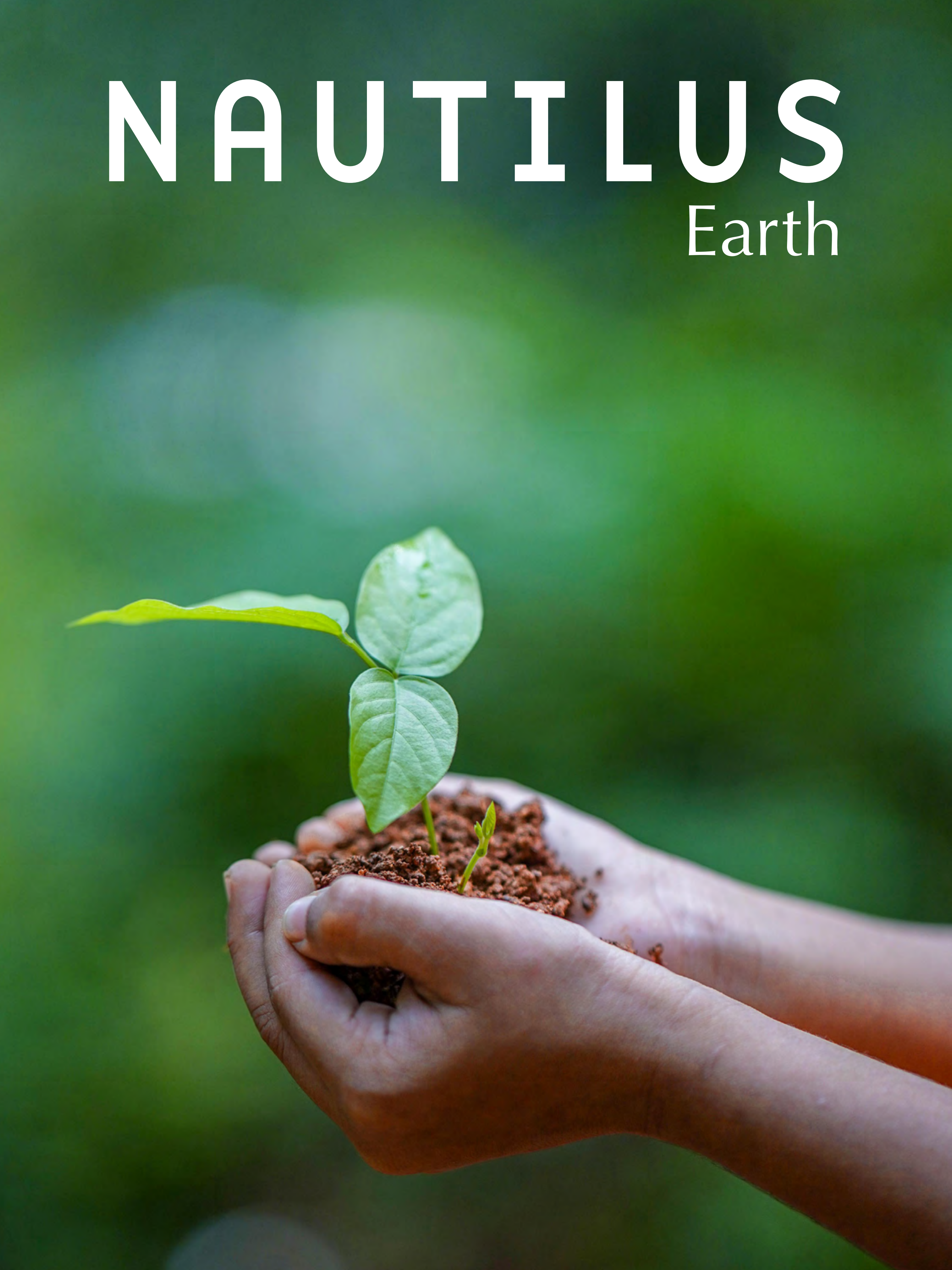
NAUTILUS

Earth



In his Pulitzer Prize-winning novel about trees, *The Overstory*, first excerpted in *Nautilus*, Richard Powers writes, "The best arguments in the world won't change a person's mind. The only thing that can do that is a good story." That sentiment guides *Nautilus* stories about the environment. With the best science, they inform you about the threats that Earth faces, as they involve you in stories that reveal change can and does happen.

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What Plants Are Saying About Us

Your brain is not the root of cognition

BY AMANDA GEFTER

I WAS NEVER INTO HOUSE PLANTS until I bought one on a whim—a prayer plant, it was called, a lush, leafy thing with painterly green spots and ribs of bright red veins. The night I brought it home I heard a rustling in my room. Had something scurried? A mouse? Three jumpy nights passed before I realized what was happening: The plant was *moving*. During the day, its leaves would splay flat, sunbathing, but at night they'd clamber over one another to stand at attention, their stems steadily rising as the leaves turned vertical, like hands in prayer.

"Who knew plants do stuff?" I marveled. Suddenly plants seemed more interesting. When the pandemic hit, I brought more of them home, just to add some life to the place, and then there were more, and more still, until the ratio of plants to household surfaces bordered on deranged. Bushwhacking through my apartment, I worried whether the plants were getting enough water, or too much water, or the right kind of light—or, in the case of a giant carnivorous pitcher plant hanging from the ceiling, whether I was leaving enough fish food in its traps. But what never occurred to me, not even once, was to wonder what the plants were thinking.

ILLUSTRATION BY **DEENA SO'OTEH**

THE PLANT WHISPERER Paco Calvo once studied artificial intelligence to determine whether it could help unlock secrets of cognition. He decided it couldn't. Plants were the key.

I was, according to Paco Calvo, guilty of "plant blindness." Calvo, who runs the Minimal Intelligence Lab at the University of Murcia in Spain where he studies plant behavior, says that to be plant blind is to fail to see plants for what they really are: cognitive organisms endowed with memories, perceptions, and feelings, capable of learning from the past and anticipating the future, able to sense and experience the world.

It's easy to dismiss such claims because they fly in the face of our leading theory of cognitive science. That theory goes by names like "cognitivism," "computationalism," or "representational theory of mind." It says, in short, the mind is in the head. Cognition boils down to the firings of neurons in our brains.

And plants don't have brains.

"When I open up a plant, where could intelligence reside?" Calvo says. "That's framing the problem from the wrong perspective. Maybe that's not how our intelligence works, either. Maybe it's not in our heads. If the stuff that plants do deserves the label 'cognitive,' then so be it. Let's rethink our whole theoretical framework."

CALVO WASN'T INTO PLANTS, either. Not at first. As a philosopher, he was busy trying to understand human minds. When he began studying cognitive science in the 1990s, the dominant view was the brain was a kind of computer. Just as computers represent data in transistors, which can be in "on" or "off" states corresponding to 0s and 1s, brains were thought to represent data in

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To understand how human minds work, he started with plants.

the states of their neurons, which could be "on" or "off" depending on whether they fire. Computers manipulate their representations according to logical rules, or algorithms, and brains, by analogy, were believed to do the same.[1]

But Calvo wasn't convinced. Computers are good at logic, at carrying out long, precise calculations—not exactly humanity's shining skill. Humans are good at something else: noticing patterns, intuiting, functioning in the face of ambiguity, error, and noise. While a computer's reasoning is only as good as the data you feed it, a human can intuit a lot from just a few vague hints—a skill that surely helped on the savannah when we had to recognize a tiger hiding in the bushes from just a few broken stripes. "My hunch was that there was something really wrong, something deeply distorted about the very idea that cognition had to do with manipulating symbols or following rules," Calvo says.

Calvo went to the University of California San Diego to work on artificial neural networks. Rather than dealing in symbols and algorithms, neural networks represent data in large webs of associations, where one wrong digit doesn't matter so long as more of them are right, and from a few sketchy clues—*stripe, rustle, orange, eye*—the network can bootstrap a half-decent guess—*tiger!*

Artificial neural networks have led to breakthroughs in machine learning and big data, but they still seemed, to Calvo, a far cry from living intelligence. Programmers train the neural networks, telling them when they're right and when they're wrong, whereas living systems figure things out for themselves, and with small amounts of data to boot. A computer has to see, say, a million pictures of cats before it can recognize one, and even then all it takes to trip up the algorithm is a shadow. Meanwhile, you show a 2-year-old human *one* cat, cast all the shadows you want, and the toddler will recognize that kitty.

"Artificial systems give us nice metaphors," Calvo says. "But what we can model with artificial systems is not genuine cognition. Biological systems are doing something entirely different."

Calvo was determined to find out what that was, to get at the essence of how real biological systems

Plants can distinguish self from non-self, stranger from kin.

perceive, think, imagine, and learn. Humans share a long evolutionary history with other forms of life, other forms of mind, so why not start with the most basic living systems and work from the bottom up? "If you study systems that look way different and yet you find similarities," Calvo says, "maybe you can put your finger on what is truly at stake."

So Calvo traded neural networks for a green thumb. To understand how human minds work, he was going to start with plants.

IT TURNS OUT IT'S TRUE: Plants do stuff.

For one thing, they can sense their surroundings. Plants have photoreceptors that respond to different wavelengths of light, allowing them to differentiate not only brightness but color. Tiny grains of starch in organelles called amyloplasts shift around in response to gravity, so the plants know which way is up. Chemical receptors detect odor molecules; mechanoreceptors respond to touch; the stress and strain of specific cells track the plant's own ever-changing shape, while the deformation of others monitors outside forces, like wind. Plants can sense humidity, nutrients, competition, predators, microorganisms, magnetic fields, salt, and temperature, and can track how all of those things are changing over time. They watch for meaningful trends—Is the soil depleting? Is the salt content rising?—then alter their growth and behavior through gene expression to compensate.

Plants' abilities to sense and respond to their surroundings lead to what seems like intelligent behavior. Their roots can avoid obstacles. They can distinguish self from non-self, stranger from kin. If a plant finds itself in a crowd, it will invest resources in vertical growth to remain in light; if nutrients are on the decline, it will opt for root expansion instead. Leaves munched on by insects send electrochemical signals to warn the rest of the foliage,[2] and they're quicker to react to threats if they've encountered them in the past. Plants chat among themselves and with other species. They release volatile organic compounds with a lexicon, Calvo says, of more than 1,700 "words"—allowing them to shout things that a human might translate as "caterpillar incoming" or "*$@#, lawn mower!"

Their behavior isn't merely reactive—plants anticipate, too. They can turn their leaves in the direction of the sun before it rises, and accurately trace its location in the sky even when they're kept in the dark. They can predict, based on prior experience, when pollinators are most likely to show up and time their pollen production accordingly. A plant's form is a record of its history. Its cells—shaped by experience—remember.

Chat? Anticipate? Remember? It's tempting to tame all those words with scare quotes, as if they can't mean for plants what they mean for us. For plants, we say, it's biochemistry, just physiology and brute mechanics—as if that's not true for us, too.

Besides, Calvo says, plant behavior can't be reduced to mere reflexes. Plants don't react to stimuli in predetermined ways—they'd never have made it this far, evolutionarily speaking, if they did. Having to deal with a changing environment while being rooted to one spot means having to set priorities, strike compromises, change course on the fly.

Consider stomata: tiny pores on the undersides of leaves. When the pores are open, carbon dioxide floods in—that's good, that's breathing—but water vapor can escape. So how open should the stomata be at any given time? It depends on the availability of water in the soil—if there's plenty more for the taking, it's worth letting the carbon dioxide in. If the dirt's dry, the leaves have to retain water. For the leaves to make that decision, the roots have to tell them about the availability of water. The leaves communicate their own needs to the roots in turn, encouraging them, for example, to form symbiotic relationships with specific microorganisms in the soil.[3]

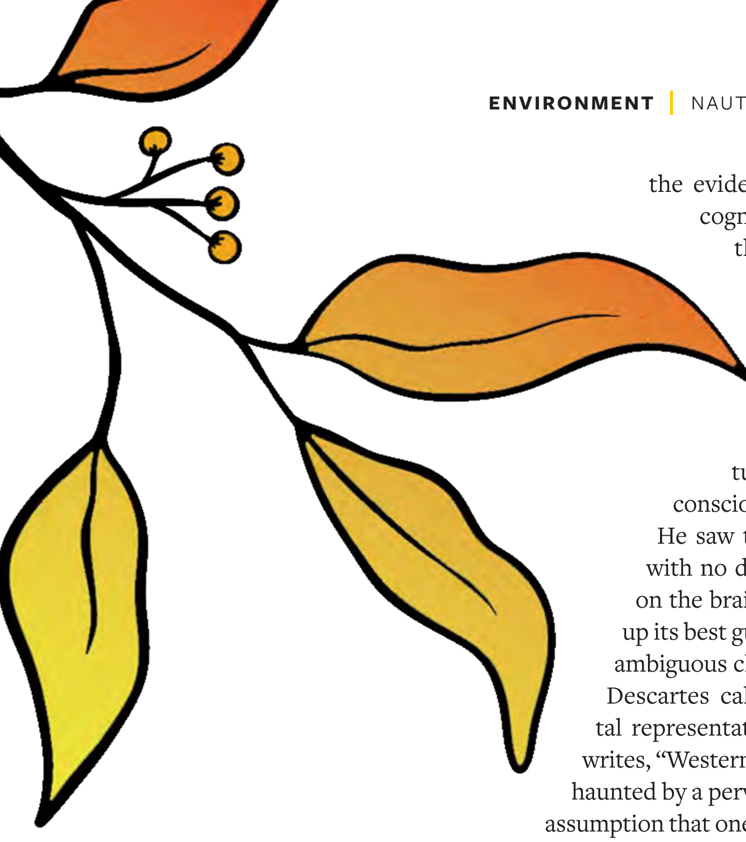
If a plant could respond to sensory information on a one-to-one basis—when the light does *x*, the plant does *y*—it would be fair to think of plants as mere automatons, operating without thought, without a point of view. But in real life, that's never the case. Like all organisms, plants are immersed in dynamic, precarious environments, forced to confront problems with no clear solutions, betting their lives as they go. "A biological system is never exposed to just a single source of stimulation," Calvo says. "It always has to make a compromise among different things. It needs some kind of valence, a higher-level perspective. And that's the entry to sentience."

