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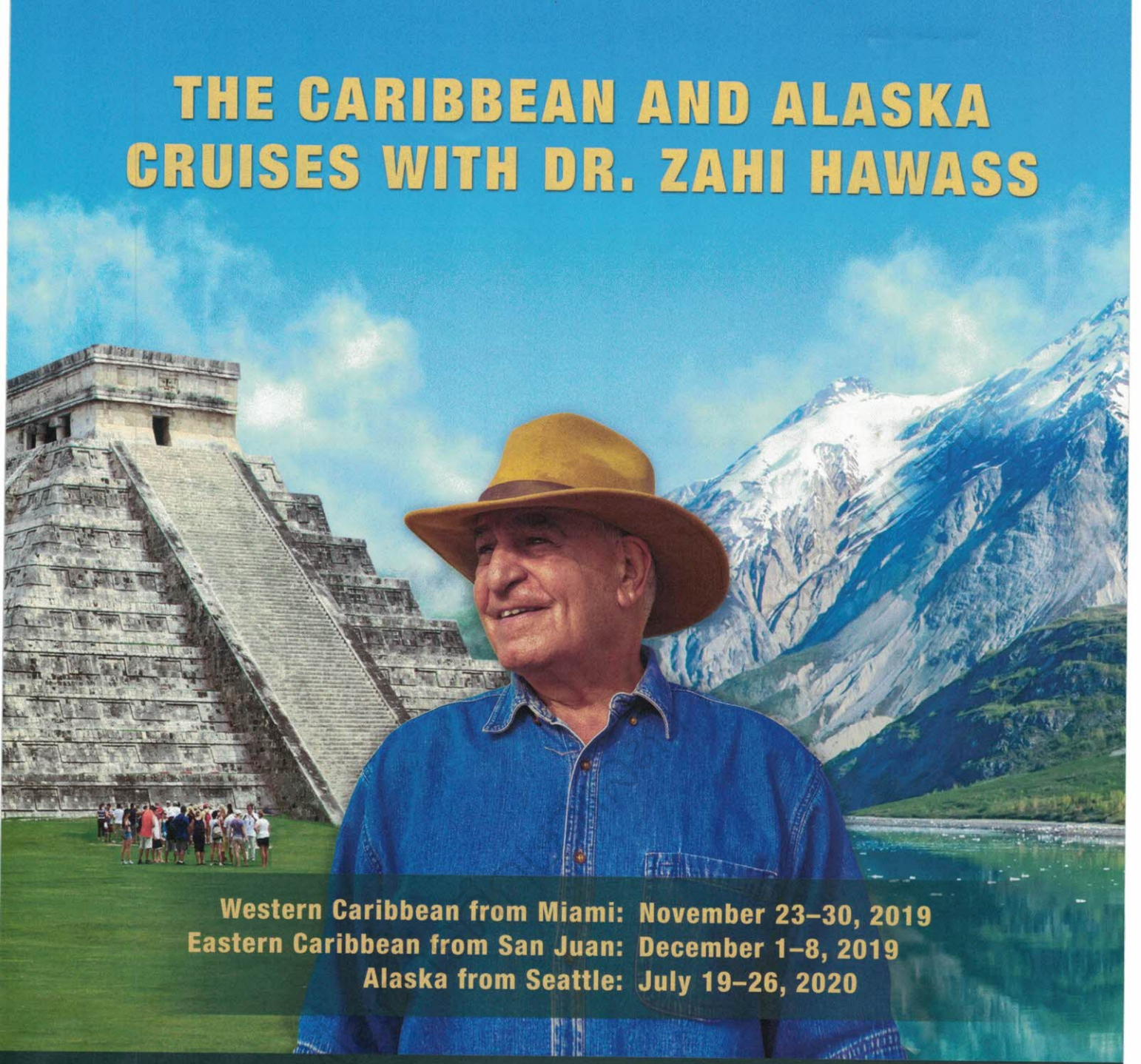

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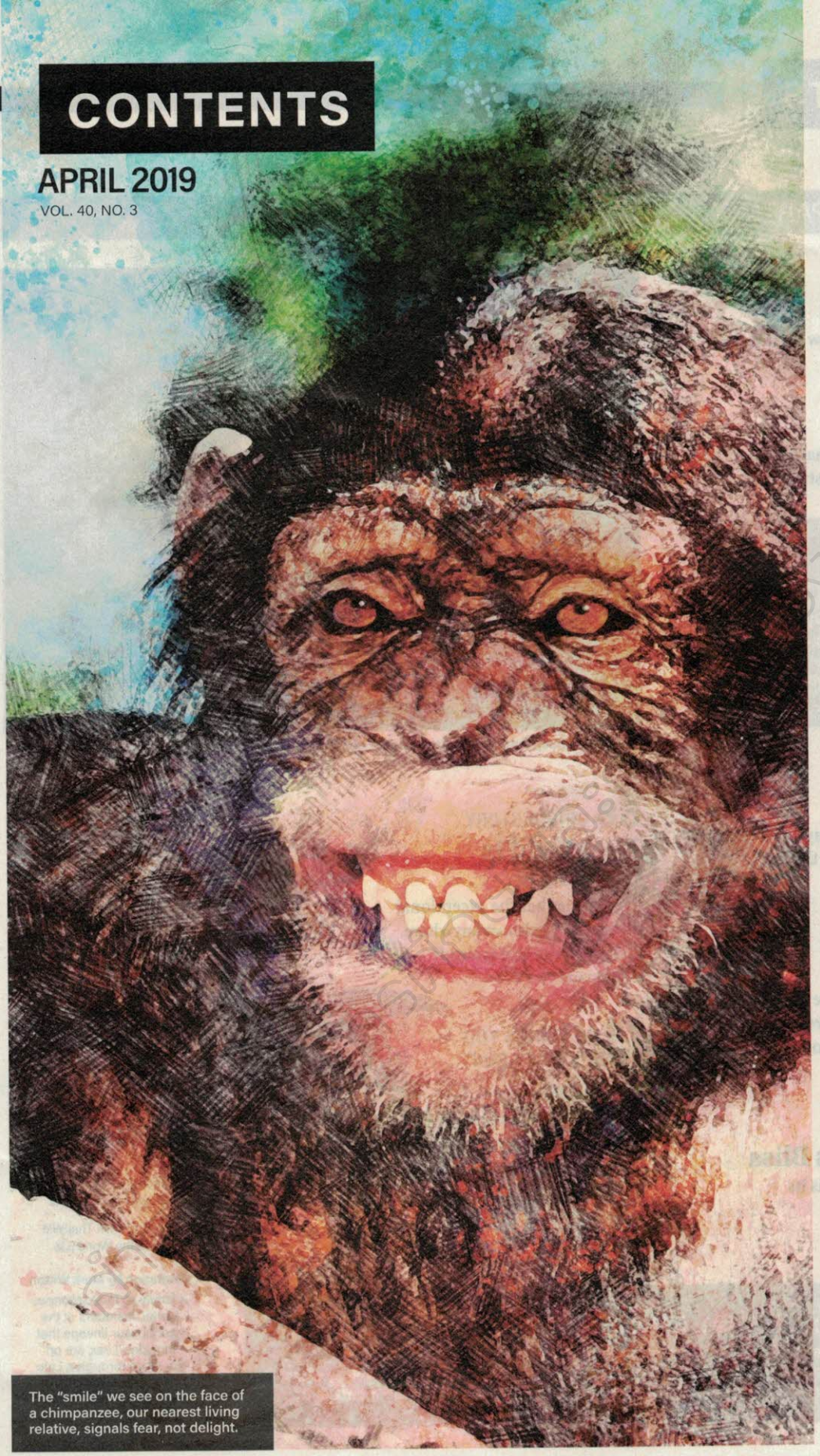

The "smile" we see on the face of a chimpanzee, our nearest living relative, signals fear, not delight.

ALISON MACKEY/DISCOVER AND AVALON/PHOTOSHOT LICENSE/ALAMY STOCK PHOTO

## FEATURES

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## COLUMNS & DEPARTMENTS



The Bajau of Southeast Asia have adapted genetically to life on the sea. More on page 68.



Arctic terns rack up frequent flier miles, flying nearly pole-to-pole during seasonal shifts.

**ON THE COVER**



**Illustration by Mark Witton**
A family of *Teratophoneus curriei*, members of the tyrannosaur lineage that includes *T. rex*, are on the move through a Late Cretaceous landscape 76 million years ago.


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# Buried in the Past

We tend to reflect on our sense of place by looking to the recent past. For example, as a kid living out West, I couldn't escape the story and path of Lewis and Clark — we can picture them navigating the familiar Missouri River valleys and winding over Rocky Mountain passes, establishing the trail for many routes of today.

It's one thing to reach back a couple of centuries, but the mind's eye has trouble when we're talking about over 70 million years ago. Whole continents and seas look nothing like our topography now. Arid landscapes hide once-tropical environments. Mountain ranges that tower over us were mere foothills then.

In this issue's cover story, we take you to such a place.

*Discover* Digital Editor Eric Betz accompanied paleontologists as they headed into the field in southern Utah, unearthing evidence of a lush, mountainous forest that ran in a skinny line along a vast sea. After more than 10 years working on a 1,000-square-foot site, they've found truckloads of dinosaur bones from the Cretaceous Period.

It's not only that they're finding all kinds of evidence; it's the type of bones and what they can tell us about behavior and lifestyle that's even more compelling. The team thinks they've got the pieces that might show that the stereotypically fierce, loner tyrannosaurs actually lived in family groups, raising their young. Not everyone's convinced, though, and readers are along with us as we parse out researchers' alternative theories.

As you make plans to travel around the country this summer, pause and think about how different this part of the world was for animals living millions of years ago — it can be a little mind-blowing.

Becky Lang,
Editor in Chief

Feel free to send comments and questions to **editorial@discovermagazine.com**



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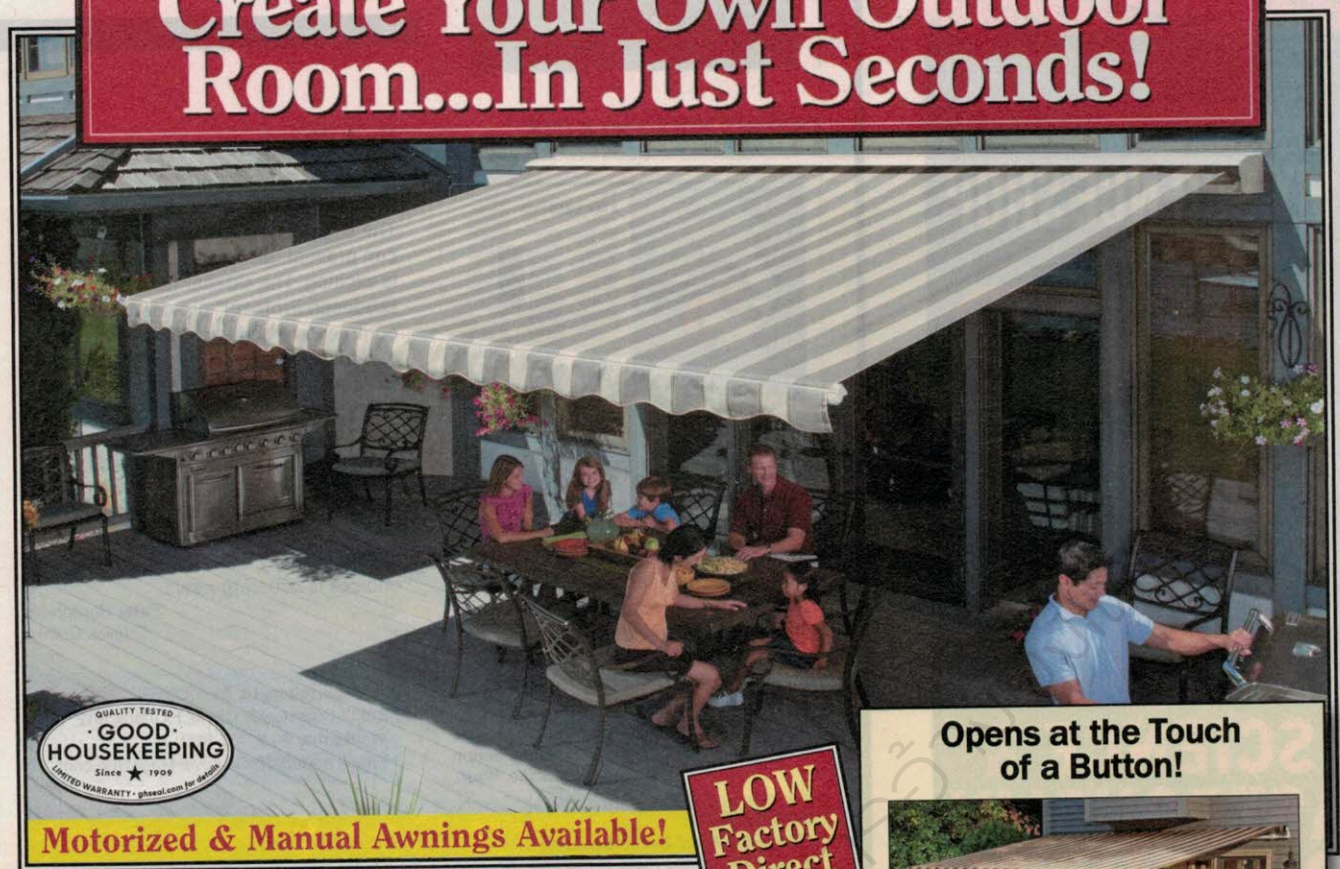


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## PRINT FEEDBACK


### Buggin' Out

*("A New Animal Farm," July/August 2018)*

Loved your July/August issue, but one statement has me reeling. In "A New Animal Farm," Carl Engelking states, "As Earth's population increases by billions in the coming decades ..." Egad! Are we humans really so clueless that we can't eventually control our own dangerous population growth in order to save this unique planet and avoid eating bugs? Unbelievable and totally scary.

Nancy Sefton
*Poulsbo, Wash.*

### Fast Changes

*("Alzheimer's Under Attack," December 2018)*

The suggestion that lifestyle changes can prevent, delay or treat Alzheimer's is exciting. The sidebar titled "The Bredesen Protocol" provides startling commentary on North American culture and feels the need to prescribe fasting to someone — that's to say, not eating for certain periods of time. Many of the other recommendations describe a healthier lifestyle that is not more than a generation or two removed from general practice. That a widespread affliction such as Alzheimer's might be the product of only a few decades' lifestyle choices is sobering news.

Peter Humphries
*Ottawa, Ontario*

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**CORRECTION**

*("Fostering Fear," December 2018)*

In our story on the roots of the anti-vaccination movement, we incorrectly described how Edward Jenner developed the smallpox vaccine. He exposed people to the cowpox virus, not the smallpox virus, to help them develop immunity to smallpox.

## MULTIMEDIA FEEDBACK

### The Biggest Step Yet

Landing a rover on Mars isn't quite the feat it used to be. Nowadays, the public is obsessed with the next frontier: landing a person on the Red Planet. In that vein, we asked our Facebook followers if they thought NASA will put humans on Mars by the 2030s. The question, it seems, was divisive.


**Frank Townsend** I'd love to see it in my lifetime.

**House Llama** I think we will have the capability long before that, but politics will prevent it from happening. I would LOVE to be proved wrong.

**Donald Stephens** I would like high-speed rail everywhere first.

**Rudranand Sahu** Anyone may or may not put humans on Mars. The question is will humans survive for long on that planet?

**Wayne Sams** NASA won't exist in the 2030s.

**Evelyn Haskins** I would HATE to see it happen. Humans are destroying their own planet. Why spread the disaster?

Feedback is edited for space and clarity.

GORODENKOFF/SHUTTERSTOCK

# THE CRUX

## THE LATEST SCIENCE NEWS AND NOTES

### A CODE FOR COLONY HEALTH

A queen ant and her nurses sport unique QR code labels as part of a study to observe how an ant colony defends itself against pathogens. European researchers observed thousands of tagged ants, photographing them every half-second to precisely document the social interaction among the different kinds in the colony. "I personally tagged 4,400 ants," says biologist Nathalie Stroeymeyt of the University of Lausanne in Switzerland. She anesthetized each ant with carbon dioxide before placing a drop of glue onto the insect's thorax to hold the tag in place. "At top speed, this takes me about one minute per ant," she adds, "so this represented over 75 hours of work." – ERNIE MASTROIANNI; PHOTO BY TIMOTHÉE BRÜSCH

At a CERN facility in Europe, a man stands inside a prototype of a detector from the Deep Underground Neutrino Experiment (DUNE). This model, like the eventual final product in South Dakota, will be filled with liquid argon. It will help experts hone how they'll detect particles called neutrinos.

BIG IDEA

# Fermilab's Ghost Hunt

Researchers hope an underground experiment will reveal an elusive particle.

**SEVENTY-THOUSAND TONS** of liquid argon, trillions of particles moving at nearly the speed of light, an abandoned mine-turned-lab a mile underground, over 1,000 scientists and more than a billion dollars — all to catch what optimistic calculations suggest will be a single particle each day.

It's a staggering amount of effort, but a search for some of the most elusive particles in the universe may just be worth it.

The objects in question are neutrinos, often called ghost particles. They're far more present than the nickname suggests, though. Trillions pass through you every second — you just never notice. They're so lightweight, their odds of interacting with other particles are enormously slim; it takes extraordinarily sensitive equipment to even detect them.

But that evasiveness makes neutrinos a tempting quarry for physicists.

"There are more neutrinos in the universe than there are protons or neutrons, or anything like that, by a factor of about a billion," says Deborah Harris, a physicist who studies neutrinos at Fermilab, just west of Chicago. "If your goal as a field is to understand the universe, you need to understand neutrinos."

To that end, Fermilab, along with the Sanford Underground Research Facility in South Dakota, is starting a new project called the Deep Underground Neutrino Experiment, or DUNE. The goal is to track and study the shadowy particles like never before.

Currently set to begin in 2026, the experiment will be an important step forward for researchers studying neutrinos. It starts with a new particle accelerator, still in development at Fermilab. The complex machines are a crucial tool for physicists studying the universe's smallest bits of matter, allowing them to examine the particles in a controlled environment. Inside, a series of electromagnetic fields will accelerate individual protons up to nearly the speed of light. Then, still underneath Fermilab's grounds, the protons will ram into a block of graphite, producing a shower of particles. As these particles decay, a stream of neutrinos is produced. A sensor will gather data on that stream before it shoots off, traveling through Earth's crust, toward South Dakota, 800 miles away.

> "If your goal as a field is to understand the universe, you need to understand neutrinos."

There, buried deep underground at the defunct Homestake Mine, will be four warehouse-sized tanks filled with supercooled liquid argon. The hope is that some of the neutrinos made at Fermilab will strike the nucleus of an argon atom, releasing a burst of light and a cascade of electrons that scientists can track.

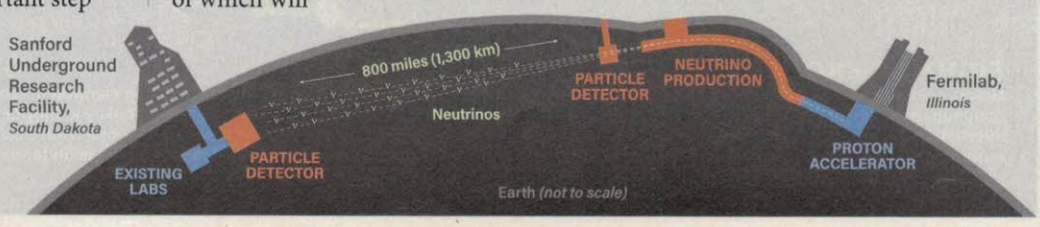
"Neutrino physics, so far, has been basically more a sort of counting experiment," says Angela Fava, a neutrino physicist at Fermilab. "You're classifying interactions and counting how many you have." But DUNE, she says, will let them begin to tell these interactions apart.

Of particular interest will be monitoring a peculiar trait of neutrinos: They change type, or flavor, as they travel. For example, the neutrinos made at Fermilab, nearly all of which will be of a flavor called muon, could arrive in South Dakota as muon neutrinos, or either of the two other flavors, tau or electron neutrinos.

By comparing the departing and arriving flavors and other data, the researchers hope to glean further insights into how the particles behave as they move through space. Most tantalizing would be hints of a potential fourth kind of neutrino, the "sterile neutrino" — so-called because, if it's real, it doesn't seem to ever interact with matter. But if there are subtle disparities in the type of particles observed at the near and far detectors, those might hint at the sterile neutrino's existence. Such a neutrino would be a candidate for dark matter, an invisible substance physicists are all but certain pervades our universe, yet have never detected.

Answers to such questions will have to wait until DUNE comes online, however, and challenges remain. Some are practical, like the fact that the particle accelerator is still in development, and others are simply logistical. For instance, transporting 70,000 tons of argon — which needs to stay cool in transit in order to remain in its liquid state — to South Dakota and then underground is a task never before attempted. While the researchers are confident they'll figure it out, it won't be easy. But that's only fitting: When looking for ghosts, things rarely are.

– NATHANIEL SCHARPING

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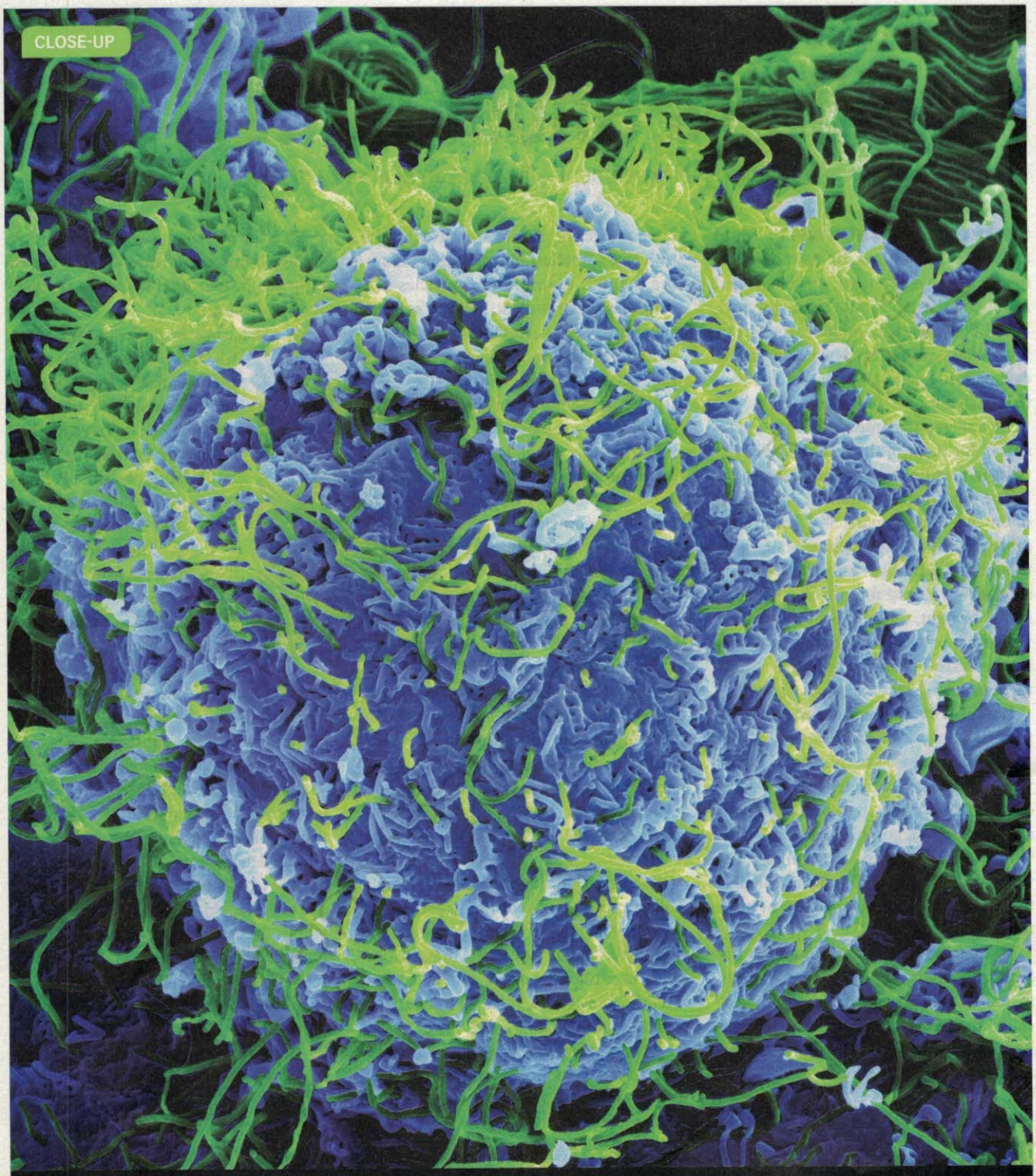


**FIGHTING EBOLA**
Green-colored strands of Ebola virus swarm a blue Vero cell in this color-enhanced image from a scanning electron microscope. One of the most common mammalian cell lines used in virology research, Vero cells ultimately come from African green monkey kidney cells developed in 1962. Today, international research groups are using the cells to develop a vaccine against the virus. More than 11,000 people with Ebola died during the 2014–2016 outbreak in West Africa; a clinical vaccine trial in the Democratic Republic of Congo, announced in November, is underway. – ERNIE MASTROIANNI; PHOTO BY NIH/NATIONAL INSTITUTE OF ALLERGY AND INFECTIOUS DISEASES

Q&A

# Take a Deep Breath

One researcher pushes to understand how an ancient yoga technique can change our cells.

**AS A CELL BIOLOGIST**, Sundar Balasubramanian never forgot his rural southern Indian roots, or the traditional practices his uncle, the village healer, exposed him to. Today, as a researcher and assistant professor at the Medical University of South Carolina, Balasubramanian has turned his focus back to those roots — specifically, to pranayama, a deep-breathing relaxation technique. He's showing that this ancient yoga practice is about more than relaxing — it can change us at the cellular level.

**Q What made you examine this technique through a cellular biology lens?**

**A** In 2005, I noticed while I was practicing pranayama, I was producing so much saliva that I was almost drooling. I wondered why and what the overall impact of that was. This led me and my team to study whether increased saliva production was a common response to the practice, and we found that it was.

**Q Most people wouldn't think much of getting spitty when they focus on breathing and relaxing. But your 2016 study in *BMC Complementary and Alternative Medicine* showed this bump in salivation seems to matter. Why?**

**A** Saliva has numerous antibodies and proteins that do everything from suppressing tumors to regenerating the liver. For example, it contains immunoglobulin, which are antibodies that bind to germs, as well as DMBT1, a tumor suppressor that blocks the conversion of normal cells to cancer cells.

**Q Your 2015 study in *International Psychogeriatrics* showed that pranayama does more than just increase salivation. Can you elaborate?**

**A** Yes, it changes the makeup of saliva by increasing the amount of nerve growth factor (NGF). When NGF is produced, it's transported to the brain, where it signals nerve cells to grow or survive longer. Increased NGF could have a major impact on aging, and specifically on some of the degenerative diseases of the day like Alzheimer's and cancer.

