parasites, while dozens of customers waited patiently in the lobby of this combined surgery, dental office, and health resort. How a parliament of so many varied species managed to form these ad hoc, mutualistic communities Evelyne still didn't know, despite a lifetime of watching. But, gliding into the site, she could see the subtle acts of retaliation and self-policing that stabilized the rules of the win-win game. Despite occasional cheating—more by cleaners than clients—the honor system worked. Creatures that anywhere else would have ended up as prey swam unharmed into the jaws of predators who held still while being serviced, even letting the cleaners steal little bites out of them. To Evelyne's eyes, the safe boundaries of this neutral DMZ resembled the magic circle of children's play.

Her pulse rose: A handful of reef manta rays—*Mobula alfredi*—hovered above a coral outcrop, faced into the current, waiting to be cleaned. A few more traced graceful circles farther back in line. Evie made out many old friends. Kaute, Sandy, Tomo: every manta had a unique pattern of spots on

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*The ray hovered above her. He drifted like a stealth jet in the world's slowest flight.*





their white underbellies, ventral patterns as distinctive as fingerprints. A serpentine mark just above the right pelvic girdle confirmed Mona, one of her favorites, who turned and floated up to say hello.

It happened more often now, when Evelyne came to the Spa. One of the mantas circling for their turn would sniff her out, curious to learn what this strange daily visitor to the seamount wanted. The lateral lines that ran along the sides of their bodies detected Evelyne's presence at a distance. Jelly-filled canals beneath pores just behind their eyes could feel her magnetic field.

Whatever senses were at play, more than one manta recognized her. Evie was sure of that. After all, these were beings who recognized their own selves in a mirror, something that dogs and cats and even some of the smartest primates failed to do. Mona slowed down around the familiar visitor, beating her fins. She banked and came about, wanting to socialize. Beaulieu, for her part, waved back to Mona, settling on a series of repeated gestures that she hoped would convey, Yes, it's me, hello, I know you, too.

She lost herself in watching, the great pleasure of her life. So her whole body jerked in alarm when a great shadow passed over her, darkening the water. She twisted around and looked up to see a creature with a wingspan wider than the house she now lived in gliding above her head: *Mobula birostris*—the giant oceanic manta ray—perhaps 30 years old and 6 meters across from tip to tip. Beaulieu watched it through flawless tourmaline—a massive male whose clasper extended well past his pelvic fins. She had glimpsed this leviathan two days before, but from a distance. Here he was, so close she could feel his wake: a great chevron-morph goliath she called the Loner.

She held her breath. He drifted above her, a floating refuge for scores of other beings. Two species of remoras clung to him, hitching rides. Copepod colonies camped out all over his surface and inside his gills and spicules. Young golden kingfish surfed the pressure waves pushed forward by the great ray's bow.

So little was known about the giant oceangoers. They were much larger than their reef cousins. Near to land, at a way post like this, they were often solitary. They roved throughout the band of tropical waters that circled the Earth. Their ampullae of Lorenzini sensed the Earth's magnetic fields and the fields generated by great currents, keeping them on a straight course through vast tracts of featureless ocean. But how far they migrated and the paths they took were so much mystery. Sailors talked about great feeding aggregations in the middle of nowhere, thousands of miles from land.

It saddened Evelyne that she would never be able to verify that. But this one, the creature in front of her at this moment: this gigantic Loner, she could verify. The ray hovered above Evelyne in the water column, blotting out a disk 20 feet across. He drifted like a stealth jet in the world's slowest flight. Impossible not to see him as a gigantic,



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*Play was evolution's way of building brains, and a giant oceanic manta sure used it.*

oceangoing bird flying through the water. No wonder that the people of these islands had long considered these creatures sacred—the spirit guardians and promoters of grace, wisdom, and flow. From underneath, looking up into the filtered sun, she found the Loner's pale belly surprisingly hard to make out—a ghost as diffuse as his black dorsal silhouette would appear to anyone looking down on him through the darkening waves. Countershading—Thayer's law: a trick that fish had used for the last 150 million years to make themselves disappear both into and against the light.

The camouflage that had worked for millions of years was no longer enough. Left alone, a manta might live for four decades or more. But life expectancy was plummeting. The odds were good that the gills of many of the creatures now grazing off this secret seamount would end up in sacks sold in markets in Guangzhou and other Chinese ports, peddled as medicines, but which did nothing at all. What was left of a ray after its chunks of feathery gill plates were cut out would be used as bait or fed to increasingly hungry coastal humans. Mantas were disappearing from places throughout the Pacific where they had once been numerous. Even now, not far from where Evie swam, shadowy boats with captive crews were busy poaching rays, and the impoverished country had no money to police the illegal trade.

So stunning was the Loner's silhouette as he passed overhead that Evelyne gasped into her air hose. Her gasp turned into bubbles that rose through the water and tickled the manta's underside. The bubbles trickled upward into his gill slits. The Loner proceeded to cough the air through his branchial filaments and out of his own mouth. The burst of bubbles dislodged all kinds of stuck particles, sending the cleaners into an orgy of feeding.

The ton and a half of cartilaginous fish circled back and slowed just inches above Evelyne's head. Startled, she blew another burst of bubbles. The ray drew them into his gills and blew them back out. There were no more trapped particles to dislodge, but the Loner persisted. What had been a purely functional maneuver became something else: novelty-seeking, or enjoyment of the feel of the air's caress.

The fish banked back around for one more go. Approaching, he studied her with his huge doe eyes. Evelyne exhaled another column of bubbles. This time, the Loner simply swiped at the bubbles with his left pectoral fin for the sheer pleasure of dispersing them.

The behavior floored her, although a part of her knew it shouldn't. Mantas had a brain-to-body ratio far higher than most fish, as high as many mammals. A giant oceanic manta ray brain was the largest and heaviest of any animal that breathed water. The telencephalon and cerebellum—parts of the brain devoted in mammals to higher functioning—were enormous. And this remarkable brain was wrapped in a rete mirabile—a “miraculous net” of blood vessels that would keep the Loner's neurons warm to depths of almost half a mile.

Years of study had convinced Evelyne that mantas were far smarter than the world suspected. She had spent too many decades of close observation to be cowed any longer by the prohibition against anthropomorphism. What began, centuries ago, as a healthy safeguard against projection had become an insidious contributor to human exceptionalism, the belief that nothing else on Earth was like us in any way. At her age, Evelyne Beaulieu had no more time for demure self-censorship. A good empiricist, she felt no qualms about giving the behavior in front of her a name. The way the Loner toyed with her air bubbles was clear enough. Call it what the evidence suggested. Call it what it looked like: The giant bird-like fish was playing.

Play was evolution's way of building brains, and any creature with a brain as developed as a giant oceanic manta sure used it. If you want to make something smarter, teach it to play. No one denied the play of mammals. She had played keep-away with dolphins off the Caymans. She'd watched bears wrestle and lions dance, a colt and an elk calf play catch, and chimps bluffing each other in something that looked like three-card monte. For years the family dog had bowed to her, begging her for a romp.

But even fish played: She needed to tell the world this, before she died. Captive cichlids played hockey with pebbles in their tanks. Bettas enjoyed tag. She'd seen cuckoo wrasses chase laser pointers around long after the sport offered nothing but exhaustion. And now a manta with no more need of her air was coming back for more.

Above Evelyne, the Loner climbed so steeply that the flat disk of his body curled over into a full backflip. The flip allowed the titan to see behind and above him, but surely the acrobatics were also fun. The great beast slipped from the loop into a barrel roll that brought him back around and pointed him at Evelyne. Ready or not, here I come.

Evelyne steadied herself as if for a pick-and-roll, and as the fish passed by once more above her, she spoke into her mouthpiece, "Your move!"

The Loner caught the bubbles of her words under one fin and held them there for as long as he could. Evelyne could almost hear the creature echo the giggle that tore out of her. Nothing in life matched a game of catch between cousins whose last common ancestor had lived 440 million years ago. ☺

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A golden retriever dog is shown from the side, standing on a pile of rubble and debris. The dog's fur is light brown and slightly damp. The background is a pile of broken concrete and bricks, suggesting a disaster site. The lighting is warm, possibly from the setting or rising sun.

# AI-Powered Rescue Dogs

*New tech might help humans find others in need faster*

**BY SARAH SCOLES**



**A** **BLUR OF GOLDEN FUR** and exuberance, the search and rescue dog bolts from a handler's side and carves a wide arc through a patchy field in Missouri.

The dog, who is part of an elite urban search-and-rescue team, knows what her duty is: Find a scent trail, locate the person at the other end of the odor, and alert her handler—guiding them to someone who might be lost, trapped, injured, or dead.

But this isn't just any training session: It's a test of new technology—a new relationship, really, between artificial intelligence, animals, nuts-and-bolts technology, and humans. In this test, AI-enabled tools are being put through their paces to see if they can enable search-dog teams to help rescuers find people faster after a catastrophic event, such as an earthquake or tornado.

High above the scene hovers a drone, gathering information about the dog's movements. Combining this data with stats on the location, including its topography and weather conditions, AI-powered software can make predictions of where someone in need of rescue is most likely to be. This information in hand, the human handler in a real rescue could then send drones equipped with cameras and infrared sensors out ahead of the dog—faster and more efficiently than either mammal could go—to pinpoint the victim.

On a tablet displaying an overview of the trial, the area is divided into a grid, which turns into a high-tech game of “hot-or-cold.” Each square within is shaded to represent the probability that the person they're searching for is in that area. Purple-blue is cold, green is getting warmer, yellow is hot. A blue line traces the dog's trajectory across the area. The pup cuts west, then loops back around to the handler. Soon, after the canine sets off again in a more pointed direction, the line representing her path becomes yellow: The program has inferred from the dog's behavior that they've caught the scent. Squares of the grid start shifting hue in response to the dog's movements, adjusting and refining the predictions of where the hiding human might be. The ones near the victim shift toward yellow as the dog gets closer.

The pup is helping to develop the Collaborative Intelligence for Olfactory Search Missions Integrating Canines and Technology (COSMIC-T). Created by an AI company called Scientific Systems, the technology aims to combine biological dog-data with digital info,

using humans as a bridge between the two—a collaboration that could help save lost hikers, victims of natural disasters, or soldiers in war by locating humans in peril faster than animal, human, or drone could.