Sentience?

Are plants clever? Maybe. Adaptive? Sure. But sentient? Aware? *Conscious*? Listen closely and you can hear the scoffing.

To feel alive, to have a subjective experience of your surroundings, to be an organism whose lights are on and someone's home—that's reserved for creatures with brains, or so says traditional cognitive science. Only brains, the theory goes, can encode mental representations, models *of* the world that brains experience *as* the world. As Jon Mallatt, a biologist the University of Washington, and colleagues put it in their 2021 critique of Calvo's work, "Debunking a Myth: Plant Consciousness," to be conscious requires "experiencing a mental image or representation of the sensed world," which brainless plants have no means of doing.[4]

But for Calvo, that's exactly the point. If the representational theory of the mind says that plants can't perform intelligent, cognitive behaviors, and



the evidence shows that plants *do* perform intelligent, cognitive behaviors, maybe it's time to rethink the theory. "We have plants doing amazing things and they have no neurons," he says. "So maybe we should question the very premise that neurons are needed for cognition at all."

THE IDEA THAT THE MIND is in the brain comes to us from Descartes. The 17th-century philosopher invented our modern notion of consciousness and confined it to the interior of the skull. He saw the mind and brain as separate substances, but with no direct access to the world. The mind was reliant on the brain to encode and represent the world or conjure up its best guess as to what the world might be based on, with ambiguous clues trickling in through unreliable senses. What Descartes called "cerebral impressions" are today's "mental representations." As cognitive scientist Ezequiel Di Paolo writes, "Western philosophical tradition since Descartes has been haunted by a pervasive mediational epistemology: the widespread assumption that one cannot have knowledge of what is *outside* oneself except through the ideas one has *inside* oneself."[5]

The mind isn't the brain. It's the body's engagement with the world.

Modern cognitive science traded Descartes' mind-body dualism for brain-body dualism: The body is necessary for breathing, eating, and staying alive, but it's the brain alone, in its dark, silent sanctuary, that perceives, feels, and thinks. The idea that consciousness is *in* the brain is so ingrained in our science, in our everyday speech, even in popular culture that it seems almost beyond question. "We just don't even notice that we are adopting a view that is still a hypothesis," says Louise Barrett, a biologist at the University of Lethbridge in Canada who studies cognition in humans and other primates.

Barrett, like Calvo, is one of an increasing number of scientists and philosophers questioning that hypothesis because it doesn't comport with a biological understanding of living organisms. "We need to get away from thinking of ourselves as machines," Barrett says. "That metaphor is getting in the way of understanding living, wild cognition."

Instead, Barrett and Calvo draw from a set of ideas referred to as "4E cognitive science," an umbrella term for a bunch of theories that all happen to start with the letter "E." Embodied, embedded, extended, and enactive cognition—what they have in common (besides "E"s) is a rejection of cognition as a purely brainbound affair. Calvo is also inspired by a fifth "E": ecological psychology, a kindred spirit to the canonical four. It's a theory of how we perceive without using internal representations.

In the standard story of how vision works, it's the brain that does the heavy lifting of creating a visual scene. It has to, the story goes, because the eyes contribute so little information. In a given visual fixation, the pattern of light in focus on the retina amounts to a two-dimensional area the size of a thumbnail at arm's length. And yet we have the impression of being immersed in a rich three-dimensional scene. So it must be that the brain "fills in" the missing pieces, making inferences from scant data and offering up its best hallucination for who-knows-who to "see," who-knows-how.

Dating back to the work of psychologist James Gibson in the 1960s, ecological psychology offers a different story. In real life, it says, we never deal with static images. Our eyes are always moving, darting back and forth in tiny bursts called saccades so quick we don't even notice. Our heads move, too, as do our bodies through space, so what we're confronted with is never a fixed pattern of light but what Gibson called an "optic flow."

To "see," according to ecological psychology, is not to form a picture of the world in your head. It stresses that patterns of light on the retina change relative to your movements. It's not the brain that sees, but the whole animate body. The result of "seeing" is never a final image for an internal mind to contemplate in its secret lair, but an adaptive, ongoing engagement with the world.

Plants don't have eyes exactly, but flows of light and energy impinge on their senses and transform in predictable ways relative to the plants' own movements. Of course, to notice that, you first have to notice that plants move.

"If you think that plants are sessile," or stationary, Calvo says, "just sitting there, taking life as it comes, it's difficult to visualize the idea that they are generating these flows."

Plants appear sessile to us only because they move slowly. Quick movements—like the nightly shuffle of my prayer plant—can be accomplished by altering the water content in certain cells to change the tension in a stem, or to stiffen a branch under the weight of heavy snow. Most plant movement, though, occurs through growth. Since they can't pick up their roots and walk away, plants change location by growing in a new direction. We humans are basically stuck with the shape of our bodies, but at least we can move around; plants can't move around, but they can grow into whatever shape best suits them. This "phenotypic plasticity," as it's called, is why it's critical for plants to be able to plan ahead.

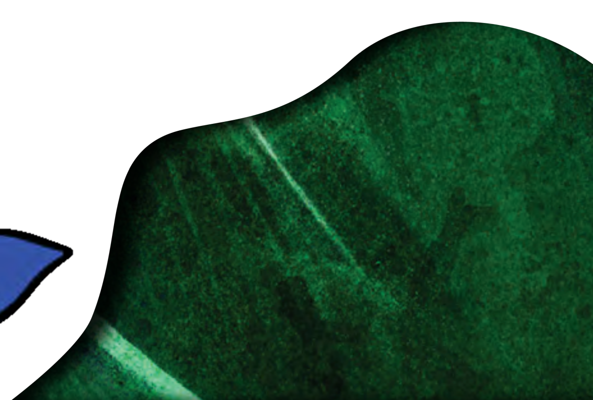
"If you spend all this time growing a tendril in a particular direction," Barrett says, "you can't afford to get it wrong. That's why prediction does seem very important. It's like my granddad said; maybe all granddads say this: 'measure twice, cut once.' "

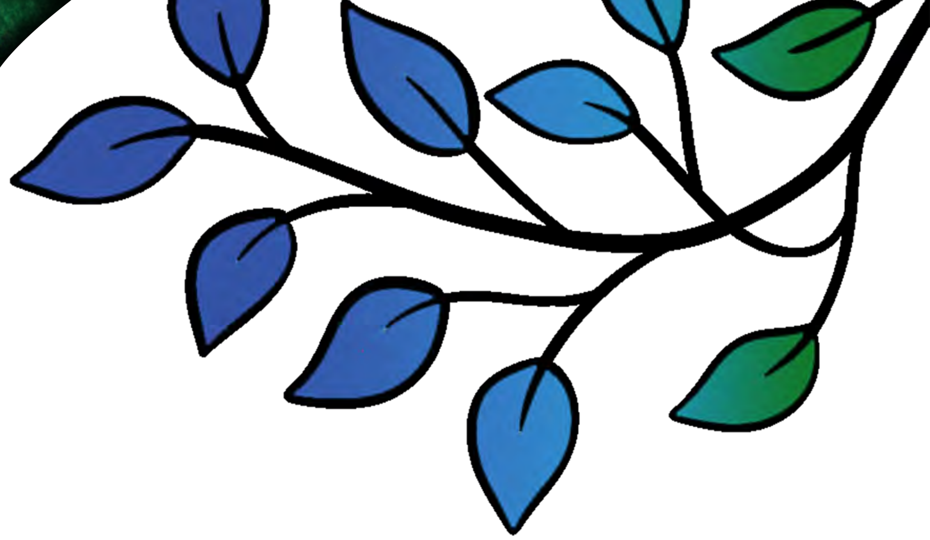
Phenotypic plasticity is a powerful but slow process—to see it, you have to speed it up. So Calvo makes time-lapse recordings, in which slow and seemingly random growth blooms into what appears to be purposeful behavior. One of his time-lapse videos shows a climbing bean growing in search of a pole. The vine circles aimlessly as it grows. Hours are compressed into minutes. But when the plant senses a pole, everything changes: It pulls itself back, like a fisherman casting a line, then flings itself straight for the pole and makes a grab.

"Once movement becomes conspicuous by speeding it up," Calvo says, "you see that certainly plants are generating flows with their movement."

By using these flows to guide their movements, plants accomplish all kinds of feats, such as "shade avoidance"—steering clear of over-populated areas where there's too much competition for photosynthesis. Plants, Calvo explains, absorb red light but reflect far-red light. As a plant grows in a given direction, it can watch how the ratio of red to far-red light varies and change directions if it finds itself heading for a crowd.

"They are not storing an image of their surroundings to make computations," Calvo says. "They're not making a map of the vicinity and plotting where the





competition is and then deciding to grow the other way. They just use the environment around them."

That might seem to be a long cry from how humans perceive the world—but according to 4E cognition, the same principles apply. Humans don't perceive the world by forming internal images either. Perception, for the E's, is a form of sensorimotor coordination. We learn the sensory consequences of our movements, which in turn shapes how we move.

Just watch an outfielder catch a fly ball.[6] Standard cognitive science would say the athlete's brain computes the ball's projectile motion and predicts where it's going to land. Then the brain tells the body what to do, the mere output of a cognitive process that took place entirely inside the head. If all that were true, the player could just make a beeline to that spot—running in a straight line, no need to watch the ball—and catch.

But that's not what outfielders do. Instead, they move their bodies, constantly shuffling back and forth and watching how the position of the ball changes as they move. They do this because if they can keep the ball's speed steady in their field of vision—canceling out the ball's acceleration with their own—they and the ball will end up in the same spot. The player doesn't have to solve differential equations on a mental model—the movement of her body relative to the ball solves the problem for her in active engagement, in real time. As the MIT roboticist Rodney Brooks wrote in a landmark 1991 paper, "Intelligence Without Representation," "Explicit representations and models of the world simply get in the way. It turns out to be better to use the world as its own model."[7]

If cognition is embodied, extended, embedded, enactive, and ecological, then what we call the mind is not in the brain. It is the body's active engagement with the world, made not of neural firings alone but of sensorimotor loops that run through the brain, body, and environment. In other words, the mind is not in the head. Calvo likes to quote the psychologist William Mace: "Ask not what's inside your head, but what your head's inside of."

WHEN I FIRST ENCOUNTERED the 4E theories, I couldn't help thinking of consciousness. If the mind is embodied, extended, embedded, etcetera, does consciousness—that magical, misty stuff—seep out of the confines of the skull, permeate the body, pour like smoke from the ears, and leak out into the world? But then I realized that way of thinking was a hangover from the traditional view, where consciousness was treated as a noun, as something that could be located in a particular place.

"Cognition is not something that plants—or indeed animals—can possibly *have*," Calvo writes in his new book, *Planta Sapiens*. "It is rather something created by the interaction between an organism and its environment. Don't think of what's going on inside the organism, but rather how the organism *couples* to its surroundings, for that is where experience is created."

The mind, in that sense, is better understood as a verb. As the philosopher Alva Noë, who works in embodied cognition, puts it, "Consciousness isn't something that happens inside us: It is something we do."[8]

And we do it in order to keep on living. The need to stay alive, to tread in far-from-equilibrium water—*that* is what separates us from machines. "Wild cognition," as Barrett puts it, is more akin to a candle flame than to a computer. "We are ongoing processes resisting the second law of thermodynamics," she says. We are candles desperately working to re-light ourselves, while entropy does its damnedest to blow us out. Machines are made—one and done—but living things make themselves, and they have to remake themselves so long as they want to keep living.

The Chilean biologists Humberto Maturana and Francisco Varela—founding fathers of embodied and enactive cognition—coined the term "autopoiesis" to capture this property of self-creation. A cell—the fundamental unit of life—serves as the prime example.