**Q Do you have any upcoming or ongoing research projects on pranayama?**

**A** We're about to start a study on patients with scleroderma, a chronic disorder that causes the body's connective tissue to swell and harden. We'll look at how these breathing techniques impact inflammation and how this relates to disease symptoms. We're also in the beginning phases of a study that will look at whether deep breathing can reduce pain, improve appetite and improve mood in cancer patients. — SARA NOVAK

BALAJI PARTHASARATHY

SCIENCE SMACKDOWN

# Are Human Astronauts Worth It?

Experts debate whether people or probes make the best space explorers.

Maybe human space explorers aren't the most efficient way to learn about the universe.

**DECADES BEFORE ANYONE HAD BUILT A ROCKET,** earthlings had already argued in science fiction about who is more suited for space travel: humans or machines. Today, the debate drags on as private players like SpaceX and government agencies like NASA vie to send people to the moon, Mars and beyond. But such missions are costly, and human bodies remain sensitive to space's harsh conditions. Maybe robots would simply prove better, cheaper, faster. In Science Smackdown, we let experts argue the evidence. – SARAH SCOLES

## The Claim

### THE HUMAN TOUCH

When Tony Antonelli was an Apollo-era kid, he wanted to be an astronaut. But not to be the first person on Mars: That person would surely land long before Antonelli grew up.

Antonelli did become an astronaut, but he overestimated how fast humans would explore space. He retired from the corps, and NASA still hasn't put anyone on Mars. Nevertheless, he wants to keep people in the launch recipe. "Robots don't explore," he says, "humans explore."

People react in real time, whereas robots require instructions, he says, which results in solid but slow progress. The martian rovers, for instance, have crawled 45 miles in 26 years, never deviating from NASA's instructions. In contrast, Antonelli recalls Apollo 15's "seatbelt rock." Astronauts saw something interesting, asked to check it out, and were told no. They then pretended a seatbelt had unbuckled, stopped the rover, and grabbed the rock anyway. Robots? Not so sly.

As a technologist at Lockheed Martin, Antonelli now guides NASA's next crewed mission, which may launch within five years. He argues keeping humans involved — through discomfort, expense and even danger — makes space travel more meaningful and productive.

## The Counterpoint

### ROBOTIC EFFICIENCY

The new space race is like the tortoise and the hare, contends Howard McCurdy. "The rabbit decides to take a nap, and the turtle just keeps coming," says the American University public policy professor and co-author of *Robots in Space*.

At the start of the space race, humans were more capable than robots. They could think, survive and see better. Then those humans developed technology that slowly but steadily upped the robot game, making uncrewed missions more attractive. For instance, compared with the Spirit and Opportunity rovers, which landed in 2004, the Curiosity rover, which touched down just eight years later, is more than three times larger and 10 percent faster, gets three times as much power from the sun, and has twice as many science instruments. And that's not to mention its advances in computing power and artificial intelligence.

Astronauts have to breathe, eat, drink and keep their demons at bay. Robots fly free of such constraints. They can do more, go more places and — because they don't require life support systems and are thus cheaper than human missions — do it all more often. But they still require human direction, don't have their own curiosity or interpretive skills, and they move slower than a crawl.

Ultimately, McCurdy envisions a "trans-human" program: Spacefaring humans would "siliconify," uploading their brains into a machine mind. "You've got a total machine that works, thinks and acts like a human being," says McCurdy. Perhaps it will take the best of both worlds to explore other ones.

COUNTERCLOCKWISE FROM TOP: NASA (2); COURTESY OF HOWARD MCCURDY

SPOTLIGHT

## SHREW IN A NEW LIGHT

To create this portrait of the North American least shrew, University of Kansas evolutionary biologist W. Leo Smith developed a novel imaging technique that better reveals detail in preserved specimens. Smith discovered that the dye Alizarin, long used by biologists as a staining agent, fluoresces under certain kinds of light, glowing, he says, like a Grateful Dead poster. By staining a specimen's bones, shining a high-energy blue light and then filtering out everything except the dye's fluorescence, researchers can examine minute skeletal details without the need for dissection. Smith also helped develop a way to pose the animals in a non-destructive gelatin mixture, allowing for more lifelike arrangements of skeletal and soft tissue — and better photos. – ERNIE MASTROIANNI; PHOTO BY M. GIRARD

INFOART

# Monumental Moves

Relocating historic structures can be tricky business.

**WITHIN THE NEXT COUPLE OF YEARS**, 80 percent of the Turkish town of Hasankeyf will be submerged. The country's water-resources agency plans to flood the area, home to 12,000 years of history, as part of the reservoir of a massive new hydroelectric dam. In preparation, workers are loading some of the town's landmark structures onto wheeled platforms and moving them to higher ground.

This isn't the first time engineers have been tasked with relocating massive structures. China has relocated a number of buildings over the past 20 years, from temples and homes to a four-story, 1,149-seat concert hall. In the U.S., the Hotel Pelham in Boston was moved way back in 1869, and other hotels — as well as theaters, office buildings and even lighthouses — have been relocated in the decades since.

These structures sometimes are moved to get them out of the path of urban redevelopment plans or infrastructure projects, other times to protect them from sea level rise and erosion — which, increasingly, leaves coastal buildings on shaky footing. Sometimes, critics oppose such moves, arguing they destroy a site's cultural context.

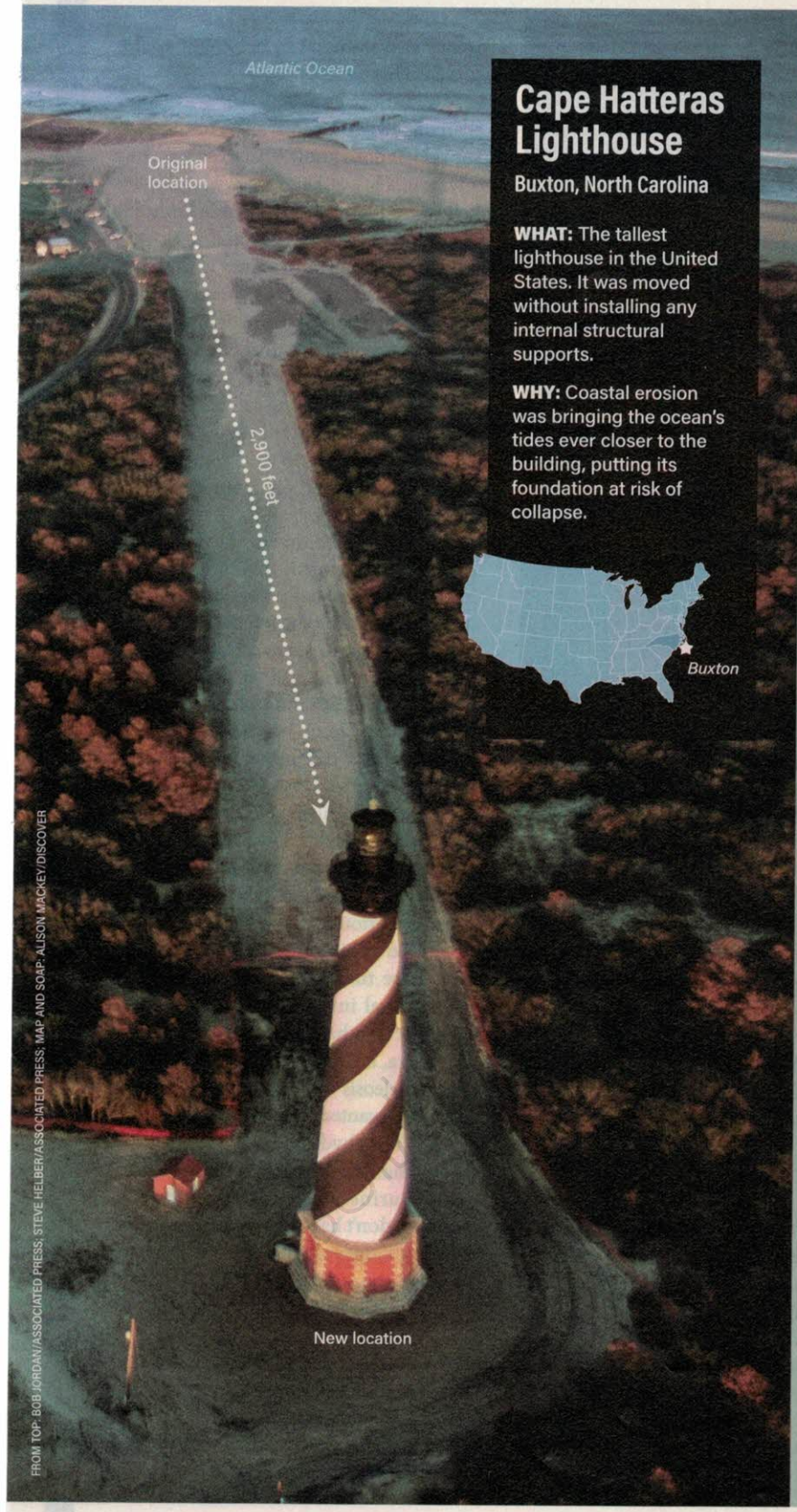
Either way, structural relocation — generally done by towing buildings whole along roads or rails, or by disassembling and then reassembling them — presents massive engineering challenges.

Here's how experts handled one of the trickiest moves in the United States, back in 1999: the Cape Hatteras Lighthouse. – JENNIFER HATTAM

The lightkeeper's house was also relocated.

To learn about other noteworthy moves, visit **DiscoverMagazine.com/movingmonuments**

KAREN KASMAUSKI




## Cape Hatteras Lighthouse

**Buxton, North Carolina**

**WHAT:** The tallest lighthouse in the United States. It was moved without installing any internal structural supports.

**WHY:** Coastal erosion was bringing the ocean's tides ever closer to the building, putting its foundation at risk of collapse.




## HOW:

- The original foundation of pine timbers and granite was replaced with a grid of steel beams that provided more support when hydraulic jacks lifted the landmark 6 feet off the ground onto a system of rollers and tracks.

- Because of the lighthouse's delicate setup, it moved for 5 feet at a time, at a pace of only about 1 inch per minute. It took 23 days to complete the 2,900-foot (roughly half-mile) trek.

- Sixty automated sensors placed inside and outside the lighthouse monitored how the load was moving, tracking things like the tilt and vibrations the structure experienced, while a weather station installed on top monitored wind conditions.

### FUN FACT

The engineers used Ivory soap to help keep the rollers moving smoothly along the tracks.


FROM TOP: BOB JORDAN/ASSOCIATED PRESS; STEVE HELBER/ASSOCIATED PRESS; MAP AND SOAP: ALISON MACKEY/DISCOVER

BY JULIA MICHIE BRUCKNER

# Teen Angst

When a grouchy boy complains about common pains, is it serious, or is he just being dramatic?

The teen shuffled past the nurse's station, grumbling and moaning. His mother lagged a few feet behind, rolling her eyes. He made it to his room, curling up on the bed and yelling at his mother to turn off the lights.

"He's back," the triage nurse quipped. "I think he's just a whiny kid. Even his mom is fed up with him."

Colin had visited our emergency room a few days before with complaints of a sore throat, headache, throwing up and belly pain. After a negative strep throat test, he was diagnosed with a minor viral infection — something his immune system could fight with help from a few days of rest and chicken soup.

But now the 19-year-old was back — and he felt no better.

## A TOUCH OF TEENAGE DRAMA?

When I introduced myself to him, Colin grunted from under a fleece blanket draped over his head and shoulders. His mother, weary and slumped in her chair, apologized on his behalf.

"He hasn't eaten anything or drank more than sips all day. He throws everything up," she said. "I don't know what to do with him anymore. He just hurts everywhere — his belly, throat, head — his whole body. He just wants to sleep all the time."

I've frequently found teens with simple illnesses like colds, sore throats or stomachaches to be prone to the dramatic. Was this just a young man in need of some fluids and ibuprofen, or was something more concerning going on?

"Colin, it's important we talk so I can figure out how to help you," I said quietly. He peeked his head out from the covers, grimacing.

He told me his throat was better but his head was worse, throbbing mostly in the front. His belly hurt on the right, under his ribs, and he felt nauseous. He'd developed no new symptoms since his last visit — no fever, no stiffness in his neck or joints, no diarrhea, no rashes.

My physical exam revealed little besides a red throat, a dry mouth and a mildly tender abdomen. Everything else — his blood pressure, heart rate, body temperature and oxygen level — was normal.

Though Colin was grumpy and reticent to cooperate, his headache did not seem to have a serious cause, such as meningitis or a bleed in his brain. He hadn't traveled anywhere that would prompt concern for unusual infections. I suspected the teenager just had a bad virus — maybe influenza, a stomach virus or infectious mononucleosis — exacerbated by dehydration. But I wanted to be sure that's all it was.

"You're dehydrated, which can cause headache," I told him, "Let's run some simple urine and blood tests to make sure you don't have issues with your electrolytes, kidneys, gallbladder or liver. We can give you some IV fluids, and medication for pain and nausea, and then see how you feel."

He grunted and curled up, pulling his sweatshirt over his eyes. He barely winced when the nurse started his IV. While he received his fluids and medications, I went to see other patients.

**I've frequently found teens with simple illnesses like colds, sore throats or bellyaches to be prone to the dramatic.**

KELLIE JAEGER/DISCOVER

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### LISTENING TO INSTINCT

The nurse found me a few hours later.

"He's not better," she said, "Still whining that everything hurts. He threw up even after taking the anti-nausea medicine, and he just spiked a fever of 101."

I ordered Tylenol for his fever and quickly reviewed the results of his lab tests. The abnormalities were subtle — a hint of anemia, a slightly low sodium level, a mildly abnormal kidney function, a small elevation of his gallbladder enzymes and dark concentrated urine.

Nothing was abnormal enough to give a clear answer. I returned to his bedside to seek other clues. He was writhing back and forth, holding his head and moaning. Was this just more melodrama? His mother sat in the corner, her arms crossed in frustration.

I always worry when a patient is not improving after treatments. Though I wasn't sure what was wrong with Colin, my gut told me it could be something more than a common virus. He needed more tests, scans and observation — something best done at a larger hospital nearby. We made arrangements to transfer him by ambulance.

As we helped him onto the stretcher, his mother pointed out that the right side of his head appeared to be swollen. It did seem a bit puffy, but he'd just spent several hours lying on that side of his head. I told his mom to make sure she mentioned it to the doctors taking over his care.

At the larger hospital, I soon learned, Colin's condition got worse. His forehead swelled, and he thrashed, cried and complained of a severe headache. His face felt numb and droopy, and his speech became slurred. These new symptoms prompted an emergency CT scan of his head. I had thought the answer was in his belly — perhaps an infected gallbladder — but in fact, the answer lay in his brain.

A colleague called from the hospital.

"He has an epidural abscess," she said.

I nearly dropped the phone. Such abscesses — bacterial infections inside or around the brain — are rare and dangerous. Colin's CT scan showed huge pockets of pus between his skull and the layer of tissue surrounding the brain.

This type of infection often stems from an untreated sinus or ear infection. The symptoms are initially subtle, similar to flu symptoms and other common viruses. But as the abscess grows, it pushes on the brain and makes it swell, leading to a worsening headache, seizures or difficulty moving or speaking.

**Sometimes patients arrive with very specific symptoms, making the diagnosis clear and immediate. But often, an illness starts off like a tree trunk — broad and capable of branching off in many directions.**

Without prompt treatment, brain abscesses lead to spreading infection, sepsis and death.

### BEYOND THE BRAIN

The doctors put Colin on powerful antibiotics and medication to prevent a seizure. But soon after, the left side of his body became limp, he began vomiting uncontrollably and his blood pressure skyrocketed — all signs his brain was swelling dangerously. The neurosurgeons whisked him to the operating room for surgery to drain the infection and give his brain room to decompress.

Still, I remained puzzled by Colin's abnormal gallbladder enzymes, which along with fever and vomiting, usually point to a gallbladder infection — something he did not actually have.

The doctors caring for Colin in the hospital had been similarly curious and performed further tests. It turns out Colin had a previously undiagnosed genetic disorder called glucose-6-phosphate dehydrogenase (G6PD) deficiency.

In a G6PD deficiency, an inherited defect in red blood cells causes them to break and burst when the body is stressed by infection, drugs or certain foods. Colin's abscess must have been too much for his red blood cells to handle.

The body's processing of these damaged blood cells creates bilirubin — a component of the bile stored in the gallbladder — and results in anemia, exactly what Colin's initial lab tests showed. These abnormalities were not due to his primary problem, but instead a complication of it, one that had led me down a wayward diagnostic path.

Sometimes patients arrive with very specific symptoms, making the diagnosis clear and immediate. But often, an illness starts off like a tree trunk — broad and capable of branching off in many directions. With time, observation for new symptoms and more testing reveal the answer — helping us identify the right branch to follow.

With weeks of antibiotics and rehabilitative therapies, Colin improved, eventually regaining normal speech and movement. His temperament got better, too — his crankiness was not just bad teenage behavior, but instead the result of an irritated brain. Within months, he returned to school and normal teenage life — only now with a scar hiding under his hair. D

***Julia Michie Bruckner*** *is a pediatrician at Children's Hospital Colorado. The cases described in Vital Signs are real, but names and certain details have been changed.*

KELLIE JAEGER/DISCOVER

BY BRENT CRANE

A mainland grizzly (*Ursus arctos horribilis*) catches a meal in Alaska's Katmai National Park and Preserve. Research is underway to see what grizzly bears might eat if they were reintroduced to California.

# Return of an Icon

Researchers lay groundwork for a potential grizzly return to the West Coast. Can California bear it?

Although the state flag suggests otherwise, nearly a century has passed since grizzlies roamed California. The last resident bear, reportedly spotted in 1924, was also the last of its subspecies: *Ursus arctos californicus*. These California grizzlies had reached an estimated population of 10,000 before Europeans arrived and triggered their steady demise.


Peter Alagona, an associate professor of history and environmental studies at the University of California, Santa Barbara, is convinced that one day grizzlies can return to California. "Reintroduction is possible," he says. "Absolutely possible."

In 2016, Alagona formed the California Grizzly Research Network, a multidisciplinary initiative made up of more than two dozen academics ranging from geneticists to historians, to respond, in part, to the public's growing interest in grizzlies. The group started by asking some practical questions that would need answers before any reintroduction: Where would the grizzlies come from? What would they eat? Where would they live? How might they affect the modern environment? How would they be received by locals?

Many of the answers lie in the past, in archival materials that mention the now-extinct California bears, as well as in paleontological clues uncovered in the field. By combining these details with modern-day conservation law and ethics, the scientists aim to paint a clearer picture of what a successful reintroduction would look like.

## THE RIGHT BEAR FOR THE JOB

All grizzlies are subspecies of the brown bear, *Ursus arctos*, which lives across the Northern Hemisphere. Not far from California, subspecies *Ursus arctos horribilis*, the mainland grizzly, is still hanging on, but mass urbanization, population growth and shrunken wilderness areas in the U.S. have restricted the bears — fewer than 1,700 live in the lower 48 states — to Montana's Northern Continental Divide region and the Greater Yellowstone area.

Although it's possible these different populations once varied in their appearance, modern genetic work has suggested the extinct California and extant mainland bears might even be genetically equivalent. Beth Shapiro, a professor of ecology and evolutionary biology at the University of California, Santa Cruz, says brown bears in the continental U.S. share a common

TOP: NATURE PICTURE LIBRARY/ALAMY STOCK PHOTO. BOTTOM: STATE OF CALIFORNIA AND GEARSTD/SHUTTERSTOCK

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maternal ancestor that migrated south from Beringia before the peak of the last ice age.

Bears from Yellowstone and Glacier national parks might be used in a modern reintroduction, especially "if they continue to grow beyond the carrying capacities of the protected parks and wilderness areas in those regions," says Alagona.

## FOOD FIT FOR A BEAR

A good deal of scientific sleuthing is happening inside Sedgwick Reserve, a 9-square-mile conservation area in the Santa Ynez Valley northwest of Santa Barbara. On a sunny morning last spring, Alagona and two UCSB researchers gave me a tour.

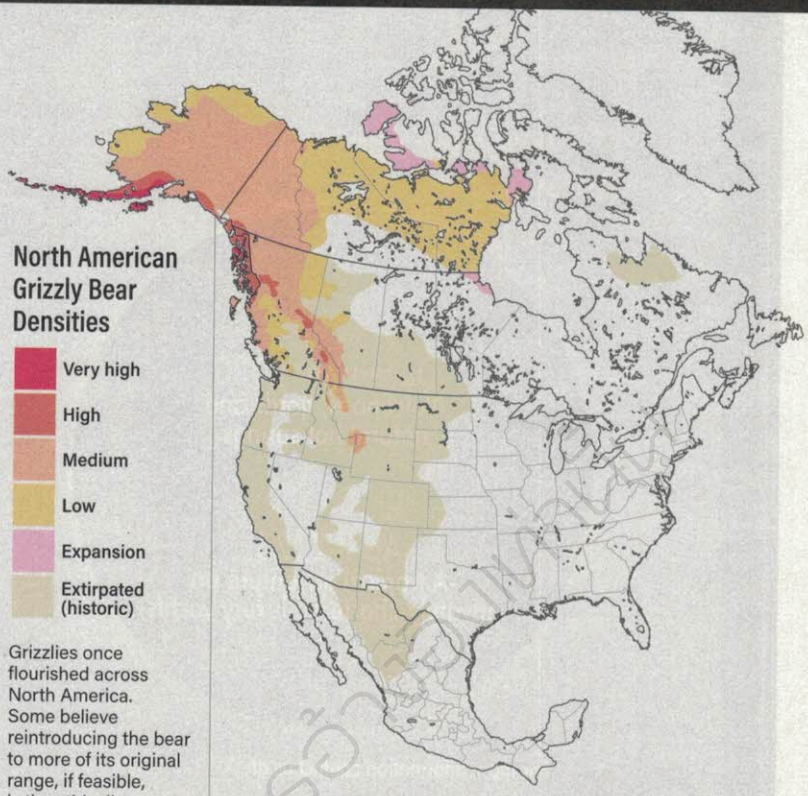
The reserve is a picturesque expanse of shrubby hills and fields of wild oats cut through with gurgling creeks. Bevies of quail patrol dirt roads, while camera traps set up near water troughs capture images of deer, mountain lions, black bears and even rattlesnakes. The "chaparral bear," the old nickname for California grizzlies, would have done just fine here, Alagona says.

While Americans tend to associate brown bears with temperate, coniferous forests, there are global populations in places as dry and barren as the Gobi Desert. "This is a very widely distributed, very diverse, very adaptive, very resilient kind of species," says Alagona.

And they're good eaters. Although Hollywood tends to focus on their teeth, grizzlies have prehensile lips that are perfect for stripping berries off branches, and their claws are ideal for digging up roots and turning over rocks to look for insects. They are opportunistic, and certainly not picky. "When you can eat anything, what do you eat?" asks Kevin Brown, one of the researchers.

Knowing the answer is crucial to predicting how grizzly bears might impact an ecosystem, and determining if their reintroduction is the right move ecologically. "If you put a significant number of large omnivores into the landscape, you're going to see some changes," says Alagona. Their presence, behavior and foraging habits could affect the behavior and foraging of a range of animals — from deer and elk to black bears and mountain lions — which could, in turn, affect the plants and other organisms lower on the food chain.

In biological circles, this ecological ripple effect is known as a trophic cascade. Alagona says it's too early to hypothesize what cascading effects grizzlies may have on habitats in California, but they're working on it.




Grizzlies once flourished across North America. Some believe reintroducing the bear to more of its original range, if feasible, is the ethically and ecologically responsible thing to do because of their natural place in the American ecosystem.

Source: "Grizzly bear (Ursus arctos): COSEWIC assessment and status report 2012," Government of Canada

A resident American black bear claims a big puddle near a trail camera in the 9-square-mile Sedgwick Reserve.

Anecdotal evidence for what California grizzlies once ate has shown up in settler journals, archival newspaper articles and historical artwork. One 19th-century artist, for example, painted a scene based on notes taken during a 1602 expedition, showing a grizzly grazing on a beached whale carcass.

To gain a more precise understanding, though, scientists have started combing Sedgwick for potential grizzly foods, such as mushrooms, roots, acorns and berries. Back in the lab, they'll analyze these edibles for chemical signatures called stable isotopes. Eventually, those will be compared with isotopes found in the bone fragments of California grizzlies stored in museum collections. This will allow researchers to pinpoint what grizzlies used to eat and what a reintroduced grizzly would likely munch on today.

## BEARS AND THEIR BOUNDARIES

While the team does consider climate change and warming environments in its possible reintroduction plans — less rainfall and drier air make fewer water resources, for example — they are more concerned with immediate threats like humans, says Alagona. "The real factor is whether people are willing to tolerate them," he says. It was, after all, humans who removed grizzlies from California in the first place.

That's where politics come in. Any potential reintroduction would need the sanction of both federal

FROM TOP: JAY SMITH AFTER P. MCLOUGHLIN; SEDGWICK RESERVE

and state wildlife agencies. But funding for these projects is hard to come by, and not everyone is convinced that reintroduction is a priority. Jordan Traverso, a spokeswoman for the California Department of Fish and Wildlife, says that while the agency "is absolutely not anti-study," it is "already inundated with human-wildlife interactions with the [animal] species that are here. ... We have no reason to assume that grizzlies would stay within some arbitrary boundary we set in a remote area of the Sierra."

The mood of the general public around reintroduction is less clear. In a statewide survey of 1,000 people by the research network, California residents didn't have strong feelings, says Alagona. A quarter of the respondents were not even aware that California grizzlies were gone. Meanwhile, a recent petition drive by the Center for Biological Diversity, an environmental advocacy organization, collected 20,000 signatures in support of reintroduction.

For doubters, it might help to look at the statistics. California may have 39.5 million people, but the vast majority of them live in cities along the coasts. Nearly 70 percent of people in California live in coastal counties. Furthermore, almost 90 percent of Californians reside in urban areas, with roughly a sixth in San Diego, Los Angeles or San Jose — less than 1 percent of the state's total land. The state also boasts more wilderness — continuous tracts of undeveloped forest land — than any state except Alaska. This means more space for grizzlies.

**California may have 39.5 million people, but the vast majority of them live in cities along the coasts.**

Alagona stresses that the research network is in it for the long haul. "We are doing some of the hard work now, I think, to set the stage for what may eventually become a really different kind of conversation around this," he says. And while he knows that any discussion of reintroduction "seems a little crazy at first," that is precisely what draws him to it.

"One of the problems with conservation is that it often fails to provide a visionary or positive vision for the future," he says. "Reintroduction is not essential, but it's also not impossible — it's a choice that we can make as a society." D

*Brent Crane is a freelance journalist based in San Diego.*

BY SOFIA DELENIV

# When Ignorance Is Bliss

Why we sometimes choose not to know.

A few months ago, out of curiosity, I took a genetic test to trace my ancestry. The results mostly confirmed what I had already suspected: I was a blend of Eastern European and Ashkenazi Jewish heritage. Then came an offer to see a medical analysis of my DNA — an opportunity to learn about the bits of my genome that increase my risk of developing disease. Again, I was curious, but as I started ticking a series of boxes informing me that I could discover something upsetting, I suddenly thought to myself, "You know what? Never mind. I don't have to know this."