The work sits partly within a field of study sometimes called “animal activity recognition,” which uses instruments such as motion sensors, now often coupled with AI, to classify what an animal is doing. It also incorporates “latent state inference,” which in this case works to interpret more indirect or hidden canine cues. The human team has applied the combo to search and rescue operations—to understand and respond to a dog's signals that they've caught a scent, and are on the trail of a “gotcha.” The same technology could also be useful for tracking down fugitives or suspected criminals, since a human scent is a human scent.

Although researchers have studied the ways that the combination of AI and animal behavior might aid search and rescue, a 2023 review paper found that fusing data from different sensors to understand what animals were up to, in general, “is still in its early stages and has yet to be fully explored.” As Humberto Pérez-Espinosa of the National Institute of Astrophysics, Optics, and Electronics in Mexico, and an author of that review, says, “Compared to advancements in interpreting human behavior using AI and sensor data, the study of canine behavior is still in its infancy.”

**FOR DECADES, DOGS** and their superior sense of smell—combined with their athletic prowess and endearing desire to please—have been essential to search and rescue teams. As early as World War I, the Red Cross trained dogs to find wounded soldiers, calling them “mercy dogs.” There were, of course, no digital algorithms or drones back then, and the analog seek-and-finds were not as efficient as they have become nearly a century later.

# Some of the magic is in the human-dog rapport.

People involved in search-and-rescue or medicine typically refer to the initial period after a person experiences a traumatic injury as the “golden hour”: the short window in which life-saving care tends to be most effective. People needing search or rescue who may not be gravely injured are still at critical risk because every minute that ticks by prolongs the time they might be subject to the elements and surviving without food or water. In December, for example, two men died of exposure in a Washington State forest and were found only after a three-day search involving human, dog, and drone search capabilities.

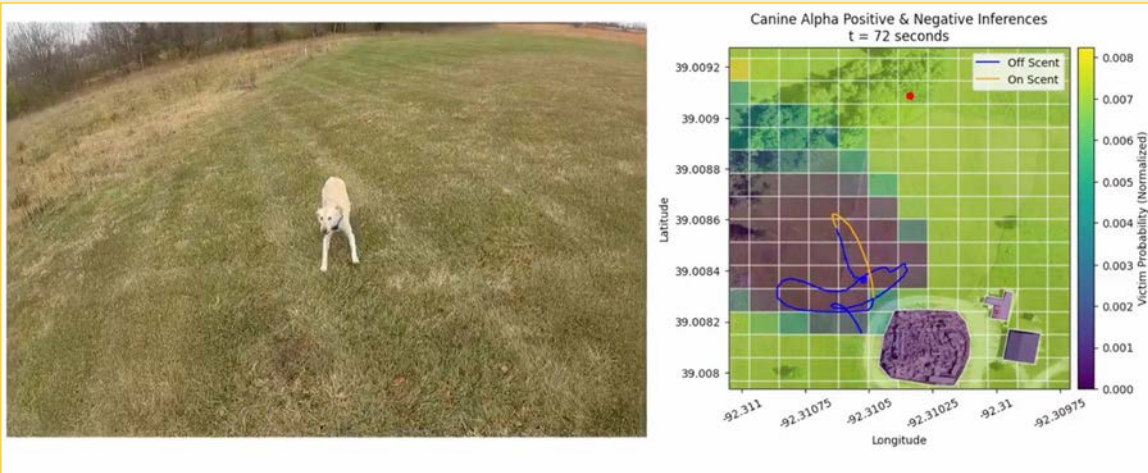
Humans still haven’t found a way to replicate a canine’s role in the search process. “We’ve spent hundreds of millions of dollars trying to make a sensor that is as good as a dog’s nose, and we’ve never gotten close,” says Mitchell Colby, the group lead for AI and machine learning at Scientific Systems. Beyond that, some of the magic is in the human-dog rapport. “AI is making great strides, but I have not seen any AI that can compete with the intuition of an operator with a lot of experience.”

Nevertheless, the handler-dog pairing can be somewhat inefficient. Each dog has one specific human partner, who has often raised them since they were a puppy, spending 800 to 1,000 hours of training to get them certified—plus countless hours after that practicing and actually saving people.

One key outcome of all that time together is a close, instinctive connection, in which a handler knows that, say, their dog lowers their body slightly when they’ve sniffed the smell they’ve been searching for. Success is in the dyad, says Jeff Hiebert, president of the organization Search and Rescue Dogs of the United States. “They rely just as much upon the handlers as the handler does on the dog.” Still, our eyes can’t parse all their movements and bodily cues to make as much sense of the shifts as AI-powered observation of the dogs can.







**TECH ON THE TRAIL** A heat map powered by AI analysis and drone imagery helps search-and-rescue teams of dogs and their handlers pinpoint the most likely location of a human in need faster.

And the intense dog-handler relationship makes scaling up canine search difficult. Scouring an earthquake-leveled block of apartment buildings for survivors is slow going if you need one particular human paired with one particular dog. “It gets really scary when we start to think about these large-scale disasters,” says Colby.

**THAT ONE-PERSON-ONE-DOG LIMITATION** was the inspiration for the exercise taking place in the Missouri field.

Colby had worked on algorithms that direct drones—and even future space robots—to work collaboratively. But what if an algorithm could improve collaboration across the biology-technology divide—and even a species one? So he came to the idea of incorporating humans, animals, and drones, augmented by AI, that could be useful in saving soldiers or civilians during catastrophes. He pitched it to the Defense Advanced Research Projects Agency (DARPA), a research arm of the U.S. Defense Department. DARPA was interested. According to Matthew Marge, a DARPA program manager, it continues the tradition of the agency’s Information Innovation Office to investigate human-machine melding—a goal first laid out in the 1960s by former DARPA director J.C.R. Linklider. “How can humans and

machines find symbiosis and achieve more together than they can separately?” asks Marge. “This type of project gets at that essence.”

After years of development, Colby and the Scientific Systems team built drone software that can perform “canine latent state inference”: basically, watching a canine scour the Earth, and inferring whether it is actively following Timmy’s scent to the well, or still seeking that trail. Then, also borrowing from the field of movement ecology, they outfitted dogs with GPS-enabled vests, to precisely watch their motion. “If an animal is trying to find something based primarily on its nose, how does it move through the environment to optimally use that sensor?” Colby asks.

The dogs are also kitted out with a microphone and speaker, allowing the humans to hear the dog’s barks or other audible alerts, and for handlers to give commands back.

The initial stages of the project tracked a canine member of the Missouri Task Force One as they jogged, snuffled, sprinted, and barked, beginning in 2018. The search team kept specifics—like the dog’s name, and other potentially biasing details—from the AI team so they wouldn’t have insider information that might affect their analysis. Colby and team used AI-driven software to ingest and interpret that behavior, so it

# Humans still haven't found a way to replicate a canine's role in the search process.

could learn to predict whether an animal is searching for a scent or actively on the trail. In the early test, the dog-human-drone-software team found a simulated victim six times faster than the search team would have without the AI.

Missouri Task Force One helped the team gather data for four years. From 2022 to 2024, they furthered this theory of dog-mind: To make sure the early dog behavior that trained the AI was more broadly applicable, the researchers tested it with dogs whose movements hadn't been part of the early training data. Once the AI-enabled software determined that the dog caught a smell, it combined that with environmental data, such as weather and wind models—inferring, for instance, that if there's a north-south breeze, and a dog is on the scent, the victim probably lies north of the dog. Autonomous drones can then make their own way in that direction, homing in on the person faster than if the dog had to lead a trotting human to them, or if the drones were searching without canine-computer guidance. Overall, depending on the specific environment of the test, the mock victims were located five to 10 times faster than they would have without the synthetic help.

Unlike traditional search and rescue—which relies on the one-to-one pairs—this approach can provide understanding of the behavior of numerous dogs, their varied behaviors, and their overall environment all at once. And with multiple animals' inputs, rescuers can seek many victims at once. “If you have multiple canines moving through the environment, and some are hitting and some aren't, you can combine all that data and get much tighter areas where you think victims might be,” says Colby.

Combine that ability with a swarm of small drones, all of which can communicate with each other, as Colby and his fellow engineers hope to do, and rescuers stand an even better chance of finding someone in those crucial early times.

**BEYOND HELP FOR HUMANS** at risk, says Pérez-Espinoza, smart sensor systems can also make sure the dogs themselves are doing okay during a search. “These missions are physically and emotionally demanding, and it is needed to monitor a dog's physiological and behavioral state in real time,” he says.

In the test in the Missouri field, watching the screen as the yellow dog and its yellow line converge with the red dot, it's easier to see this future materializing. As the dog approaches the northern end of the map and slows down, the square they're in suddenly turns yellow, too. The highly trained animal is right on top of her target: contact!

Of course the dog found the hidden person: That's what search dogs do. But the watchful drone, in its way, understood where the dog was heading before the dog did, and passed that information on to help help arrive sooner. ☺

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# How Animals Understand Death

*Intimations of mortality are not ours alone.*

BY BRANDON KEIM



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**OW DO ANIMALS** understand death? That is the question animating this story, which convention dictates I start with an anecdote. But which one?

While working on the story a friend told me how his dog saw his closest canine friend run over; the dog becomes disconsolate and agitated whenever they pass the street where it happened. My algorithms surfaced a story about a grief-stricken widower goose who found new love. Someone I follow on social media argued that it's ethically acceptable to kill animals because they don't know what death is. I read about a primatologist who runs an animal sanctuary in Costa Rica; every year, a monkey she rescued brings her latest baby to the sanctuary for introductions, but one year the monkey brought a dead baby. Perhaps she hoped a human who once helped her could help again. There was nothing the primatologist could do, though, and after several hours the mother monkey, seeming to admit defeat, screamed.

I read dozens of scientific papers—about a mother dingo who carried her dead pup for days, elephants who appear to bury their dead, dolphins who would not let a deceased podmate sink—and debates about how those behaviors should be interpreted. I often did so while cradling my cat Maya, then dying from kidney disease, and thought sometimes of Ingmar, my cat who died last winter from cancer. On the final night of her life, her body hollowed, she summoned the energy to visit her favorite spots, as if paying them a last visit. I thought often about the inevitable death of those I love, which troubles me constantly. I thought sometimes about my own death, which for now is less of a concern. I attended the passing of a goat named Caramel at the sanctuary where I volunteer. Goats have very large pupils, and near the end, as he lay on his side, they were like galaxies.