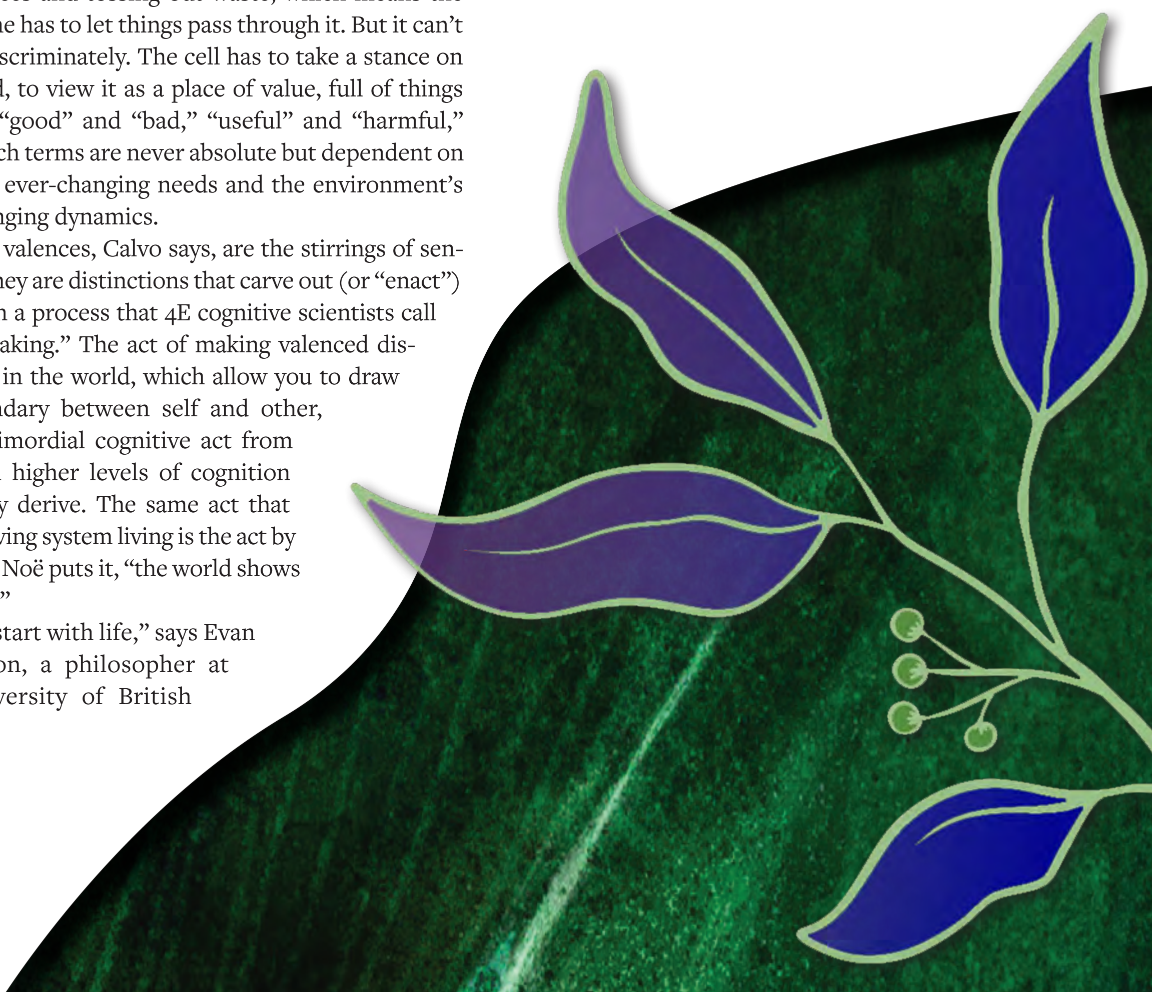
Cells consist of metabolic networks that churn out the very components of those networks, including the cell membrane, which the network continuously builds and rebuilds, while the membrane, in turn, allows the network to function without oozing back into the world. To keep its metabolism going, the cell needs to be in constant exchange with its environment, drawing in resources and tossing out waste, which means the membrane has to let things pass through it. But it can't do it indiscriminately. The cell has to take a stance on the world, to view it as a place of value, full of things that are "good" and "bad," "useful" and "harmful," where such terms are never absolute but dependent on the cell's ever-changing needs and the environment's ever-changing dynamics.

These valences, Calvo says, are the stirrings of sentience. They are distinctions that carve out (or "enact") a world in a process that 4E cognitive scientists call "sense-making." The act of making valenced distinctions in the world, which allow you to draw the boundary between self and other, is the primordial cognitive act from which all higher levels of cognition ultimately derive. The same act that keeps a living system living is the act by which, as Noë puts it, "the world shows up for us."

"You start with life," says Evan Thompson, a philosopher at the University of British Columbia and one of the founders of the enactive approach. "Being alive means being organized in a certain way. You're organized to have a certain autonomy, and that immediately carves out a world or a domain of relevance." Thompson calls this "life-mind continuity." Or as Calvo puts it, echoing the 19th-century psychologist Wilhelm Wundt, "Where there is life there is already mind."

From a 4E perspective, minds come before brains. Brains come into the picture when you have multicellular, mobile organisms—not to represent the world or give rise to consciousness, but to forge connections between sensory and motor systems so that the organism can act as a singular whole and move through its environment in ways that keep its flame lit.

"The brain fundamentally is a life regulation organ," Thompson says. "In that sense, it's like the heart or the kidney. When you have animal life, it's crucially dependent for the regulation of the body, its maintenance, and all its behavioral capacities. The brain is facilitating what the organism does. Words like cognition, memory, attention, or consciousness—those words for me are



We should question whether neurons are needed for cognition at all.

properly applied to the whole organism. It's the whole organism that's conscious, not the brain that's conscious. It's the whole organism that attends or remembers. The brain makes animal cognition possible, it facilitates and enables it, but it's not the *location* of it."

A bird needs wings to fly, Thompson says, but the flight is not *in* the wings. Disembodied wings in a vat could never fly—it's the whole bird, in interaction with the air currents shaped by its own movements, that takes to the sky.

"Plants are a different strategy of multicellularity than animals," Thompson says. They don't have brains, but according to Calvo they have something just as good: complex vascular systems, with networks of connections arranged in layers not unlike a mammalian cortex. In the root apex—a small region in the tip of a plant's root—sensory and motor signals are integrated through electrochemical activity using molecules similar to the neurotransmitters in our brains, with plant cells firing off action potentials similar to a neuron's, only slower. Like the human brain, the root apex allows the plant to integrate all of its sensory flows in order to produce new behavior that will generate new flows in ways that keep the plant adaptively coupled to the world.

The similar roles played by an animal's nervous system and a plant's vascular system help explain why the same anesthetics can put both animals and plants to sleep, as Calvo demonstrated using a Venus flytrap in a bell jar. Normally, the plant's traps snap shut when an unfortunate insect triggers one of its sensor hairs, which protrude from the trap's mouth like sharks' teeth. (Actually, the clever plant awaits the triggering of a second hair within seconds of the first before expending the costly energy to bite. Once closed, it awaits three more triggers—to ensure there's a decent bug buzzing around in there—before it releases acidic enzymes to digest its meal. As Calvo sums it up, "They can count to five!") Using surface electrodes, Calvo watched as the triggered hairs sent electric spikes zapping through the plant, sparking its motor system to react. With anesthesia, all of that stopped. Calvo tickled the trap's hairs and it just sat there, its mouth agape. The electrode reading flatlined.

"The anesthesia prevents the cell from firing an action potential," Calvo explains. "That happens in both plants and animals." It's not that the anesthetic is turning down the dial of consciousness inside the brain or root apex, it's just severing the links between sensory inputs and motor outputs, preventing the organism from engaging as a singular whole with its environment. Once "woken," though, the groggy Venus flytraps quickly returned to their usual behavior.

"Clearly," Thompson says, "plants are self-organizing, self-maintaining, self-regulating, highly adaptive, they engage in complex signaling among each other, within species and across species, and they do that within a framework of multicellularity that's different from animal life but exhibits all the same things: autonomy, intelligence, adaptivity, sense-making." From a 4E perspective, Thompson says, "there's no problem in talking about plant cognition."

In the end, Calvo's critics are right: Plants aren't using brains to form internal representations. They have no private, conscious worlds locked up inside them. But according to 4E cognitive science, neither do we.

"The mistake was to think that cognition was in the head," Calvo says. "It belongs to the relationship between the organism and its environment."

AFTER TALKING WITH CALVO, I looked around my apartment overrun with plants—at the pothos and bromeliads, rocktrumpet vines and staghorn ferns, at the peace lilies and crowns of thorns, snake plants, Monstera, ZZs, and palms—and they suddenly appeared very different. For one thing, Calvo had told me to think of plants as being upside-down, with their "heads" plunged into the soil and their limbs and sex organs sticking up and flailing around. Once you look at a plant that way, it's hard to unsee it. But more to the point, the plants appeared to me now not as objects, but as subjects—as living, striving beings trying to make it in the world—and I found myself wondering whether they felt lonely in their pots, or panicked when I forgot to water them, or dizzy when I rotated them on the windowsill.

It wasn't just the plants. I felt myself differently, too: less like a passive spectator, snug inside my skull, and more like an active life form, tendrilled and strange, moving through the world as the world moved through me.

"Plants are not that different from us after all," Calvo had told me, "not because I'm beefing them up to make them more similar to us, but because I'm rethinking what human perception is about. I'm neither inflating them nor deflating us but putting us all on the same page."

It was hard not to wonder whether, from that page, the story of our planet might unfold differently. The "E" approaches ask us to question what we are, how intimately we're entangled with the world, and whether we can rightly see ourselves as standing apart from nature or whether the destruction we wreak is steadily diminishing our own wild cognition.

"Human nature," wrote John Dewey, the pragmatist philosopher, "exists and operates in an environment. And it is not 'in' that environment as coins are in a box, but as a plant is in the sunlight and soil. It is of them."[9]

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The Great Forgetting

Earth is losing its memory

BY SUMMER PRAETORIUS

IT HAD ONLY SNOWED a dusting the day before, but my brother Jebsen had gone snowboarding at the local hill anyway. He and his friends had discovered a secret spot behind a small shopping plaza in Saugerties, New York, where they would build jumps on an undeveloped hillside in the woods. The packed piles of snow were more resistant to melting, so all they needed was a thin layer to freshen things up and they would disappear there for the day.

As my mother and I pulled up to the curb to pick him up, I noticed an unusual tiredness hung in his hunched shoulders. He had a dull stare that seemed to barely register our arrival, and his snowboard was sprawled halfway into the parking lot, as if he couldn't be bothered to tend to it.

Slumping into the back seat, he complained of a headache. It came out a few miles down the road that he had hit his head on a rock and blacked out after going off one of the jumps. He said he wasn't sure how long he was out for, but when he regained consciousness, he decided to shake it off and keep snowboarding with the guys for the rest of the day.

I could hear my mother's deep inhalation, her eyes flipping up to assess him in the rearview mirror. "You probably have a concussion," was her matter-of-fact assessment, masking the sudden tension that had set in. Back then, concussions were viewed as unfortunate but passing injuries, and Jebsen had many previous concussions that seemed to resolve just fine. Rather than view his prior record as a risk factor for more serious brain damage, it was easier to see it as evidence of resilience. "You should take it easy for a few days," my mother said.

At a stoplight, however, we noticed something different this time. When my mother mentioned events of the previous day, Jebsen didn't know what she was talking about. I laughed, thinking he was kidding, but when I swung my head back to exchange a smile with him, his face was slackened with confusion.

We volleyed back and forth on the way home, checking the big stuff first—names, people, places—until we homed in on the line that divided his intact memory from the events that had been swept clean: two weeks. The past two weeks of his life had been eroded at a sharp contact, like an underwater turbidity current that sweeps off the topmost sediment as it barrels downslope.

I was relieved that everything important, everything central to his identity, was still intact. On the surface, it seemed a minor loss, an otherwise mundane cache of daily routines. But it would be a lie to omit the unease I felt emanating from that scarp in his memory. It was like a sinkhole that suddenly pockmarks the ground; we rope it off with caution tape and cones, trying to reassure ourselves that the dangers have been safely delineated.

This is what the paleoclimate archives provide: They show us how the real world breaks.

As a paleoclimatologist, my work revolves around the tenet that the past provides context and constraints for better understanding the future. Knowing how much the planet warmed when atmospheric carbon dioxide was as high or higher than it is today provides insight into the possible future trajectories of climate under rising greenhouse gases.[1]

Earth records provide us with this information: Ice cores, tree rings, ocean sediments, stalactites and stalagmites in caves, growth rings in corals, tusks, and mollusks. These archives accrete memories on time periods varying from months to millions of years, allowing us to see a spectrum of Earth changes on various temporal and spatial scales—how biology, ocean, and ice respond to climate change in signature patterns, and the points at which those systems are pushed past thresholds.

This is one of the most important insights that paleoclimate archives provide: They show us how the real world breaks. How resilience folds into catastrophic failure. They show us the edges and asymmetries of the climate system: the thresholds of tolerance in ecological networks; the slow steady slog of diversification and the quick ax of extinction; the long timescales it takes for ice sheets to grow—accumulating million-year memories—and how fast they can melt, puddling history into storm surges that erode the banks of our futures.

As I watch the unfolding of extreme events across our planet, I find myself continuously relocated to that moment in the car with my brother. The sense of fracturing that ripples from a single shock event, even if the full extent of damage is yet to reveal itself.

PAGES 16-17: LIGHTSPRING / SHUTTERSTOCK

We didn't go to the hospital that day after my brother's snowboarding accident. We went home instead. My mother cooked dinner. Jebsen retreated to his room to lie down. But from that point on, he continued to retreat farther and farther from us.

The signs were subtle at first. He lost weight. He became more withdrawn, more angry about the world's injustices, but it was hard to tease out what was the normal moodiness of a teenager and what veered off into stranger territory. He had been reading Krishnamurti at the time, and he seemed to take on the mantle of an ascetic—most acutely with food and eating, which he suddenly viewed as a grotesque act of consumption. I tried to be an ally, but everything I did was wrong—the simple act of eating dinner disgusted him.