This decision was out of character. I *always* want to know things, preferably as soon as possible. After a job interview, I constantly refresh my inbox, impatient to hear back. But finding out if I get the gig sooner rather than just a few hours later changes very little.

**The brain treats the chance to obtain a reward and to gain information as equally exciting.**

Knowing my genetic risks and ways to mitigate them, however, is potentially life changing. So why was I so content to stay in the dark? As a neuroscience grad student, I decided to do a little digging to learn how humans can be so curious, yet simultaneously harbor such a love of ignorance.

## THE STORY OF DOPAMINE

As I searched through the science, it became clear that our desire to know things — or not — is closely tied with dopamine, the chemical messenger of the brain's reward centers.

For decades, researchers have known that dopamine-releasing brain cells become highly active when we expect a reward or when we encounter rewards that are better than we anticipate. For example, if you assume you'll do well on a test but unexpectedly ace it, your dopamine levels will spike. This spike compels us to repeat the same behavior or return to the same environment in search of more. But more recently, scientists discovered that dopamine cells don't just care about tangible rewards. They also seem to care about information, even if it's useless.

The key study came in 2009. Scientists at the National Institutes of Health trained monkeys to look at a screen in exchange for drops of water. Next, the monkeys got to choose between looking at a meaningless image or one that revealed the size of their next water drop. Getting this heads-up didn't influence whether or not they got water, but the monkeys still heavily preferred the hint over ignorance. What's more, dopamine-releasing neurons that buzzed with activity in the buildup to getting water also fired up when the monkeys were waiting to learn how big their next drop would be.

This discovery points to a fascinating possibility: The brain's dopamine system treats the chance to obtain a reward and the chance to gain information as equally exciting. This might offer a clue as to why we often "just want to know."

In the next few years, researchers

DELPHINE LEE

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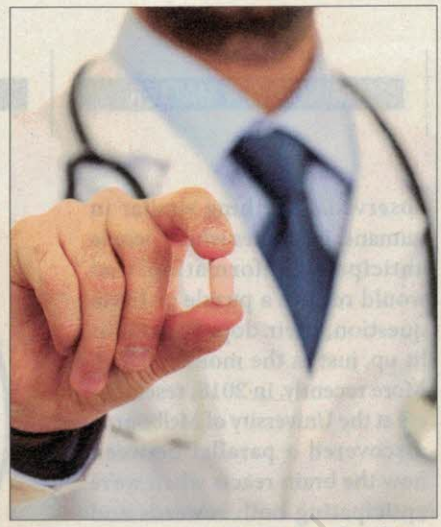

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### Taking CoQ10 is not enough

"There's a little-known NASA nutrient that multiplies the number of new power generators in your cells by up to 55%," says Dr. Al Sears, owner of the Sears Institute for Anti-Aging Medicine in Royal Palm Beach, Florida. "Science once thought this was impossible. But now you can make your heart, brain and body young again."

"I tell my patients the most important thing I can do is increase their 'health span.' This is the length of time you can live free of disease and with all your youthful abilities and faculties intact."

***Medical first: Multiply the "power generators" in your cells***

Al Sears, M.D., recently released an energy-boosting supplement based on this NASA nutrient that has become so popular, he's having trouble keeping it in stock.

Dr. Sears is the author of over 500 scientific papers on anti-aging and recently spoke at the WPBF 25 Health & Wellness Festival featuring Dr. Oz and special guest Suzanne Somers. Thousands of people listened to Dr. Sears speak on his anti-aging breakthroughs and attended his book signing at the event.

Now, Dr. Sears has come up with what his peers consider his greatest contribution to anti-aging medicine yet — a newly discovered nutrient that multiplies the number of tiny, energy-producing "engines" located inside the body's cells, shattering the limitations of traditional CoQ10 supplements.

### Why mitochondria matter

A single cell in your body can contain between 200 to 2,000 mitochondria, with the largest number found in the most metabolically active cells, like those in your brain, heart and skeletal muscles.

But because of changes in cells, stress and poor diet, most people's power generators begin to malfunction and die off as they age. In fact, the Mitochondria Research Society reports 50 million U.S. adults are suffering from health problems because of mitochondrial dysfunction.

Common ailments often associated with aging — such as memory problems, heart issues, blood sugar concerns and vision and hearing difficulties — can all be connected to a decrease in mitochondria.

### Birth of new mitochondria

Dr. Sears and his researchers combined the most powerful form of CoQ10 available — called ubiquinol — with a unique, newly discovered natural compound called PQQ that has the remarkable ability to grow new mitochondria. Together, the two powerhouses are now available in a supplement called ***Ultra Accel II***.

Discovered by a NASA probe in space dust, PQQ (Pyrroloquinoline quinone) stimulates something called "mitochondrial biogenesis" — a unique process that actually boosts the number of healthy mitochondria in your cells.

In a study published in the *Journal of Nutrition*, mice fed PQQ grew a staggering number of new mitochondria, showing an increase of more than 55% in just eight weeks.

The mice with the strongest mitochondria showed no signs of aging — even when they were the equivalent of 80 years old.

### Science stands behind the power of PQQ

*Biochemical Pharmacology* reports that PQQ is up to 5,000 times more efficient in sustaining energy production than common antioxidants.

"Imagine 5,000 times more efficient energy," says Dr. Sears. "PQQ has been a game changer for my patients."

"With the PQQ in ***Ultra Accel II***, I have energy I never thought possible," says Colleen R., one of Dr. Sears' patients. "I am in my 70s but feel 40 again. I think clearer, move with real energy and sleep like a baby."

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Along with an abundance of newfound energy, users also report a sharper, more focused mind and memory, and even younger-looking skin and hair.

Jerry M. from Wellington, Florida, used ***Ultra Accel II*** and was amazed at the effect.

"I noticed a difference within a few days," says Jerry. "My endurance almost doubled. But it's not just in your body. You can feel it mentally, too," says Jerry. "Not only do I feel a difference, but the way it protects my cells is great insurance against a health disaster as I get older."

### Increase your health span today

The demand for this supplement is so high, Dr. Sears is having trouble keeping it in stock. "My patients tell me they feel better than they have in years. This is ideal for people who are feeling or looking older than their age… or for those who are tired or growing more forgetful."

"My favorite part of practicing anti-aging medicine is watching my patients get the joy back in their lives. ***Ultra Accel II*** sends a wake-up call to every cell in their bodies… and they actually feel young again."

### Where to find *Ultra Accel II*

Right now, the only way to get this potent combination of PQQ and super-powered CoQ10 is with Dr. Sears' breakthrough ***Ultra Accel II*** formula.

To secure bottles of this hot, new supplement, buyers should contact the Sears Health Hotline at 1-877-353-0632 within the next 48 hours. "It takes time to get bottles shipped out to drug stores," said Dr. Sears. "The Hotline allows us to ship the product directly to the customer."

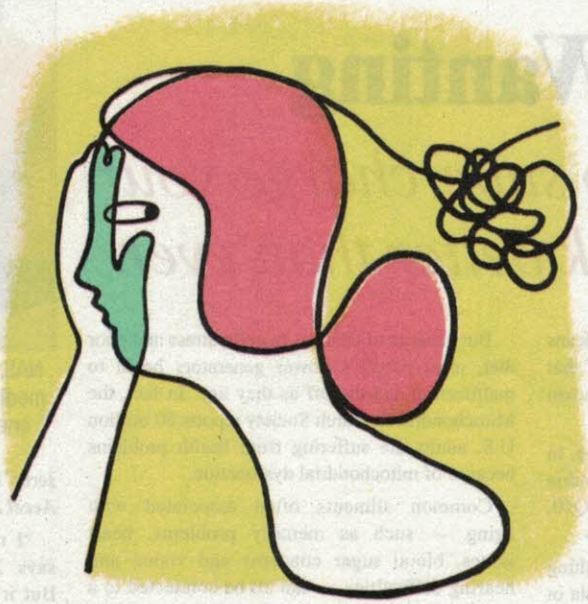
Dr. Sears feels so strongly about this product, he offers a 100%, money-back guarantee on every order. "Just send me back the bottle and any unused product within 90 days, and I'll send you your money back," said Dr. Sears.

The Hotline will be taking orders for the next 48 hours. After that, the phone number will be shut down to allow them to restock.

Call 1-877-353-0632 to secure your limited supply of ***Ultra Accel II***. You don't need a prescription, and those who call in the first 24 hours qualify for a significant discount. To take advantage of this great offer use Promo Code **DISC0319UA** when you call in.

observed something similar in humans. In studies where people anticipated information that would resolve a puzzle or trivia question, their dopamine hubs lit up, just as the monkeys' had. More recently, in 2018, researchers at the University of Melbourne discovered a parallel between how the brain reacts when we're anticipating both rewards and information, and how it reacts when those things fail to live up to our expectations.

Their study, published in the journal *Scientific Reports*, recorded the electrical activity of 22 participants' brains while they played a series of lottery games involving cards. Players had two options: remain ignorant of the lottery results until the end, or pay a fee, deducted from any winnings, to learn the outcome in advance. No matter their decision, players saw five cards, revealed one by one to be either black or red. For players who chose not to know the lottery outcome ahead of time, these cards didn't matter. But for those who did want the scoop, a black majority signaled an upcoming win. Whenever participants saw a red card revealed, indicating they could be on their way to a loss, their brains produced a specific electrical signal. But it wasn't the only time this signal showed up.



**We may avoid being uncertain about the future so we don't waste time on fruitless pursuits.**

Sometimes, a card — either red or black — that made the outcome less certain would be revealed to a player who'd opted to learn the results in advance. Interestingly, when this happened, that same electrical signal showed up, regardless of the card's color. Apparently, when the promise of obtaining useful information is denied, the brain reacts as if it missed out on an actual reward.

### THE THRILL IN KNOWING

Practically speaking, this neurochemical entanglement might explain why I often want to know things just out of curiosity. If both tangible rewards and information can be cashed in for a dopamine rush, then both have legitimate crave-worthy value. Now I wonder if my paying for my technically useless ancestry report is part of a drawn-out chase for a hit of dopamine. Accepting that my brain really does value information as much as it does physical rewards, that brings me to my next question: Why?

The research of Marco Vasconcelos, an animal behaviorist at Portugal's University of Aveiro, gives me some insight. In a 2015 study on starlings, he describes how he gave the birds a choice between pecking two buttons. One button immediately informed them about whether they were about to be rewarded; the second provided no information but resulted in a higher chance of rewards. Shockingly, the starlings heavily preferred the informative, lower-reward button.

To Vasconcelos, this makes perfect evolutionary sense. "If uncertainty is not eliminated as soon as possible," he explains, "an animal may [pursue prey that has] a reasonable probability of escaping."

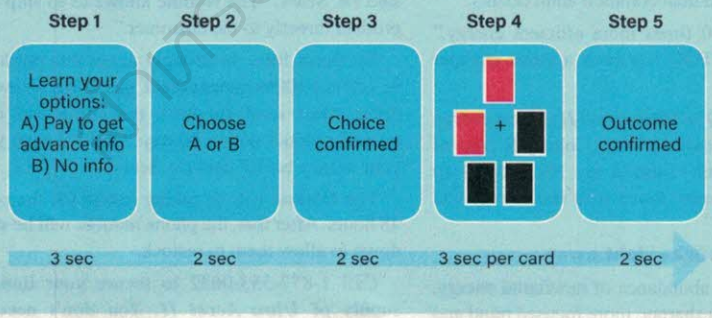
Similarly, we may actively avoid being uncertain about the future so we don't waste time on fruitless pursuits — something that might have meant going hungry back when resources were scarce. This drive could have hard-wired our brains to constantly seek information. On a subjective level, this idea makes sense: I definitely hate uncertainty.

### A FEAR OF THE UNKNOWN

Still, this doesn't mesh with my choice to avoid seeing the medical analysis of my genome. How to explain that choice? Researchers at University College London

## Tell Me, Tell Me Not

In one study testing how the brain treats information, volunteers played lottery games involving a series of cards. Players could choose to pay some of their winnings to learn the outcome of the next lottery in advance. Then, they were presented with a series of cards, either red or black. If they'd opted to learn the outcome in advance, they knew that a majority of black cards signaled an impending win. If they chose not to learn the outcome ahead of time, the ratio of colored cards didn't matter.




TOP: DELPHINE LEE. BOTTOM: DAN BISHOP/DISCOVER

and Washington University in St. Louis published a paper that helped me better understand.

In their study, published in 2018 in the *Proceedings of the National Academy of Sciences*, the team set up a lottery scenario where participants had no control over the outcome. Players went through multiple rounds where they could either win or lose money at random and collect their total earnings at the end. But at the start of each round, they saw their odds, framed as a percentage chance either of winning or of losing on that turn. Once they knew the odds, players could then give their preference for learning the round's outcome. Crucially, though, they knew their choice wouldn't affect their total earnings. All the while, the researchers tracked the players' brain activity.

The team found that, when probabilities were framed as chances of winning, people were much more likely to choose to be informed. And on those occasions, their reward circuits were highly active. But when probabilities were framed as a potential loss — even when the odds of winning and losing were the same — fewer people chose to be informed.

And their brains reflected this paradoxical behavior with lower levels of activity in brain areas that pump out dopamine.

It seems that the biological equation *information = reward* comes with a serious caveat. "Our brains treat positive information as a reward to be approached, but negative information … more as a punishment to be avoided," says Caroline Charpentier, the study's lead author.

When I ask her why we evade negative information, she argues that it comes down to the value of beliefs. "When we have positive beliefs about what's about to happen to us — we are about to get a salary raise — we feel good," she says. "Meanwhile, if we have negative beliefs — we are about to receive negative feedback on an assignment — we feel bad." So avoiding potentially negative information not only helps us reduce the uncertainty in our lives, it can help us try to keep our positive beliefs intact.

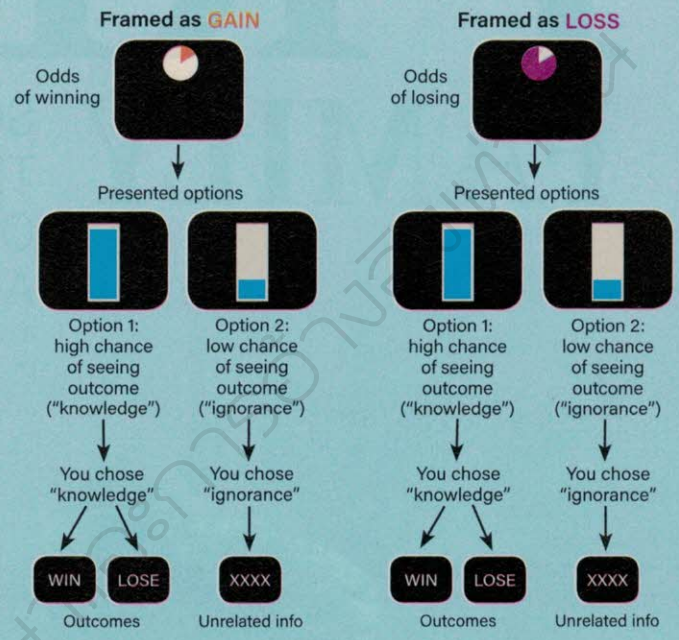
When I look back on my decision to remain ignorant of my genetic risks, I wonder if it was the potential of learning some bad medical news that trumped my usual frustration with uncertainty. After all, my years of studying the brain have made me all too aware of how untreatable many neurological conditions really are.

Ultimately, I agreed with my brain's reasoning: Maybe it's better not to know. D

***Sofia Deleniv*** *is a neuroscience graduate student at Oxford University.*

## It's All About How You Frame It

This lottery-based experiment investigated how the way information is framed impacts how inclined people are to want to learn it. Lottery rounds were presented as either a participant's odds of winning, or their odds of losing. In each scenario, players were presented with two options: little to no chance of seeing your lottery outcome or a high chance of seeing your lottery outcome. They next made their choice, which was confirmed in the following step. Finally, if they chose to know their odds of winning or losing, they saw the results. If they chose to remain ignorant of the results, they were shown unrelated information.




**Avoiding potentially negative information can help us keep our positive beliefs intact.**

LEFT: DELPHINE LEE. RIGHT: DAN BISHOP/DISCOVER

# MEET THE T-REX FAMILY

## SCIENTISTS RETHINK THE SOCIAL NETWORK OF THE ICONIC PREDATOR AND ITS ANCESTORS.

BY ERIC BETZ ILLUSTRATION BY MARK WITTON
PHOTOGRAPHY BY JAKE BACON

Before *Tyrannosaurus rex*, numerous other tyrannosaurs called North America home, including *Teratophoneus curriei* (shown). A recently found group of fossils may belong to the species.

A truck barrels down a dusty desert road in southern Utah's vast Grand Staircase-Escalante National Monument, speeding through canyons and along cliffs toward a towering sandstone formation known as the Kaiparowits Plateau. Alan Titus, a Bureau of Land Management paleontologist here for nearly 20 years, is behind the wheel, his shaggy hair flapping in the July wind as Led Zeppelin blasts from the speakers.

Titus stops the truck on a shrubby hill. With his passenger, University of North Florida paleontologist Barry Albright, he sets off on a small foot path into the high desert.

The two men, longtime friends and collaborators, are heading to the scene of a catastrophe — and, possibly, the biggest find of Titus' decades-long career.

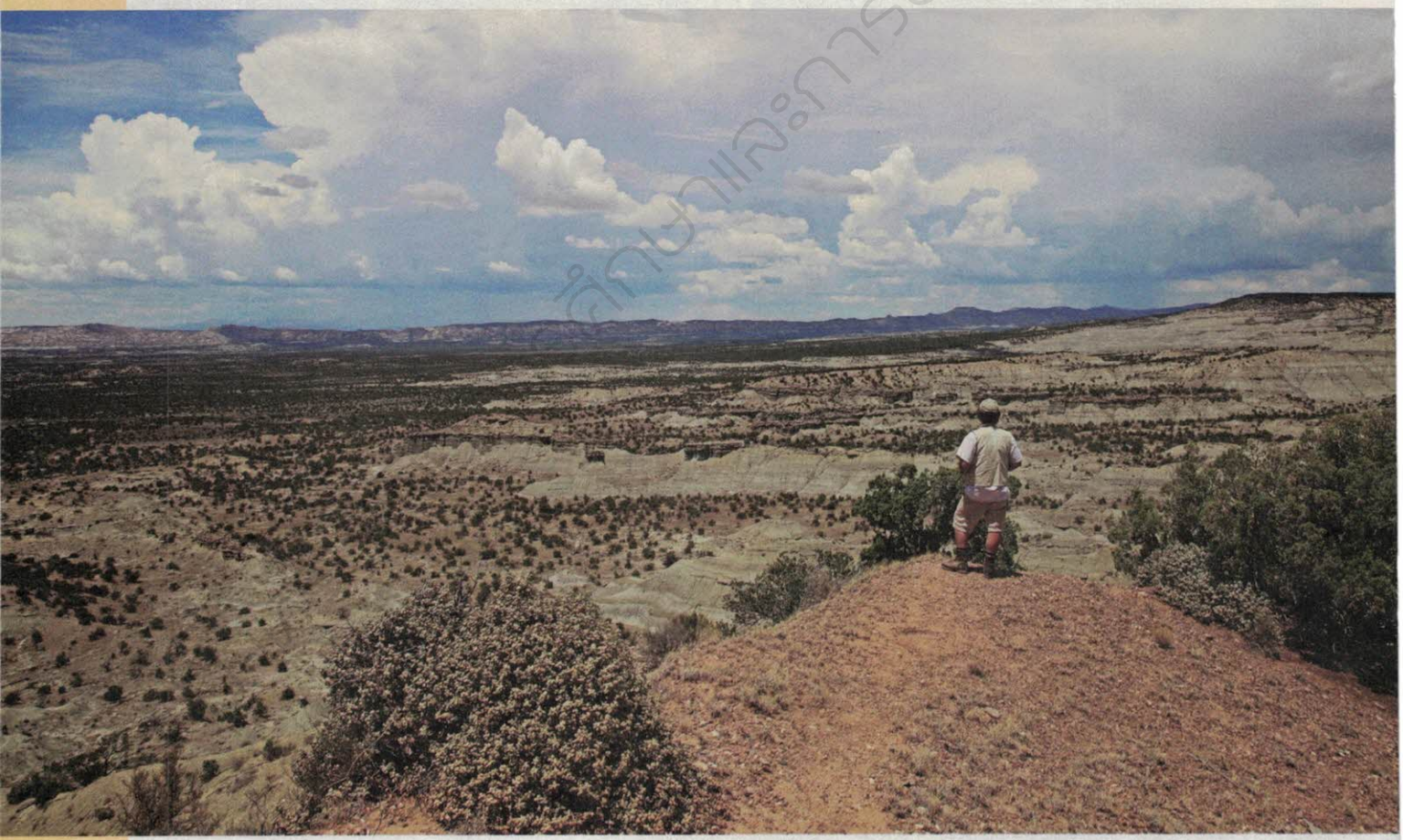
In 2014, Titus was prospecting for dinosaurs when he kicked over a bit of bone beside a scraggly old juniper tree. It was a piece of skull from a tyrannosaur — animals that include *Tyrannosaurus rex* and dozens of related and ancestral species. Since that chance find, Titus and his team have recovered remains from four tyrannosaurs — an adult, a teenager and two juveniles — from a site about 1,000 square feet in size. Titus thinks these tyrannosaurs died together some 76 million years ago during the Cretaceous Period. If he's right, it could confirm a controversial idea about one of the most iconic dinosaurs that ever lived.

Tyrannosaurs have been found from the Arctic Circle to the subtropics. And for decades, paleontologists have debated whether these top predators were social creatures. But fossil evidence has been hard to find. "That's why this is exciting," Titus says. He believes that "these animals are the direct ancestors of *Tyrannosaurus rex* living in a complex social group."

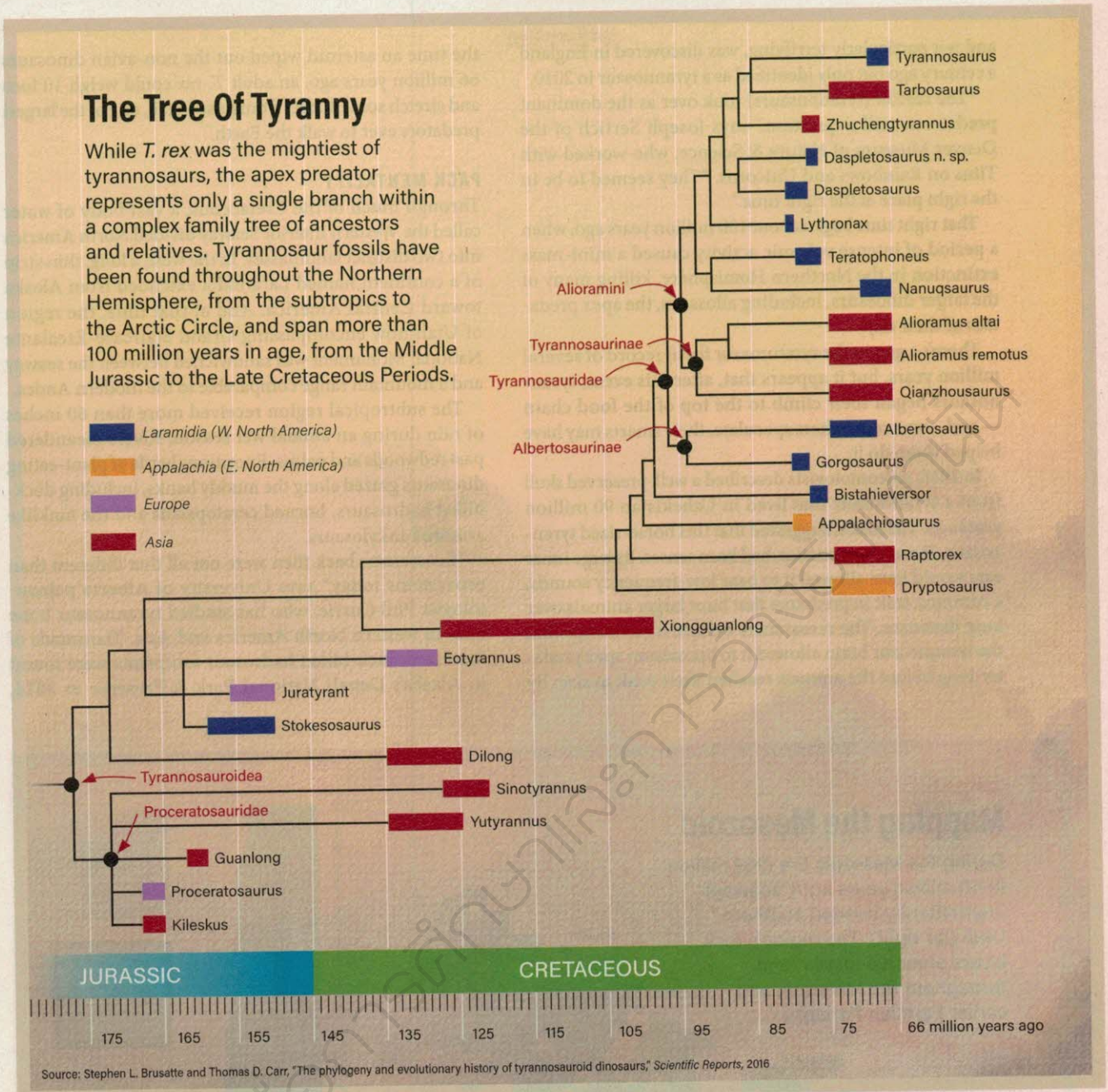
But not everyone is convinced. "It's hard to tell just from bones," says Albright, who helped work the site. He pauses and adds, "Their brains are too small to hunt in packs."

Titus isn't dissuaded. Even the site's nickname is a nod to his enthusiastic optimism. Team members call it "Rainbows and Unicorns."

Pop culture usually portrays tyrannosaurs as loners ravaging the landscape (remember *Jurassic Park*?), not animals with complex social relationships. But a handful of recent discoveries may be prompting a revision. In 2014, for example, paleontologists announced a trio of tracks in British Columbia from adult tyrannosaurs, possibly



Paleontologist Alan Titus surveys the vast landscape of southern Utah from the Kaiparowits Plateau, part of the Grand Staircase-Escalante National Monument. The area is rich in fossil remains from the Late Cretaceous Period — including what may be a family group of tyrannosaurs.




*Albertosaurus*, walking together in the mud. The following year, a study in the journal *PeerJ* described fossil evidence that suggested tyrannosaurs often bit at each other's faces, likely during competition. Titus and some of his colleagues believe that these finds suggest the predators may have moved in packs, jockeyed for social hierarchy and perhaps even cared for their young through adolescence.

Many modern predators exhibit these behaviors, but the long-standing dinosaur stereotype is that their brains just weren't big enough for such sophisticated relationships.