ILLUSTRATION BY MYRIAM WARES



# How much of what matters most in our experience of death is found not in what is unique to us, but in what we share?

The conventional wisdom, among scientists and much of the public as well, holds that animals know little about death. They perceive it, obviously, and may distinguish between dead and alive, but do not grasp it. When a rabbit runs from a fox, then, they flee pain rather than the end of experience. The successful fox, for his part, knows that his prey is immobile, not that they have ceased living. They have no concept of death; it is not part of their mental models, much less a source of anguish or concern or motivation. Or so the thinking goes.

“Mortals are they who can experience death as death. Animals cannot do this,” wrote the philosopher Martin Heidegger. “The knowledge of death is reflective and conceptual, and animals are spared it,” pronounced anthropologist Ernest Becker in *The Denial of Death*. Becker was notably contemptuous of animals—“Inside they are anonymous,” he wrote. “They live and they disappear with the same thoughtlessness”—but even Charles Darwin, who embraced the mental commonalities between humans and other animals, thought them incapable of understanding that they could die.

For all that people now appreciate the minds of other animals, understanding death has remained a clear divide. In the last few years, though, more scientists have turned their attention to the subject. They argue that some exceptionally intelligent creatures can indeed comprehend death. The comprehension

might be rudimentary compared to that of a typical 21st-century adult, but it’s close enough to blur the divide. And some researchers and scholars want to go even further: Understanding death, they argue, is not so complicated, is meaningful even in simpler forms, and may be shared by many creatures rather than just a few.

Far from being a divide, a knowledge of death may be something we have in common with other animals. Rather than framing this in terms of how their understandings resemble our own, we might consider how ours resemble theirs. In doing so we are confronted by a question with implications for how we relate to animals, and indeed to ourselves: How much of what matters most in our experience of death is found not in what is unique to us, but in what we share?

**IN LATE NOVEMBER OF 2008**, Pansy, the elderly chimpanzee matriarch of a small troop living at a safari park in the city of Stirling, Scotland, fell ill with a respiratory virus. She was already in her 50s—ancient for a chimpanzee—and not strong enough to recover. Patsy started nesting on the ground instead of climbing up to the chimps’ usual sleeping platforms. The other chimps followed suit and started sleeping on the ground beside her.

An afternoon came when Pansy clearly wouldn’t live much longer. She found the strength to pull herself up

to her platform one last time, lying down in a nest her daughter made the previous night. Her breathing was now labored; the end was near. The chimps' caretaker thought about removing Pansy from the group and euthanizing her, but decided that would be traumatic. He also remembered the video cameras installed over the platforms for a research project on chimpanzee sleep patterns. He turned them on, thus recording the chimpanzees' behaviors at the end of Pansy's life and the hours following her death.

Chimpanzee deaths had been observed a few times before, but never in such intimate detail. "When we looked at the videotapes, I was just stunned," recalls James Anderson, a primatologist at Kyoto University who studies primate cognition. "Nobody had ever seen this precise moment, and it was clear that the surviving chimpanzees understood that something momentous had happened."

As night fell, the three members of Pansy's small troop were unusually attentive. They groomed and caressed her with unusual frequency. They peered into Pansy's face as her breathing slowed and then stopped, at which point they gently shook her body. One of them, named Chippie, pounded on her chest—and then, when Pansy did not move, ran away. They slept poorly that night; Rosie, Pansy's daughter, stayed up late and then slept beside her mother's body, while the other two chimps huddled together and groomed one another as much that night as they would over the course of a month. Chippie "attacked" Pansy three more times—although those interactions could just as easily be interpreted as denial or anger, or an attempt to rouse her, wrote Anderson and colleagues in an analysis of the event, which was published in the journal *Current Biology*.

The next day zookeepers removed Pansy's body. The chimps were "profoundly subdued," wrote Anderson's team, and for a week afterward they avoided the platform on which she had died. For weeks after that the chimpanzees remained subdued; they were lethargic, ate less than usual, and were unusually quiet. By all appearances they seemed to be grieving—not just the absence of Pansy, but her *death*.

"Without death-related symbols or rituals, chimpanzees show several behaviors that recall human responses to the death of a close relative," wrote the

researchers. "Are humans uniquely aware of mortality? We propose that chimpanzees' awareness of death has been underestimated."

That this was a tentative, controversial claim to make about humanity's closest living relative speaks to just how radical the idea was in scientific circles. Some scientists pushed back: Though Anderson and colleagues were careful to say the chimps' behavior *could* be evidence of awareness of death, not that it *was*, they accused Anderson of careless, anthropomorphic speculation.

Controversial as it was, though, the idea had entered the realm of serious consideration. It catalyzed the field of comparative thanatology, as the scientific study of death-related cognition, emotion, and behavior in other animals is known. Scores of studies have since been published. We are still far from knowing what they think, but it helps to start by reflecting on what it means to understand death.

It is not the same thing as recognizing death. Many ants remove dead kin from their colonies, but this is a reflexive rather than reflective process. Dab a living ant with oleic acid, a chemical produced by decomposition, and their nestmates will carry them out even as they struggle. No true understanding is involved. In a similar vein, opossums and hognose snakes feigning death to escape from predators need not realize they are feigning *death*. They're simply performing an instinctive set of movements.

In humans, by contrast, psychologists have codified a mature concept of death as containing several components: non-functionality, irreversibility, causality, universality, personal mortality, and inevitability. To understand death is to know that it ends physical and mental functions; that the dead cannot return to life; that death is caused by the breakdown of life-sustaining processes; that all living beings can die; that you can die; and that you and everyone else *will* die. This understanding can have more layers, such as belief in an afterlife, and the ostensibly immature understandings possessed by children are a subject to which we'll return, but it's a foundational framework.

Most scientists who study the topic would agree that no animal has this level of understanding, though a few species—certain great apes, elephants, and some cetaceans—have the cognitive sophistication to grasp





non-functionality, irreversibility, and perhaps causality and a limited sense of universality. Beyond them, though, understanding death in any meaningful way is considered rare or nonexistent. Certainly it's not something one would expect to find.

Yet to Susana Monsó, a philosopher and author of *Playing Possum: How Animals Understand Death*, the belief that death is difficult to understand is mistaken. It overemphasizes the mature human understanding of death. Instead Monsó proposes that only two components suffice for what she calls a “minimal concept of death”: irreversibility and non-functionality. To recognize that an animal no longer does what they used to, and realize that this state is permanent, is the essence of understanding death. It is at once simple and profound, and the cognitive requirements are basic.

Mechanisms for distinguishing between animate and inanimate entities emerged early in evolutionary history and are widespread among animals. Add the ability to generate expectations about how an animal ought to behave, then an encounter with a dead body, and voilà: It is an opportunity to recategorize that body from one who does what is expected of them to one that does not, and will not again. A concept of death can be born.

“From my point of view, death is nothing but broken bodies,” says Antonio Osuna-Mascaró, an animal cognition researcher at the University of Veterinary Medicine Vienna. Take away the big ideas and mythology, he says, “and we end up facing death as death should be looked at in nature. We find out that understanding death is recognizing when a body is broken.”

ILLUSTRATION BY MYRIAM WARES

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*To know that you can die is one form of understanding death; to know that you and everyone else will die is another.*

This minimal concept is a foundation, say Monsó and Osuna-Mascaró. Many animals will be able to add other aspects of death, such as causality and a knowledge of their own mortality—not necessarily that they will die, but that they could—yielding an even richer awareness. How many species are capable of this? “It’s too early to give a well-grounded answer to that question,” Monsó says. “But definitely way more species than scientific and philosophical history would have you believe.”

**JAMES ANDERSON THINKS** dolphins and elephants are capable of understanding death at a level “roughly equivalent to a human adolescent.” When I asked what he thought of Monsó’s ideas, he agreed that non-functionality and irreversibility are likely the first components of death that an animal may grasp. But to him, this minimal concept of death contains such a dim impression of what is being understood that it barely counts as an understanding. To be meaningful, it needs something more: a grasp of causality, perhaps of universality.

As Anderson answered, I was reminded, however, of my experiences with death as a child—first a rabbit, later a babysitter. I understood those deaths in terms of irreversibility and non-functionality, with only a faint knowledge of what caused them and none of death’s universality. By the standards of developmental psychology my understanding was far from mature—yet those were still powerful experiences. “I don’t think universality is required at all. I don’t think inevitability is required at all. There are so many things about the concept of death that I think are superfluous. They are not required for having a concept of death that is meaningful to us,” says Osuna-Mascaró.

Interestingly, when researchers in the early to mid 20th century studied how children understood death, they found that children often thought about it in terms of partings in which the departed lived on, but could not return for practical reasons: Heaven was too far away, the coffin was nailed shut. Some children construed death as a sleep from which one could not wake. Which isn’t to say some animals conceive of death this way—although I do wonder—but to illustrate how even a concept of death that contains a faulty grasp of non-functionality and irreversibility, those most elemental components, can be powerful.

Anderson recommended I talk to André Gonçalves, a fellow primatologist at Kyoto University with a particular interest in comparative thanatology. Gonçalves had reservations about the ability of animals to flexibly extend a concept of death from one occurrence to other situations. Humans are especially good at this sort of thinking, Gonçalves said. Though some animals display the necessary cognitive abilities, for many it may be difficult or impossible.

We also talked about anthropocentrism—the tendency to think of humans as superior to and fundamentally different from other animals—and whether it has made comparative thanatologists reluctant to recognize understandings of death in other animals. To Gonçalves, being open to the possibility that other animals can understand death is the opposite of anthropocentric. His colleagues are simply studying this phenomenon rigorously. It is difficult to measure and to interpret; even highly suggestive behaviors have many possible explanations. Seeming anthropocentrism is actually rigor.

What strikes me as anthropocentric, however, is not some sense of human superiority among comparative thanatologists, or close-mindedness to the richness of animal experience, but rather how the default hypothesis is always that animals do not understand death. Why start there, rather than from the position that animals might, or even that they do?