One day, I came into the kitchen and saw him pouring orange juice onto our potted orange tree. When I asked what he was doing, he told me the tree would grow better if given more of the nutrients it needed to produce its fruit. "I don't know if that's how it works," I said, a younger sister still afraid to contradict her older brother. "It might not be good for the soil." He looked at me for a long time from across the room, more in pity than rebuff, and I could feel his eyes starting to perceive me as an outsider instead of a sibling who had shared the same chaotic upbringing.

On weekends, the two of us would still go to the junkyard where we grew up to work odd jobs for my father. But Jebsen became increasingly unreliable, unfocused, and when my father found him huffing gasoline one day, he kicked him

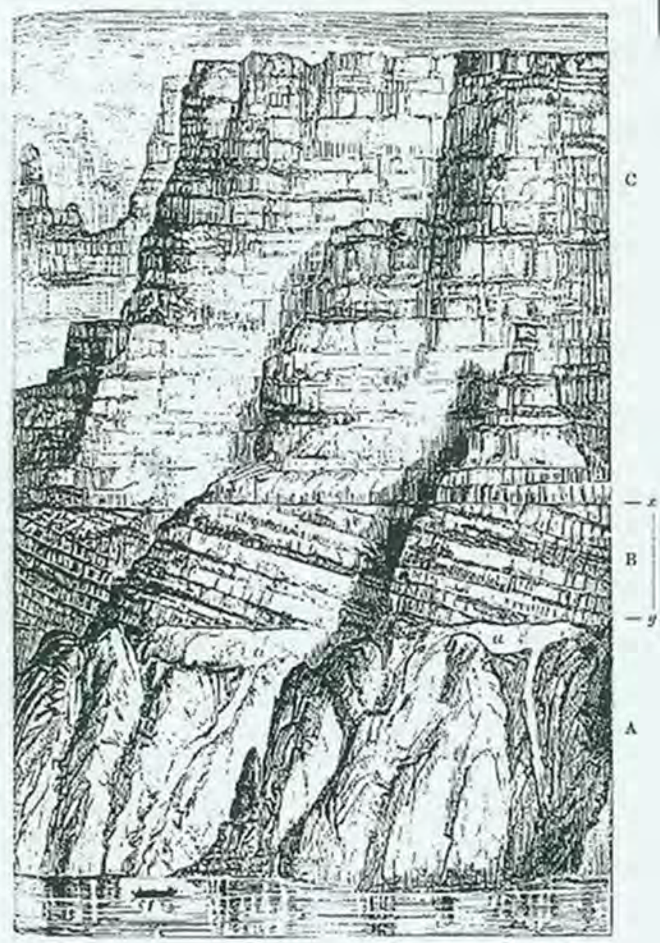

Figure 79.—Section of wall in the Grand Cañon.

EARTH AMNESIA The Great Unconformity (near the y above), a massive gap in the geologic record, was noted in 1875 by pioneering American geologist John Wesley Powell, in the Grand Canyon.

OUR BACKYARD In 2017, author Summer Praetorious took this photo in the junkyard where she and brother Jebsen grew up, played together, and worked for their father.

off the junkyard and told him he wasn't allowed back until he got his act together. My father thought it would shock the sense back into him, but for Jebsen it severed a touchstone of his identity.

As kids, the two of us were often left to navigate the treacherous, lost world realms of the junkyard together—acres of vine-encrusted carapaces of old cars, broken school buses, and rotting wooden ships, all scattered around the swamp and bluestone cliffs that ran through our property in upstate New York. We pillaged for presents for my mother in trunks of cars and burned-out trailers. We skated the swamp in winter, shoveling labyrinthine paths around the trees and root islands. We pretended to drive the crumpled convertibles and sail the ships that slowly filled with the soil of fallen leaves. As hostile a place it may have seemed to outsiders, to us the junkyard was an island of consistency, a comforting place with the aging faces of the cars that had stood watch over our childhoods. To be banished from the junkyard was to send my brother out to sea.

In geology, an "unconformity" represents an aberration in the normal accumulation of sediment, a glitch in the record-keeping of Earth's history. "A stratum of amnesia in the geological record, where overlying rock, significantly younger than what lies below, represents some break in an otherwise continuous story of formation," is how writer and poet Kim Stafford defined it.[2]

The longest lacuna in Earth's history is known as the Great Unconformity. It represents a temporal gap ranging from a hundred million years to over a billion years, depending on the location. It's visible in the Grand

SUMMER PRAETORIUS

Canyon as the boundary between the Precambrian Vishnu Schist and the Cambrian Tapeats Sandstone, between which there is a billion years of missing time between about 1,600 and 600 million years ago. Looking at this line in the strata, it is hard to fathom all that would have conspired across that vast gulf of time, for which there is simply *nothing*. If it were instead to have been the last billion years that was erased, it would obliterate the entire history of complex life. No trace of a single animal having ever walked the land. No dinosaurs, no whales, no humans, no pyramids.

How does a billion years go missing? The Great Unconformity has long been a geological mystery, in no small part because it is a challenge to reconstruct history when records of history are missing.

It turns out, ice sheets are good shredders. Recent research[3] suggests that the Great Unconformity may be a result of Snowball Earth—when the planet descended into deep cold (about 700 million years ago), and glaciers covered most of the land. A billion years of history was ground down by ice and bulldozed into the seafloor, where it was subducted into the Earth's mantle and recycled into magma, ready to be remade into new history—albeit with a few hidden remnants of the past stored safely away in subterranean crystals.[4]

While the erosive action of ice sheets may have been responsible for the largest unconformity in the Earth's lithosphere, ice sheets themselves are some of the best memory banks on our planet. Greenland stores over 100,000 years of history. Antarctica stores over a million. These ice sheets are written by the daily weather, each snowstorm condensed into the jagged rhythms of ice age cycles that steadily build into mile-high mountains—the great brains of our planet, perched on the poles.

It was hard to tease out what was the normal moodiness of a teenager and what veered off into stranger territory.

Ice sheets can recall the large volcanic eruptions that occurred throughout their lifetimes and the turn of the weather those years. Antarctica remembers the levels of carbon dioxide in the atmosphere 800,000 years ago and its natural variations since—the consistently bounded maximums and minimums of glacial and interglacial cycles,[5] and the harrowing departure from those bounds in recent decades.[6] Greenland remembers when Romans started smelting silver, as the toxic lead dust settled over the ice; it knows too when Rome fell, from the cessation of this dust.[7] Information is best preserved on ice.

But the world's glaciers are now hemorrhaging their histories. Mountain glaciers are peeling at their edges like smoldering paper, while Greenland sweats off a million tons a minute.[8] On bad days, it is enough water to submerge entire states.[9] Between 1994 and 2017, 30 trillion tons of ice have been lost globally,[10] and things are just starting to heat up. In August of 2021, it rained on the summit of Greenland. A melt layer will form to mark the event—a dire sign for the top of an ice sheet. Coastal areas along Greenland have become too slushy to drill into, preventing scientists from retrieving ice cores in those regions, rendering its history inaccessible.[11]

Antarctica has been the slowest beast to awaken, but the icy tentacles that reach out to moor the giant are starting to slip. These floating ice

LOST WORLDS The rise of global temperatures is dismantling valuable climate archives stored in Earth's glaciers.

ACHIM BAQUE / SHUTTERSTOCK

shelves extend out from where the ice sheet is grounded to the bedrock, helping to stabilize the interior, but now they are starting to weaken from the forces of ocean warming and rising seas. As the ice shelves disintegrate into the ocean, the ice upstream accelerates its descent, increasing sea level.

In 2022, double heat waves hit the Arctic and Antarctic, temperatures soaring close to 40 degrees Celsius higher than usual. The Conger ice shelf in East Antarctica said its final farewell following this heat wave. West Antarctica has long been considered the more vulnerable to near-term ice shelf loss, but now, even the East is starting to show its fray. Heat makes easy work of forgetting.

Months went by as my brother's condition continued to deteriorate, but all attempts to get him to see a doctor had failed. When he turned 18, my mother couldn't force him to go despite her efforts. Emaciated from self-starvation, his head bent over, he looked like a ghost of his former self. Any attempts to nudge him toward help were met with slammed doors and further retreat.

As I came back home one day from a hike in the woods, I noticed a wall of blackberries covering an old fence at the campground next to our property. I remember the distinct feeling of hope I had at the sight of them, the momentary illusion of a solution. I thought Jebsen would gladly eat the berries because they were wild and didn't cost anything, so I hurried home and got a colander to collect them.

How does a billion years of Earth's history go missing?

I knocked on his bedroom door, my colander full to the brim of blackberries. "Look what I found across the street," I said, holding out the berries as a peace offering. He looked up at me and met my eyes for the first time in months. "What will the birds eat?" he asked, searching for my decency. So I took the colander full of berries and flung them back outside, along with my hopes of him getting better.

By autumn, my mother gave him an ultimatum: Go to the doctor or move out of the house. He left instead, disappearing into the autumn chill without so much as a warm jacket. A few weeks later, my mother found him living in our uninsulated outdoor basement. He had been sleeping on the ground next to the water heater, surrounded by mouse traps. She took him back in, thankful he was alive.

We hobbled along for a few more months, in the limbo of knowing something had to give. Finally, one night my mother told me, "It's going to happen tomorrow. Uncle Bill is coming. And dad. The police will come." When I got off the school bus that day, Jebsen wasn't home. He had been committed to a psychiatric hospital. I asked my mother what happened, but she just shook her head. "They had to restrain him," was all she said. In the following days, he was diagnosed with schizophrenia.

MEMORY BANKS Earth's ecosystems have deep memories that allow them to recover, like the hidden seeds in a forest that sprout after a wildfire.

JULIA SENKEVICH / SHUTTERSTOCK

In the biosphere, resilience is deeply entwined with memory—it is the ability of a system to find its way back to an equilibrium state following a perturbation, which requires memory of previous states. For example, ecological memory in forest ecosystems can be thought of as containing "information and material legacies" that map out adaptive strategies to disturbances such as fire, drought, or temperature changes.[12] Material legacies include seeds that sprout after a fire and dead logs that become home to plants and fungi.

Material legacies, however, can be lost or diminished as environmental conditions change. Often those changes are driven by humans, such as the extinction of species or the introduction of invasive ones. Those changes can generate a "resilience debt," the reduced capacity of a system to recover. That debt, though, is apparent only after an ecosystem is disturbed. Given that ecosystems naturally respond slowly to environmental changes, from decades to centuries, those changes to observers may be mistaken for resilience, making it difficult to predict future responses to new perturbations.

The importance of memory isn't just in the information it contains. In the Earth system, components with large memories act as buffers to short-term variability. They are a form of inertia, slowing the initial response to a perturbation. Oceans absorb atmospheric heat and carbon dioxide; forests cool their environments through carbon uptake and evapotranspiration, a process that transfers water back into the atmosphere and helps to stabilize the hydrological cycle.[13] Ice sheets keep the planet cool through their high albedo, a measurement of how much light is reflected by their surface. As the ice sheets melt, more solar radiation is absorbed by Earth, driving up temperatures and increasing melting in a positive feedback.

But the complexity of memory is also what sets it up for failure when it is pushed past its limits. The same structure that can stabilize in the face of small perturbations, can topple catastrophically when the rates and magnitudes of change become too great.

Before a tipping point in a complex system, there are early warning signals that may be detected.[14] The most widely applicable of these early warning signals is "critical slowing down"—the phenomenon we are all familiar with before our computer crashes, and rather than heed the implications of this slower processing power, we jam at the keys in frustration, doubling down on our demands until the computer blacks out. These are the times information is most likely to be lost if it hasn't been secured in long-term storage.

He left, disappearing into the autumn chill without so much as a warm jacket.

Critical slowing down indicates the system is losing its ability to attain its previous equilibrium and is instead becoming attracted or pulled into an alternate state. It is a loss of resilience, a loss of the negative feedbacks that help keep a system rooted in stability. Various subsystems that are sensitive to thresholds—such as the Amazon rainforest—are already showing signs of critical slowing down.[15]

Given the complexity of the Earth System, it is hard to fathom the extent of information loss currently underway. There are, however, attempts to quantify the memory loss in the Earth System.

In one model, where anthropogenic CO_2 emissions are the stressor, and the strain on the system is the ability of the land and ocean to sequester carbon, researchers show the latter is inherently slower than the former. They estimate that 60 percent of Earth's memory had already been degraded by 1959, and that the ability for Earth to build-up memory has been impaired, reducing its capacity to respond to stresses within its natural stress-strain regime.[16] Estimates of persistence in this model—akin to critical slowing down—are increasing, signaling a departure from the bounds of Earth's natural regime well before 2050, if the stressors of rising atmospheric carbon dioxide continue their current trajectory. The ocean is undergoing memory loss too, increasing variability and reducing predictability of future temperature patterns.[17]

The intractable problem we face is the asymmetry of timescales: It takes time to build memory, but it can be erased in a geological instant. Like so many things we take for granted, it is difficult to see these stabilizing forces until they are gone. As we untether the anchors of the past, the future becomes unmoored.

Jebsen's health and memory continued to deteriorate. During one low point, he stopped taking his medications and was kicked out of the house where he had been living. For weeks he was homeless, somewhere in the woods of Phoenicia, not answering calls. When he resurfaced, my cousin, aunts, uncles, and half-brothers pooled resources to put him up in a motel. I was on the West Coast, with a young child, unable to visit often. But we talked on the phone regularly. I could hear in his voice that his health was worsening, but he made me promise not to get the doctors involved anymore.