"A lot of that is simple bias against reptiles," says University of Maryland paleontologist and tyrannosaur expert Thomas Holtz Jr. "Crocodilians engage in play, deception and problem solving, things that people once thought they didn't have the brains to do." And because tyrannosaurs were brainier for their body size than any crocodile, it's reasonable to expect they'd be capable of even more complex behaviors, Holtz says. It's possible, in fact, that tyrannosaur brains explain their rise to dominance in the first place.

## THE AGE OF TYRANNOSAURS

The first animals to be considered tyrannosaurs show up in the fossil record 170 million years ago. But if you were placing bets on a future superpredator, you wouldn't have put your money on them. *Proceratosaurus*, shorter than a human

DAN BISHOP/DISCOVER

and not particularly terrifying, was discovered in England a century ago but only identified as a tyrannosaur in 2010.

"The reason [tyrannosaurs] took over as the dominant predator is still a question," says Joseph Sertich of the Denver Museum of Nature & Science, who worked with Titus on Rainbows and Unicorns. "They seemed to be in the right place at the right time."

That right time began about 100 million years ago, when a period of intense volcanic activity caused a mini-mass extinction in the Northern Hemisphere, killing many of the larger dinosaurs, including allosaurs, the apex predators of their day.

There's a gap in the tyrannosaur fossil record of several million years, but it appears that, after this event, tyrannosaurs began their climb to the top of the food chain — and, some researchers speculate, their smarts may have helped them do it.

In 2016, paleontologists described a well-preserved skull from a tyrannosaur that lived in Uzbekistan 90 million years ago. The fossils suggested that this horse-sized tyrannosaur, *Timurlengia euotica*, had keen senses. Its large inner ears would have allowed it to hear low-frequency sounds, a common trait in predators that hunt larger animals over long distances. The researchers believe it's evidence that the tyrannosaur brain allowed it to become an apex predator long before the animals reached their peak in size: By the time an asteroid wiped out the non-avian dinosaurs 66 million years ago, an adult *T. rex* could weigh 10 tons and stretch some 40 feet from nose to tail, one of the largest predators ever to walk the Earth.

## PACK MENTALITY

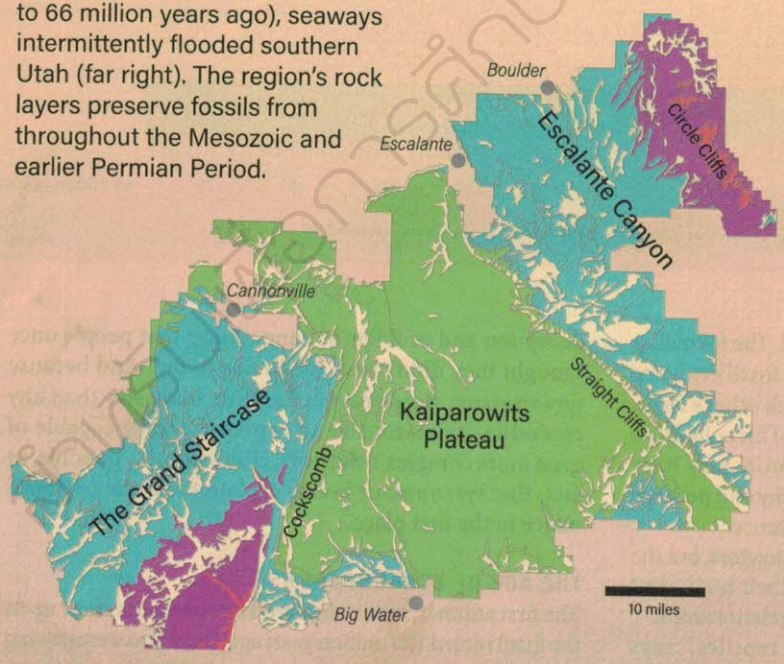
Through much of the Cretaceous, a vast body of water called the Western Interior Seaway divided North America into two distinct landmasses. In the west, a long, thin strip of a continent named Laramidia extended from Alaska toward Central America. And at that time, the region of Utah now encompassing Grand Staircase-Escalante National Monument was sandwiched between the seaway and a mountain range comparable to the modern Andes.

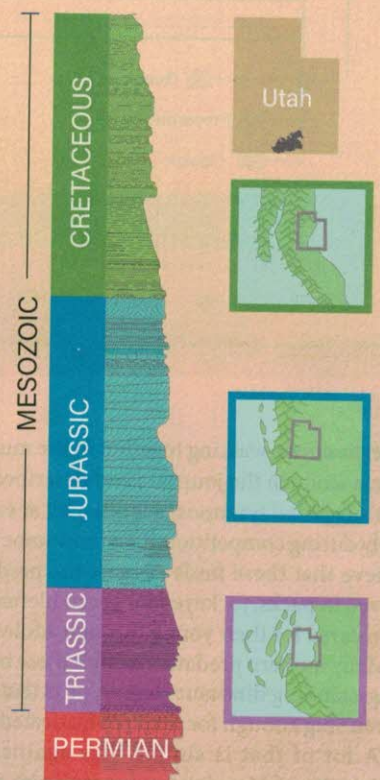
The subtropical region received more than 60 inches of rain during an annual wet season. Rivers meandered past redwoods and palms. Enormous herds of plant-eating dinosaurs grazed along the muddy banks, including duck-billed hadrosaurs, horned ceratopsians and the tanklike armored ankylosaurs.

"Ecosystems back then were not all that different than ecosystems today," says University of Alberta paleontologist Phil Currie, who has studied tyrannosaur bone beds in western North America and Asia. Thousands of fossilized duck-billed hadrosaur footprints were found in Alaska's Denali National Park & Preserve in 2014,

## Mapping the Mesozoic

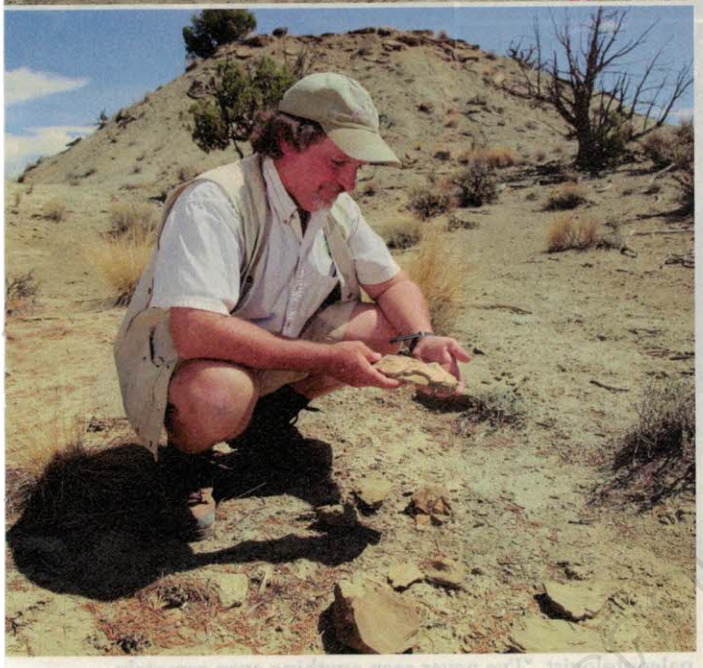
During the Mesozoic Era (252 million to 66 million years ago), seaways intermittently flooded southern Utah (far right). The region's rock layers preserve fossils from throughout the Mesozoic and earlier Permian Period.




Source: The Society for Vertebrate Paleontology

DAN BISHOP/DISCOVER



Titus and longtime collaborator Barry Albright excavate the site they call Rainbows and Unicorns (top); Titus examines a fossilized partial turtle shell, which provides clues to the Cretaceous ecosystem (above); and different types of rock at the site reveal a complex story of flood and drought (below).

showing the animals moved like elephants in large herds of both young and old. And by analyzing other herbivores' teeth for elements that can provide a record of location, scientists say they found evidence that some dinosaurs migrated seasonally.

These plant-eater herds would have been well protected against a lone predator, Currie says. But a group of tyrannosaurs could break up the herd to take on a single large animal.

"In today's ecosystems, where you have big groups of herbivores, you have big groups of carnivores," Currie says. We shouldn't expect animals to behave so differently back then, he says.

In 1996, Currie was at the American Museum of Natural History in New York, rummaging through the collections of Barnum Brown, the famed dinosaur hunter who discovered the first *T. rex* skeleton back in 1902. When Currie opened a cabinet drawer, he found the left foot of the smaller tyrannosaur *Albertosaurus*, which Brown had brought back from a field expedition in 1910.

"I opened the next drawer, and there's another foot," Currie says. By the time his team finished going through the cabinets, they had found fossils from nine individuals. Currie's luck wasn't up yet. The archives had pictures of a dig site on a distinctive ridge at Dry Island Buffalo Jump Provincial Park in Alberta, Canada. He set off to find it the following year.

"It ended up being one of the hottest days of the year, so when I found the ridge, I was at heat exhaustion," Currie says. "I didn't think of looking around my feet. The next day we came back, and there was *Albertosaurus* bone everywhere."

Back in 1910, Brown worked only a 65-by-65-foot section. The larger site that Currie's team excavated held bones belonging to possibly 20 or more tyrannosaurs killed in a single event some 70 million years ago. Growth rings on the bones show the animals' ages ranged from 2 to 24 years old — possibly parents and offspring.

How young tyrannosaurs made their way in the world has long been a hotbed of speculation. At 2 years old, an infant *T. rex*, for example, was the size of a golden retriever, with teeth not much bigger. Some paleontologists believe sexual maturity came around 18 years old. Along the way, their proportions morphed from sleek-bodied, narrow-skulled youth into school bus-sized adults with broad skulls and teeth as big as bananas.

Based on the size range of animals at the Dry Island site, Currie wonders if the younger, faster tyrannosaurs might have run into herds, flushing out prey for the adults, suggesting a division of labor within a hunting pack.

"As a scientist, you've got to be cautious," Carthage College paleontologist Thomas Carr says of the *Albertosaurus* mass grave and some of the speculation about it. Other animals, such as Komodo dragons, for example, gather in groups to feed but lack complex social relationships. "We've just got to wait to see if scientists find more bone beds [like it] to see if that holds up. It's just one site."

Clockwise from upper left: At his lab in Kanab, Utah, Titus examines an adult tyrannosaur skull still encased in rock; volunteer Deb Shanahan uses a compressed air tool called an air scribe to reveal an infant tyrannosaur skull; Titus shows off an adult tyrannosaur tooth; four toe bones from tyrannosaurs of different ages found at the Rainbows and Unicorns site illustrate the animals' size disparity; lab manager Katje Knoll prepares one of the larger bones found at the site.

Back in Utah, Rainbows and Unicorns could back up Currie's Dry Island hypothesis. But the finds from the Kaiparowits Plateau have yet to be published.

## THOUSANDS OF PUZZLE PIECES

At Titus' lab in Kanab, Utah, in a room the size of a large garage, bones are scattered across every flat surface. Half a dozen volunteers — mostly local retirees — huddle over workstations, using compressed air scribes that look like tattoo guns to pick minuscule chunks of rock from tyrannosaur fossils in plaster jackets. It's tedious work.

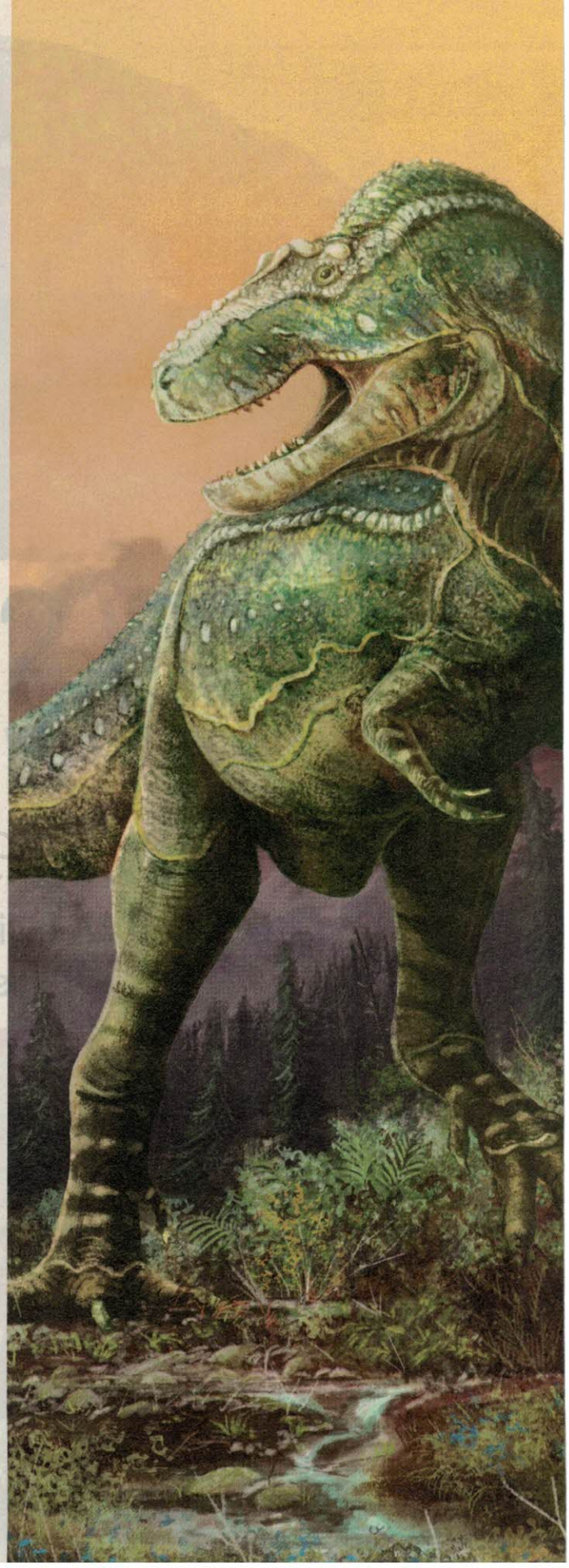
Studying the site has proven to be a monumental task, in part because the rock is exceptionally hard. The fossils themselves are mostly what Titus calls "kibbles and bits," thousands of jumbled pieces from dozens of different puzzles. Each fragment must be cataloged, studied and, if possible, reassembled.

"Rainbows and Unicorns is a very unusual bone bed," says Sertich, the Denver Museum of Nature & Science paleontologist. "I've never seen anything even remotely like it. It's like a spaghetti noodle cluster of bones."

How these creatures died, however, may prove to be less of a puzzle. The tyrannosaur remains were found near each other, but the larger dig site also holds half a dozen 3-foot-plus turtle shells, along with remnants of giant fish called gars, parts of a 20-foot crocodile and other bones. Other than the tyrannosaurs, the other fossils are mostly aquatic creatures.

That's because the site was once a roughly mile-wide lake. Titus believes the tyrannosaurs drowned there together, possibly washed in by a flood. The lake eventually dried up in a subsequent drought, killing off the fish and other aquatic animals.

In a corner of the lab, volunteer Deb Shanahan wears a face mask and lab coat as she chisels away at an infant tyrannosaur skull encased in rock. She started on the skull back in September 2016. With each new section of fossil exposed, Shanahan becomes the first to see an animal that's been locked up in rock for 76 million years.



On a large table nearby, Titus and another volunteer are revealing the menacing grimace of an adult tyrannosaur's massive skull and teeth. The team suspects their dinosaurs could belong to a species called *Teratophoneus curriei*, or "monstrous murderer," named after Currie. The species lived in this region but is known only from a partial specimen. Having four more individuals could reveal details about the species' development from infancy to adulthood.

However, unlike *T. curriei* and other local tyrannosaurs, all four of the new specimens have a flat lacrimal bone, which sits above the eye socket. That could indicate it's a new species altogether. The team won't know for some time. They've been chipping away material from the adult's giant skull for more than two years, but months of work remain.

Titus isn't in a rush. "I'll only get one shot in my career to work on something this cool," he says. "It's a disservice to my co-authors and to science to not take my time." D

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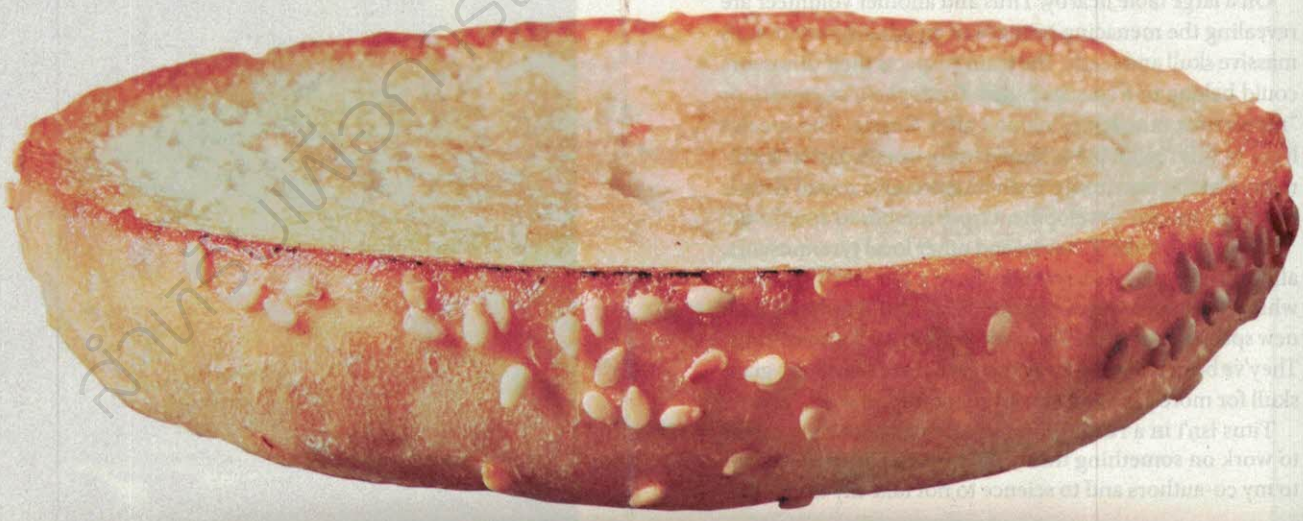
***Eric Betz*** *is digital editor of* Discover.
*Follow him on Twitter:* ***@ericbetz***

# RAISING THE STEAKS

There are 7.5 billion of us and counting. What's for dinner?



BY MARTA ZARASKA

ARTJAZZ/SHUTTERSTOCK


# STRETCHED ALONG A RIVER IN THE HEART OF THE NETHERLANDS, THE TOWN OF WAGENINGEN IS NOT POSTCARD-PRETTY.

It doesn't have Amsterdam's historic canals or Rotterdam's bold modern architecture. Wageningen's only claim to fame, in fact, is its university, ranked as the world's top agricultural research hub. Much of the institution focuses on how to feed humanity in the coming decades, and the work is badly needed: By 2050, Earth, now home to about 7.5 billion people, may have nearly 2 billion more.

At the top of research priorities in Wageningen is protein, or rather, how to find more of it — and we'll need to look beyond meat-based diets. Obtaining 1 pound of animal protein uses about 7.5 pounds of plant proteins, which are consumed by the animal as it grows. About 80 percent of agricultural land is already used for grain that's fed to livestock. The calculus is simple: If we don't change the way we eat, and quickly, there won't be enough protein for our expanding population.

The good news is that scientists in places like Wageningen are working hard to find alternatives to animal products other than soy, the current staple: plant-based steaks, duckweed, microalgae, seaweeds and edible insects — and creating poop machines, literally, to evaluate them all.


In the Netherlands, Wageningen University researchers are pioneering the future of plant-based proteins. From top: Vivid green microalgae fill photobioreactor tubes at a growing facility; the agrotechnology building is a hub for cutting-edge innovation in the field; the greenhouselike microalgae growing facility looks out onto open fields.

FROM TOP: ALISON MACKEY/DISCOVER (MAP); WAGENINGEN UNIVERSITY; ROBIN UTRECHT (2)

# MICROALGAE

Set up in the middle of an open field, the microalgae growing facility in Wageningen is eerily quiet. Snow fell yesterday, and the contrast between the white powder and the vibrant green of the photobioreactors, dozens of tubes as thick as an arm spread over an area the size of a basketball court, is otherworldly.

Production at the facility has slowed with the arrival of the cold, but Maria Barbosa, a bioprocess engineer, says the colors are even more stunning when the microalgae are actively growing. Some of the glass tubes snake horizontally on the ground, while others are arranged in vertical rows like giant green radiators. Farther out, there is a small pond, also for microalgae. By comparing seasonal growth in the different systems, the researchers are learning which method has the best balance of high productivity and low energy consumption. In a 2017 study, for example, Barbosa and her colleagues found that, in autumn, cultivating microalgae in horizontal tubes requires up to 30 percent less electricity than it does in vertical ones. An open pond, meanwhile, can be a good idea in the summer — but winter rains and lower temperatures can disrupt production.

In theory, microalgae could make for a great protein source. Some, such as spirulina, can contain up to 70 percent protein in dry weight, and have all the essential amino acids that humans need to survive. But there's a reason why you can't buy spirulina steaks just yet. Cultivation of these microscopic organisms is still inefficient and expensive — something that Barbosa and her colleagues in Wageningen hope to change.

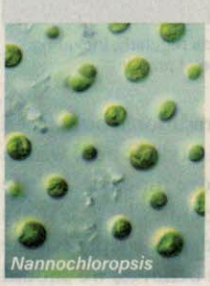
Barbosa's favorite microalgae are *Nannochloropsis*, a genus of several easy-to-grow marine species. Another of her top choices, intensely green *Tetraselmis*, is so productive that even in the cool climate of the Netherlands, you can get 30 tons per hectare — about 74 tons per acre. "That means 15 tons of *protein* per hectare," she says. By comparison, 1 acre of land used to raise cattle yields less than a pound of beef. What's more, microalgae could be produced in places

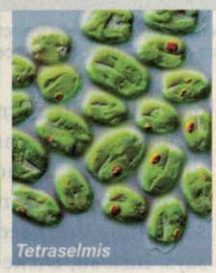
BELOW, CLOCKWISE FROM LEFT: NOUT STEENKAMP; CSIRO; GERD GUNTHER/SCIENCE SOURCE; ROBIN UTRECHT

FAR RIGHT FROM TOP: WAGENINGEN UNIVERSITY; SINCLAIR STAMMERS/SCIENCE SOURCE

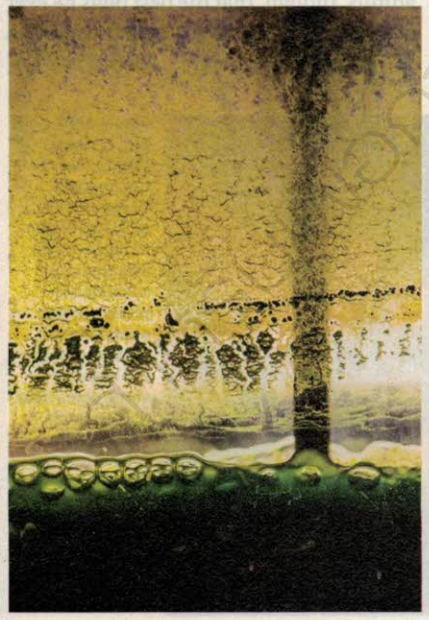
where nothing else can be grown, such as marginal lands or even at sea.

Barbosa believes that the first large application for microalgae protein will be feed for salmon or shrimp. Microalgae protein could also be added to existing foods, such as bread — it's already happening in bakeries around Wageningen. Barbosa has also tried microalgae ice cream and pizza cooked up with her colleagues. Although she admits the taste can be a little on the fishy side, she believes we'll see microalgae protein added to many products over the next few years. *Nannochloropsis* steaks are likely further off in the future, though "in principle, you could also use the protein from microalgae to make these kind of textures," she says.




Bioprocess engineer Maria Barbosa grows microalgae inside room-long photobioreactor tubes that are designed for high production and low energy consumption. Varieties cultivated, such as *Nannochloropsis* and *Tetraselmis*, may one day be cheap and sustainable protein sources, blended into foods or fed to farmed fish. A cross-section of one of the tubes (below) shows growing solution bubbling with microalgal life.

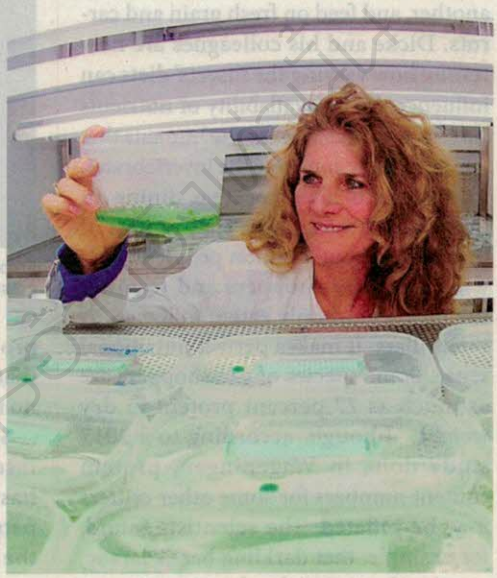


## DUCKWEED

Ingrid van der Meer, a plant biotechnologist at Wageningen University, opens a petri dish and fishes out some duckweed with her fingers. She slides a few of the pinhead-sized plants into her mouth and starts chewing. "It has a nutty taste," she says, then adds, smiling, "It's such a nice plant. But it sticks to everything — when you are working with it, you end up with duckweed everywhere. It's their way to spread around."

Duckweed is one of the fastest-growing plants on Earth. Its biomass can double in size in as little as 16 hours — it's so fast that in 2004, the government of Venezuela declared a state of emergency due to the spreading duckweed cover on Lake Maracaibo. A NASA photo taken that year showed the large body of water resembling an enormous green glob.

Although duckweed can be a nightmare for environmentalists, it may also be one of the best shots at an environmentally friendly future food. The plant is packed with protein. "We've calculated that you can produce 10 times more protein per hectare per year with duckweed compared to soybean," van der Meer says. As for the name, though, she and her colleagues prefer to call the plant "water lentils" (from the Old Dutch *waterlinsen*). "It's a much better name," she says, her mind on potential future consumers.



Wageningen biotechnologist Ingrid van der Meer shows off some of the duckweed she grows in her lab. The fast-growing, pin-sized plants (right), also known as water lentils, can be a nightmarish invasive species in some areas, but they also hold promise as a protein source.

In her Wageningen lab, van der Meer researches how to harvest duckweed in the most efficient and safest ways — but she is also investigating how good it really is as a protein source for humans. Her team has recently finished a clinical trial comparing protein from duckweed with that of soybeans, inviting volunteers into their lab for a taste of boiled duckweed, which could be mistaken for a bowl of spinach. The scientists collected blood samples from the volunteers before and after the meal to check their amino acid levels, which would provide an insight into how well duckweed protein is digested. Although the results haven't been published yet, van der Meer believes duckweed is good for us: "It really contains a lot of vitamins. Its B5 is very high, and B1 is very high, too, and it has a lot carotenoids. So I do not only see it as a nice source of protein — it could also be just a good vegetable."

Wageningen University is already collaborating with several companies in the Netherlands to introduce duckweed to consumers. Products planned include ready-to-eat mixes of mashed potatoes and duckweed (based on a Dutch staple, *stamppot*) and soy-based "meats" with added water lentil protein.