An instructive example of an excessive reluctance—in my eyes—to recognize animal understandings of death involves the discourse around why mammal mothers sometimes carry their infants for days or even weeks after they die. This has been observed in many species, including sea otters, dingoes, and some



# An understanding of death is not required to grieve, but it perhaps makes grief more powerful.

cetaceans, but is especially well-documented in primates. At a glance it seems maladaptive: It's tiring, makes it harder to forage, and leaves mothers more vulnerable to predation. What, then, could explain it?

Many hypotheses have been floated. The most obvious is that a mother's love for her baby is not sundered by death. Mothers still care; they are grieving. There are other possible explanations, though.

Maybe carrying one's dead baby is a form of practice that improves future mothering. Perhaps, for primates in societies where females benefit from the status conferred by motherhood, they carry the corpse in order to keep getting extra grooming and support. It has been suggested that some primates are attracted to anything mammal-like, whether it's a living baby or a corpse or just a stick with hair attached. In fact mothers may not even recognize their baby any more; they might perceive the corpse as an interesting baby-shaped object. Or it could be that female mammals are innately attracted to infants and want to nuzzle them, dead or alive. In fact, mothers may not even realize their babies have died, especially when the causes are not obvious.

Confronted with these uncertainties, where should one end up? There is no clear scientific answer. My own hunch is that mothers know their babies are dead—perhaps not immediately, but certainly after a few days—and cannot let go, figuratively or literally. It seems the most parsimonious explanation; the one truest to the experience of motherhood. Alecia Carter, an anthropologist at University College London, favors that explanation for the baboons she has studied. In an interview with the *Many Minds* podcast she called infant

corpse-carrying “an extension of maternal care and inability to break the maternal bond.” As for the behavior's deeper function, Carter said the best explanation “is that it's a form of grief management.”

An understanding of death is not required to grieve, but it perhaps makes grief more powerful. The presence of grief in animals is also debated, as seen in the famous case of Tahlequah, the orca who held her dead calf above water for 17 days in the summer of 2018, swimming more than 1,000 miles and becoming a global celebrity. Some scientists called this grief; others resisted. They insisted that it was impossible to know for sure and that, lacking this certainty, the default explanation should be that Tahlequah failed to realize her calf was dead and simply hoped she would revive. To think otherwise was a matter of faith, not science.

It was a case study in anthropocentrism. And I would offer this: It is possible to imagine that Tahlequah both grieved her baby's death and hoped she would revive. Many of us have stood beside the casket of someone we loved, looking for movement. Of course we know they are dead. The desperate, irrational wish to reverse what cannot be reversed is part of our grief.

**IN EARLY 2024**, researchers studying Asian elephants in northern Bengal reported something extraordinary: Five accounts of elephant calves found buried in tea plantation irrigation ditches, with their legs aboveground and pointed toward the sky. The soil around them was patted level. Footsteps and dung deposits showed that the burials were performed by the calves' herds.



**A MOTHER'S LOVE** A mother macaque and her infant embrace. These deep emotional bonds likely explain why many primate mothers continue to carry their babies, even after the babies have died.

The burials took place at night. Nearby villagers heard loud trumpeting but none witnessed the events. Later autopsies showed the calves were in poor health and died of natural causes, not from drowning in the ditches. Bruise patterns on their bodies suggested they were carried long distances by their legs and trunks. A camera trap snapped a picture of two elephants walking together, one dragging the tiny figure of a calf by her trunk across a plantation's red earth.

The researchers—Parveen Kaswan, an officer in the Indian Forest Service, and Akashdeep Roy, a political ecologist at the Indian Institute of Science Education and Research—interpreted the burials as intentional. Burial “reflects the care and affection of the herd member(s),” they wrote. Although elephants are celebrated for their intelligence and social complexity, nothing like this had ever been reported. Headlines followed.

In humans, mortuary practices—rituals and customs, such as burial, for disposing of the deceased—emerged roughly 100,000 years ago. Anthropologists consider it a defining moment for *Homo sapiens*, in which a recognition of death combined with symbolic thought to give deeper meaning to loss and also to life. That elephants might have their own such practices was viscerally powerful.

There were, of course, other explanations. Perhaps the elephants indeed carried their dead calves but lost hold while crossing ditches, then dislodged loose soil from the banks as they tried to recover them. Distinguishing intentional from inadvertent is difficult “unless we directly observe the elephants carrying a carcass to a particular site for ‘burial,’” opine elephant biologist Nachiketha Sharma of Kyoto University and Sanjeeta Pokharel, a behavioral ecologist with the Indian Institute of Science.\* “We are not dismissing the

\* Sharma and Pokharel commented jointly by email; so their statements are attributed to both.





possibility that elephants can or do bury their dead”—but from what was observed, who could know?

Several years ago, Sharma and Pokharel published three detailed accounts of Asian elephants attending to dead or dying kin. One involved two adult females seen beside the body of an elderly female who died from disease; when forest officials chased them away to inspect the body, they found withered leaves and twigs deposited around the dead elephant’s head. Once again it is tempting to impute some greater significance, some ritual of farewell or gift for the afterlife. Once again it is impossible to know.

“Placing twigs and leaves could be a symbolic gesture. However, there could be other explanations,” say Sharma and Pokharel. Perhaps elephants dropped what was in their mouths, or lost interest in eating, while inspecting the dead elephant. “We can only speculate,” they say. Yet the fact that such speculation is plausible speaks to the marvelous intelligence of elephants and raises the question of how complex their understanding of death could become. Might some elephants comprehend not only that death is the end of the being they once knew, but also that death will someday come, for themselves and for others?

DANSZABO / SHUTTERSTOCK



**OPEN QUESTIONS** Nobody has yet studied whether monk parakeets understand death—but as long-lived, highly intelligent animals with complex social relationships, their life history is conducive to learning of it.

Understanding that oneself could die is arguably not too complicated. Monsó gives the example of a monkey who sees other monkeys die after falling from trees or being eaten by leopards. To associate death with those events, and then extrapolate that more monkeys—including oneself—could experience a similar fate were they to fall or be eaten is not so difficult. It requires induction and analogical reasoning, which are found in many animals, and the opportunity to learn about death from experience, of which nature provides no shortage. Quite a few animals might be able to do this.

What about understanding that one *will* die, though? As will everyone else? For Monsó, understanding death's inevitability and the full scope of universality is likely a uniquely human trait, or at least dependent on the ability to talk about it. Modern humans, after all, learn through stories or lessons that death comes to all. Monsó thinks it unlikely that other animal communication systems have the conceptual abstraction necessary to convey this.

Anderson agrees that communicating about death has not yet been documented, but he is open to the possibility. He is fascinated by how chimpanzees and other primates communicate as they attend to their dead. "They are certainly expressing communication about what has happened," he says. "What we don't have any evidence of yet—and this will be an amazing step, if that happens—is if there's some signal," such as a vocalization or gesture, "that conveys death." Pokharel and Sharma recorded the trumpeting of elephants beside their dead, and think it possible that elephants speak about death, but this has yet to be studied.

Anderson thinks chimpanzees may be able to learn about death's universality and inevitability. Pokharel

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*If an animal did comprehend the inevitability of death, what then?*

and Sharma say the same about elephants, but "empirically substantiating this would be extremely difficult, if not impossible."

Yet again we are confronted with the tension—central to comparative thanatology, and indeed to the study of animal behavior—between what may be possible and what can be scientifically ascertained. It is important for scientists

to be careful in their empirical claims, but the limits of our measurements should not prescribe the limits of possibility.

And if an animal did comprehend the inevitability of death, what then? The late geneticist Danny Brower hypothesized that awareness of one's own mortality brings such paralyzing fear and anxiety that it's an evolutionary dead end. Humanity survived the realization by devising intellectual workarounds. "Man cannot endure his own littleness unless he can translate it into meaningfulness," wrote Ernest Becker in *The Denial of Death*. In the 1980s, Becker's work inspired terror management theory, which postulated that much of human behavior is shaped by a deep-seated fear of death. The theory also distinguished between complex forms of terror management—transcendent values, religious frameworks—and simpler ones, like contributing to one's community and caring for loved ones.

According to psychologist Tom Pyszczynski, one of the theory's architects, there are three cognitive requirements: the ability to think symbolically, to think about the future, and to reflect upon one's own life and self. Forms of these capacities are found in many species. I asked Pyszczynski: Might some animals engage in mental activities akin to what is described in his theory? Not the complex forms, but the simpler ones. Might a monk parakeet find some sense of greater



# To know what death may mean to other animals is to take each life seriously and to honor them.

purpose in adding sticks to the car-sized, multi-generational colonial nests in which they live? Could a gorilla groom a friend with extra care, knowing such moments are finite?

“That is certainly possible. I don’t think we know,” said Pyszczyński. He is uncomfortable speculating about the inner lives of other animals, but “every decade or so, we learn that things are a lot more complicated—and other animals are more sophisticated and capable—than we used to think.”

**THERE EXIST CAVES** used continuously for thousands of years by hibernating bears. Inevitably some bears die during hibernation and so the caves are full of skeletons. Might not some bears—creatures whose intelligence is little-studied but may compare to that of great apes—look upon and smell those remains, grasp their ancience even as they feel time’s passage in their own bones, and intuit what must happen? How might a monk parakeet conceive of the greater good? Those are speculative, possibly unknowable questions, but others are more immediate and tractable.

At his lab at the University of Veterinary Medicine Vienna, Osuna-Mascaró is developing methods for testing whether Goffin’s cockatoos comprehend irreversibility and non-functionality. Another question is whether that understanding can be flexibly applied, and also how readily it is acquired. If a fox can come to understand death as they hunt mice, how many must they kill for the lesson to sink in? Can they make inferences from when they chased beetles as a kit? And

perhaps researchers could adapt methods used in studies of terror management theory, in which people are presented with reminders of death as a way of assessing whether it’s on their mind and how they cope. “Expose the animal to a dead conspecific and then see if that leads them to engage in more nurturing or protective behavior,” suggests Pyszczyński.