Every time we talked, he would recount the same few stories, as if everything else had been whittled away, leaving only the unerodable core of his memories. Most were from the early days, the junkyard days. Many involved some sort of peril—the time I got stuck in my father's van, rolling backward down our driveway as Jebsen ran alongside, urging me to jump out the window, or the time my father's finger got sliced off by a falling car window and he asked Jebsen to go get some paper towels from the house. He would end the story by saying, "Uh, Dad, I think you're going to need more than paper towels," and we would both laugh.

A few months before his 39th birthday, Jebsen died of cirrhosis.

The bounds of Earth's memory are being severely tested. Biodiversity is in stark decline.[18] Complex ecosystems that contain libraries of genetic information—potential medicine cabinets for ailments yet unleashed—are being degraded into monocrops. Rates of extinction in recent decades are 10 to 100 times greater than the last 10 million years and over 1 million species face extinction in the coming decades. Extinction represents the ultimate memory loss: an end of the line for information that had been continuously transcribed in the Earth's living library for hundreds of millions of years.

Wildfires are razing ancient forests and entire towns—thousand-year histories contained in towering redwoods mixed with decades of human history, billowing in pyrocumulous clouds that puncture the stratosphere like volcanic eruptions. These charred landscapes are everywhere in California: Burn scars reach from the Santa Cruz Mountains to the ocean.

I wanted to believe in the limitlessness of resilience.

The ridges of northern Sonoma look like a shaved dog's back of bristled matchsticks. Crows perch in black snaggle Manzanita. Charcoal limbs are scattered at broken bone angles through the Echo Summit pass, the only evidence of the houses that once stood are the stone chimneys standing in ashes, like ancient cairns in abandoned landscapes.

Everywhere on Earth, amnesia is smoldering. Ash from our most ancient libraries is raining down on us, lofted into toxic smoke that circles the globe, darkening glaciers that accelerate their melting, sending thousands of years of history pouring into the ocean, where it steadily rises up to erode the banks of our futures. Those who can't shake the shivers of ill ease are the ones who have always sought wisdom from the past, and suddenly there is an eerie silence—stumps of history, no longer talking back.

While I can never know whether the snowboarding accident was directly linked to Jebsen's schizophrenia, when I think back to the tragic turn of his trajectory, I fixate on that moment in the car when he first showed signs of amnesia. I fixate on our immobility; on the lack of actions we took to assess the larger damages that may have been hiding beneath that hole in his memory. It wasn't for lack of concern, but a lack of money that kept us away from hospitals, and an excess of momentum that kept us rutted in the daily grind. I plead with my former self to encourage my mother to take him to the hospital. I even imagine that I am the source of ill ease I felt that day, peering back at my past with such unforgiving that I have burned a hole straight through spacetime.

Even if we couldn't have changed the outcome, we would have tried, and maybe we would have been more prepared for what was to come. We wouldn't have ignored the troubling signs that were easy to overlook in their progressive slippage, until one day, he was skin and bones, hunched and mumbling, unable to look me in the eye, and all I could ask myself was: How could I not have seen it all unfolding? The answer is that I did see it, but I wanted those warning signs to be aberrations; I wanted to believe in the limitlessness of resilience.

Near the end of Jebsen's life, he shared one memory that was different from all the other stories he normally retold. It was about a road trip from Oregon to Northern California with my mother and me—the only time he ventured west. We were headed to Mt. Shasta but made a diversion to Humboldt Redwoods State Park to see the giant trees. What I remember from that day was how quiet Jebsen was, and I assumed he was anxious from the challenges of traveling.

But in one of our final conversations, he recounted vivid details of driving through the Avenue of Giants, the tallest trees in the world. I was surprised by the clarity of this memory and mentioned how I had interpreted his silence as disinterest at the time. He corrected me, saying, "No, those trees were just the most amazing things I'd ever seen in my life."

SUMMER PRAETORIUS is a paleoclimatologist who uses ocean sediment records and marine microfossils to reconstruct past changes in ocean circulation and climate. Her work focuses on understanding the causes and effects of abrupt climate change in the Northern Hemisphere, with a focus on the Pacific Ocean.

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Why Our Intuition About Sea-Level Rise Is Wrong

A geologist explains that climate change is not just about a global average sea rise

BY DANIEL GROSSMAN

JERRY MITROVICA has been overturning accepted wisdom for decades. A solid Earth geophysicist at Harvard, he studies the internal structure and processes of the Earth, which has implications for fields from climatology to the timing of human migration and even to the search for life on other planets. Early in his career he and colleagues showed that Earth's tectonic plates not only move from side to side, creating continental drift, but also up and down. By refocusing attention from the horizontal of modern Earth science to the vertical, he helped to found what he has nicknamed *postmodern* geophysics. Mitrovica has revived and reinvigorated longstanding insights into factors that cause huge geographic variation in sea level, with important implications for the study of climate change today on glaciers and ice sheets.

OE RAEDLE / GETTY IMAGES

We caught up with Mitrovica in his airy office next to Harvard's renowned mineral collection. Though a practiced public speaker and recipient of numerous awards, in person he speaks softly and deflects plaudits. He refers frequently to the colleagues, graduate students, and mentors who have inspired him and contributed to his work.

Some of your recent research follows from the attraction of ocean water to ice sheets. That seems surprising.
This is just Newton's law of gravitation applied to the Earth. An ice sheet, like the sun and the moon, produces a gravitational attraction on the surrounding water. There's no doubt about that.

What happens when a big glacier like the Greenland Ice Sheet melts?
Three things happen. One is that you're dumping all of this melt water into the ocean. So the mass of the entire ocean would definitely be going up if ice sheets were melting—as they are today. The second thing that happens is that this gravitational attraction that the ice sheet exerts on the surrounding water diminishes. As a consequence, water migrates away from the ice sheet. The third thing is, as the ice sheet melts, the land underneath the ice sheet pops up; it rebounds.

So what is the combined impact of the ice-sheet melt, water flow, and diminished gravity?
Gravity has a very strong effect. So what happens when an ice sheet melts is sea level falls in the vicinity of the melting ice sheet. That is counterintuitive. The question is, how far from the ice sheet do you have to go before the effects of diminished gravity and uplifting crust are small enough that you start to raise sea level? That's also counterintuitive. It's 2,000 kilometers away from the ice sheet. So if the Greenland ice sheet were to catastrophically collapse tomorrow, the sea level in Iceland, Newfoundland, Sweden, Norway—all within this 2,000 kilometer radius of the Greenland ice sheet—would fall. It might have a 30 to 50 meter drop at the shore of Greenland. But the farther you get away from Greenland, the greater the price you pay. If the Greenland ice sheet melts, sea level in most of the Southern Hemisphere will increase about 30 percent more than the global average. So this is no small effect.

SIMON WERDMULLER, COURTESY OF MAUREEN RAYMO

What happens with melting in Antarctica?
If the Antarctic ice sheets melt, sea level falls close to Antarctic. But it would rise more than you'd otherwise expect in the Northern Hemisphere. These are known as sea-level fingerprints, because each ice sheet has its own geometry. Greenland produces one geometry of sea level change and the Antarctic has its own. Mountain glaciers have their own fingerprint. This explains a lot of variability in sea level. It's also a really important opportunity. If you have people denying climate change because they say there's geographic variation in sea level changes—it doesn't go up uniformly—you can say, "Well, that is incorrect because ice sheets produce a geographically variable change in sea level when they melt." You can also use that variability to say this percentage is coming from Greenland, this percentage is coming from the Antarctic, and this percentage is coming from mountain glaciers. You can source the melt. And that's an important argument from a public-hazard viewpoint.

Why is the source of the melt important?
If you're living on the U.S. east coast, or Holland, you don't need to worry what global average sea-level rise is doing. I was in Holland a few summers ago and was trying to convince the Dutch that if the Greenland ice sheet melts, they have less to worry about than

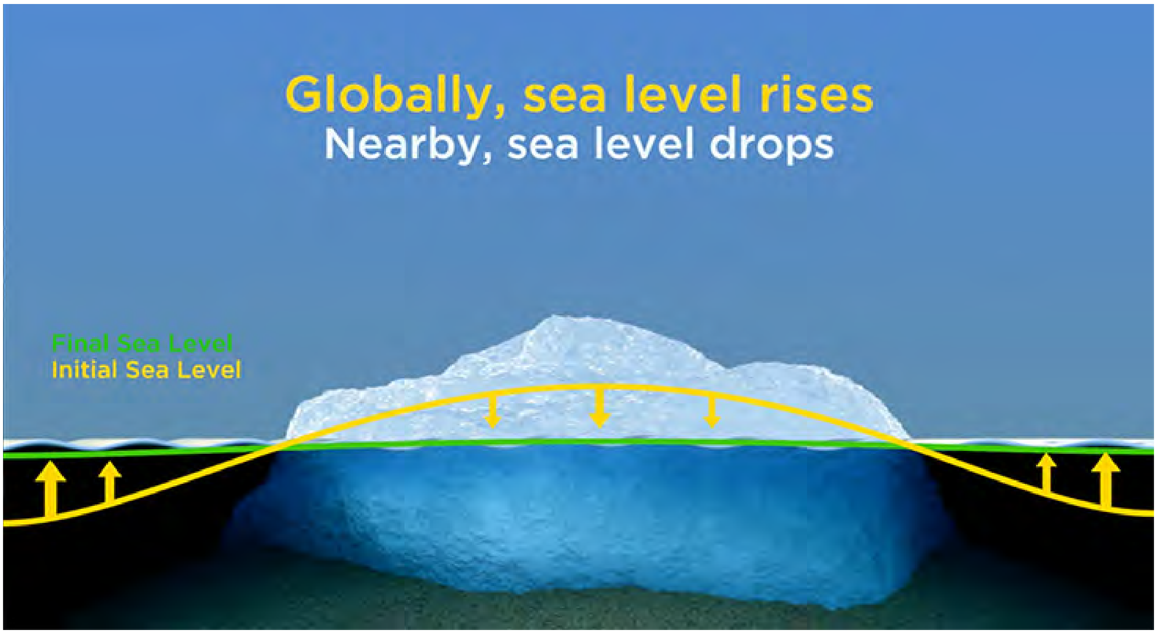
> The last time we were as warm as we are today, the ice sheets that we think of as the least stable disappeared.

the Antarctic ice sheet melting. But it doesn't register. When I give public talks, people just shake their heads. They don't believe it when I show this bull's-eye around the melting [Greenland] ice sheet, which is an area where sea level will fall. Our intuition is built from walking along a shoreline or turning a tap on. It isn't from considering what would happen if a major large-scale ice sheet melts.

Why are you so confident that the world's glaciers, including the polar ice sheets, will keep melting?
One way to understand where we're heading in this warming world of ours is to run a climate model. The other way is to look to the past and ask what the ice sheets did the last time we were this warm or a little bit warmer. We're currently in an interglacial—a warm period between glacial cycles. If humans weren't warming the climate, Earth might be poised to enter into another Ice Age in the future. The last interglacial prior to the present one was about 120,000 years ago. Of course, 120,000 years ago, humans weren't having any impact on climate. That was natural climatic variability.

What did the ice sheets do the last time the climate was this warm?
The last time we were as warm as we are today, the ice sheets that we think of as the least stable disappeared, albeit over a protracted period. So why should we expect that the issue is going to be any different in the next few hundreds to thousands of years? There's no reason to believe it, unless we do something to reverse what we're doing.

OK. So we'd expect warming to cause ice sheets to melt and raise sea level. But what's the evidence that we're seeing that now?
The average sea level change in the 20th century was 1.2 millimeters per year. What we've seen in the last 20 years is an average of three millimeters per year—that's a factor of two-and-a-half increase from the 20th century to now. So that's a nice way to address the skeptic's argument that it hasn't changed or that it's not getting worse. It's already gotten worse. And if you look back thousands of years, you have a wide range of tools at your disposal. One is eclipse records, and one is the Roman fish tanks.



RISE AND FALL A melting ice sheet has two effects on sea level. Diminished gravitational attraction lowers the sea near an ice sheet. At the same time, water flowing into the ocean raises it. So if the Greenland ice sheet collapsed into the sea, the melt water would dramatically raise global sea levels. But nearby countries would see sea levels dip.

What do Roman fish tanks tell us about sea levels?
Wealthy Romans at the time of Augustus were building fish holding tanks. The fishermen would come in with the fish, they'd put them there so that the fish were fresh when they ate them—they wanted to keep them alive for a few days or weeks or whatever. The Romans were engineers, so they built these fish tanks at very precise levels relative to sea level at the time. You didn't want the walls to be too low because at high tide the fish would swim out; you didn't want it to be too high because you wanted tides to refresh the water within the tanks.

Kurt Lambeck, a professor at the Australian National University, recognized that by looking at the present day elevation of those fish tanks, we could say something about how sea level had changed over the 2,500 years since then. If sea level over the last 2,500 years was going up at the rate that it went up in the 20th century, those fish tanks would be under 4 meters of water—12 feet of water—and I can assure you they're not. You can see them. You can walk along the coast, they're visible. What that tells you is that it is impossible that sea level went up by the rates that we saw in the 20th century for any extended period of time earlier than that. Sea level has not gone up over the last 2,500 years like it has in the 20th century.