# INSECTS

The insect culture lab at Wageningen University is hot, humid and all abuzz. Here, entomologist Marcel Dicke studies methods of rearing insects for human consumption and animal feed. The small room where his team raises black soldier flies smells of the insects' preferred habitat and food source, decaying plant matter. The crickets' home, nearby, is easier on the nose: The bugs live inside empty egg cartons stacked high one atop another, and feed on fresh grain and carrots. Dicke and his colleagues are now testing how varying the insects' diets can influence the bioavailability of nutrients such as iron and zinc for the humans that will eventually consume the invertebrates.

From a global perspective, dining on insects is nothing new. They're part of the diet of about 2 billion people worldwide, with grasshoppers and termites the most commonly eaten, followed by caterpillars. It makes perfect nutritional sense. Some species of grasshoppers are as much as 77 percent protein in dry weight, although, according to a 2017 study done in Wageningen, protein content numbers for some other critters may be inflated. The scientists found, for example, that darkling beetle larvae, commonly reported to be 58 to 65 percent protein, are only 49 percent. But that's still a great nutritional value. And producing insects for consumption is far more environmentally friendly than, say, cattle farming. Measured pound for pound, raising grasshoppers, for instance, produces a third of the carbon dioxide that results from raising beef cattle, and no methane whatsoever.

Entomologist Marcel Dicke notes that about 2 billion people worldwide eat insects regularly, including grasshoppers like the ones he's holding. The animals are an Earth-friendly source of protein.

Since he began research on edible insects more than 20 years ago, Dicke has seen significant change in how people in the West perceive them. In the Netherlands in particular, he says, people have gotten used to the idea of snacking on bugs. Dicke believes that Westerners have a responsibility to eat insects — although, in theory, we don't need any more protein since most of us already eat about twice as much as we require. In developing countries, people often give up their traditional bug-based dishes for Western-style foods, which they perceive as more modern. "We're exporting a McDonald's diet. . . . That's something that needs to be stopped," he says. Instead, Dicke believes, we should focus on exporting more sustainable eating habits.

In Wageningen, one restaurant already offers bagels baked with crickets, mealworms and grasshoppers, and Dicke himself often cooks insects at home. He admits, though, that the best bugs he ever ate were in China: "Dragonfly larvae, with some peppermint leaves, deep-fried."

Mealworms (left) and crickets (right), two of the animals being studied at Wageningen for large-scale production of sustainable protein, have already found their way onto the menu of some cafes near the research university.

ROBIN UTRECHT (5)

## SEAWEED

The protein content of seaweed may not be as high as that of duckweed or insects, but Jelle van Leeuwen, a process engineer at Wageningen University, believes they still carry great feed-the-world potential.

Van Leeuwen says a biorefinery approach — similar to the way oil refineries create multiple products out of a single raw material — would allow us to "get the most products out" of seaweed. First, fuels such as biogas or ethanol would be extracted. Then, health care products and plastics would be made. And, almost as a byproduct, there would be protein. The Dutch government is already exploring whether it makes financial sense to grow that raw material around near-shore wind farms, where existing infrastructure would make the farms much cheaper to set up and run than starting from scratch farther off shore. "There are a lot of seaweed farmers at the moment who are thinking about installing their farms near these windmills," says Adrie van der Werf, van Leeuwen's colleague.

In his lab, van Leeuwen opens a cooler and pulls out a large sheet of frozen, brownish seaweed. In his hand, the leaves soon thaw, and become soft and stretchy. "That's sugar kelp — this is the one we work on the most. It is a very easy species to cultivate in the North Sea. So we are now focusing on extracting all kinds of components out of it," he says.

Humans eat quite a lot of seaweed already. According to the United Nations' Food and Agriculture Organization, we consume about 9 million tons of seaweed a year in recognizable form, such as the nori that wraps around your California roll. That amount is even higher if you include seaweed used as food thickeners and gelling agents. Van Leeuwen imagines that protein could be extracted out of seaweed and used in its pure form, similar to the way soy is used now. "I think that might be a few years away still," he says. "But it's possible — it's technically possible."

Numerous species of seaweed, such as sugar kelp (above), may be multitasking powerhouses for a sustainable future, providing fuel, health care products and protein. Wageningen process engineer Jelle van Leeuwen (below) works with the material to find new uses for the plant and optimal ways of growing and processing it.

## PLANT STEAKS

Back in November 2015, big news came out of Wageningen — a group of local scientists led by a food engineer, Atze Jan van der Goot, created a 15-pound steak made entirely from plants. Although burgers consisting of minced soy "beef" and cubes of bird-free "chicken" have been widely available for years, before 2015, no one had produced a piece of mock meat so large that it could actually be sliced and carved.

Couette Cell, the machine that van der Goot and his team invented, uses shear-cell technology to make "meat" out of protein powders, water and gluten. It resembles something between a spaceship and a meat grinder, with one cylinder nested inside another. The inner drum rotates, causing strands of heated soy and gluten to wrap around each other and create fibrous structures. "It is basically just heating while deforming," van der Goot says. "You could compare it a little bit with dough kneading."

Plant meats that are currently on the market, such as the Impossible Burger and the Beyond Burger, use an older technology called high-moisture extrusion. In comparison, the Couette Cell could not only make bigger cuts with more meatlike textures, but it could also make them much cheaper.

For now, van der Goot uses mostly soy for his steaks, but he also researches other potential protein sources, such as peas, beans and rapeseed. "It's a great challenge," he admits. Peas, for example, would be ideal, since they are a "very sustainable source," but they produce a softer structure than soy does. Duckweed, too, is difficult to process, so we shouldn't expect water lentil steaks in any near future.

Van der Goot hopes soy steaks, though, could hit the market by 2021. He's currently collaborating with several Dutch companies, including some in the meat industry, to achieve this goal.

Food engineer Atze Jan van der Goot (above) shows off a 15-pound steak made from soy and other animal-free ingredients. The Couette Cell (right), a machine that uses heat and rotation to create fibrous structures, made the impressive slab of mock meat.

### The Dutch Weed Burger

When you put the words *Dutch* and *weed* into one sentence, most people do not think of seaweed. The Dutch Weed Burger may change that.

The company, founded in 2012, already sells its products in more than 200 restaurants across the Netherlands and neighboring regions. Co-founder Mark Kulsdom dreams big, though. He wants to be in 700 joints soon.

I decided to see for myself what the future of protein might look like. I picked a corner table at Bagels & Beans cafe on Wageningen's main shopping street and placed an order for what was advertised on the menu as a "juicy patty" made with "Royal Kombu, a tasty and healthy winter weed, sustainably cultivated in the Dutch region of Zeeland." In other words: a type of seaweed that grows in winter off the coast of the Netherlands, just south of Rotterdam. The bun was enriched with chlorella, a microalga, and the sauce laced with sea lettuce, another common algae.

When my order arrived, I couldn't help but eye the burger with suspicion. I expected something far more green and seaweedy, I guess. Instead, the patty seemed unremarkable, brown and beeflike. Once I took a bite, my suspicion deepened. It tasted good, if a bit dry. Very meaty. Too meaty.

A panicked thought crossed my vegetarian mind: Was it really seaweed, or maybe just regular beef with some algae added to it? The more I ate, the more I became convinced that I was, indeed, eating meat.

I asked the waiter to bring the detailed ingredient sheet for the product. Together, we confirmed: The burger was vegan. The future fooled me, that's for sure. — *M.Z.*

FROM TOP: ROBIN UTRECHT; NIELS BLEKEMOLEN (COUETTE CELL); ROBIN UTRECHT

## WHAT GOES IN MUST COME OUT

To an outsider, the smell in the lab where SHIME sits is almost unbearable. That's hardly a surprise. The machine, whose full name is the Simulator of Human Intestinal Microbial Ecosystem, consists of five jarlike containers called reactors. Through controlled temperature, moisture and acidity, each reactor replicates a different part of the human gastrointestinal tract, including the colon. Also inside the reactors: human feces, donated regularly by one of the researchers, which provides the microbial populations naturally found in the human gut to digest whatever protein is loaded into the device. The Dutch media have nicknamed it the "poop machine."

Yet the smell does not seem to bother Harry Wichers, a biochemist who spends hours in the SHIME lab, studying the digestibility of various proteins. He feeds different types of protein — insect, fungi or plant — into the reactors and observes how well they're broken down into amino acids. "Not everything you eat is equally digested," Wichers says. In November, his team began conducting human trials on two novel proteins, collecting blood, fecal and urine samples from participants to measure their amino acid profiles before and after consumption.

Wichers' ultimate goal is not necessarily to come up with the ultimate protein to replace meat and dairy in the average diet, but instead to develop a broader understanding, a "toolbox" of plant-based proteins appropriate for different applications, such as ensuring optimum amino acid consumption, or even breeding more nutritious crops.

Like Wichers, the other scientists working in Wageningen aren't hunting for a single perfect meat replacement. It won't be *just* duckweed. Or *just* microalgae. Or *just* insects. What they hope for is a future in which all of these protein sources help us significantly reduce our dependence on meat, dairy and eggs.

"I don't see duckweed or seaweed as a competition to microalgae. I think there is a place for all of these different protein sources, just like we now have beef and pork and chicken. It would be very boring to have just one source of novel protein," Barbosa says, the green tubes of the microalgae photobioreactors glittering in the snow behind her. D

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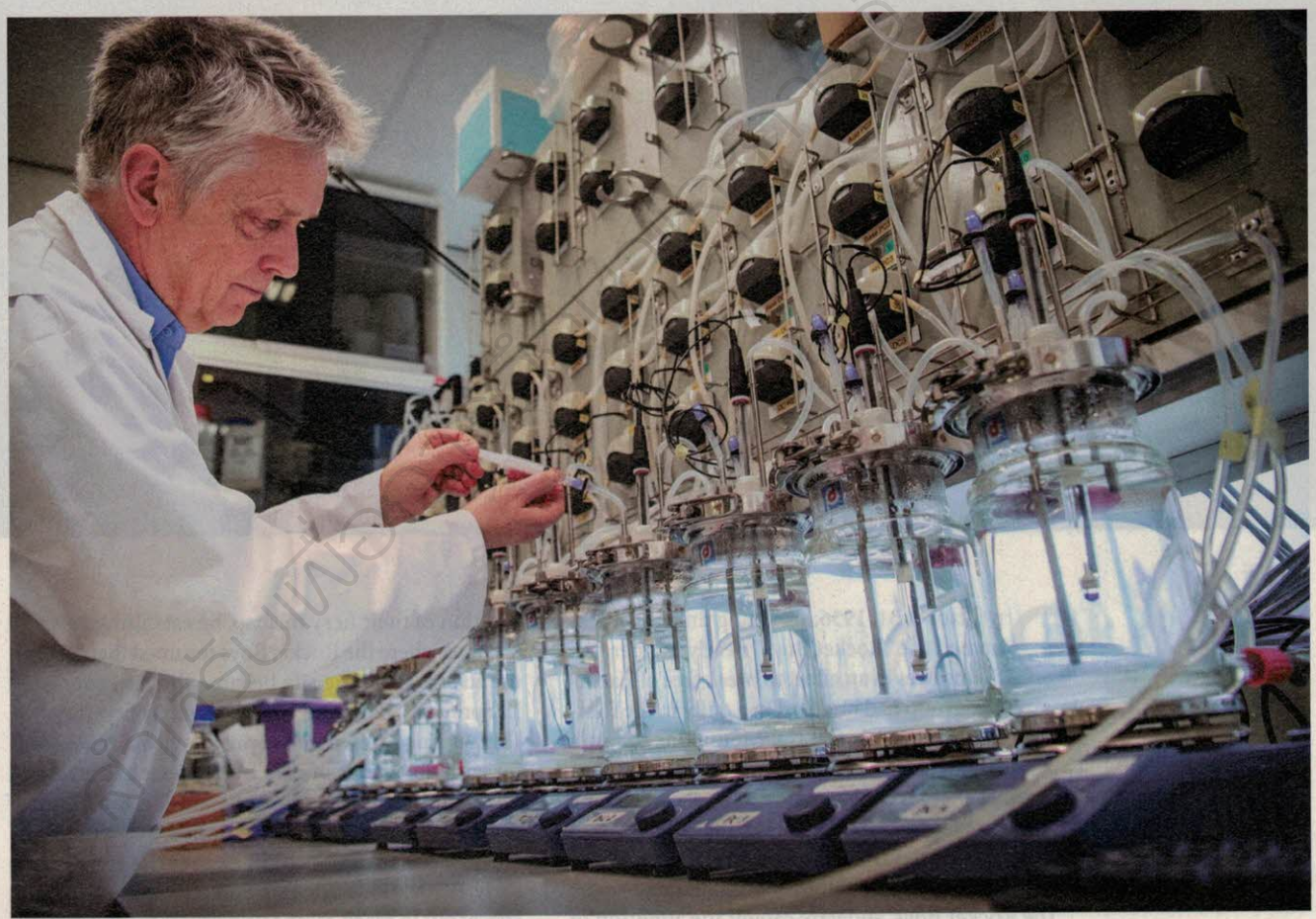
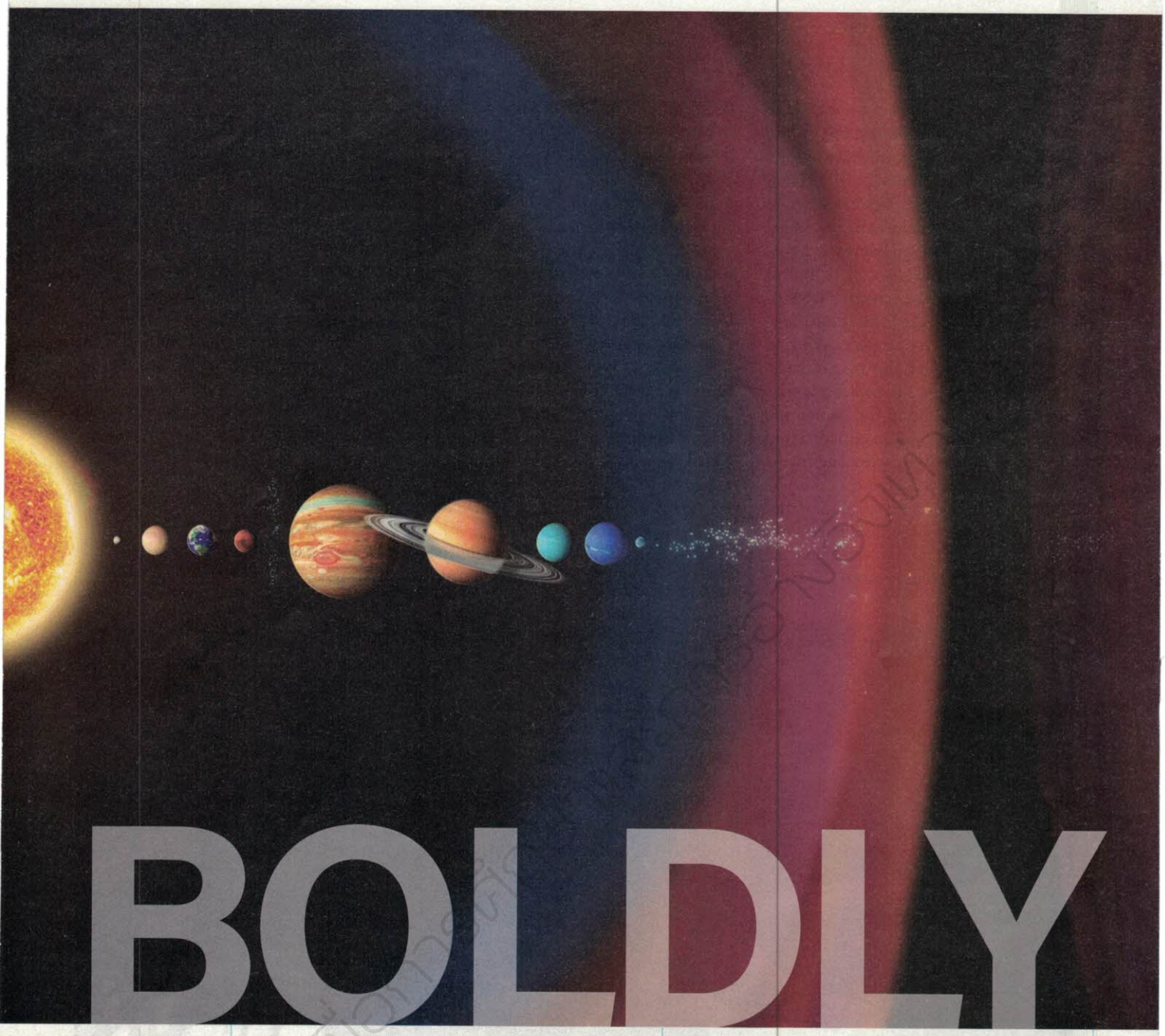
***Marta Zaraska**, a science writer in France, is the author of* Meathooked: The History and Science of Our 2.5-Million-Year Obsession With Meat.



ROBIN UTRECHT

Biochemist Harry Wichers works with reactors that simulate conditions in the human gastrointestinal tract, including the colon, right down to diverse microbiomes. Volunteers provide samples of their gut bacteria to the lab to help Wichers and his team test how experimental proteins might be digested in humans. The work may help identify an unconventional protein that our systems can break down easily into amino acids for optimal nutrition.



# BOLDLY

On October 31, 1936, six young tinkerers nicknamed the "Rocket Boys" nearly incinerated themselves in an effort to break free of Earth's gravity. The group had huddled in a gully in the foothills of California's San Gabriel Mountains to test a small alcohol-fueled jet engine. They wanted to prove that rocket engines could venture into space, at a time when such ideas were widely met with ridicule. That goal was disrupted when an oxygen line caught fire and thrashed around wildly, shooting flames.

The Rocket Boys' audacity caught the attention of aerodynamicist Theodore von Karman, who already worked with two of them at Caltech. Not far from the location of their fiery mishap, he established a small test area where the Rocket Boys resumed their experiments. In 1943, the site became the Jet Propulsion Laboratory (JPL), and von Karman its first director. JPL has since grown into a sprawling NASA field center with thousands of employees, yet it has managed to retain its founding motivation: test the limits of exploration, convention be damned.

They've had many successes over the years. In the early 1970s, JPL engineers built Pioneer 10, the first spacecraft to reach escape velocity from the solar system. A few years later, they followed up with Voyagers 1 and 2, the fastest of the many objects aimed at

CHARLES CARTER/KECK INSTITUTE FOR SPACE STUDIES VIA NASA

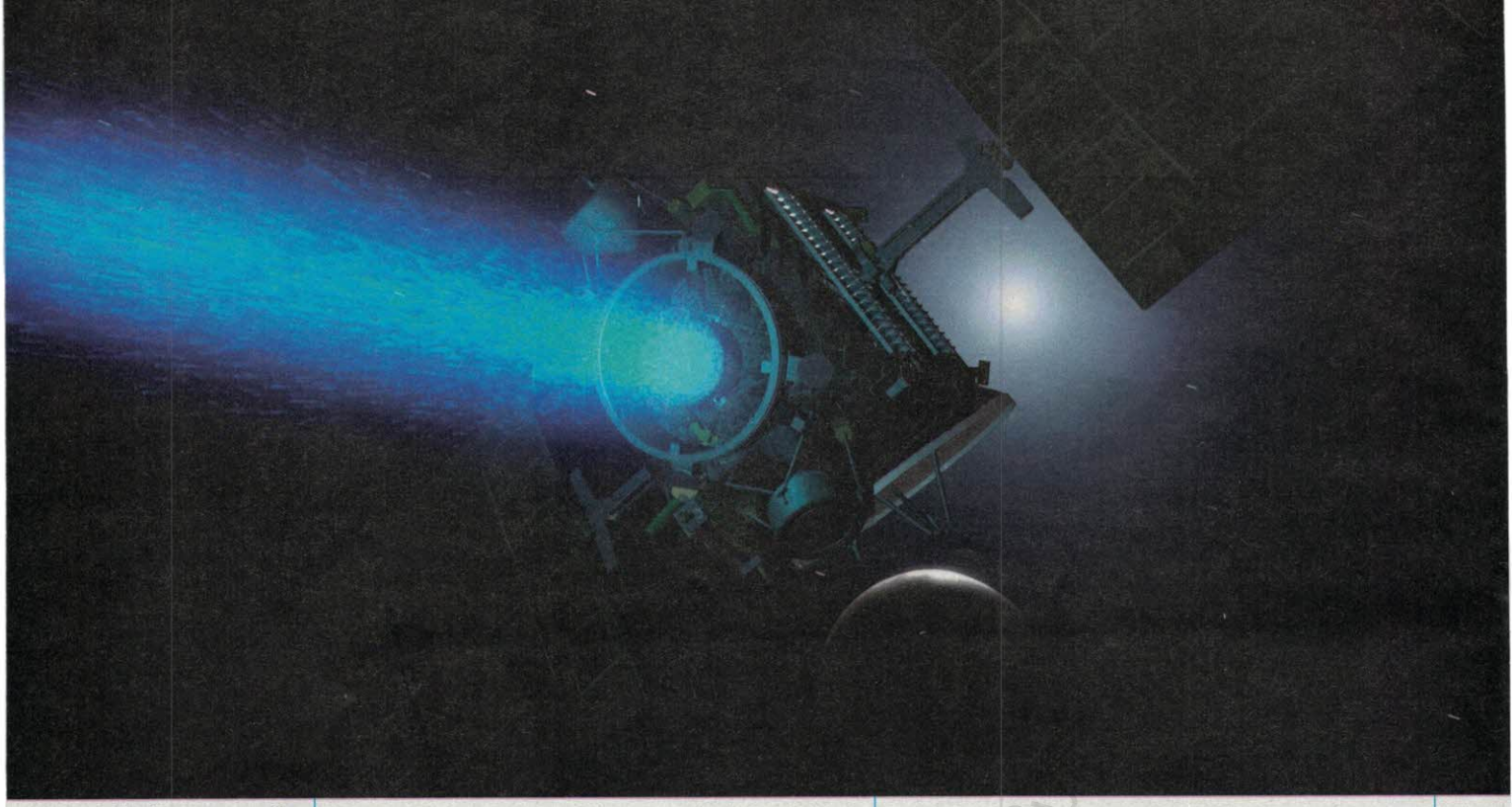
# GO

Long relegated to science fiction, speeding amid the stars may soon be within reach. BY COREY S. POWELL

interstellar space. From the beginning of the Space Age to the launch of the Voyager spacecrafts — a span of just two decades — rocket scientists more than doubled flight speeds. But in the decades since, only one more spacecraft has followed the Voyagers out of the solar system, and nothing has done so at such a high speed. Now JPL's rocketeers are getting restless again, and quietly plotting the next great leap.

The consistent theme of the new efforts is that the solar system is not enough. It is time to venture beyond the known planets, on toward the stars. John Brophy, a flight engineer at JPL, is developing a novel engine that could accelerate space travel by another factor of 10. Leon Alkalai, a JPL mission architect, is plotting a distant journey that would begin with an improbable, Icarus-esque plunge toward the sun. And JPL research scientist Slava Turyshev has perhaps the wildest idea of all, a space telescope that could provide an intimate look at a far-off Earth-like planet — without actually going there.

These are all long shots (not *entirely* crazy, according to Brophy), but if even one succeeds, the implications will be huge. The Rocket Boys and their ilk helped launch humans as a space-faring species. The current generation at JPL could be the ones to take us interstellar.



The Dawn spacecraft used ion propulsion to explore Ceres. Future missions could take the tech even further.

## ROCKET REACTIONS

For Brophy, inspiration came from Breakthrough Starshot, an extravagantly bold project announced in 2016 by the late Stephen Hawking and Russian billionaire Yuri Milner. The ultimate aim of the project is to build a mile-wide laser array that could blast a miniature spacecraft to 20 percent the speed of light, allowing it to reach the Alpha Centauri star system (our closest stellar neighbor) in just two decades.

John Brophy

Brophy was skeptical but intrigued. Ambitious aspirations are nothing new for him. "JPL encourages people to think outside the box, and my wacky ideas are getting wackier in time," he says. Even by that standard, the Starshot concept struck him as a little *too* far from technological reality. But he did begin to wonder if he could take the same concept but scale it down so that it might actually be feasible within our lifetimes.

What especially captivated Brophy was the idea of using a Starshot-style laser beam to help deal with the "rocket equation," which links the motion of a spacecraft to the amount of propellant it carries. The rocket equation confronts every would-be space explorer with its cruel logic. If you want to go faster, you need more fuel, but more fuel adds mass. More mass means you need even more fuel to haul around that extra weight. That fuel makes the whole thing heavier still, and so on. That's why it took a 1.4 million-pound rocket to launch the 1,800-pound Voyager probes: The starting weight was almost entirely fuel.

Since his graduate student days in the late 1970s, Brophy has been developing a vastly more efficient type of rocketry known as ion propulsion. An ion engine uses electric power to shoot positively charged atoms (called ions) out of a thruster at high velocity. Each atom provides just a tiny kick, but collectively they can push the rocket to a much greater velocity than a conventional chemical rocket. Better yet, the power needed to run the ion engine can come from solar panels — no heavy onboard fuel tanks or generators required. By squeezing more speed out of less propellant, ion propulsion goes a long way toward taming the rocket equation.

But ion engines come with drawbacks of their own. The farther they get from the sun, the more limited they are by how much electricity their solar panels can generate. You can make the panels huge, but then you add a lot of weight, and the rocket equation slams you again. And ion engines have such gentle thrust that they can't leave the ground on their own; it then takes them a long time in space to accelerate to their record-breaking speeds. Brophy knows these issues well: He helped design the ion engine aboard NASA's Dawn spacecraft, which just completed an 11-year mission to asteroid Vesta and dwarf planet Ceres.

**The consistent theme of the new efforts is that the solar system is not enough. It is time to venture beyond the known planets, on toward the stars.**

TOP: NASA/JPL-CALTECH; BOTTOM: NASA

Even with its formidable 65-foot span of solar cells, Dawn went from zero to 60 in an unhurried four days.

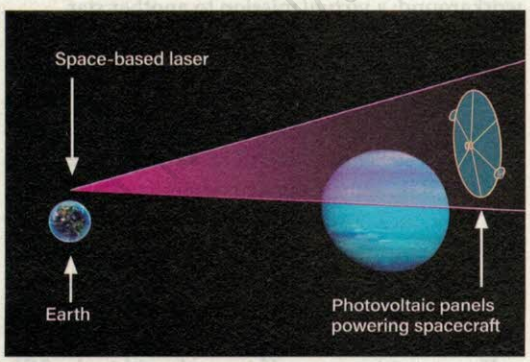
## ION THE PRIZE

While Brophy was pondering this impasse between efficient engines and insufficient solar power, the Breakthrough Starshot concept came out, and it got the gears turning in his head. He wondered: What if you replaced sunshine with a high-intensity laser beam pointed at your spacecraft? Powered by the more efficient laser, your ion engine could run much harder while still saving weight by not having to carry your power source on board.