Many more species need to be studied, too. Comparative thanatology has focused mostly on primates, with elephants and cetaceans also receiving some attention. Few other animals have been studied, a disparity that reflects circumstance rather than potential. Parrots are obvious candidates, says Osuna-Mascaró. Anderson mentioned wildebeests and monogamous birds. A few years ago a camera trap set up for an 8-year-old Arizona boy’s science fair project recorded a herd of collared peccaries who visited a fallen comrade for 10 days, sleeping beside her body and defending it from coyotes. It was the first such observation in peccaries and a testament to how much remains to be learned.

There will be limits to what can be studied. Some are ethical: Gonçalves, for example, balks at playing recordings of a deceased chimpanzee to her family in order to see how they react. Other limits are fundamental. “There are certain questions that we can ask, but that we’re not going to be able to address scientifically,” says Monsó. “That’s okay.” Is there any way to truly know whether my cat Ingmar, visiting her old haunts on her final night, knew the end was near? Or was she simply seeking psychological comfort in a time of great pain?

I want neither certainty nor the rigorous weighing of competing hypotheses. And even what we do understand is necessarily partial; an ocean exists between scientific description and lived experience. It may be true that grief emerges from dissonance between a brain's model of the world and its new reality, but those words are incommensurate with the experience.

What should we do with our knowledge and our uncertainties? "One question is paramount," says anthropologist Barbara King. "How might research around animal responses to death compel us to be better and do better for animals?"

There are low-hanging implications. Anderson mentioned the importance of allowing chimpanzees in captivity to spend time with deceased kin, rather than immediately removing the body, so that they might understand what has happened and have some sense of closure. Monsó made the same point about companion animals.

The most important implications, though, are in how we relate to animals. In the study of calf burial in Indian tea plantations, the researchers described how local people's attitudes reflect their appreciation of elephant sentience. To believe they bury their calves and mourn their dead "strengthens the morale of coexistence," the researchers wrote. People there care about elephant conservation less because of their ecological roles than because of the ethical regard due to them as intelligent beings.

King stresses that understanding death should not be a litmus test. Every being deserves our respect. And given how many of us spend much of our lives oblivious to death, we ought not find animals wanting for being incapable of more. But to know what death may mean to other animals is to take each life seriously and to honor them. We are called, says King, to consider the lives we treat so casually: animals kept in captivity for entertainment, or killed for the sake of knowledge or a soon-forgotten meal, whose suffering may be compounded by an awareness of death and loss. Where people follow those ethical implications will vary, but that animals could share with us some understanding of death, not necessarily identical to our own but similar in some ways—and in ways that matter deeply to our own experience—is grounds for a deeper kinship.

Which is not to deny that some human understandings may be singular. If anything is truly unique to us, I think, it is our ability to refract death through our extraordinary capacity to imagine possible futures and alternate histories. Perhaps no other animal is capable of being annoyed at a loved one's irritating habit, then feeling sadness at the thought of how someday that habit will be remembered with affection and regret. Perhaps no other animal can be consumed by how death could have been averted, or what they might have done differently. Perhaps no other animal judges themselves for this, or forgives.

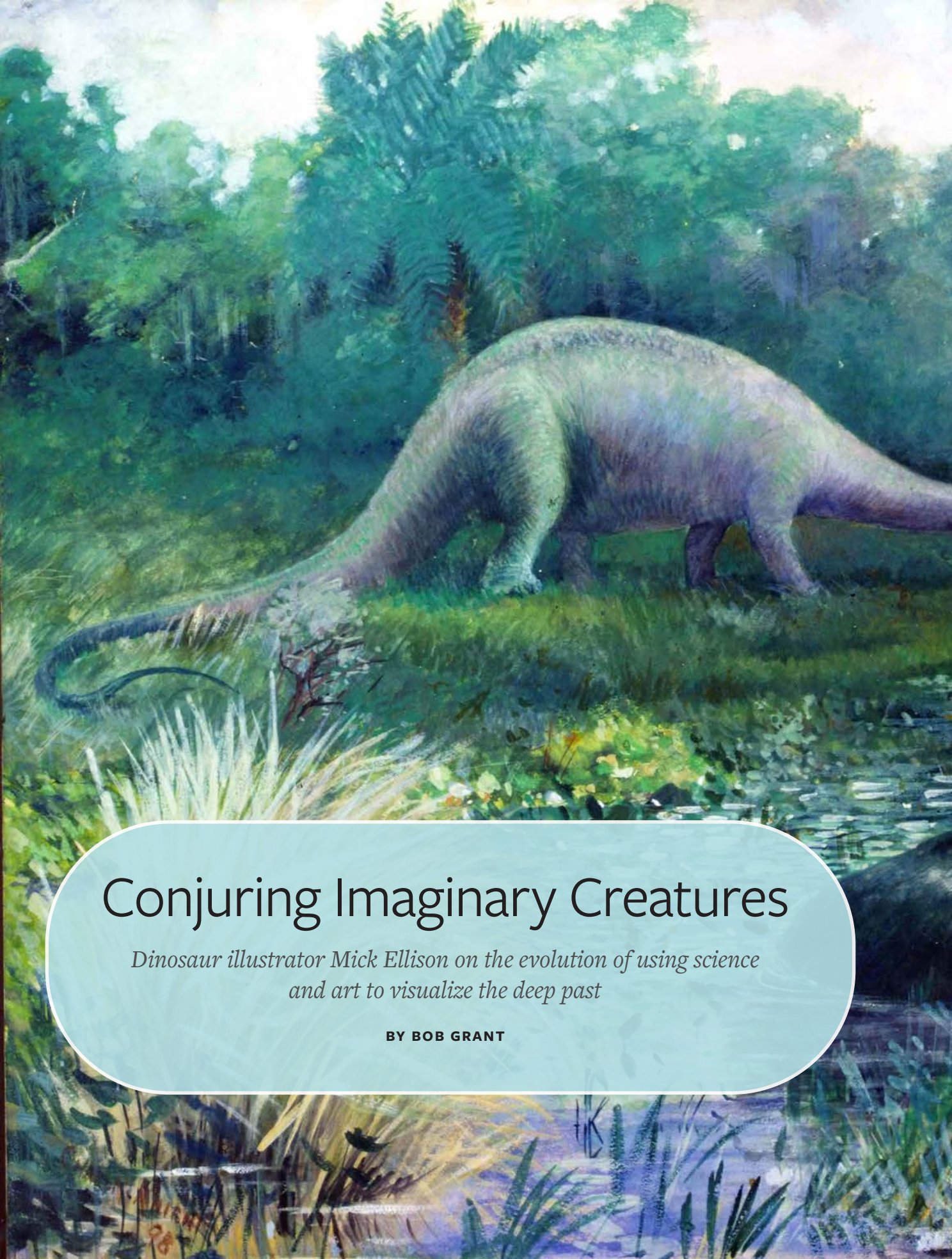
What is more important, though: the differences between how humans and other animals understand death, or the similarities? To me it is the latter. The common essence of life's preciousness and the finality of its loss.

In the thanatological literature, much attention is given to the ritual trappings of death: the ceremonies, the mythology, the symbolism. Those, it is said, are deeply human. I think about the peccaries' vigil and of the funerals I have attended and will. Long after the funeral is over, we still stand by the grave. ☺

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BRANDON KEIM is a freelance journalist and contributing editor at *Nautilus*. His latest book, *Meet the Neighbors*, explores what the science of animal intelligence means for how we understand and live with the wild creatures around us.





# Conjuring Imaginary Creatures

*Dinosaur illustrator Mick Ellison on the evolution of using science  
and art to visualize the deep past*

**BY BOB GRANT**





**OLD MASTERS** This 1897 painting of swamp-bound *Brontosaurus* and land-dwelling *Diplodocus* is considered a masterpiece from the progenitor of paleoart, Charles R. Knight. Though beautiful, the work is inaccurate—Paleontologists later determined that *Brontosaurus* was not aquatic, and *Diplodocus* did not drag its tail behind it.



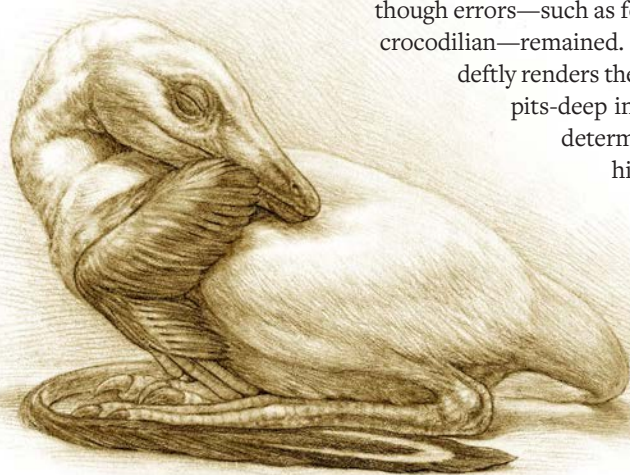
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**INOSAURS HAVE ALWAYS BEEN** imaginary creatures. When the world was introduced to these prehistoric animals in 1824, with the description of “Megalosuarus” fossils, natural philosophers relied on the public to imagine what these beasts might have been like. But as other fossil finds followed—Iguanodon in 1825 and Hylaeosaurus in 1832—they began enlisting artists to help transform the bare-bones science into pulsating prehistoric life.

Some of these early efforts were inaccurate at best, comical at worst. But 19th-century artists can be forgiven for their rudimentary recreations, working, as many were, with scant fossil evidence and little exposure to whole branches of the tree of life. Or even the concept of evolution (Charles Darwin’s *On the Origin of Species* wouldn’t even be published until 1859). As more fossils emerged from the Earth and the field of paleontology blossomed, scientific information about dinosaurs accumulated, making the artists’ job a little easier. Still, though, the cartoonish character of dinosaur reconstructions persisted. Animals were depicted as giant, lumbering lizards with exaggerated chameleon-horned faces, dragging tails, and stocky, hippopotamus-like bodies.