What can records of Babylonian eclipses 2,500 years ago tell us about climate change?
When we look at eclipse records, we can say "here's when a Babylonian eclipse was recorded." Now, I can do a calculation and ask when that Babylonian eclipse should have occurred if the present rotation rate of the Earth had stayed constant in the time between the eclipse and present day. And you can do that for Greek, Arabic, Babylonian, Chinese eclipses, and this is what a professor in the U.K., F. Richard Stephenson, did. He tabulated, as others did before him, a large suite of

such eclipses that show a clear slowing of the Earth's rotation rate over the last few thousand years. Say you have two clocks synchronized 2,500 years ago. One kept time perfectly and the other was connected to the Earth whose rotation rate was slowing. Over 2,500 years, they would go out of sync by about four hours. That's kind of the level of slowing. So what we know is that the Earth's rotation rate has slowed over the last 2,500 years. But the Earth's slowing isn't what we would predict exactly.

Why would you expect the Earth's rotation to slow at all?

I published this paper in *Science Advances* on something called Munk's Enigma. What we showed is that it comes from three different effects. One is what's known as "tidal dissipation." Tides crash into the shoreline and each time they do they dissipate energy, and for a variety of reasons they slow the Earth's rotation. Another thing we talk about is that there is a very subtle coupling between the core of the Earth, which is iron, and the rocky part of the Earth, the mantle, which acts to change the Earth's rotation rate we see sitting on the surface of the planet.

Is it like the friction of the fluid in a car's a transmission; it has to do with how viscous the connection is between the inner and outer parts of the planet?

It's not friction, but it's pretty darn close. It's the fact that you've got one fluid moving against another fluid that's moving at a different rate. If they come out of sync, their rates will influence each other. But it is as you say, a connection.

So, this is another effect. We have the tides crashing in and what geophysicists would call core-mantle coupling. We can predict both of those pretty accurately, but you're still left with a difference and that difference is due to the ice age and we model that. We've got tidal dissipation, core-mantle coupling, and now we add the Ice Age Effect, which I'm the expert on. And lo and behold, when I add that to these other two effects, I get precisely the four-hour slowing I saw.

What is the Ice Age Effect?

The Earth is growing more spherical because 20,000 years ago we had a lot more ice at the poles. When ice sheets were at the poles they kind of squished the Earth from both poles and the Earth flattened a little bit. When those ice sheets melted, that flattening started to rebound and we're becoming spherical, so our spin rate should be increasing, like a ballerina or a figure skater. The ice age correction is a speeding up of the rotation rate.

> This is an entirely different way to show that ice sheets are melting.

So these three factors—core-mantle coupling, post ice rebounding of poles, and tidal dissipation—explain changes in the speed of the Earth until the 20th century. What's happening now?

We want to take that same ice age model and correct for 20th-century changes in Earth's rotation. When we do, we get a difference that we haven't explained yet. So now we say; well, maybe that's due to polar ice sheet melting or polar glacier melting.

The way to do that is to go to the IPCC, their last assessment report, and look at the calculation of mountain glacier melting, because those tabulations suggest that the ice sheets weren't changing that much in the 20th century. Ice sheets have only really started to melt in the last 20 years or so, but the glaciers were popping off all through the 20th century. We take that glacier melting that the IPCC tells us, compute its effect on rotation, and one effect would be to slow the Earth's rotation just like the figure skater, and compare it to these ice-age corrected observations.

Is water moving off glaciers, slowing the Earth's rotation, this time analogous to a figure skater putting arms out?
Right. Glaciers are mostly near the axis. They're near the North and South Poles and the bulk of the ocean is not. In other words, you're taking glaciers from high latitudes like Alaska and Patagonia, you're melting them, they distribute around the globe, but in general, that's like a mass flux toward the equator because you're taking material from the poles and you're moving it into the oceans. That tends to move material closer to the equator than it once was.

So the melting mountain glaciers and polar caps are moving bulk toward the equator?
Yes. Of course, there is ocean everywhere, but if you're moving the ice from a high latitude and you're sticking it over oceans, in effect, you're adding to mass in the equator and you're taking mass away from the polar areas and that's going to slow the earth down. That's the calculation we did. We also computed how those glaciers would affect the orientation of poles. In both cases, when you do that calculation and you compare it to this ice age corrected satellite and astronomical observations, you fit them precisely.

What we showed in this recent paper is that when you look at the modern data on rotation and you correct for ice age, you have a leftover, and that leftover is precisely what it should be if it were due to the kind of melting that global change scientists believe happened in the 20th century.

With all those steps, it's amazing that the calculations work out.
This is an entirely different way to show that ice sheets are melting. It's a very good way because if you're looking

GLOBAL MELTING Though it may seem counterintuitive, melting glaciers in one area may cause local sea levels to drop—while causing a rise in sea levels farther away.

There are some things that you can explain, but as a scientist you're always going to face things that are counterintuitive.

at Greenland and you say, "Oh, it's melting in the southern sector, I can see ice diminishing," you don't necessarily know what it's doing in the northern sector. You don't get a good integrated view of what the Greenland ice sheet is doing. But rotation doesn't care about north vs. south, it just cares about how much mass is moving from Greenland into the oceans. And so rotation provides what a scientist would call a really elegant integrated measure of the mass balance of polar ice sheets.

What inspired you to become a scientist?

In my family, we had more discussions about Renaissance history than we ever did about science. I'm the only scientist in my family. I went into what's called an engineering science or engineering physics program. I took a course in plate tectonics in my third year, and I thought, "Whoa!" And my first paper—it wasn't my idea, it was my advisor's idea—about what caused the flooding of the western part of North America 50 to 80 million years ago—that was quite a thrill. You're a few years into research graduate school, and you've just published a paper that explains why North America was underwater, the western part.

What is the explanation?

Some said it was some ice effect, that ice volumes had changed. More often people thought that it was linked to changes in the rate at which tectonic plates were created. But in my work and that of some colleagues we've shown that those sorts of events when continents flood typically are due not to some global change in sea level. Rather, it's due to the vertical motion of the continent itself reacting to the flow that's driving plate tectonics and driving continents up and down.

So many of your results seem abstract and counterintuitive. Is that a coincidence?

There are so many interesting problems in our science that you can see with your eyes. But your eyes can fool you. Richard Feynman, the great physicist, used to start his physics lectures by showing students their intuition could take them a long way. They could do things just through intuition that would get them roughly the right answer. Then he used to throw some counterintuitive examples at them. Then he said, "This is why you need physics. You need to understand when your intuition might go wrong." I firmly am a Feynman acolyte. There are some things that you can explain, but as a scientist you're always going to face things that are counterintuitive. You're never going to understand that water is falling near an ice sheet from your everyday experiences of the bathtub. You need to bring in something more; in this case, Newton's second law of gravitation. You have to bring in physics; otherwise, you're never going to explain that.

Where do your "A-ha!" moments come from?

I think some scientists would disagree with me, but I think you really do have to give yourself time to think. You need to have some way in your life as a scientist to mull over what you're seeing. And I strongly encourage my graduate students to have other interests, because the best way to have that time is to take a break from science. I've had moments where I've seen something in my models that I'd never seen before and I think, "Well, you know, a good scientist is never going to walk away from that." A good scientist at that point sort of burrows in and says, "Why am I seeing that?" Because to see the unexpected is the reward of science.

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Pirates, Killer Whales, and Cheap Jewelry: A Life in Science

Near the end of my long career, I want to save the animal that started it.

BY PETER WARD

IN 1984 I WAS on an expedition outside the barrier reef in New Caledonia, an archipelago 750 miles east of Australia. The expedition was formed to study the daily migrations of the nautilus, the longest-lived animal survivor known to science. I was accompanied by, among others, Mike Weekley, a 26-year-old marine biologist, who had worked at the Waikiki Aquarium. Mike was a veteran of nautilus research trips, seemingly fearless, and an expert diver.

On our fifth day of research, we saw thieves approaching one of our holding cages, roped to a buoy, where 10 nautiluses were being kept for future experiments. Nearby, tied to the reef edge, a long piece of rope stretched down to a deep cage, where we were performing a crucial experiment: What was the maximum depth at which the nautilus could empty its chamber?

From a mile away, we set off for the pirates, with our French captain loading his rifle. But the thieves had a fast boat. We were still a half-mile away when we saw them lift the buoy of the first cage. Had they discovered the other rope? Mike and I quickly hit the water. Both the rope and deep cage were still there. As I dove deeper to check the rope for wear, Mike's job was to keep any aggressive white-tip sharks off my back. After five minutes, I turned to motion to Mike, who was supposed to be only a few feet behind me. But when I turned there was no Mike. Only an almost imperceptible "hoot" from below me.

The water in the New Caledonia reefs is crystal clear. Looking down, I saw a small human-like form impossibly far below me, a stick figure, motionless. I powered down past the 100-foot mark of a nearly vertical reef wall, seeing the still figure come ever clearer. I could feel my heart pounding, feel my fear. I willed the shape to move. As I passed the 200-foot mark, nitrogen in my brain smashed me with narcosis. When I reached Mike, he was resting in black coral, like a child held carefully in a mother's arms. I saw that his regulator was not in his mouth and I pushed it back in, hoping he would breathe. It all seemed like a joke, but when I looked into his eyes, I saw the truth, I saw life, I knew that somewhere in his brain he was silently screaming in fear and terror, some parts of him not yet dead.

I pulled Mike from the place he had settled and headed up, trying to squeeze out any air in his lungs before it would expand. It was for naught. The ascent burst his lungs.

Two hours later, in the emergency room of a New Caledonian hospital, Mike lay dead on the tiled floor. His would-be rescuer, and possibly his killer, lay naked, wetsuit cut away and copious amounts of blood being pumped out of his stomach. I had involuntarily swallowed blood while doing mouth-to-mouth and heart massage to Mike for what seemed like eternity on the dive boat. I never learned why Mike sunk to the bottom. It is the nightmare of all divers, a sudden loss of consciousness, or a sudden stoppage of the heart, possibilities even for a young man.

I spent the next year on crutches. My left hip, shoulder, and ankle had been destroyed by nitrogen bubbles. In the decades that followed, the left side of my skeleton has become increasingly made of titanium, ceramic, and rubber, as doctors robotized me, joint by necrotic joint.

Tragedy changes a person. The nautilus had made me a scientist. Yet that same animal caused the death of a close friend. Was his death due to chance, or the human equivalent of bad genes—and, if genes, Mike's or mine? How could it be explained?

In his book *Wonderful Life*, the late, great paleobiologist Stephen Jay Gould argued that chance has had the single greatest influence on the history of life. He wrote about a thought experiment that he called "replaying life's tape." It was an illustration of how unlikely it would be for the biota of Earth to re-evolve in the same fashion that it has over the past almost 4 billion years. Recently, as I have begun to look back at my lifelong preoccupation with *Nautilus pompilius*, better known as the Chambered Nautilus, I have begun to replay my own tape and see how a series of random, chance events have directed my own life and career.

For 25 years the overarching theme of my work as a paleobiologist has been a need to know the identities of which species lived, and which died, in the great mass extinctions, the five intervals in geological time, going back 540 million years to the dawn of animal life, when a majority of species were killed off. I have been able to tell a very plausible evolutionary story about how the nautilus has survived over 500 million years by sidestepping the dinosaur-killing asteroid and every other menace the earth and cosmos have thrown it. It was not because it was especially adaptable, it was because it had the incredible good fortune to prefer deep waters and a metabolism suited to life in the slow lane.

But there is one chance element that I never foresaw in my field notes. Humans—present on Earth only because the dinosaurs died out—find the nautilus, with its mother-of-pearl interior, and tiger-striped outer coloring, so beautiful, and so suitable for jewelry, that they are managing to do what mass extinctions never could: drive the nautilus to extinction.

In recent years I have contributed to the breakthrough discovery that ancient Nautilus pompilius is in fact many separate species, which has overturned the widespread reference to it as a "living fossil." Yet the human toll on the nautilus may be the last discovery that I ever make about this remarkable animal. Looking back at the myriad decisions, tests, detours, and the rest of the messy contradiction and actions that we call life, I have to marvel at the waves of chance that swept the nautilus and me into its rough seas.

MY SCIENTIFIC JOURNEY, now professionally far nearer its end than its beginning, has been more akin to a pinball descending through a field of random bumpers than some ordained conclusion. And not just in the positions I won (and lost), or the books and papers I wrote, or had rejected. The very topic of my research came into my life by a combination of random events combining with a newly grown tool (the brain and body of a young boy) capable of reacting to chance influence and being transformed by it.

My journey began with the 1954 Disney movie *20,000 Leagues Under the Sea*—the first movie I ever saw on a big screen, at the ripe old age of 5. The star of the show was the submarine, or rather Disney's rendering of the storied craft at the center of Jules Verne's tale: a surprising shape of curves and straight lines, an extended diamond of a ship exuding strength and speed, difficult to remember in detail beyond an inchoate vision of grace. Much of the movie took place underwater, a highly romanticized underwater at that. Growing up next to Washington state's Puget Sound, with its wonderful tide pools and salmon, whales and seabirds, was itself an invitation to love science and marine biology.

> My job was to be in the water with the whales and separate mothers from their young. The going price for an orca was $50,000. I was paid $50 a day.

This dual love of a shape and place—submarine and the ethereal underwater world it owned—was soon augmented by an even more seductive shape. In 1956, on a trip to Hawaii, I was suddenly confronted by the real thing: the chambered nautilus. The shell shop was on a quiet corner, a block from the beach. I moved from display to display, pleased by the cornucopia of shapes and exuberant colors that the tropical mollusks possess. With its beguiling curves and chambers, the whole proclaiming a mathematical embrace of function by form, I was hypnotized. In this I know I am not alone. Many of my colleagues who study ancient nautiloids and their cephalopod cousins, the beautiful and extinct group of swimming animals known as ammonites, have confessed to falling under a similar spell.