Two years after his epiphany, Brophy is giving me a tour of an SUV-size test chamber at JPL, where he puts a high-performance ion engine through its paces. His prototype uses lithium ions, which are much lighter than the xenon ions Dawn used, and therefore need less energy to attain higher velocities. It also runs at 6,000 volts compared with Dawn's 1,000 volts. "The performance of this thing would be very startling if you had the laser to power it up," he says.

There's just one minor issue: That laser does not exist. Although he drastically downsized the Starshot concept, Brophy still envisions a 100-megawatt space-based laser system, generating 1,000 times more power than the International Space Station, aimed precisely at a fast-receding spacecraft. "We're not sure how to do that," he concedes. It would be by far the biggest off-world engineering project ever undertaken. Once built, though, the array could be used over and over, with different missions, as an all-purpose rocket booster.

As an example, Brophy describes a lithium-ion-powered spacecraft with 300-foot wings of photovoltaic panels powering a full-size version of the engine he is developing at JPL. The laser would bathe the panels in light a hundred times as bright as sunshine, keeping the ion engine running from here to Pluto, about 4 billion miles away. The spacecraft could then coast along on its considerable velocity, racking up another 4 billion miles every year or two.

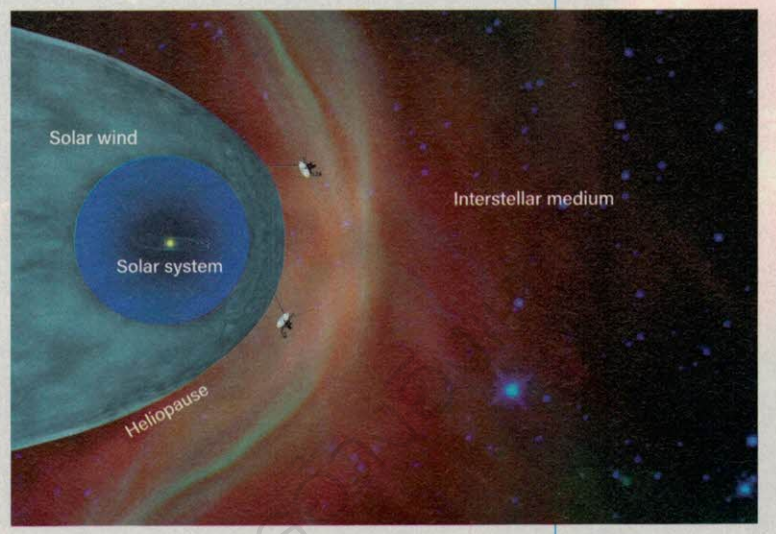



An orbiting laser system could power an ion propulsion vehicle through the solar system, and prove reusable.

TOP: NASA/JPL-CALTECH. BOTTOM: JAY SMITH

At that pace, a spacecraft could rapidly explore the dim areas where comets come from, or set off for the as-yet-undiscovered Planet 9, or go ... almost anywhere in the general vicinity of the solar system.

"It's like we have this shiny new hammer, so I go around looking for new nails to pound in," Brophy says dreamily. "We have a whole long list of missions that you could do if you could go fast."




Only the Voyager probes have passed the heliopause, leaving the sun's influence. New probes may one day study the interstellar medium lying beyond.

## INTERSTELLAR MEDIUM WELL

After Brophy's genial giddiness, it is a shock to talk to Alkalai, in charge of formulating new missions at JPL's Engineering and Science Directorate. Sitting in his large, glassy office, he seems every bit the no-nonsense administrator, but he, too, is a man with an exploratory vision.

Like Brophy, Alkalai thinks the Breakthrough Starshot people have the right vision, but not enough patience. "We're nowhere near where we need to be technologically to design a mission to another star," he says. "So we need to start by taking baby steps."

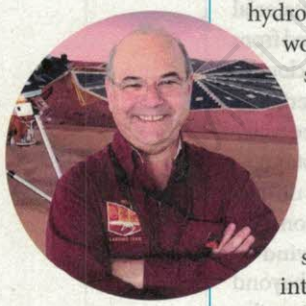
Alkalai has a specific step in mind. Although we can't yet visit another star, we can send a probe to sample the interstellar medium, the sparse gas and dust that flows between the stars.

"I'm very interested in understanding the material outside the solar system. Ultimately, we got created from that. Life originated from those primordial dust clouds," Alkalai says. "We know that there's organic materials in it, but what kind? What abundances? Are there water molecules in it? That would be huge to understand."

The interstellar medium remains poorly understood because we can't get our hands on it: A constant blast of particles from the sun — the solar wind — pushes it far from Earth. But if we could reach beyond the sun's influence, to a distance of 20 billion miles (about 200 times Earth's distance from the sun), we could finally examine, for the first time, pristine samples of our home galaxy.

NASA's Parker Solar Probe, illustrated here, will travel closer to the sun than ever before possible. Future missions may do the same to gain tremendous speeds.

Alkalai wants answers, and he wants to see the results firsthand. He's 60, so that sets an aggressive schedule — no time to wait for giant space lasers. Instead, he proposes a simpler, albeit still unproven, technology known as a solar thermal rocket. It would carry a large cache of cold liquid hydrogen, protected somehow from the heat of the sun, and execute a shocking dive to within about 1 million miles of the solar surface. At closest approach, the rocket would let the intense solar heat come pouring in, perhaps by jettisoning a shield. The sun's energy would rapidly vaporize the hydrogen, sending it racing out of a rocket nozzle. The combined push from the escaping hydrogen, and the assist from the sun's own gravity, would let the ship start its interstellar journey at speeds up to 60 miles per second, faster than any human object yet —and it only gets faster from there.



Leon Alkalai

"It's very challenging, but we're modeling the physics now," Alkalai says. He hopes to begin testing elements of a thermal-rocket system this year, and then develop his concept into a realistic mission that could launch in the next decade or so. It would reach the interstellar medium another decade after that. In addition to sampling our galactic environment, such a probe could examine how the sun interacts with the interstellar medium, study the structure of dust in the solar system and perhaps visit a distant dwarf planet along the way.

It would be a journey, Alkalai says, "like nothing we've done in the past."

## CATCH A GLIMPSE

Solar thermal rockets and laser-ion engines, impressive as they may be, are still absurdly inadequate for crossing the tremendous gulf between our solar system and exoplanets — planets orbiting other stars. In the spirit of the Rocket Boys, Turyshev is not letting absurdity stop him. He is developing a cunning workaround: a *virtual* mission to another star.

Turyshev tells me he wants to send a space telescope to a region known as the solar gravitational lens (SGL). The area begins a daunting 50 billion miles away, though that's still hundreds of times closer than our closest stellar neighbors. Once you get far enough into the SGL, something marvelous happens. When you look back toward the sun, any object directly behind it appears stretched out, forming a ring, and hugely magnified. That ring is the result of our star's intense gravity, which warps space like a lens, altering the appearance of the distant object's light.

If you position yourself correctly within the SGL, the object being magnified from behind the sun could

THIS PAGE FROM TOP: NASA/JOHNS HOPKINS APL/STEVE GRIBBEN; COURTESY OF LEON ALKALAI
OPPOSITE, CLOCKWISE FROM TOP: COURTESY OF SLAVA TURYSHEV; THE AEROSPACE CORP.; JIM DELUCA/JIMITICUS VIA YOUTUBE (2); JAY SMITH

**"We could peek under the clouds and see continents. We could see weather patterns and topography, which is very exciting."** — SLAVA TURYSHEV

be an intriguing exoplanet. A space telescope floating at the SGL, Turyshev explains, could then maneuver around, sampling different parts of the light ring and reconstructing the snippets of bent light into megapixel snapshots of the planet in question.

I have to interrupt him here. Did he say megapixel, like the resolution you get on your camera phone? Yes, he really is talking about an image measuring 1,000 by 1,000 pixels, good enough to see details smaller than 10 miles wide on a planet up to 100 light-years (600 trillion miles!) away.

"We could peek under the clouds and see continents. We could see weather patterns and topography, which is very exciting," Turyshev says. He doesn't mention it, but he doesn't need to: That kind of resolution could also reveal megacities or other giant artificial structures, should they exist.

Assuming the JPL boffins can solve the transportation issues of getting to the SGL, the mission itself is fairly straightforward, if enormously challenging. Turyshev and his collaborators (Alkalai among them) will need to develop a Hubble-size space telescope, or a mini-fleet of smaller telescopes, that can survive the 30-year journey. They will need to perfect an onboard artificial intelligence capable of running operations without guidance from home. Above all, they will need a target — a planet so intriguing that people are willing to spend decades and billions of dollars studying it. NASA's TESS space telescope is doing some of that reconnaissance work right now, scanning for Earth-size worlds around local stars.

"Ultimately, to see the life on an exoplanet, we will have to visit. But a gravity lens mission allows you to study potential targets many decades, if not centuries, earlier," Turyshev says merrily.

A journey to the SGL would take us beyond Alkalai's baby steps, well onto the path toward interstellar exploration. It's another audacious goal, but at least the odds of catching fire are much lower this time around. D

Slava Turyshev

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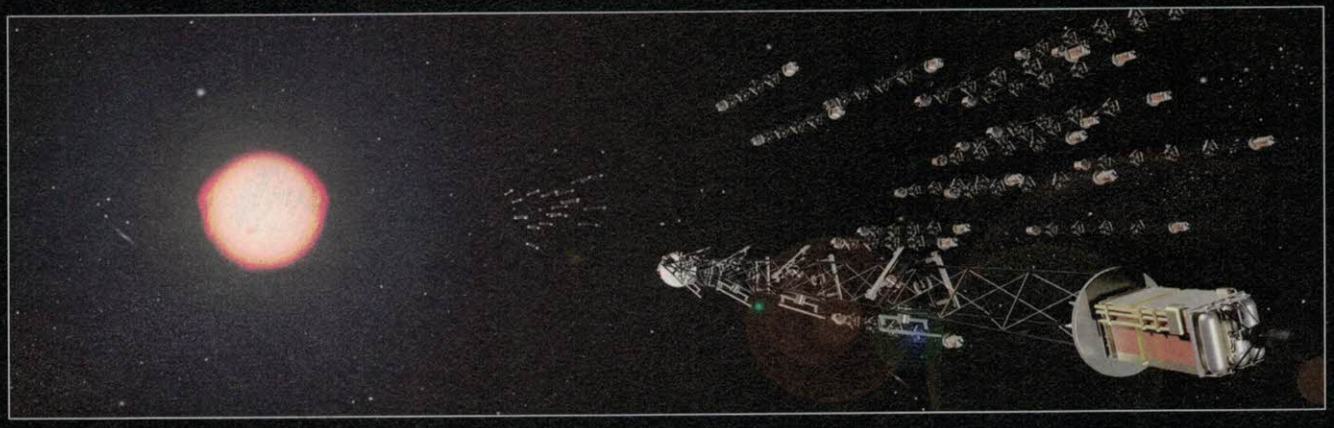
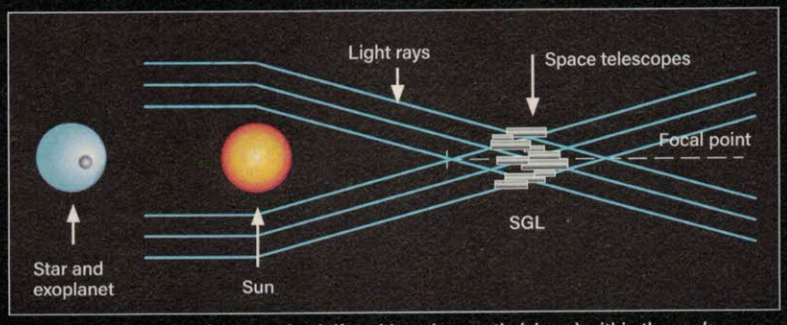
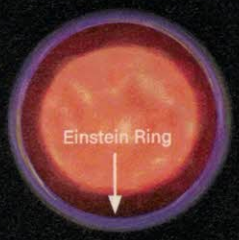
***Corey S. Powell**, a contributing editor of* Discover, *also writes for the magazine's Out There blog. Follow him on Twitter:* ***@coreyspowell***

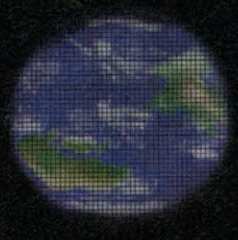





A small fleet of space telescopes (top), if positioned correctly (above) within the sun's solar gravitational lens (SGL) region, could use our star's light-distorting gravity to focus and zoom in on the light of a distant exoplanet.

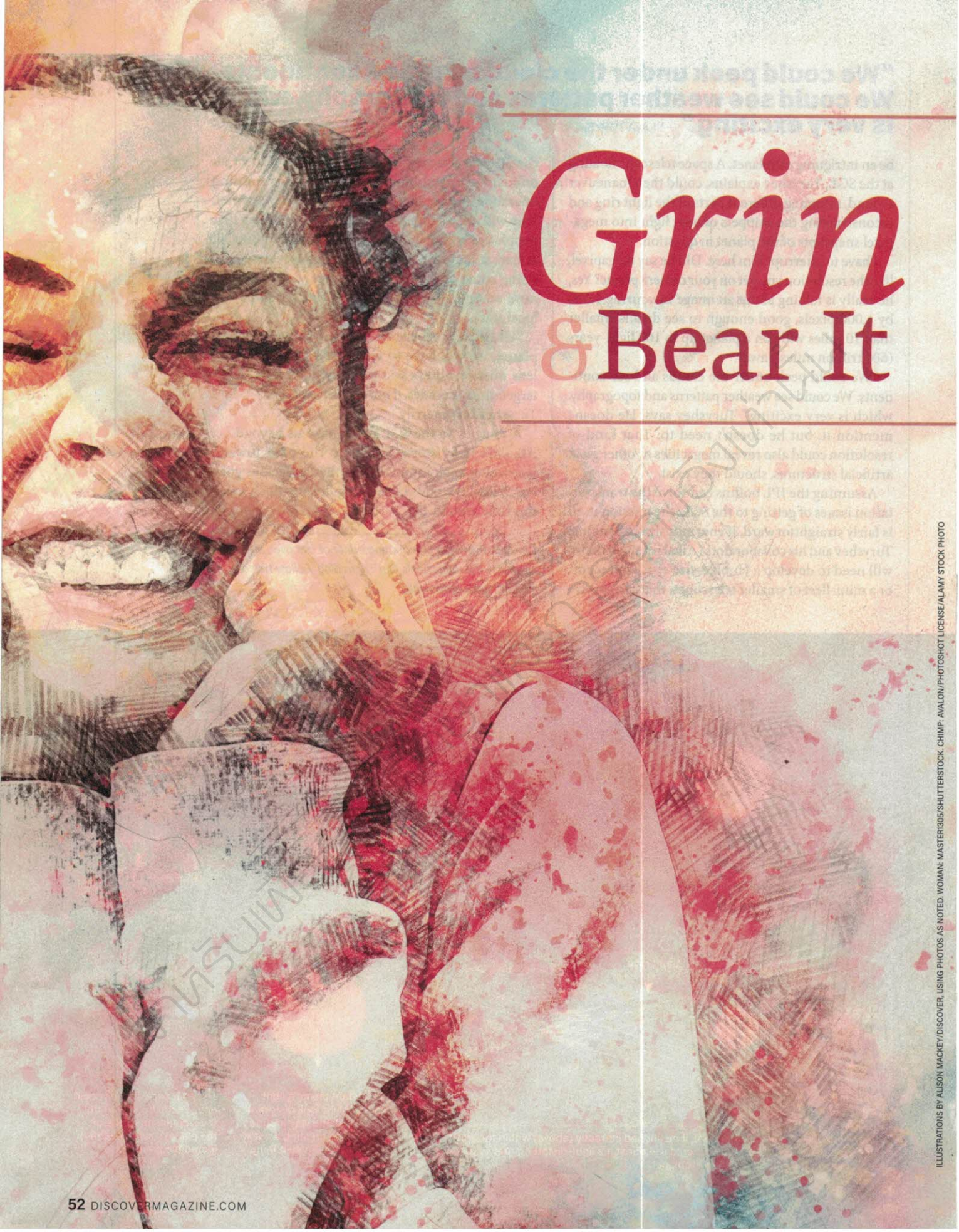



The distant planet's light would at first look distorted, warping all the way around the sun and creating what's known as an Einstein Ring.



The space telescopes could analyze the Einstein Ring to re-create an image of the planet's surface with incredible precision.

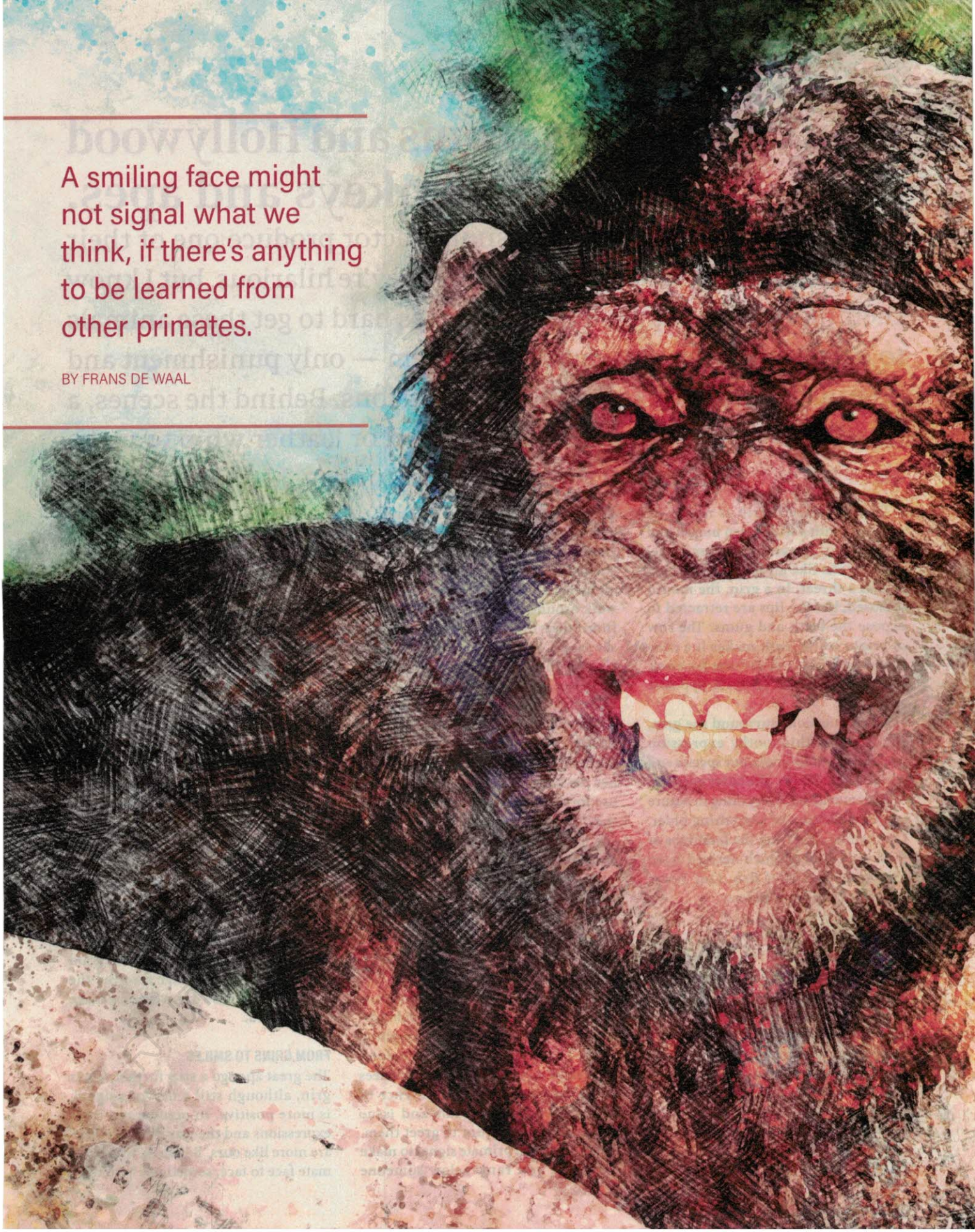
# Grin & Bear It



ILLUSTRATIONS BY ALISON MACKEY/DISCOVER; USING PHOTOS AS NOTED. WOMAN: MASTER1305/SHUTTERSTOCK. CHIMP: AVALON/PHOTOSHOT LICENSE/ALAMY STOCK PHOTO

A smiling face might not signal what we think, if there's anything to be learned from other primates.

BY FRANS DE WAAL



# I can't stand TV sitcoms and Hollywood movies featuring monkeys and apes.

**Every time I see a dressed-up simian actor produce one of their silly grins, I cringe. People may think they're hilarious, but I know their mood is the opposite of happy. It's hard to get these animals to bare their teeth without scaring them — only punishment and domination can call forth these expressions. Behind the scenes, a trainer is waving his electric cattle prod or leather whip to make clear what will happen if the animals fail to obey. They are terrified.**

The bared-teeth grin is not to be confused with a wide-open mouth and intense staring eyes. That fierce face, which looks like an intention to bite, acts as a threat. In a grin, the mouth is closed, but the lips are retracted to expose the teeth and gums. The row of bright white teeth makes it a conspicuous signal, visible from far away, yet its meaning is the exact opposite of a threat.

Many questions surround the grin, such as how this toothy expression became a friendly one in our species and where it came from. The latter question may seem odd, but everything in nature is a modification of something older. Our hands came from the forelimbs of land vertebrates, which derived from the pectoral fins of fish. Our lungs evolved out of fish bladders.

### A SOCIAL SIGNAL

The grin, it seems, derives from a defensive reflex. For example, when we peel a citrus fruit — an action that risks spraying drops of acidic juice into our face — we automatically pull our lips back from our teeth. I've observed baboons grinning to avoid perforating their lips while eating a succulent cactus.

Fear and unease also pull at the corners of our mouths. Films of people riding roller coasters often show not delighted smiles but terrified grimaces. The same happens in other primates. In a rhesus monkey group at the Vilas Park Zoo in Madison, Wisconsin — where I studied as a primatologist — the mighty alpha female, Orange, needed only to walk around to evoke the expression from others in her troop. All the females she passed would flash her grins — especially if she walked in their direction, and even more so if she honored their huddle by joining them. None of them moved out of her way, but the expression told her, "I'm subordinate, I'd never dare challenge you." Orange was so secure in her position that she rarely needed to use force, and by showing their teeth, the other females removed any reason she might have had for throwing her weight around.

Among rhesus monkeys like Orange and her troop, this expression is 100 percent unidirectional: It is given by the subordinate to the dominant, never the other way around. As such, it is an unambiguous marker of the hierarchy. Every species has signals for this purpose, though. Humans signal subordination by bowing, groveling, laughing at the boss's jokes, kissing the don's ring, saluting and so on. Chimpanzees lower themselves in the presence of high-ranking individuals and issue a special kind of grunt to greet them. But the original primate signal to make clear that you rank below someone else is a grin with the mouth corners pulled back.

However, far more underlies this expression than fear. When a monkey is simply scared, such as when it spots a snake or predator, it freezes to avoid detection or else it runs away as fast as possible. This is what plain fear looks like.

The grin, though, is an intensely social signal that mixes fear with a desire for acceptance. It is a bit like the way a dog may greet you, with flattened ears and tucked-in tail, while rolling on his back and whining. He exposes his belly and throat while trusting that you will not use weaponry on his most vulnerable body parts. No one would mistake the canine rollover for an act of fear because dogs often behave this way while approaching the other as an opening move. It can be positively friendly. The same applies to the monkey grin: It expresses a desire for good relations. Hence, Orange received the signal many times a day, whereas a snake never would.

### FROM GRINS TO SMILES

The great apes go a step further: Their grin, although still a nervous signal, is more positive. In many ways, their expressions and the way they use them are more like ours. Bonobos, who often mate face to face, sometimes bare their

teeth in friendly and pleasurable situations, such as during sexual intercourse. One German investigator spoke of an Orgasmusgesicht (orgasm face) given by females while they stare into their partner's face. They may also use the same expression to calm down or win over others and not purely along one-sided hierarchical lines, as in the monkeys.

Dominant individuals also bare their teeth when they try to reassure others. For example, when an infant wanted to steal a female's food, she dealt with it by gently moving the food out of his reach while flashing a big grin from ear to ear. This way she prevented a tantrum. Friendly grins are also a way to smooth things over when play gets too rough. Only rarely do apes lift up their mouth corners during a grin, but if they do, it looks exactly like a human smile.

Sometimes, though, a grin isn't welcome. Male chimpanzees — who are always in the business of trying to intimidate one another — don't like to reveal anxieties in the presence of a rival; it's a sign of weakness. When one male hoots and puts up his hair while picking up a big rock, it may cause unease in another because it announces a confrontation. A nervous grin may appear on the target's face.

Under these circumstances, I have seen the grinning male abruptly turn away so that the first male can't see his expression. I have also seen males hide their grin behind a hand, or even actively wipe it off their face. One male used his fingers to push his own lips back into place, over his teeth, before turning around to confront his challenger. To me, this suggests that chimpanzees are aware of how their signals come across. It also shows they have better control over their hands than over their faces.

The same is true for us. Even though we can produce expressions on command, it's hard to change one that comes up involuntarily. To look happy when you are angry, for example, or to look angry when in reality you are amused (as may happen to parents with their children), is nearly impossible.

The human smile derives from the nervous grin found in other primates. We employ it when there is a potential for conflict, something we are always worried about even under the friendliest circumstances: We bring flowers or a bottle of wine when we are invading other people's home territory, and we greet each other by waving an open hand, a gesture thought to originate from showing that we carry no weapons. But the smile remains our main tool to improve the mood. Copying another's smile makes everyone happier, or as Louis Armstrong sang: "When you're smiling, the whole world smiles with you."

Reprimanded children sometimes can't stop smiling, which risks being mistaken for disrespect. All they're doing, though, is nervously signaling non-hostility.

I seriously doubt that the smile is our species's "happy" face, as is often stated in books about human emotions. Its background is much richer, with meanings other than cheeriness. Depending on the circumstances, the smile can convey nervousness, a need to please, reassurance to anxious others, a welcoming attitude, submission, amusement, attraction and so on. Are all these feelings captured by calling them "happy"?

Our labels grossly simplify emotional displays, like the way we give each

> The grin, it seems, derives from a defensive reflex. For example, when we peel a citrus fruit — an action that risks spraying drops of acidic juice into our face — we automatically pull our lips back from our teeth.

BRONWYN PHOTO/SHUTTERSTOCK

emoticon a single meaning. Many of us now use smiley or frowny faces to punctuate text messages, which suggests that language by itself is not as effective as advertised. We feel the need to add nonverbal cues to prevent a peace offering from being mistaken for an act of revenge, or a joke from being taken as an insult. Emoticons and words are poor substitutes for the body itself, though: Through gaze direction, expressions, tone of voice, posture, pupil dilation and gestures, the body is much better than language at communicating a wide range of meanings.

## ONE AND THE SAME

There is an old claim, repeated over and over in the scientific literature, that we have hundreds of muscles in our faces, far more than any other species. But there is really no good reason why this should be so. When a team of behavioral scientists and anthropologists finally tested the idea by carefully dissecting the faces of two dead chimpanzees, they found the exact same number of muscles as in the human face — and surprisingly few differences.