#### DINO AT REST

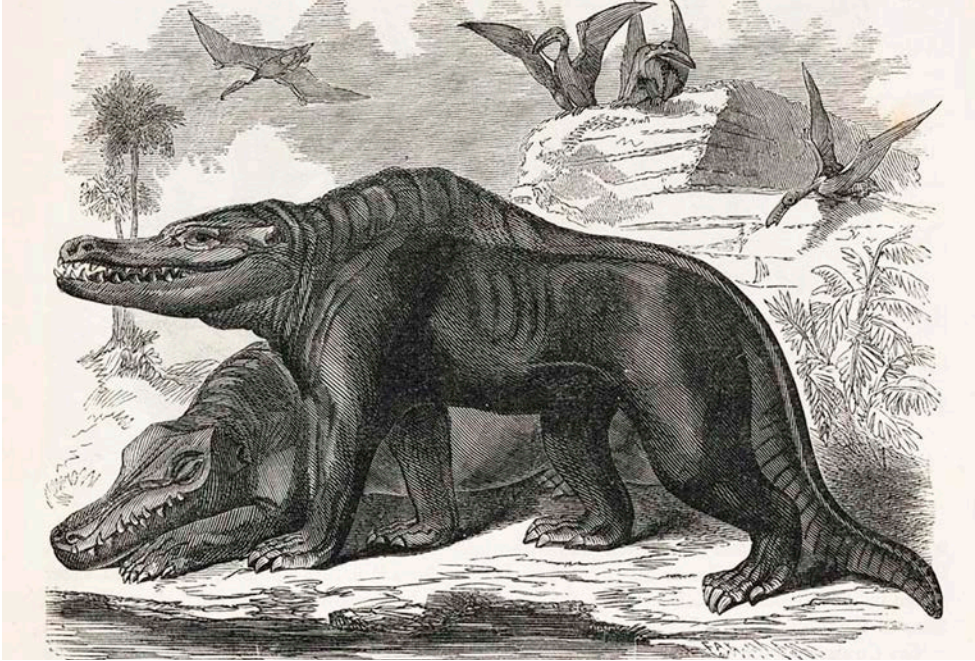
A reconstruction of *Mei long*, a small, troodontid dinosaur, that Ellison created by studying fossils.



By the turn of the 20th century, the fossil record was expanding, and artists such as Charles R. Knight were incorporating art movements of the day into illustrations of dinosaurs and other extinct organisms. His impressionist backdrops framed detailed paintings of dinosaurs that were more accurate than the creations of his predecessors. For example, in Knight’s 1897 painting *Leaping Laelaps*, the artist depicts a species of theropod dinosaur now known as *Dryptosaurus* with features closer than ever to modern reconstructions, even though errors—such as forelimbs with too many digits and skin that was too crocodilian—remained. In another of his works from the same year, Knight

defly renders the recently described *Brontosaurus*, but places it arm-pits-deep in a primordial wetland (paleontologists would later determine that the species was not in fact aquatic). Still, his work remains visually iconic and laid the foundations for popular imaginings—lingering inaccuracies and all—of these animals for generations.

And the evolution continues, of course. Contemporary technologies, such as scanning electron microscopy, ancient DNA extraction, and 3-D printing, allow paleontologists to burrow ever further into the fabric of prehistoric life—and scientific illustrators to incorporate those insights into their work.



### EARLY DINO ART

This 1859 reconstruction of *Megalosaurus* and *Pterodactylus* by Samuel Griswold Goodrich, depicts a dinosaur with a decidedly mammalian body.

*Nautilus* caught up with Mick Ellison, senior principal artist in the division of paleontology at the American Museum of Natural History in New York City. We talked about the past, present, and future of bringing dinosaurs and other extinct creatures to life on the page and in the public imagination.

#### First, I have to ask: What's your favorite dinosaur?

I guess it depends on what I'm working on currently. I would say right now my favorite dinosaur is one called *Citipati*, which is a kind of oviraptor. They're just fascinating and very odd, very cool.

#### How has your answer to this question changed in recent years?

I think one of my other favorite dinosaurs is *Microraptor*, which I also had a chance to work on. And that will always remain one of my favorites. It's just such an incredible animal.

#### How did you end up becoming a scientific illustrator—and someone who illustrates extinct animals, of all things?

I knew I would be an artist of some kind since I was very young, but I was always also interested in science. I went to art school in Baltimore. I was taking classes at John's Hopkins University for medical illustration, but I realized early on that I just didn't feel like I wanted to pursue that career. I wanted to try other things. So, I kind of drifted away. I wasn't even aware of scientific illustration.

to know them and try to get insight into how I could eventually get a job here. It was actually just showing up and asking security guards, "Can you introduce me to an artist that works here?" And it's funny, it just was chance, I guess. But the security guard actually contacted an artist who worked in paleontology at the time. So that was serendipitous, but it was great because he walked me through the department, even as a stranger, and showed me what these guys do from day to day.

#### Do you have a favorite fine artist?

I have so many. When I was young, I would do children's books, I would do all kinds of illustration. I was always fascinated with what they call the "Golden Age of American Illustration," and the artists who were working around the turn of the 20th century.

My favorite is Edmund Dulac. He was a French-British artist who worked mostly in watercolor. His drawings are beautiful. Everyone's line work around that time was just gorgeous. You would have more graphic things going on like Harry Clark or Aubrey Beardsley, that sort of more stylistic approach.

And I feel like maybe some of that shows through a little bit in my style of the dinosaurs that I do. I always thought if you're doing a reconstruction, I always like the idea of not only having it be scientifically accurate, but you could also make it artistic as well. There's no real in-house style. In that way it was very open, and I could use some of the influences that I have from the art world to use in scientific illustration.





**IN STUDIO** Mick Ellison works surrounded by anatomical inspiration in his attic studio.

**As you became familiar with the world of paleoart, were there specific early dinosaur illustrators or paleo artists that you sought to emulate?**

Of course there's Charles Knight. He was a fabulous artist, and his paintings—in the way they were executed, his style, his looseness or his tightness—it just made those paintings masterpieces. And he deserves to be called the father of paleo illustration. His paintings are all over the museum here. I love to look at them. They're just gorgeous.

I know that he had a deep understanding of nature and animals as well. He would spend weekends going to the Central Park Zoo or the Bronx Zoo and sketching animals. He had a true understanding—I feel like a lot of these early artists did. There was a real emphasis on anatomy. And so all of these artists who were doing work in paleontology would have had a really deep background and training in animal anatomy. And I think that shows through their representation of dinosaurs—it looks like a living animal.

But I discovered Erwin Christman, who was a contemporary of Charles Knight. And he was just an amazing draftsman, an amazing artist, an amazing scientist. The work that he did was just phenomenal. It really inspired me. It still does. He was a master. He could sculpt, he did wonderful, beautiful etchings, line drawings. He could do everything. He was a great painter. Unfortunately, he died very young from appendicitis in the early 1900s. But the amount of work that he produced in his short lifetime was just phenomenal.

COURTESY OF MICK ELLISON

**From your perspective as a contemporary dinosaur illustrator, how do you think we should view those early, often inaccurate, efforts at reconstructing dinosaurs for the public?**

They look dated now from our perspective. But I think at the time they were just using what limited information they and the scientists had. A lot of those may not be accurate anymore, but they're certainly iconic. And it's kind of cool to see the progression. Paleontological art is an everchanging field.

I could do a reconstruction today based on all the information we have about a certain fossil, but you'll never get it completely right. And I know that a few years down the road—and I hope for this—that another fossil will be found that explains it even better. And then I can see where I fell short in the previous one. I know some scientific artists who are constantly updating their old drawings. They're modifying them to keep them current, and I sometimes will do that too.

**How do you see your role as an illustrator bridging the gap between science and the public? I'm wondering if, when you sit down to work, you have an audience in mind? Are you drawing for the kid like you who is interested in dinosaurs? Are you drawing for scientists?**

I think primarily I'm doing it for myself, out of curiosity. I don't really know what it's going to look like before I start. To me, the whole process is a process of discovery. And I also do it for the scientists. So it's not like I'm working in isolation. It's a team effort usually, and I'm often asking a lot of experts. It's a back-and-forth conversation.

Then it's thrilling to start to see an animal emerge, to start to see what it may have looked like. It's always surprising to me.

**How, day to day, do you use science and data in your art work?**

I was talking about Microraptor—this small, feathered dinosaur from China that has feathers on its hind limbs as well as its forelimbs. It was just remarkable. I remember seeing that fossil for the first time. I was like, "What am I looking at? That is incredible." I spent many months doing this anatomical reconstruction. At the same time, some of the scientists on the

*If you look at a lot of dinosaur artwork, they're always running full speed ahead with their mouths gaping open.*

#### FEATHERED FRIEND

Ellison's reconstruction of Sinornithosaurus, a feathered dinosaur.





*If you're doing a reconstruction, I like the idea of not only having it be scientifically accurate, but artistic as well.*

team were working with these things called melanosomes that you can detect through SEM [scanning electron microscopy]. And it will actually give an indication of color. I remember I had just finished the reconstruction. I was considering patterns on the body and the feathers. And when I do that, I start to look at the environment that they were living in. I'm using a lot of things as templates. But then it came in at the 11th hour, and they were like, "We just found out this animal was jet black." It was iridescent black actually, like a grackle or a crow. And that was just really cool. I had to kind of reshift everything really quickly.

Nowadays we also do a lot of CT [computed tomography] scanning. That enables you to see things that you could never see before. We have preparators that are physically extracting the fossils from whatever matrix they're in, but a lot of times there's soft tissue or there's just things so delicate that they couldn't be physically prepped. And in the past, you just wouldn't know they were there. But today, CT scanning is another example where you can see so much more information than you could ever see before.

And you can also now have it on your computer. You can be rotating it in three dimensions. And it's just all opening up more understanding, which is great.

**Is there a specific thing about how dinosaurs have been depicted or reconstructed in the past or present that particularly irks you?**

It's probably the same one that we all say. But when I see, in really popular franchises like *Jurassic Park*, when they depict an animal like a Velociraptor and they have its size wrong and it's not feathered. A lot of these theropods, or meat-eating dinosaurs—we know now, there's no debate over it anymore—were feathered. But I think people just want to hang on to whatever icon it was from the past. That is one that irks me.

If you look at a lot of dinosaur artwork, they're always running full speed ahead with their mouths gaping open, which just seems to be the template that people use when they're doing a dinosaur illustration. But I like to observe animals. And if you do have predators out there, you don't really see that kind of behavior exhibited very much. If you talk about living birds, who are the descendants of dinosaurs, they're not going around with their beaks gaping open all the time.