My obsession was further stoked in 1958, when the world's first nuclear submarine, the USS Nautilus, made the first transit beneath the ice-covered North Pole. Soon I was doodling the damned spiral with its regularly increasing chambers on every school paper, and was probably certifiable. Nautilus, nautilus, nautilus. What emerged was a merging of submarine and romance, a witchcraft induced by three different nautilus submarines: one celluloid, one biological, and one armed with torpedoes. My course was set. Here was a living submarine, wrapped in mystery, inhabiting the Pacific in the hallowed places where my father had fought a bloody war a decade earlier, a creature linked to dinosaurs and the undersea. What better star to become attached to? All I had to do was get good enough grades to get into college, not flunk out and get sent to Vietnam to be killed or maimed, as so many who did wash out of organic chemistry class were, get into grad school, and end up as a professor at a major research university. Because any number of things could have easily ended my quest, it is quite apparent that luck was my guardian angel. Sheer luck on the scale of winning a lottery.

Because the nautilus lives in the sea, I needed to be water-wise and water-tested. I had the great fortune to grow up on a lake. A 15-foot dive to its muddy bottom, required in the games of sponge tag that the gang of boys in my neighborhood endlessly played, taught me to respect rather than fear water. From early on I was un-flummoxed by being in the dark, cold wet. At age 16, I built a scuba tank out of an old fire extinguisher bottle, acquired a $15, used regulator and an old hand-me-down (and piss-stinking) wet suit, and began diving in Puget Sound after a single scuba lesson. I went on to teach and certify more than 1,000 people to dive, while putting myself through college as a commercial salvage diver, which led me to one of my most fateful jobs: a diver for Sea World, catching live killer whales.

In 1970 and 1971, I was part of the infamous Penn Cove (Washington) whale hunts. At that time the Puget Sound region, or its salmon-fishing community, despised

STILL DIVING AFTER ALL THESE YEARS Peter Ward catches up with a nautilus in Vanuata in November, 2014. The author learned the Allonautilus, the rare genus he co-discovered, faces extinction by fishermen seeking to profit from sales of its luminous shell.

JOB VELOJOS

the orca, which routinely ate half the salmon returning each year to spawn. Trapping was applauded. We encircled pods of 30 to 40 whales with seine nets thrown from fishing boats, and culled and captured with ropes the babies for aquaria. My job was to be in the water with the whales and separate mothers from their young. (I once found my leg down the throat of an enraged mother, who spit me out). Rumor had it the going price for an orca was $50,000. I was paid $50 a day.

But another part of my job was to dive down into the seine nets at night, should the whales try to break out. During those nights I learned more about fear than I ever wanted to know—down 40 feet in low visibility, with a dive light in one hand and a knife in the other to confront the poorly seen but certainly felt struggles of a gigantic, multi-ton behemoth fighting for its life in a heavy net, its massive tail thrashing through the blackness. We mostly succeeded in cutting the whales loose from the nets. But not always. That brought about shame, followed by rage, at myself, and at the greedy, voracious men who then, as now, make money from the incarceration of these intelligent creatures.

Following an expose of the hunts by Seattle TV news reporter Don McGaffin in 1971, some of my fellow divers and I testified to state authorities that our employers had been covering up evidence of whales killed in the hunts. Our proof helped launch a state and then federal law to prevent capturing whales in U.S. territorial waters and giving them a life sentence in solitary confinement. It remains the most important work of my life: helping stop the obscene captures.

Nautilus lives in the sea. It also lives in the past. In college I pursued a course of study that married marine biology with paleontology. I was admitted into graduate school in geology (I earned my Ph.D. at McMaster University in Ontario) and conducted studies that got me as close to the nautilus as academics could then go—the study of fossils. I waited and watched and hoped that chance would provide me entrée into my real dream, the chance to study the living nautilus in the wild.

My lottery number came up in 1975. One spring day I happened to be on the University of Washington campus, when I saw a poster announcing a scientific talk to be given by a hero of mine, the great physicist-turned-marine biologist Eric Denton, of the famous marine laboratory at Plymouth, England, about the nautilus and buoyancy.

Since the nautilus first came to the attention of European naturalists in the 1600s, there was intense speculation on how it used its chambered shell to attain weightlessness. For almost four centuries it was believed that when each new chamber was formed, the animal secreted gas into it. It was the same principle, or so it was thought, used by submarines: Gas pumped into ballast tanks generates buoyancy.

Between 2007 and 2010, more than half a million nautilus shells or artifacts—cheap jewelry—were imported into the United States alone.

But Denton, working in large buckets and tide pools on the tropical island of Lifou in the mid 1960s, discovered that each new chamber, sequentially produced by a growing nautilus, was filled with a saline bodily fluid, not gas like a submarine. Through osmosis, carried out by a permeable siphuncle, which spirals through the shell's chambers, the nautilus pumps salt ions from the chamber liquid, causing the "fresher" liquid to be secreted as urine. While gas, circulating in the nautilus' blood, diffuses back into the chamber, it has no effect. It's the liquid leaving the chamber that grants the nautilus its famous weightlessness. Denton and his colleague John Gilpin Brown did show that the name nautilus was appropriate for the animal and submarine in one sense: both have the same design flaw—a finite depth at which both are crushed by too much pressure. In the sea creature's case, about 2,500 feet.

The development of buoyant shells by the nautiloid was one of life's great evolutionary innovations. Some 500 million years ago, the time before fish, all animal life lay on the ocean floor. Then along came an animal that could "float" in the water. For the first time a mobile carnivore could descend on its prey, with eyes and sensory apparatus that could look ahead but never up. For the crustacean-like trilobites, the main prey of the first nautiloids, it was slaughter.

The nautiloids were probably the smartest creatures in the sea. When they evolved from snail-like ancestors, more than 520 million years ago, they were energetic, thanks to enormous gills and a new kind of blood pigment, the copper-based haemocyanin (oxygenated nautilus blood is blue). With all that oxygen coursing through their bodies, a new type of organ became possible: a large and perhaps calculating brain, certainly the highest level of intelligence seen in the animal world up to that point. Nautiluses also carried a lethal weapon—parrot-like jaws with cutting edges capable of slicing through arthropod exoskeletons. With brains and brawn, the nautiloids ruled the seas for millions of years.

In the audience at Denton's talk was a University of Washington professor, Arthur Martin, who had managed to acquire funds to travel to New Caledonia that summer to study the nautilus in the fabled Aquarium de Noumea, the first aquarium to maintain living coral, and the first to put the nautilus on exhibit. By chance I overheard Martin asking Denton for advice on the Aquarium, where Denton had done pioneering work. With heart in throat, I interrupted the pair and invited myself to accompany Martin to New Caledonia as his assistant, volunteering to find the money to pay my way on the three-month trip.

New Caledonia is the only place on Earth where nautilus swim in water shallow enough for a scuba diver to see them. On dark nights, I was able to follow them in their native habitat, the first scientist to ever do so. With a tough, ex-military French buddy, I spent many nights diving outside the vast reef that parallels the Great Barrier Reef of Australia. Every night we would spend an hour stabbing through the clear water with our dive lights, our probes reaching into the blackness, illuminating the white shells of the ascending nautilus. We would follow them, on moonlit nights with our lights off, as they swam right into the surf zones of the shallowest parts of the outer barrier reef. Their forays into the shallows was to find food—not live food, we learned, but fresh molts of lobster. That was a surprise. The nautilus, it turns out, is an obligate scavenger, and can find carrion from many miles away, thanks to an exquisite olfactory system.

Our research paid off in other ways too. I learned how the nautilus had lived through the dinosaur-killing asteroid impact, 66 million years ago, when its cephalopodan cousins, the beautiful and extinct group of swimming animals known as ammonites, did not. The shallow-water ammonites, living in and feeding on plankton, were either killed directly or starved to death in a charnel house that the shallow ocean depths had suddenly become. Far below the carnage, at about 1,000 feet, the nautiloids continued a life in the slow lane, rarely feeding, floating through life without the actions and metabolic costs of actively swimming organisms, such as squid and fish. They grow slowly but unlike other cephalopods, do not die after breeding. Some living nautilus might be a century old or older.

My trip to New Caledonia utterly changed my life. It brought me research papers, professorships, books, a marriage, and a son. It would send me on quests first to Europe and then into the Caucasus Mountains of Asia Minor to further understand the cause of the event that removed ammonites from Earth, yet spared the Nautilus. It sent me to South Africa to study an even more ancient extinction, then Australia, New Zealand, South America, and Antarctica. It was more adventure than ever imaginable by that 5-year-old boy in 1955, staring wide-eyed at the giant squid being fought to a draw in the climactic scene in Disney's astonishing movie.

Chance, though, is not just the purveyor of gifts. After Mike's death in 1984, I quit studying the nautilus. In fact, I quit science altogether. In the pit of my depression, fortune intervened in the person of Stephen Jay Gould. From his perch at Harvard, Gould had taken an abiding interest in all of us younger paleontologists, but a particular interest in my research, which showed that the ammonites disappeared suddenly after the cataclysmic asteroid, in contrast to the prior view that they went extinct gradually. Gould encouraged me to keep researching, beyond the ammonites. He helped me switch to the study of death writ large.

With Gould's advice, I went deeper into the Cretaceous–Paleogene extinction event, surely life's worst day on Earth, when the world's global forest burned to the ground, absolute darkness from dust clouds encircled the earth for six months, acid rain burned the shells off of calcareous plankton, and a monster tsunami picked up all of the dinosaurs on the vast, Cretaceous coastal plains, drowned them, and then hurled their carcasses against whatever high elevations finally subsided the monster waves.

I helped stop the harvesting of killer whales when I was young. Now I will finish my life trying to ensure that the longest living animal remains just that—living.

In his novel *The First Circle*, Aleksandr Solzhenitsyn noted that there were more paleontologists in the USSR during the grimmest period of the Stalin regime than any other kind of scientist. He told his readers why. Of all the sciences, paleontology allows its practitioners to abandon a hideous present to live in a more fascinating past. When I first read this, as a grad student, I didn't understand it. After Mike, I did. For more than 20 years I lived in the deep past, writing books, trying to come to grips with Mike's death.

My quest ultimately circled back to the present. In 2010, scientists in the United States government asked me to go back to the Pacific to study the nautilus, now being killed off by indigenous fishermen trying to feed their families in the southern Philippines.

During my absence of 15 years, others, notably Bruce Saunders, of Bryn Mawr College; Neil Landman, of the American Museum of Natural History; and Andy Dunstan, of the University of Queensland, continued research into nautilus. They discovered, through DNA analysis of the living nautilus, more species than the four that were known during my decades in the Pacific. What had been called *Nautilus pompilius* in Indonesia, Palau, Fiji, Vanuatu, Samoa, both sides of New Guinea, the Great Barrier Reef of Australia, the long barren coast of Western Australia, and most recently in Thailand, was found to consist of many distinct species. The term "living fossil," which suggested a species with a low diversity, had to be overturned.

The research added a new chapter to the story of the nautilus. It revealed that the nautilus had dispersed longer distances than scientists had ever known, to establish safe harbors, and had evolved into smaller sizes to capitalize on scarce resources. Most of all, the new research showed that an ancient group wasn't flickering out but had radiated into magnificent new species.

In 2011 and 2012 I returned to my old study sites in the Pacific, and collected DNA samples that helped confirm that *Nautilus pompilius* is many separate species. But I also discovered that unlike in the deep past, perhaps only a few thousand individuals make up each species. A few thousand individuals swimming long distances to be caught in a baited trap, from which they are hauled to the surface, killed, and sold for $1 a shell. For buttons and cheap tourist jewelry.

It's a savage irony. Although the nautilus ruled the oceans for hundreds of millions of years, Earth's changing conditions dwindled the number of species, about 3 million years ago, to less than a handful—or even a single species. Then came the advent of the Ice Ages and a radical drop in global sea level and temperatures, which, combined, created cool, highly oxygenated oceanic conditions similar to those when hundreds of nautiloid species existed. The nautilus was making a huge comeback in diversity, to the point where it may have been poised to once again be a presence in every ocean, rather than its current confinement to the western tropical Pacific.

But as recently as 50 years ago, the comeback hit a roadblock: us. In the Philippines and Indonesia, the distant nautilus species are being harvested to extinction. Between 2007 and 2010, the United States Department of Fish and Wildlife discovered that more than half a million nautilus shells or artifacts were imported into the United States alone. Fleets of nautilus boats now scour the coastlines of the South China Sea.

The life of the nautilus is providing its last lesson about chance events. But this time it's about bad luck. It's bad luck that nautiluses use their olfactory system rather than vision to find prey, because this trait makes them ludicrously easy to catch. Worse luck comes from a trait over which they never had control: they produce a shell with a visual power that humans covet—a covetousness, I can never forget, that contributed to Mike's death.

This is not a death I can escape from, nor want to. I continue to travel to the Pacific islands to compile data to raise awareness about just how rare the nautilus has become. My work has been partly supported by two remarkable young fundraisers, Josiah Utsch, and Ridgely Kelly, of Maine, who launched a Web site, Save the Nautilus, after reading a 2011 article, "Loving the Chambered Nautilus to Death," by science journalist William Broad, in The New York Times. They collect money, usually $1 at a time, from school kids, and so far have raised over $10,000.