> The human smile derives from the nervous grin found in other primates. We employ it when there is a potential for conflict, something we are always worried about even under the friendliest circumstances.

We could have predicted this, of course, because Nikolaas Tulp, the Dutch anatomist immortalized in Rembrandt's painting *The Anatomy Lesson*, had reached a similar conclusion long ago. In 1641, Tulp was the first to dissect an ape cadaver and said that it was the spitting image of the human body in its structural details, musculature and organs.

Despite these similarities, the human smile differs from the ape equivalent in that we typically pull up our mouth corners and infuse the expression with even more friendliness and affection. This applies only to the real smile, though. We often wear plastic smiles with no deep meaning whatsoever. The smiles of airplane personnel and smiles produced for cameras ("say cheese!") are artificial, for public consumption.

Only the so-called Duchenne smile is a sincere expression of joy and positive feeling. In the 19th century, the French neurologist Duchenne de Boulogne tested facial displays by electrically stimulating the face of a man who lacked pain perception. Duchenne produced and photographed all sorts of expressions this way, but the man's smiles never looked happy. In fact, they looked fake.

One time, Duchenne told the same man a funny joke and triggered a much better smile because instead of just smiling with his mouth, as he had been doing thus far, he now narrowed the muscles around his eyes as well. Duchenne perceptively concluded that while the mouth can produce a smile on command, the muscles near the eyes don't obey as well. Their contraction completes a smile to indicate genuine enjoyment.

## A WINDOW INTO OUR EMOTIONS

That our faces most of the time mirror true feelings may seem obvious enough,

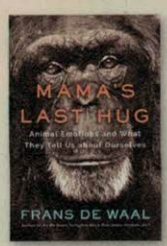
MONKEY: CAMERIS/SHUTTERSTOCK. MAN: KOLDUNOVA ANNA/SHUTTERSTOCK

but even this simple idea was once controversial. Scientists strenuously objected to Charles Darwin's use of the term *expression* as too suggestive, as implying that the face conveys what's going on inside. Even though psychology literally is the study of the psyche — Greek for "soul" or "spirit" — many psychologists didn't like references to hidden processes and declared the soul off limits. They preferred to stick to observable behavior and regarded facial displays as little flags we wave to alert those around us to our future behavior.

Darwin won this battle too, because if our facial expressions were mere flags, we should have no trouble choosing which ones to wave and which to leave folded. Every facial configuration would be as easy to summon as a fake smile. But in fact, we have far less control over our faces than over the rest of our bodies. Like chimpanzees, we sometimes hide a smile behind a hand (or a book, or a newspaper) because we're simply unable to suppress it. And we regularly smile, or shed tears, or pull a disgusted face while we are unseen by others, such as when we are talking on the phone or reading a novel. From a communication perspective, this doesn't make any sense. We should have completely blank faces while talking on the phone.

Unless, of course, we evolved to communicate inner states involuntarily. In that case, expression and communication are the same thing. We don't fully control our faces because we don't fully control our emotions. That this allows others to read our feelings is a bonus. Indeed, the tight link between what goes on inside and what we reveal on the outside may well be the whole reason why facial expressions evolved. D



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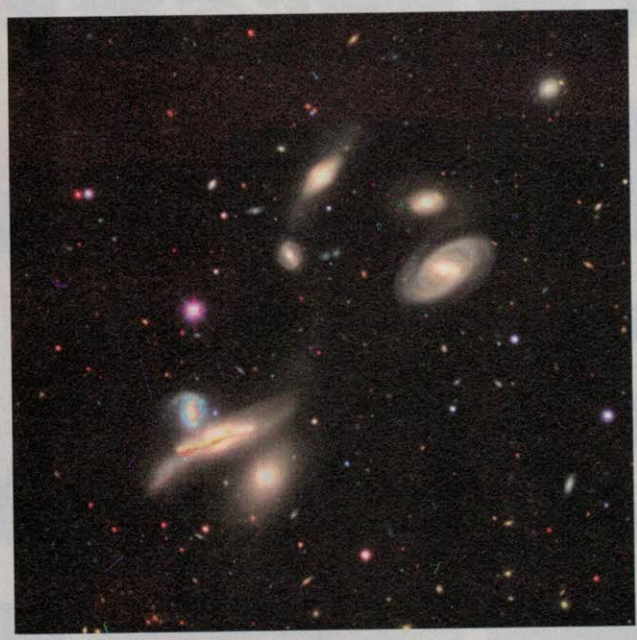
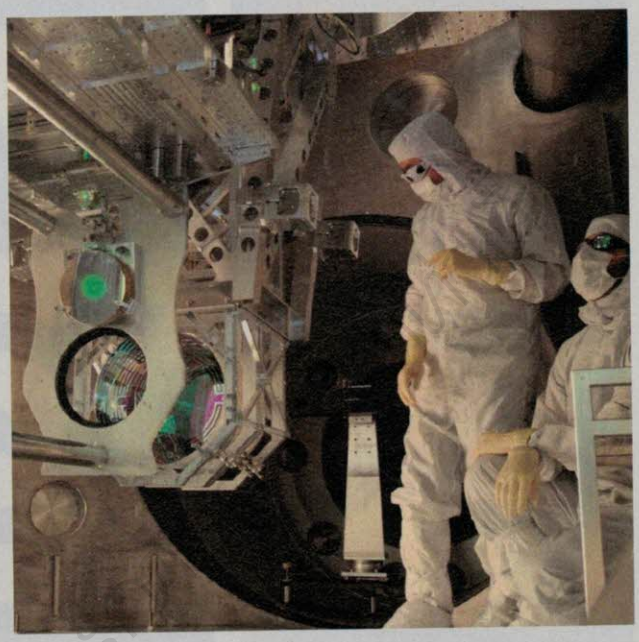
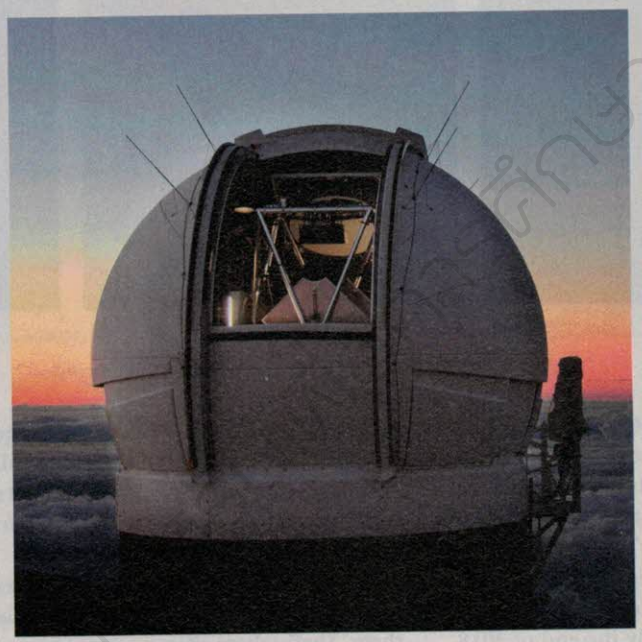
# OUT THERE

## POWERED BY *ASTRONOMY* MAGAZINE





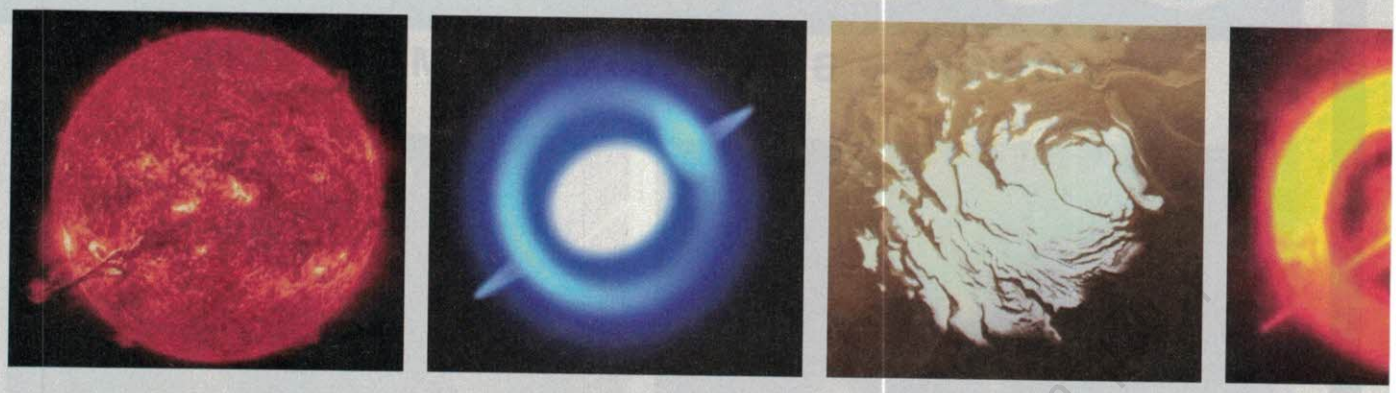


CLOCKWISE FROM TOP LEFT: DARK ENERGY CAMERA LEGACY SURVEY; CALTECH/MIT/LIGO LAB; ESA/DLR/FU BERLIN; ROB RATKOWSKI

### POWER OF THE PEOPLE

Many scientific pursuits are now generating streams of data so enormous that just finding the signals in a universe of noise has become challenging. To help close the gap, citizen scientists — millions of them — are lending a hand in an ever-growing number of fields, including astronomy. Read more about Zooniverse, a gateway to research projects that need your help, on the next page. Zooniverse's efforts include (clockwise from upper left) the Galaxy Zoo, Gravity Spy, Planet Four: Terrains, and Supernova Hunters. – ERNIE MASTROIANNI

BY ALISON KLESMAN



# ZOONIV

Zooniverse allows you to take part in cutting-edge research with nothing more than an internet connection.

Astronomy is entering a new regime of "big data." The volumes of information being collected are staggering, and future projects promise data sets of ever-increasing size. The total data volume of the Sloan Digital Sky Survey's Data Release 14 tops out at over 156 terabytes (TB). By the end of 2018, the Dark Energy Survey, which took up to 2.5 TB of data per night, mapped 5,000 degrees of the Southern Hemisphere sky, including 300 million galaxies, to ultimately produce about one petabyte (1,000 TB) of data. When the Large Synoptic Survey Telescope begins full science operations in 2022, its 3,200-megapixel camera will be able to collect 15 to 30 TB of data every night.

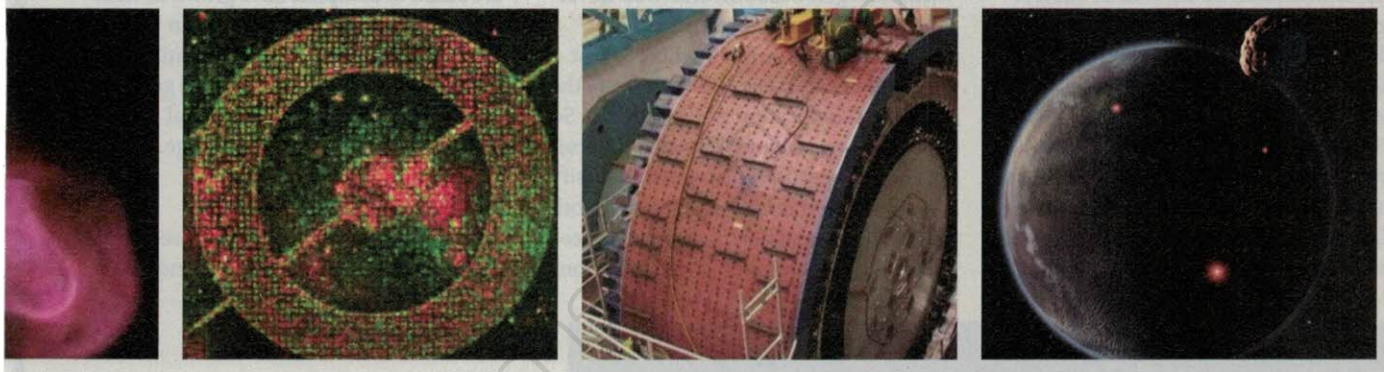
With such huge volumes of data comes the need for an increased ability to handle them. That's where citizen science comes in, filling a unique role to propel science forward.

Zooniverse is a self-proclaimed platform for people-powered research. This unique website connects citizen scientists

ZOONIVERSE TEAM

# ERSE

## A citizen science success story



Artwork and logos from various Zooniverse projects hint at the rich variety of volunteer research opportunities for citizen scientists.

— you — with professional researchers, to promote collaboration and discovery using vast catalogs of data.

It's not just astronomy and physics that have benefited from this amazing platform. Zooniverse's diverse project categories include biology, history, climate science, the arts, medicine, ecology, and the social sciences. If you grow tired of studying transit data from the Kepler space telescope (Exoplanet Explorers: exoplanetexplorers.org) or characterizing glitches in the LIGO instruments to improve gravitational wave detection (Gravity Spy: gravityspy.org), you can easily switch to counting Weddell seals in Antarctica's Ross Sea (Weddell Seal Count: zooniverse.org/projects/slg0808/weddell-seal-count). Or perhaps sorting through fragments of Middle Eastern and Mediterranean texts dating from the 10th to 13th centuries is more your style (Scribes of the Cairo Geniza: zooniverse.org/projects/judaicadh/scribes-of-the-cairo-geniza).

Regardless of the projects you choose to explore, you'll be taking part in scientific research alongside some 1.6 million volunteers around the world.

"Zooniverse is inclusive. It's about discoveries we can make together," says Chris Lintott, Zooniverse's founder and principal investigator, and professor of astrophysics at the University of Oxford.

Founded in 2007, Zooniverse is a collaboration between the Adler Planetarium, the University of Oxford,

and the broader Citizen Science Alliance. Over the past 10 years, the platform has grown from a single project to over 125 current and completed "zoos" that connect professional researchers with citizen volunteers to produce otherwise unattainable results.

### A GALAXY ZOO

Just like its name, Zooniverse began with a zoo. In 2007, Lintott developed Galaxy Zoo, calling upon volunteers to look at digital images of galaxies from the Sloan Digital Sky Survey and classify them as spirals, ellipticals, or mergers. There are a lot of galaxies in the universe, posing a challenge for astronomers who need to classify data sets rich with millions of them. When he was a graduate student at Oxford, Kevin Schawinski, an original team member, spent a month doing nothing but classifying galaxies for roughly 12 hours a day, topping out at about 50,000.

That's impressive, but it's not a realistic pace to maintain. So instead of subjecting one person to such a huge task and risking that objects might be missed or misclassified — or that the researcher may lose their mind — what if the task could be distributed to volunteers? Despite what you may think, it doesn't take years of studying astrophysics to recognize a galaxy's type by its shape and structure. It only takes a little bit of practice, and anyone — from schoolchildren to retirees — can do it.

Zooniverse was founded in 2007 by the University of Oxford (left) and the Adler Planetarium. These institutions still serve as the headquarters for most of the Zooniverse team.

In fact, human volunteers can do it better than computers, which can easily get confused or even miss galaxies altogether in images. The human brain is far better at picking out patterns than any computer algorithm yet devised.

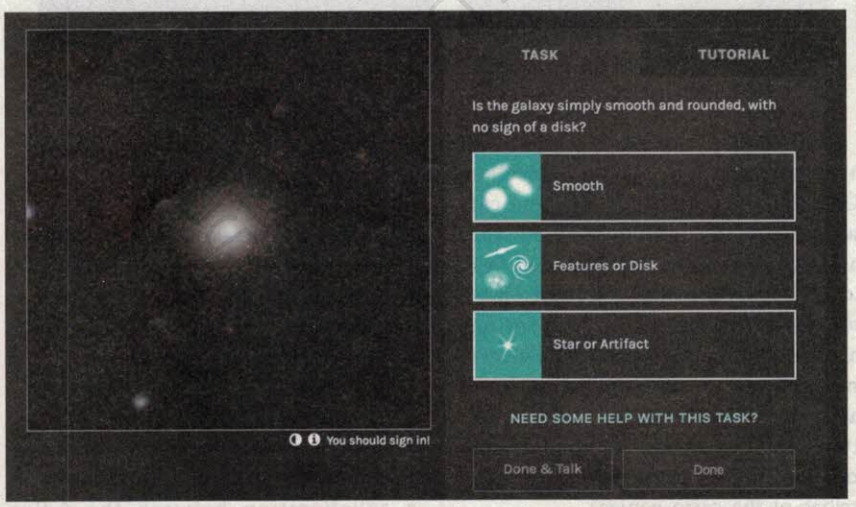
That's the true power behind Zooniverse. "The things that we ask of our volunteers are things that computers are not really good at," emphasizes Zach Wolfenbarger, a Zooniverse web developer at the Adler Planetarium.

The more volunteers who look at a single galaxy or image, the more likely the resulting classification is to be correct. So if you're worried about influencing a project's results because you might misclassify an object, don't be: Each image you'll work with is viewed and classified by many people, and as the number of classifications increases, the most common answer grows in statistical significance.

When Galaxy Zoo launched, the response was overwhelming, says Lintott. Within a day, the site was receiving nearly 70,000 classifications per hour. Within a year, more than 50 million classifications had been submitted by over 150,000 participants. And 12 years later, Galaxy Zoo is still running (galaxyzoo.org), albeit with a few changes, including a vastly expanded data set. The tasks volunteers are asked to complete have grown as well, from initially putting galaxies in one of just a few groups to now estimating the roundness or flatness of elliptical galaxies or the number of arms in a spiral galaxy and the size and shape of its bulge.

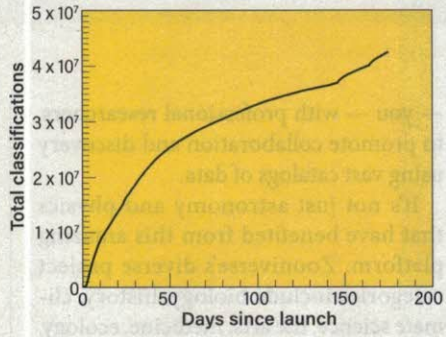
### MAKING DISCOVERIES TOGETHER

So far, this sounds like a pretty sweet deal for researchers. After all, why spend hours




Galaxy Zoo is the project that started it all. Users are asked to view digital survey images and classify galaxies based on their shape and other characteristics.

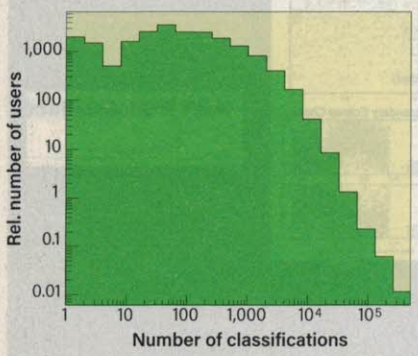
### Classifications Pour In




When Galaxy Zoo launched, the team was overwhelmed by the public's response. This graph shows the number of cumulative classifications in the project's first 200 days, including notable jumps at 145 and 160 days, which are associated with email newsletters.

CLOCKWISE FROM TOP LEFT: PETER TRIMMING; GOCHICAGOCARD BLOG; ASTRONOMY/ROEN KELLY; AFTER LINTOTT ET AL., 2008; ZOONIVERSE (GALAXY ZOO; GALAXYZOO.ORG)

## Classifications Per User




The Zooniverse team has charted the number of classifications in Galaxy Zoo per user. Most single users provide about 30 classifications, with fewer people providing progressively more. A small group of individuals has completed more than 100,000 classifications each.

scouring data yourself when you can get volunteers to do it in their spare time — for free?

But the benefits of the Zooniverse go both ways. Researchers find the help they need to manage large data sets and make new discoveries, and volunteers become part of a community that facilitates exploration, communication, and scientific advancement. Volunteers' names are listed alongside project leaders' on discovery papers, and dozens of volunteers are co-authors on articles in which they have participated in the data analysis and discussion. They help moderate online discussion forums for each project and sometimes participate in secondary, more in-depth scientific tasks. Their feedback on new projects under development guides researcher and developer efforts to improve Zooniverse.

By providing the public with a role in the scientific process, Zooniverse puts the power of science in your hands. The platform also gives volunteers a firsthand look at how science progresses from raw data to real results. "We're very much focused on engaging people in the process of scientific discovery," says Michelle Larson, president and CEO of the Adler Planetarium. "We learn about science in a formal setting in so much of our lives, and don't have a full appreciation of the mystery and discovery. Zooniverse is very well aligned with that focus. We want you doing the discovery," she stresses.

Each Zooniverse project provides a primer that explains the project's goal and task. The development team is constantly improving the site to provide volunteers with the information they need in a simple, fun, and straightforward way. "We strive to never waste the volunteers' time," says Laura Trouille, Zooniverse co-investigator and director of citizen science at the Adler Planetarium.

This sentiment is echoed by the entire web development team, which seeks feedback through Zooniverse's Talk feature (a project-specific online discussion board) and is constantly working to adapt the specific needs of each new project into code and tools for use throughout the platform. That feedback comes not only from the volunteers, but also the research teams running the projects. Facilitating an open line of communication between the two has allowed Zooniverse to grow and evolve into a worthwhile, engaging, and versatile citizen science tool.

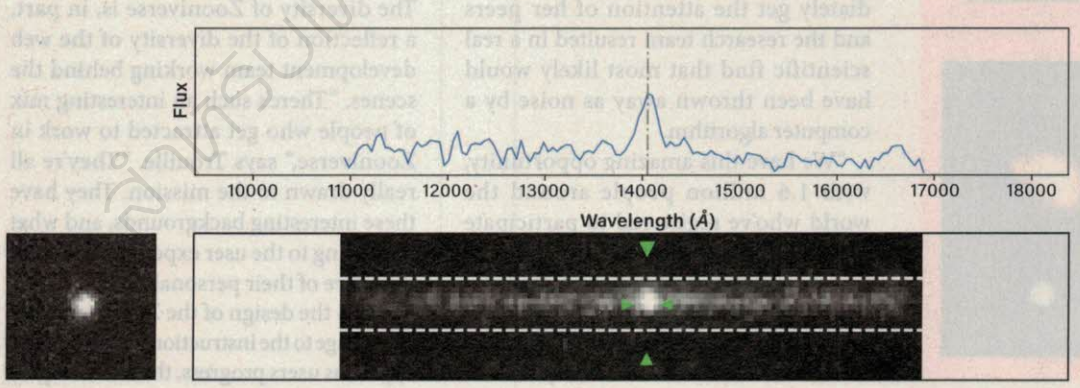
The online discussion boards keep the

## ACCESS THE ZOONIVERSE

Zooniverse.org is the main gateway to the Zooniverse. The homepage provides extensive background about the platform and a full listing of all active and past projects. Through the website, you can contribute to any project — anytime and from anywhere with an internet connection. User registration on the site is free.

The site also contains resources that include news, blogs, frequently asked questions, and resources available for use if you're interested in writing or talking about the Zooniverse platform or any of its projects.

But you don't need a web browser to take part in citizen science. The Zooniverse app, available for both iOS and Android devices, lets you take many of the platform's projects with you on the go. The app allows you to participate in projects just as if you were on a computer. You can also opt to enable push notifications and receive updates about the subjects that interest you most, or scroll through a list of publications based on Zooniverse results to dig deeper into your favorite projects and the impact of your contributions on cutting-edge science.




Galaxy Nurseries was Zooniverse's 100th project. Now complete, it asked users to identify emission lines in galaxies spotted with the Hubble Space Telescope to derive their distances. The project singled out young "baby" galaxies forming stars in the early universe to study how they age over time to become the local galaxies we see today.

FROM TOP: ASTRONOMY/ROEN KELLY, AFTER LINTOTT ET AL., 2008; ZOONIVERSE (GALAXY NURSERIES: ZOONIVERSE.ORG/PROJECTS/HUGHDICKINSON/GALAXY-NURSERIES)

## SPACE WARPS' SUCCESS

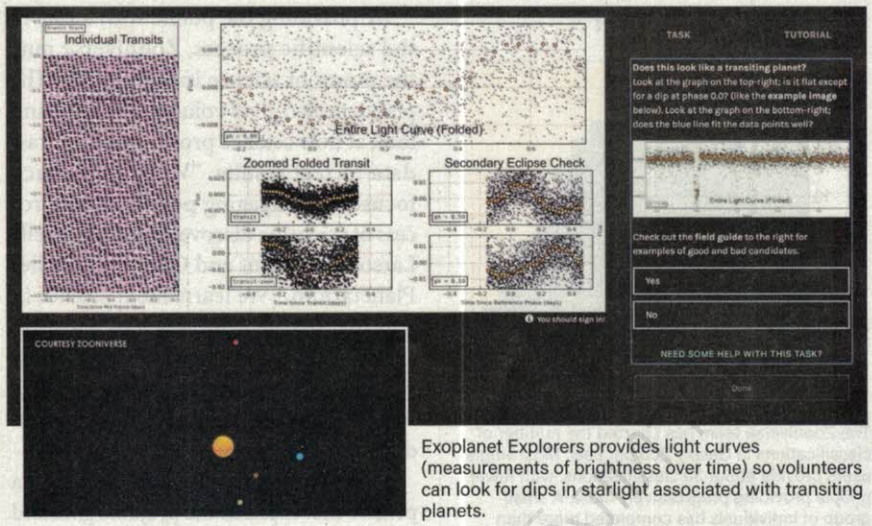
Space Warps is a search for gravitational lenses — galaxies whose gravity bends the light from distant objects, magnifying it and allowing astronomers to study objects otherwise too distant and too dim to see.

The human brain is much better at identifying the strange shapes created by gravitational lenses than any existing computer program, so Space Warps volunteers hunt through images to find gravitational lenses that computer algorithms may have missed.

On April 27, 2018, Zooniverse and Science Friday (sciencefriday.com) announced the weeklong Space Warps 1 Million Classification Challenge. Between April 27 and May 4, the site challenged volunteers to provide 1 million classifications on over 70,000 images obtained with the Hyper Suprime-Cam instrument on the 8.2-meter Subaru Telescope in Hawaii.

Within minutes of the initial announcement, the project had gained about 1,000 volunteers providing hundreds of classifications a minute. At the end of the one-week challenge, more than 3,500 people from around the globe had provided over 1.2 million classifications. They made more than 3,000 comments on the project's discussion forum and connected with volunteer moderators and the research team.

The challenge resulted in the discovery of 40 new candidate gravitational lenses for scientific follow-up in just one week. Since then, volunteers have contributed an additional 1 million classifications to the project.




Exoplanet Explorers provides light curves (measurements of brightness over time) so volunteers can look for dips in starlight associated with transiting planets.

volunteers around, Trouille believes. Every project has one, she says, and about 40 percent of volunteers go there to interact with each other and the researchers running the project. This extra layer of engagement allows for greater collaboration and, ultimately, discovery, Trouille explains.

"When a researcher says, 'I want to do a Zooniverse project,' they commit to being active on the discussion board," she says. "They commit to providing blog posts, giving updates on their research, about who they are, what the broader research context is. The key to an engaged volunteer community and enabling the scientific discoveries is really the interaction on the discussion boards."