#### **AS THE DINO-CROW FLIES**

Microraptor, as reconstructed by Ellison based on fossil and molecular evidence.

# I like to do the poses where they're at rest, because you can see that animal in a deeper way.

I'm trying to bring something a little different. And when I think about some of these animals I'm reconstructing, I'm just thinking about what would be a behavior or an action that would be more realistic, that would make more sense.

## **Can you give me some examples of those more sensible behaviors that you've put into your artwork?**

I try to do a lot of these dinosaurs in a very still kind of moment. Because if you do look at animals, most of the time, they are contemplating the environment around them. They are being still. I do understand that action poses—if they're lunging for food or something—are exciting, and I will do that. But I like to do the poses where they're at rest more, because then I think, as a viewer, you can see that animal in a deeper way. You can look a little longer without being overwhelmed by the energy or the action of the moment.

## **As a paleo artist, how is AI changing this whole process? Is there something that generative AI misses that human illustrators bring to the table?**

Probably AI will replace all of us at some point. But right now, anyway, I've tested it out, and I feel secure that I can still bring something to the table that AI can't quite figure out. If you're doing an anatomical

reconstruction of an animal that lived 200 million years ago, you're taking from a lot of sources. You're putting a lot of information into that final drawing, painting, sculpture, whatever it is. And so far, I don't see AI being able to make all of those subtle, informed connections.

## **Do you see AI-generated paleo art around, and can you identify it when you see it?**

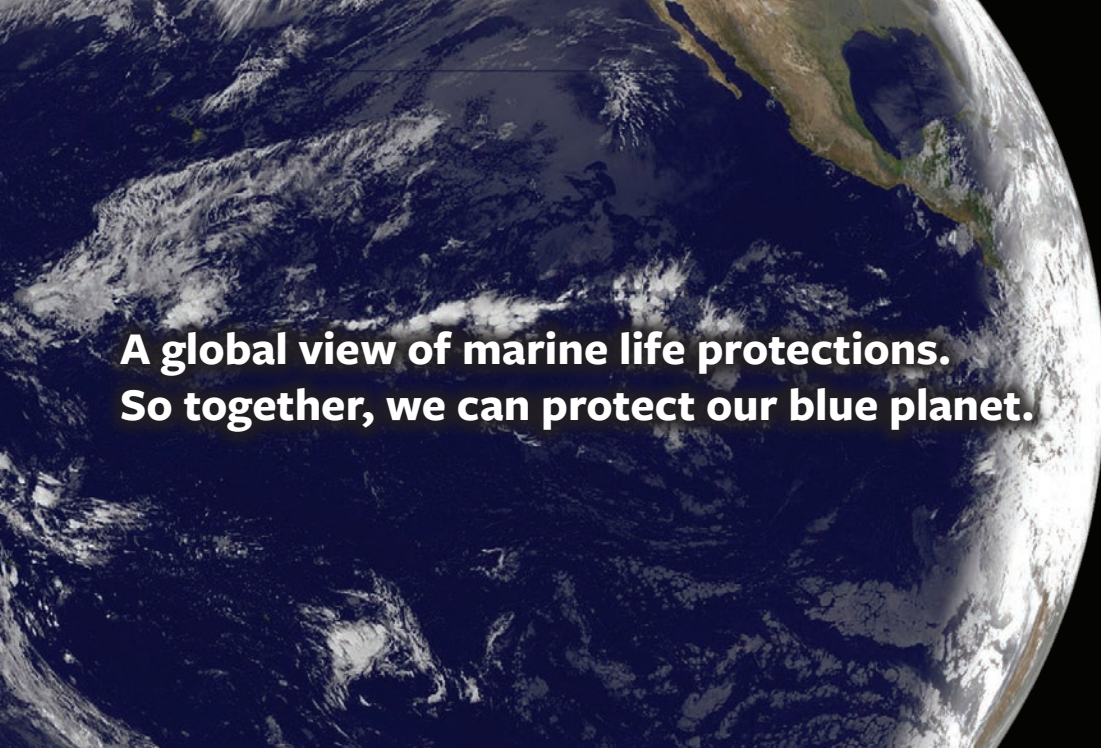
Oh yeah. All the time. And yes, I can pick it out. We get together, my colleagues and I and or my friends and I, and what we notice over the last years, months is that the things that you could obviously pick out, they're being corrected. So each time it gets a little more refined. And I know eventually it will get to the point where I won't be able to figure it out. But right now, anyway, I can see it. A lot of AI-generated artwork is terrible. So when it comes to scientific reconstructions, it's awful.

I like to test it every once in a while. I'm working on projects day-to-day, and I'll just plug something in. I'm like, "I wonder what AI would come up with for what I'm doing today?" And I just see the results and I'm like, "Okay, okay. Still a ways off." 🌀

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BOB GRANT is the deputy editor at *Nautilus*.





**A global view of marine life protections.  
So together, we can protect our blue planet.**



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**220**  
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**41**  
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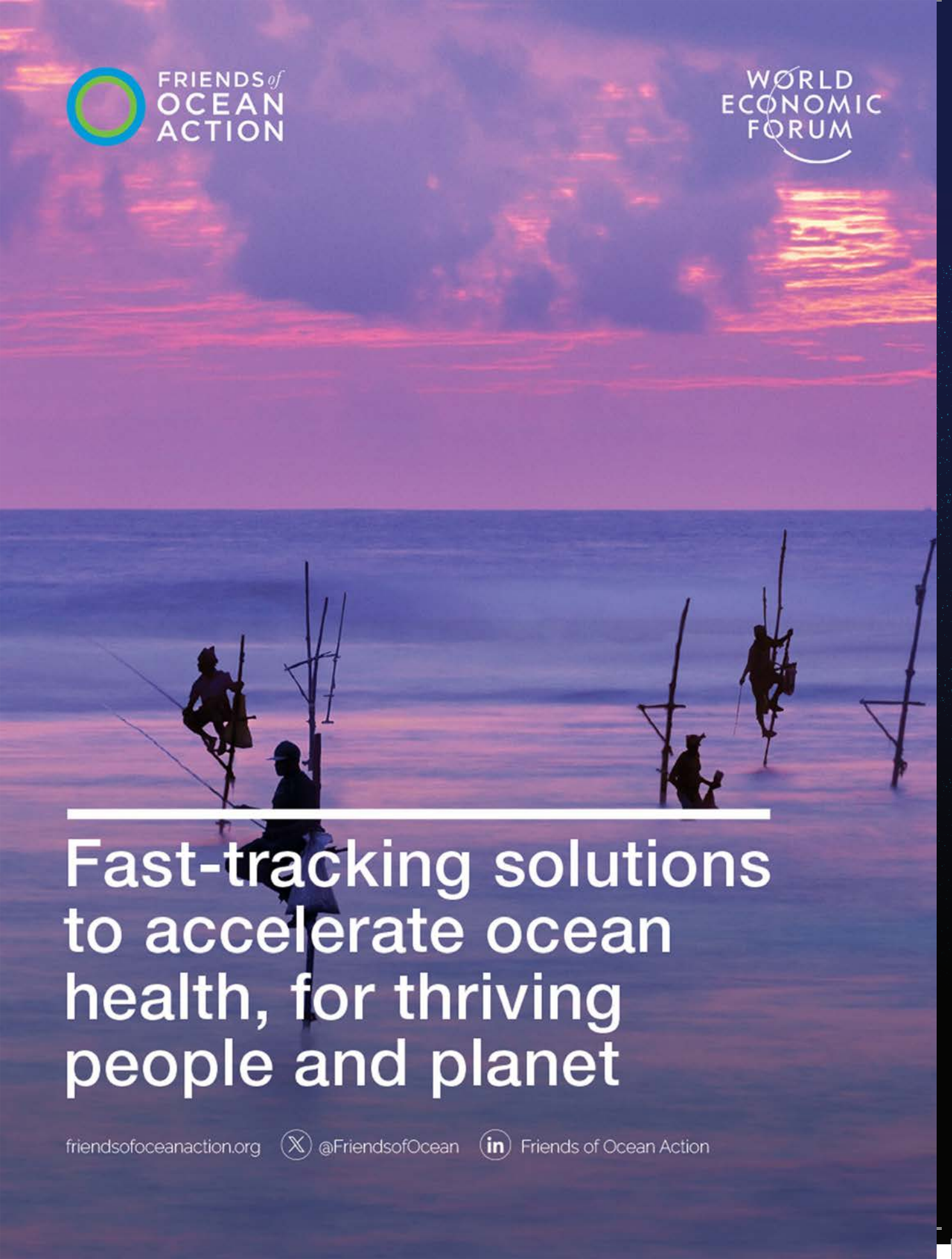
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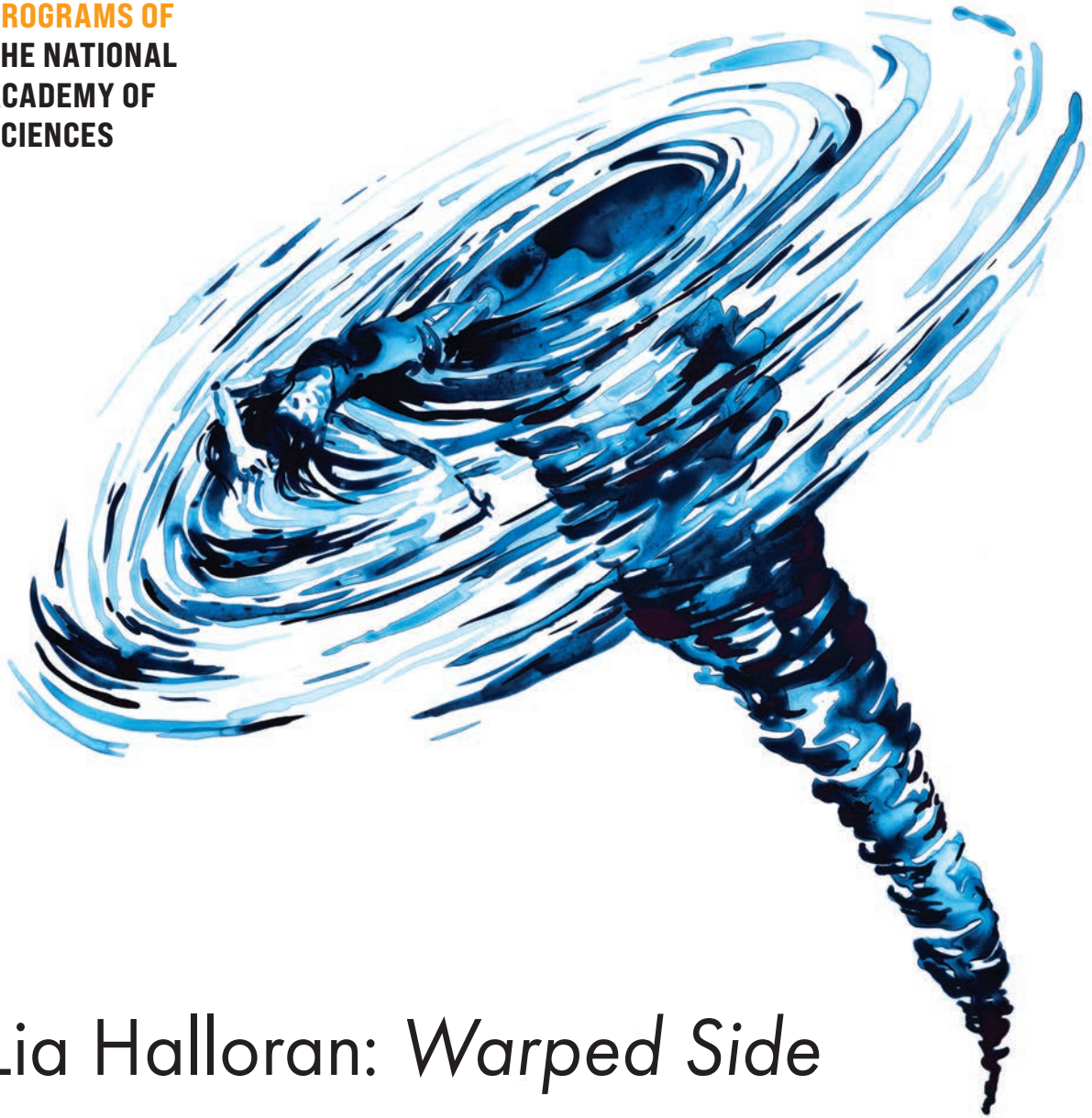
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## Lia Halloran: *Warped Side*