In 2014 I traveled to the places in the Philippines and Vanuatu where I did my nautilus research in the '80s. So much has changed. Far more industry, far more pollution, far more people. And far fewer nautiluses. Using underwater cameras for documentary evidence, we could for the first time make rather accurate population estimates. One population of nautiluses in the Philippines, a dwarf species isolated on a small island named Siquijor, is now extinct. Fished to extinction. All other populations are near that point. Many bear numerous shell breaks and scars from failed attacks by their human predators. The biggest irony and biggest sadness concerns the Allonautilus, the genus that my colleague Saunders and I named in 1997. Because of its rarity, the Allonautilus has become that much more collectible. Now a single shell of my genus can fetch up to $500, a fortune to the people in the remote region of Papua New Guinea where it lives.

Not a day goes by that I do not relish the luck of my own wonderful life. Nor does a day go by that I do not rue the chances that cost a young man his life. I helped stop the harvesting of killer whales when I was young, strong, and immortal. Now I will finish my life trying to ensure that the longest living animal known to science remains just that—living. Because this time if the nautilus survives, it will not be from chance.

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The Mystery of the Healthy Coral Reef

A reef off the coast of Honduras should be a disaster. Instead it's thriving.

BY JULI BERWALD

PHOTOS BY ANTAL BÖRCSÖK

LOCAL HONDURAN FISHERS mostly avoid fishing in Tela Bay on the country's Caribbean coastline. Nonetheless, they have a name for the shapes and forms on the seafloor that waft in and out of view with the shifting glint of the sun. They call them "*rocas*" or rocks.

SECRET OASIS
Tela Bay, Honduras is hot, polluted, and the last place anyone expected to find a thriving coral reef—but species dying out elsewhere in the Caribbean have continued to flourish in its waters.

DIVING DETECTIVES Researchers want to know why this particular reef is doing so well when so many others are failing.

Just over a decade ago, Antal and Alejandra Börcsök, newly-trained divers, heard about the *rocas* and, curiosity piqued, donned their scuba gear to explore. On the seafloor, rather than inorganic geologic forms, Antal and Alejandra discovered rocks that were very much alive. Everywhere they looked they saw growing, thriving coral.

The Börcsöks knew that Caribbean coral were plagued by disease, bleaching, and death. Yet as novice divers, they hadn't seen enough to judge Tela's coral. So, they invited friends who were active in coral monitoring to have a look.

Back on the surface, Antal recounts how their friends gushed, "That is the greatest reef we've ever visited! Is there more like that?" Now, having dived throughout more of Tela Bay than anyone, Antal can say that there is. In fact, there's a lot more reef like that.

But why so much healthy coral exists is mysterious. "We should have nothing in Tela," Antal says. "Everything that's bad, we do in Tela."

That no one seems to have looked beneath the surface of Tela Bay before the Börcsöks did is probably because it's such an unlikely spot for a thriving reef. About 10 kilometers west of Tela Bay, the Ulúa River, Honduras' largest, empties into the Caribbean. It is loaded with sediments, which are typically problematic for coral. Sediments cloud sunlight required for photosynthesis by algae that live inside the coral's tissues and supply as much as 90 percent of their nutrition. Sediments can also physically smother reefs.

"Not only that," says Antal, "this is the place where the banana republic started." In 1913 the United Fruit Company, which later became Chiquita, received concessions from the Honduran government to operate a rail line into the city of Tela as well as 162,000 hectares of land for banana plantations. Today the remains of the 1,000-foot wharf where boatloads of bananas were exported still rise above the surface of the water. But the banana trees have largely been replaced by African oil palms, and those plantations have expanded.

Tela receives more than a meter of rainfall a year; as it runs into the bay it brings fertilizers from the plantations with it. Compounding the agricultural runoff is waste from Tela's roughly 100,000 inhabitants. The city has no sanitation system except for pipes that run directly into the bay.

Corals evolved to live in the sea's deserts, places where organic molecules like those in fertilizers and sewage are nearly absent. When exposed to elevated concentrations of these nitrogen-rich compounds, they often sicken.

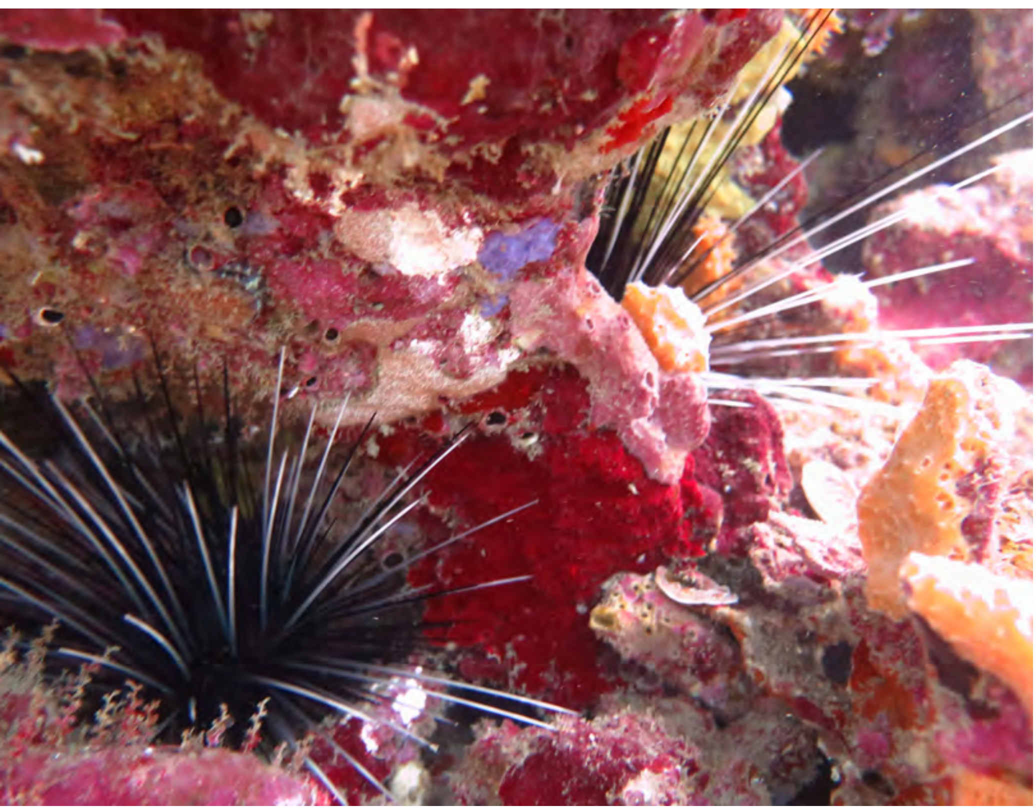
Yet after more than a century of inundation by sediments, agricultural runoff, and sewage, the corals in Tela are unaccountably thriving. The reason the fishers avoid the reef is because it is so abundant and complex that small fish can hide from predation. Big fish don't bother hunting there, and neither do the fishers.

Diseases that have ravaged other Caribbean reefs are apparently absent from Tela Bay.

DISCOVERING THE REEF galvanized Antal and Alejandra. They started a project to protect it, and within two years saw the passage of a local law to do so. Their company, Tela Marine, partnered with an English tour operator, Project Wallacea, which helps graduate students develop field projects.

Dan Exton, the head of research at Operation Wallacea, recalls standing on the beach in Tela with Antal for the first time and thinking there couldn't possibly be a coral reef beneath the murky water. "I almost cancelled the dive," he said. But as soon as he descended, Exton saw "mind-blowing coral. I'd never seen a reef like that. Everywhere you looked, something unusual was happening."

Since then, Exton has overseen the work of more than 500 students in Tela Bay; their findings confirm the unusual richness of the reef. Whereas at the nearby island of Utila, coral cover—the proportion of a reef's surface where healthy coral grows—hovers around 20 percent, in Tela it remains more than threefold greater.



SPINY GARDENERS
Sea urchins graze on algae that can easily overgrow coral, so they're vital for a healthy reef. Disease wiped out urchins across the Caribbean, but the urchins in Tela Bay remain untouched.

SAFE HAVEN Because the reefs provide so many tiny nooks for little fish to hide in, big fish tend to stay away—and so do the human fishers.

Elkhorn and staghorn coral species that are critically endangered in the rest of the Caribbean grow in rich thickets along the bay's shores. Mountainous star coral, another endangered species, grows in massive plated colonies as big as backyard sheds. Lettuce corals unfurl in long, rich carpets. Their blades form tiny three-dimensional apartments for shrimp, snails, clams, worms, and tiny sea stars, and provide spaces where small fish can hide from predators.

One important observation is that diseases that have ravaged other Caribbean reefs are apparently absent from Tela Bay.

Since 2014, stony coral tissue loss disease has decimated reefs throughout the Caribbean, melting more than 20 species of brain, maze, and pillar coral tissue like hot wax. These species are found in Tela Bay, yet no one has seen the disease there.

Here and there, the pick-up-sticks spines of sea urchins wave curiously from within crevasses. These clementine-sized urchins are critical to reef health, grazing algae that can easily overgrow coral. In the 1980s an epidemic wiped out urchins throughout the Caribbean, and they have never rebounded. In Tela Bay, the numbers of urchins remain at pre-pandemic levels, roughly 100 times more abundant than elsewhere in the region.

Another outlier are giant barrel sponges. On nearby Roatan, divers used to pose for pictures inside millennium-old sponges so big that the dive spot was referred to as "Texas," because everything is so big in Texas. But in 2018, an affliction called orange band disease killed the ancient organisms in just four months. In Tela Bay, barrel sponges were unaffected.

One more threat facing reefs is heat. As Earth warms, half of all coral reefs are thought to have already succumbed to bleaching, in which a coral's symbiotic algae departs the partnership, leaving the coral bereft of color and nutrition. Bleaching is caused by warming waters. Tela Bay's reefs, however, have handled the heat.

Anne Cohen, a marine biologist at Woods Hole Oceanographic Institution who searches out heat-tolerant reefs, performed a preliminary estimation of heat stress on Tela Bay's corals for this article. Her team found that, although sea surface temperatures reached 31 degrees Celsius—hot enough to blanch any reef in Florida—there had been comparatively few episodes of the types of heat waves that are especially conducive to bleaching.

As a result, her lab's models suggest that bleaching would only have been expected once, in 2017. "It just hasn't gotten hot enough there," Cohen says. That jives with Antal's observations. He rarely sees bleaching in Tela.

In 2018, armed with reef survey data, and working with local NGOs and the Ministry of Agriculture, Tela Marine shepherded an act through Congress establishing the first Marine Wildlife Refuge in Honduras, strengthening protections for Tela Bay from the local to national level.

But just when the future seemed assured, a Chinese company proposed developing an iron mining operation along the Ulúa River. It had the potential to dump heavy metals toxic to marine life into the bay. "That was going to kill the reef, basically in a year," Antal said.

Ultimately, the mining operation was halted, in part because of public testimony against it, but the threat showed just how little stood between the reef's survival and economic forces. Even an act of Congress was a flimsy line of defense.

"We realized that the biggest problem was that nobody knew there was a reef there, right?" Antal points out. "So how do we take people to the reef?"

In a place where a small fraction of the population dives, the answer was to bring the reef to them. Tela Marine opened the only public aquarium in Central America. Twelve thousand visitors a month already pour through the aquarium doors, which puts it on track to be one of the largest attractions in the country.

An intentional part of the draw is the price of admission: free, except for an eight-minute speech from Antal or one of the aquarists on why the colorful corals, creeping seastars, spiny urchins, and darting fish they are about to see are such a treasure.

HEAT RESISTANT A feather star atop a piece of coral. These mesmerizing invertebrates evolved 200 million years ago and have proved resilient to warming waters.

While the Börcsöks work to protect the reef, questions remain about what makes it so healthy. Is there something about the bay that protects its corals from bleaching? Have the corals adapted to a century of runoff? How do they thrive with so much sediment? Is there something special about their symbiotic algae? What prevents diseases from spreading in Tela when they rampage through the rest of the Caribbean? Are the coral, urchins, or sponges genetically different? Most importantly, can this reef continue to survive?

Currently, answers are unknown. Like the public, few scientists are aware of the reef's existence. Aside from Operation Wallacea, little scientific attention has been paid to the reef. Research has largely involved observation and monitoring, although plans for more detailed studies are now in the works.

Even before those questions are answered, when Antal stands before a crowd of enthusiastic aquarium visitors he can already say, "We have something that we can be proud of in Honduras. This reef is unique. As far as we know, there isn't any other reef in the world that looks like this."

So far, that is. Dan Exton notes that the implications of finding the reef stretch well beyond Tela Bay. "It can't be the only one out there that's like it," he says. Exton suspects that scientists searching for healthy coral might have looked in the wrong places as seas shift to warmer, more polluted conditions.

"If you were to look at other turbid, cloudy, impacted bays around the Caribbean, you may well find other healthy reefs," says Exton.

To him that's a reason for optimism. "We get so bogged down in coral reef science by the idea that, in 50 years' time, corals won't exist anymore," Exton continues. "I think there's a lot more hope for reefs than we give them credit for sometimes. For me, my personal hope comes from Tela Bay."

JULI BERWALD is a science writer and author of *Spineless: The Science of Jellyfish and the Art of Growing a Backbone* and *Life on the Rocks: Building a Future for Coral Reefs*. More about her writing can be found at juliberwald.com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Where Do Our Minds Go?
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