The boards provide a place to spotlight strange finds such as Hanny's Voorwerp, a "blue cloud" near the galaxy IC 2497 flagged by Dutch schoolteacher Hanny van Arkel in 2007. The ability to immediately get the attention of her peers and the research team resulted in a real scientific find that most likely would have been thrown away as noise by a computer algorithm.

"We have this amazing opportunity, with 1.6 million people around the world who've registered to participate in Zooniverse, to help in the process of learning about science, learning about the nature of science, learning how science works," says Trouille. The ability to contact a researcher directly is "sort of lifting the veil on who researchers are, that they're just people."

And Zooniverse is designed so researchers can "grow in their communication skills through engaging with volunteers" as well, Trouille says. It provides professional researchers the opportunity to create citizen science projects within their comfort zone, allowing them to promote their research via targeted communication and receive feedback directly from volunteers during the development and testing stage.

"I think we can get a bit lost in the idea of academia being for academics," says Samantha Blickhan, a postdoctoral fellow at the Adler Planetarium. "Zooniverse does a really great job of showing the academic community that you can involve the public in your work."

### BUILDING A ZOO

The diversity of Zooniverse is, in part, a reflection of the diversity of the web development team working behind the scenes. "There's such an interesting mix of people who get attracted to work in Zooniverse," says Trouille. "They're all really drawn to the mission. They have these interesting backgrounds, and what they bring to the user experience is really reflective of their personalities."

From the design of the Zooniverse.org homepage to the instructional pop-ups that appear as users progress, those developers

FROM TOP: ZOONIVERSE (EXOPLANET EXPLORERS; EXOPLANETEXPLORERS.ORG); ZOONIVERSE (SPACE WARPS — HSC; SPACEWARPS.ORG)

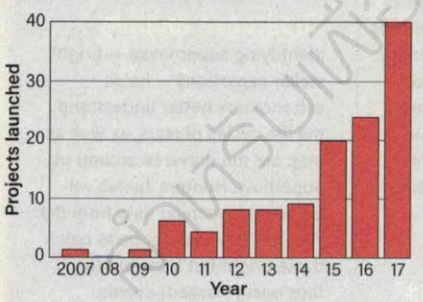
## PUBLISHING THE RESULTS

**The efforts of volunteers don't simply disappear after they've closed the browser or app. Zooniverse classifications have resulted in more than 150 scientific posters and publications, including peer-reviewed articles in journals such as *Icarus*, *Monthly Notices of the Royal Astronomical Society*, and *The Astrophysical Journal*. Many of these articles list Zooniverse volunteers as co-authors. The Zooniverse projects with the most associated publications to date are Galaxy Zoo (58 publications), Planet Hunters (12 publications), and Supernova Hunters and Solar Stormwatch (seven publications each).**

**In addition to research performed with Zooniverse results, the platform has also spawned more than 30 meta studies on the Zooniverse itself, exploring topics that range from how museums and other public institutions can better engage with the public to the tools that researchers can use to assess the quality of crowdsourced data. These studies date back to 2010, when researchers published a paper in the journal *Astronomy Education Review* looking into the motivations of the citizen science volunteers who had made the original Galaxy Zoo project such a resounding success.**

are constantly working to facilitate better research and an improved user experience on both ends. They keep track of which interactive feedback is best and what keeps volunteers willing to stay and contribute. For example, "We have a lot of camera traps throughout the Serengeti, and we found that if we removed all the images where the wind moved a branch or something, with no animals in sight, users actually classified fewer images," says Amy Boyer, another member of Adler's team of Zooniverse web developers. It's the thrill of discovery that keeps volunteers engaged, and that thrill is what the developers seek to maintain from project to project, all while keeping the value of volunteers' time and effort in mind.

**Zooniverse Projects Per Year**




In Zooniverse's first years, the web development team produced each new project, resulting in about five to 10 each year. In mid-2015, the release of Zooniverse's free project builder tool increased the number of projects created each year to over 20 in 2016.

ZOONIVERSE TEAM

One of the biggest steps forward for the Zooniverse in recent years was the release of its free project builder tool, which was funded by a Google Global Impact Award and a Sloan Foundation grant. Launched in July 2015, this tool puts the power to create effective crowdsourced research directly in researchers' hands. Before its release, it would take the web development team a year to build about five projects, Trouille says. That number jumped to over 20 in 2016 and 40 in 2017.

New projects that want promotion via Zooniverse still undergo a rigorous beta testing phase, but the tool is available to anyone regardless of whether they want an association with Zooniverse or not. And all of Zooniverse's code is open source, available for researchers and volunteers alike to view and, if so inclined, improve.

### 100 PROJECTS AND BEYOND

In 2017, Zooniverse celebrated its 10th anniversary with the launch of its 100th project: Galaxy Nurseries. By identifying emission lines associated with particular elements in a given galaxy, one can estimate its distance based on the amount its light is shifted due to the expansion of the universe. With accurate distances, astronomers can single out faraway "baby galaxies" to study the universe when it was much younger.

Galaxy Nurseries has now reached its goal, ending with more than 400,000

## STRANGE FINDS

While hunting for signals or classifying objects, Zooniverse volunteers often come across strange, unexpected finds that yield surprising new scientific results. Here are just a few.

### TABBY'S STAR

KIC 8462852, also known as Tabby's star, is one of the most famous — and most intriguing — stars in our galaxy. The star's strange behavior was first discovered by volunteers classifying data for the Zooniverse Planet Hunters project. When they couldn't determine the cause of the star's sudden and random dips in brightness, they contacted the project's science team (including Tabetha Boyajian at Louisiana State University, for whom the star is named), and the object has been the subject of scientific speculation ever since.

### GREEN PEAS

"Green pea" galaxies are so named for their compact appearance and greenish color, which arises from ionized oxygen emission. These galaxies were largely discovered by Galaxy Zoo volunteers, who had noted several of these strange-looking objects in the project's discussion forum and wondered what they were. Thanks to the volunteers' hard work identifying and collecting "peas," researchers were able to follow up on the findings, and the first volunteer-inspired Galaxy Zoo paper was submitted for publication in the *Monthly Notices of the Royal Astronomical Society* in 2009.

### PLANET HUNTERS 1

Planet Hunters tasks volunteers with sifting through data from the Kepler space telescope, hunting for dips in starlight associated with transiting planets. The project's first discovery was a doozy: Dubbed Planet Hunters 1 (PH1), the first confirmed planet discovered by the project was also the first planet ever discovered in a four-star system. This circumbinary planet orbits a double star system, but that double star is in turn orbited by a second pair of binary stars 90 billion miles (145 billion kilometers) away. Not only is PH1 a fascinating world, but it is also helping astronomers better understand how and where planets form.

classifications and over 27,000 subjects. It is one of the latest in a long line of engaging projects made possible by the Zooniverse platform and its project builder tool.

The platform is now being embraced by more researchers in more disciplines than ever before. The review process for the first Galaxy Zoo paper, Trouille says, was "horrendous because [crowdsourced science] was totally new." That's no longer the case, and now there are more than 150 peer-reviewed publications associated with Zooniverse discoveries. The AnnoTate zoo has proven that volunteers can transcribe handwritten materials with a 95 percent accuracy rate compared with experienced specialists. "[Specialist skills are] absolutely necessary, but we're showing how researchers and volunteers are supplementing one another. They're working together, strengthening the community," Blickhan stresses.

The assembled Zooniverse team, including founder and principal investigator Chris Lintott (back row, center), poses for a group photo.

Furthermore, "we have some pretty exciting results that suggest that humans and computers working together can actually produce better results than either one alone," says Boyer. In addition to the scientific papers that come out of projects, she says, several "meta research" papers examine the process of citizen science itself.

"Zooniverse continues to push itself as well," says Larson. "The Gravity Spy project has a machine learning component to it. Humans are doing the work that computers can't ... and then feeding their knowledge back to the computer, which moves the programming forward, and the process begins again. That's the magic of Zooniverse, that it's about scientific progress."

That magic has seen the platform through a decade of success. "Galaxy Zoo was not supposed to still be running 10 years later," says Lintott. Yet it is, and it has successfully spawned a wealth of private and public projects that have carried science into a new era of big data and bigger discoveries.

It wouldn't be possible without the millions of registered Zooniverse users donating time and sharing excitement as part of the modern scientific process. Are you one of them? D

*__Alison Klesman__, an associate editor of Astronomy, has enjoyed leading students in galaxy classification using Galaxy Zoo.*

## JUMP RIGHT IN!

Are you ready to get started? Here are a few of the currently active Zooniverse astronomy projects that need volunteers like you to classify real data and contribute to new scientific discoveries.

### Backyard Worlds

What lurks in our own backyard? The outer solar system still hides many objects, and Backyard Worlds aims to uncover them in data from NASA's Wide-field Infrared Survey Explorer mission. From the theorized Planet Nine to brown dwarfs and other low-mass stars, you could discover a celestial neighbor we never knew we had.

**backyardworlds.org**

### Disk Detective

The Disk Detective project puts you at the forefront of planet formation studies by asking volunteers to identify young stars surrounded by the dusty, gas-filled debris disks that birth planets, comets, and asteroids. You'll click through images taken by NASA's Wide-Field Infrared Survey Explorer, which has mapped the entire sky at infrared wavelengths — the perfect regime in which to search for young, forming planetary systems.

**diskdetective.org**

### Galaxy Builder

Have you ever wanted to build a galaxy? If the answer is yes, then you should check out Galaxy Builder, a project that lets you assemble galaxies piece by piece to help astronomers better model these immense systems and determine how their past shapes their present.

**zooniverse.org/projects/tingard/galaxy-builder**

### Galaxy Zoo

In the latest version of the project that started it all, Galaxy Zoo lets volunteers loose on images from the Dark Energy Camera Legacy Survey. This data set is 10 times more sensitive than the Sloan Digital Sky Survey used in the initial Galaxy Zoo project. You'll be asked to note each galaxy's shape, as well as any strange features such as tidal tails, dust lanes, gravitational lensing, or overlapping objects.

**galaxyzoo.org**

### Gravity Spy

Want to join the hunt for gravitational waves? Gravity Spy needs volunteers to characterize glitches and false signals in the extremely sensitive instruments used to detect gravitational wave events. These glitches then can be used to teach algorithms how to filter out false signals — and identify real ones.

**gravityspy.org**

### Planet Four: Terrains

Closer to home, Planet Four: Terrains focuses on the Red Planet with images taken with the Context Camera on the Mars Reconnaissance Orbiter. You'll be asked to identify terrain types in Mars' south polar regions such as "spiders," "channel networks," and "swiss cheese" to help researchers discern impact craters from natural terrain.

**zooniverse.org/projects/mschwamb/planet-four-terrains**

### Supernova Hunters

Identifying supernovae — bright stellar explosions — helps astronomers better understand the life cycles of stars, as well as map out the universe around us. Supernova Hunters invites volunteers to examine data from the Pan-STARRS1 Telescope to catch these bright but transient (and thus easily missed) events.

**zooniverse.org/projects/dwright04/supernova-hunters**

ZOONIVERSE TEAM

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BY BRIDGET ALEX

# The World Is Our Niche

Our unique adaptability may explain why we're the last humans on Earth.

Humans have gone where no ape has gone before. Unlike our closest primate cousins, who are confined to the tropics, *Homo sapiens* inhabit all corners of the planet, including harsh deserts, oxygen-thin altitudes and Arctic lands.

"People just don't seem to have a lot of constraints on where they could live," says Brian Stewart, an archaeologist at the University of Michigan.

**You won't find Arctic species in the Sahara, or mountain creatures in marshland — except for *Homo sapiens*.**

Which is odd, ecologically speaking. Most animals stick to particular habitats, related to where they fall on a continuum between generalist and specialist. Creatures like raccoons are textbook generalists, which inhabit varied environments and consume diverse foods. Specialists, such as koalas, have a limited range and diet.

Stewart says *Homo sapiens* may "uniquely have the ability to tack back and forth ... along that continuum," allowing them to live just about anywhere. This calls for an entirely new ecological classification — the generalist specialist — an idea he proposed with co-author Patrick Roberts in a 2018 *Nature Human Behavior* article. According to their hypothesis, as a species, modern humans are generalists, subsisting on a broad array of resources across the planet. At the same time, certain cultures have become specialists, biologically and culturally adapted to particular environments, including really tough ones.

"I haven't seen any cases of other animals that can do that," Stewart says. You won't find Arctic species in the Sahara, or mountain creatures in marshland — except for *Homo sapiens*.

Stewart and Roberts believe this capacity to slide along the generalist-specialist scale was missing from other hominins, or species in the human family tree, such as *Homo erectus*. After evolving in Africa, this early ancestor began moving into Eurasia about 1.8 million years ago, but it appears to have stuck to landscapes similar to the grasslands and forests of Africa. While some of the sites are in hostile environments today, they were hospitable when early *Homo* came through, based on studies of ancient climate.

For example, stone tools and faunal remains found in the Nefud Desert of Saudi Arabia were likely deposited between 300,000 and 500,000 years ago by an unknown hominin predating *Homo sapiens*. Today, the site lies in barren desert, with scorching summer temperatures and less than half an inch of rainfall each year. However, the animal bones belonged to species that need

FROM TOP: CHONG KEAT KIM/ALAMY STOCK PHOTO; A. BOUGAULT/NATIONAL GEOGRAPHIC CREATIVE; CRISTINA MITTERMEIER/NATIONAL GEOGRAPHIC CREATIVE

reliable water, like elephants and aquatic birds. In 2018, researchers also measured elements preserved in the fossil teeth that reflect past aridity and vegetation conditions. Their conclusion: Long ago, the region was humid grassland, similar to present-day East Africa. The Nefud would have been a familiar environment for *H. erectus* and other archaic hominins.

## THE HIGHLANDERS

As generalist-specialists, however, *Homo sapiens* have survived and thrived well beyond that ancestral habitat. Neanderthals and Denisovans — our extinct sister species — also branched out to colder climes and possibly higher elevations, but neither came close to matching the geographic breadth of our species. While versatility is a species-wide trait, countless culturally unique adaptations have allowed specific groups to conquer extreme environments.

*Homo sapiens* have survived and thrived well beyond our ancestral habitat.

High-altitude sheep herders in Peru (top) and deep-diving Bajau fisherman in Southeast Asia (above) are uniquely adapted for their extreme environments.

The best-studied case is high elevation. Far above sea level, people face intense cold, aridity and ultraviolet rays. Food is limited, but most critically, so is breathable air. Compared with sea level, there is about 17 percent less oxygen available in Denver — and that's merely the "Mile High City." Around 1.5 miles up, with oxygen reduced about 27 percent, most people experience hypoxia, or insufficient oxygen, which can lead to shortness of breath, nausea and insomnia.

More than 80 million people worldwide reside above that 1.5-mile mark, however, including in cities such as Quito, Ecuador; Lhasa, Tibet; and La Paz, Bolivia. Even lowlanders can acclimate, eventually producing extra red blood cells, which contain hemoglobin, the protein responsible for transporting oxygen throughout the body. This quick fix ensures sufficient oxygen to the tissues but has long-term costs: It thickens the blood, which can lead to cardiovascular and pregnancy complications.

Some people, however, don't experience either altitude sickness or the negative consequences of the body's quick fix for it. Anthropologist Cynthia Beall has measured sea level-like hemoglobin values in hundreds of Tibetans living more than 2 miles high. "It's almost as if they're not at altitude," says Beall, a professor at Case Western Reserve University.

Beall and others have shown that Tibetans, as well as highlanders of Ethiopia and the Andes, have adapted to elevation. Unlike the temporary acclimation lowlanders gain within weeks, these changes became fixed in their DNA over many generations.

In Tibetans, the changes involve at least two genes, *EPAS1* and *EGLN1*, which suppress the body's normal production of extra red blood cells in response to low oxygen. Recent research suggests the *EPAS1* variant was inherited from another archaic hominin through interbreeding more than 45,000 years ago. However, other high-altitude groups show different, uniquely *H. sapiens* adaptations. While less studied, at least one Ethiopian ethnic group has, like Tibetans, a sea level-like amount of hemoglobin, but it's influenced by a different gene. Andeans, meanwhile, have high hemoglobin levels like acclimated lowlanders, but seem to be protected from the consequences of thickened blood by genes related to cardiovascular development.

Many questions remain, though, including the most basic: How *do* Tibetans get enough oxygen without elevated levels of hemoglobin? "I wanted to have this all figured out by now, but I don't," says Beall.

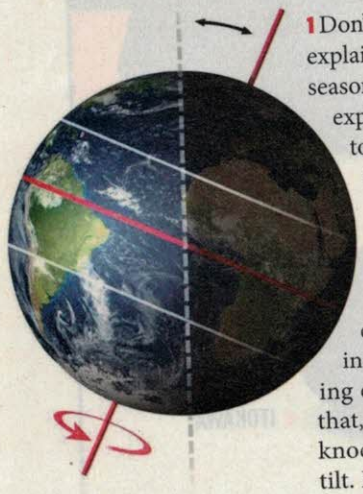
Also unresolved: Who first settled high elevations and when? Indisputable fossils and artifacts from human ancestors between 700,000 and 1.5 million years old have been found at sites up to — but not exceeding — 1.49 miles, just below the hypoxia threshold. In 2018 in the *Journal of Paleolithic Archaeology*, researchers described stone tools found 1.8 miles above sea level on Mount Dendi in Ethiopia. Based on the artifact style, the authors claimed a species predating *H. sapiens* made the items. The site lacks dates, associated human fossils or other supporting evidence, however.

**20 THINGS YOU DIDN'T KNOW ABOUT...**

# Seasons

BY GEMMA TARLACH

Tern, tern, tern.



Our planet's tilted axis, which wobbles over a 40,000-year cycle, gives plants distinct seasons of growth and dormancy.

**1** Don't look to Pete Seeger's lyric "turn, turn, turn" to explain the seasons. It's really tilt, tilt, tilt. Earth has seasons because its axis is tilted about 23.5 degrees, exposing the Northern and Southern hemispheres to fluctuating amounts of direct sunlight during the year. **2** Contrary to popular belief, Earth's distance from the sun, which changes along its elliptical orbit, has nothing to do with seasonal differences in temperature and sunlight. (That orbit shifts over a roughly 100,000-year cycle, however, and, at its most extreme, may increase solar radiation by up to 30 percent, affecting overall climate.) **3** Most astronomers believe that, about 4.5 billion years ago, a Mars-size body knocked into our young planet, causing the axial tilt. By the way, that tilt, or obliquity, varies over a roughly 40,000-year cycle, from 22.1 to 24.5 degrees. **4** More tilt means hotter summers and colder winters; decreased tilt results in less-extreme swings in temperature. **5** Scientists don't yet know how common wobbly planets like ours are, but Earth's seasonality may help them find signs of life elsewhere, according to a 2018 paper in *The Astrophysical Journal Letters*. **6** Current exoplanet analyses look for atmospheric oxygen, methane and other gases necessary for, or produced by, living organisms. But hunting for these so-called biogenic gases is imprecise and assumes lifeforms have metabolisms similar to earthly beings. **7** A more reliable exoplanet biosignature, say the authors of the 2018 research, might be seasonal changes in atmospheric composition, which reflect the connection between the planet and the life adapted to live on it. **8** On Earth, for example, carbon dioxide levels are lower in summer, when most plants are actively absorbing it, than in winter, when vegetation dies or goes dormant. **9** Animals, meanwhile, have a host of seasonal adaptation strategies, such as migration, which may mean a change in altitude, latitude or hemisphere. Birds are perhaps the most famous migrators, including the Arctic tern, which flies from far northern breeding grounds to Antarctica and back again every year. **10** Many marine animals also migrate, even if they don't move geographically. Seasonal changes in oxygen levels force many fish, crustaceans and mollusks to relocate higher or lower within the water column. **11** All four species of African lungfish, however, stay right where they are, even in the dry season when their freshwater habitats may disappear. They survive thanks to estivation. **12** Like hibernation, which is an adaptation strategy for prolonged cold, estivation is a state of lowered metabolism and inactivity — but it occurs during hot or dry seasons. **13** Depending on the species, African lungfish estivate after burrowing into the soil to find permanent moisture, or even secreting their own comfy mucus onesie. **14** Some insects have evolved seasonal variation within a single population. Take *Apis mellifera*, the Western honeybee, for example. In temperate climates, worker bees born in spring and summer live for a few weeks, rearing brood and foraging for nectar and pollen. **15** In the same colony, however, winter workers — which emerge as foraging opportunities decline in autumn — may live for six months or more. These winter bees spend most of their time in a cluster around the queen to keep warm. **16** The seasonal difference in life span is linked to vitellogenin, a protein in hemolymph, the honeybee equivalent of blood. Winter bees have significantly higher levels of the protein, which may sustain them. **17** Seasonal sustenance can change microbial colonies that larger organisms — including humans — harbor. A 2017 *Science* study of Tanzanian hunter-gatherers found that entire bacterial families came and went from the participants' guts, reflecting seasonal changes in diet. **18** The research focused on microbiome changes during the two tropical seasons: wet and dry. Globally, not just in the tropics, climate change is exacerbating these extremes. **19** Released in November, the Fourth National Climate Assessment noted the wildfire season in the U.S. has already lengthened, in part due to prolonged drought. The period of risk is also expanding in many other countries as the planet warms, largely because of human activity. **20** The global cyclone season, meanwhile, has become more intense in the Atlantic and shows signs of increasing activity in the Pacific. Let's hope Seeger was right after all about all that turn, turn, turning: "I swear it's not too late." D

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Even if earlier species ventured to highlands for short stays, there's no indication they settled there permanently. For year-round occupation, "I think there's a lot to be said for *Homo sapiens* being the only likely candidate," says Mark Aldenderfer, an archaeologist at the University of California, Merced, and an expert on high-elevation sites.

To identify full-time occupation, archaeologists look for clues such as chemical signatures in bones that distinguish locals from migrants and the geographic provenance of raw materials. Such evidence suggests that, by at least 7,000 years ago, people permanently resided above 2 miles, in both Tibet and the Andes.

## PEOPLE OF THE ICE AND SEA

Scientists also have begun investigating how people have evolved to live in other extreme conditions. The work requires comparing thousands of genomes, hunting for versions of genes that are common among people adapted to particular habitats but rare in other populations.

Among Arctic peoples, for example, Greenland Inuit and Northeast Siberians both have unique gene variants involved in fat metabolism, suggesting an adaptation for diets heavy on blubber-rich sea creatures. And, according to a 2018 study in *PLOS Genetics*, a DNA mutation that alters activity of *TRPM8*, a gene involved in cold sensitivity, may make living in cooler climes easier. Strengthening the case for its beneficial role in cold adaptation: The prevalence of the mutation increases with latitude. It's found in 88 percent of European Finns, but only 5 percent of African Yoruba.

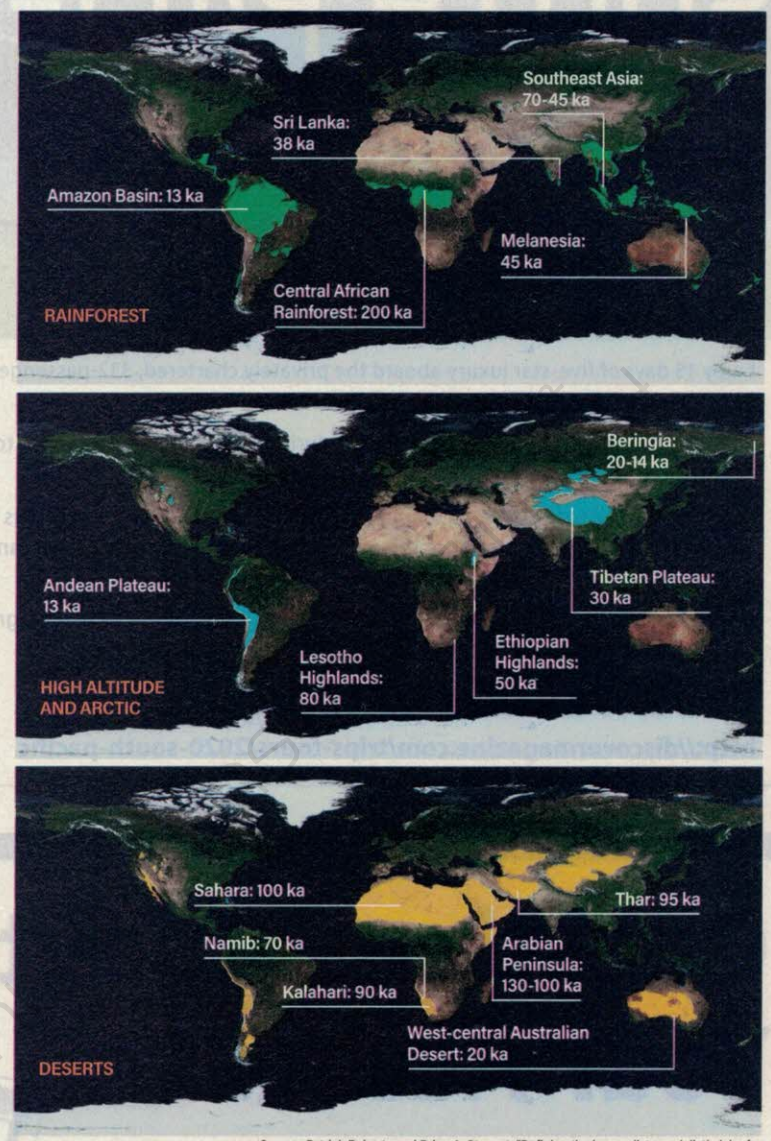
In addition to harsh environments, some groups have adapted to extreme lifestyles. Take the Bajau of Southeast Asia. Known as sea nomads, these marine foragers spend roughly 60 percent of their workday underwater, diving for food nearly 230 feet deep without scuba gear. As a genetics doctoral student, Melissa Ilardo was determined to see if DNA changes explain their incredible breath-holding abilities.

Finding firm evidence of this kind of environmental adaptation in modern humans is rare, but Ilardo was undaunted — she collected saliva for genomic sequencing from both the Bajau and a neighboring group without an aquatic lifestyle. She also took ultrasound measurements of their spleens; earlier research, on seals, found the size of the organ correlated with how long the marine mammals could stay underwater. "I was basically betting my Ph.D. on this working out," says Ilardo.

The bet paid off. Her results, published last year in the journal *Cell*, identified two genetic changes in Bajau that improve diving by giving them larger spleens and potentially directing blood to important organs when oxygen is in short supply, as it is during a deep dive.

The study, like those of Arctic and highland peoples, "gives us a chance to learn about natural selection and evolution happening in our own species," says Ilardo, now a National Institutes of Health postdoctoral researcher.

It's living proof that humans are indeed still evolving — generalist-specialists going deeper, higher, farther than any hominin before.




Maps show approximate dates (in thousands of years [ka]) of earliest human habitation in selected extreme environments.

Source: Patrick Roberts and Brian A. Stewart, "Defining the 'generalist specialist' niche for Pleistocene Homo sapiens," *Nature Human Behaviour*, 2018

***Bridget Alex*** *is an anthropologist at Harvard University and a frequent contributor to Discover.*

MAP: ANTON SHAHRAI/SHUTTERSTOCK