February 3 through June 1, 2025

This art exhibition represents the culmination of the friendship and collaboration between artist Lia Halloran and Nobel Prize-winning astrophysicist Kip Thorne. Together, they have woven science, art, and poetry into an exploration of black holes, wormholes, gravitational waves, and other strange phenomena made from warped space and time.

Lia Halloran, WS117, 2016. Ink on duralar, 22x17 inches

Halloran and Thorne will speak at the National Academy of Sciences during Space Science Week on **Wednesday, April 2, 2025, at 6:30 p.m.**

NAS Building, 2101 Constitution Ave., N.W.,  
Washington, D.C. Upstairs Gallery.

FOR MORE INFORMATION, VISIT [WWW.CPNAS.ORG](http://WWW.CPNAS.ORG).

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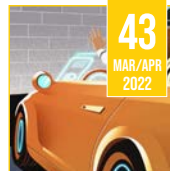
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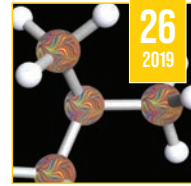
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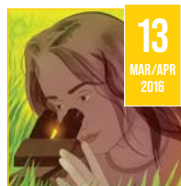
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# Learning Medicine from Animals

*The author of Doctors by Nature: How Ants, Apes, and Other Animals Heal Themselves on what animals can teach us about medicine*

BY JAAP DE ROODE

## 1

### HUMAN HEALERS HAVE LEARNED FROM ANIMALS FOR THOUSANDS OF YEARS

In North America, Native Americans call many human treatments “bear medicine” because they discovered them by watching bears.

Oshá root is a good example—it is used as an immune booster to treat coughs, colds, bronchitis, and flu—but bears may also have been the first discoverers of aspirin. Healers around the northern hemisphere would see bears coming out of hibernation and eating the bark of willow trees. They copied this behavior to treat inflammation, and scientists later isolated and improved the willow’s salicylic acid to create aspirin.

In Tanzania, healers have developed treatments for stomach upset and bloody diarrhea by copying elephants and porcupines. In South America, people learned about the stimulatory effects of coca leaves by witnessing llamas. In Chinese medicine, healers use a plant called horny goat weed to treat erectile dysfunction. As you can guess from the name, people discovered its properties by witnessing that goats become frisky when eating the plant.



## 2

### MY MINIATURE POODLE IS AN ACCOMPLISHED PHARMACIST

Many domesticated animals would no longer make it without our help, but they are much more clever than we give them credit for. During the COVID-19 pandemic, my family welcomed a miniature poodle into our home. Like so many dog owners before me, I quickly started noticing Tukkier eating grass, and then witnessed his vomiting on several occasions. I learned that many carnivores share this behavior, including wolves, mountain lions, and bobcats. They do it to purge parasites and other unwanted objects from their stomachs and guts. Now I am just in awe when Tukkier eats grass, and I won’t try to stop him (provided I am not worried about pesticides and fertilizers).

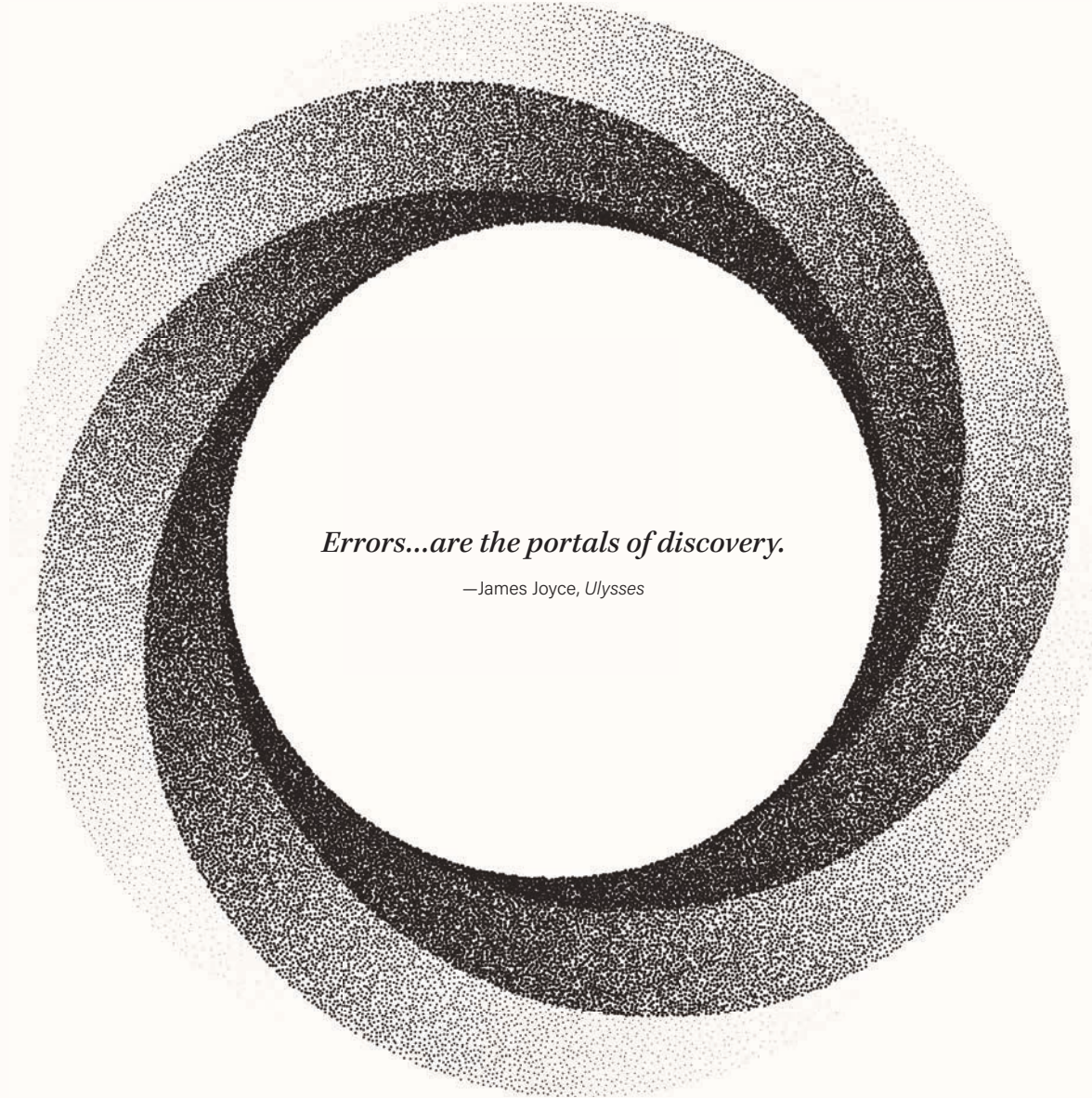
## 3

### SOME ANIMAL MEDS ARE BETTER THAN OURS

When humans keep livestock, we provide animals with a standardized diet that supposedly contains everything the animal needs. The problem is that these diets do not contain animals’ natural medicines, so we throw in tons of pharmaceuticals to kill bacteria and parasitic worms. But the bacteria and worms quickly evolve resistance. We see a similar story with honeybees.

These insects like to collect resin, and mix it with wax to produce propolis, which protects the bee colony from all sorts of disease-causing pathogens. Beekeepers don’t like it because it makes it difficult to handle the bees. So, beekeepers have selected bees that make less propolis, and they remove it when they can. But now bees are doing poorly, and many hives die out each year because of disease. And the chemicals we use to treat their diseases don’t work well anymore because of resistance. That’s why scientists are developing new hive boxes that allow bees to incorporate plenty of propolis without aggravating beekeepers. Allowing animals to use their own medical knowledge can make animals healthier and protect our own food supply. 🍯

PHOTO BY HERBERT KUPER / ADVANCED PHOTO & IMAGING, SANDY SPRINGS, GEORGIA



*Errors...are the portals of discovery.*

—James Joyce, *Ulysses*

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