

NAUTILUS

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The Precarious Issue

LIFE IN THE BALANCE

ISSUE 67

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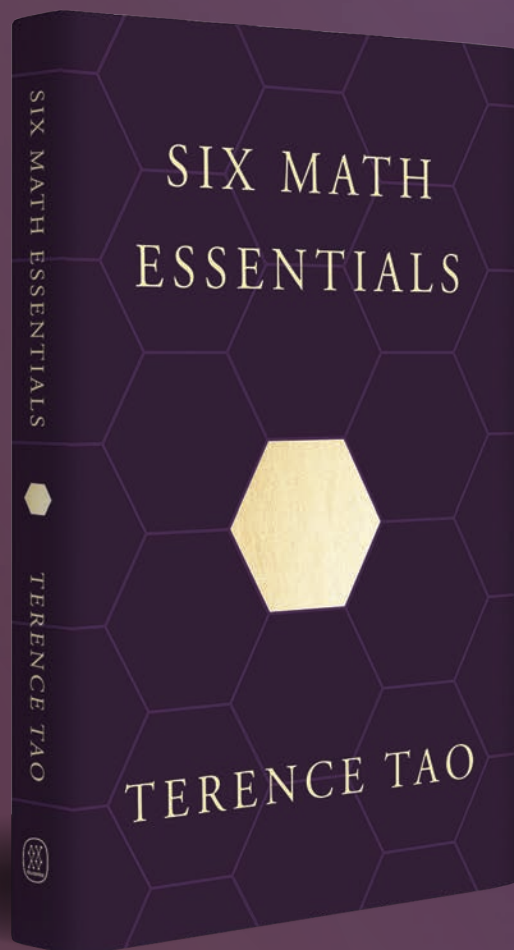
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BY KEVIN BERGER



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NAUTILUS

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Unvanquished

BY BOB GRANT

ANYONE WHOSE LIFE HAS been touched by rare disease knows what it's like to live in a constant state of limbo. Uncertainty becomes an uneasy, unwelcomed companion. What does the future hold? Should I plan for the worst at the expense of the present? In such a liminal existence one strains to perceive even the faintest glimmer of hope. My own family is touched by a rare disease, so I welcomed the chance to edit a story, "For Every Patient Their Own Drug," written by Brady Huggett about pioneering drug developer Stanley Crooke.

Crooke and n-Lorem, the nonprofit he founded in 2020, has provided that ray of hope for more than 30 families. The organization has administered custom-made, protein-expression altering drugs to patients with "nano-rare" mutations, those that afflict less than 30 people worldwide. Some of these patients, many of whom are children, have experienced improvements in their rare conditions thanks to n-Lorem's efforts.

The foundation's novel drug development, testing, and treatment strategies have given dozens of families something—hope, options, action—where only uncertainty existed before.

Elsewhere in this issue are other stories of precarious situations and other glimmers that might give us hope in our uncertain times.

Curious readers will learn of an amazing, historic confluence of events on one day in 1939 that could have spelled the end of our universe. They didn't.

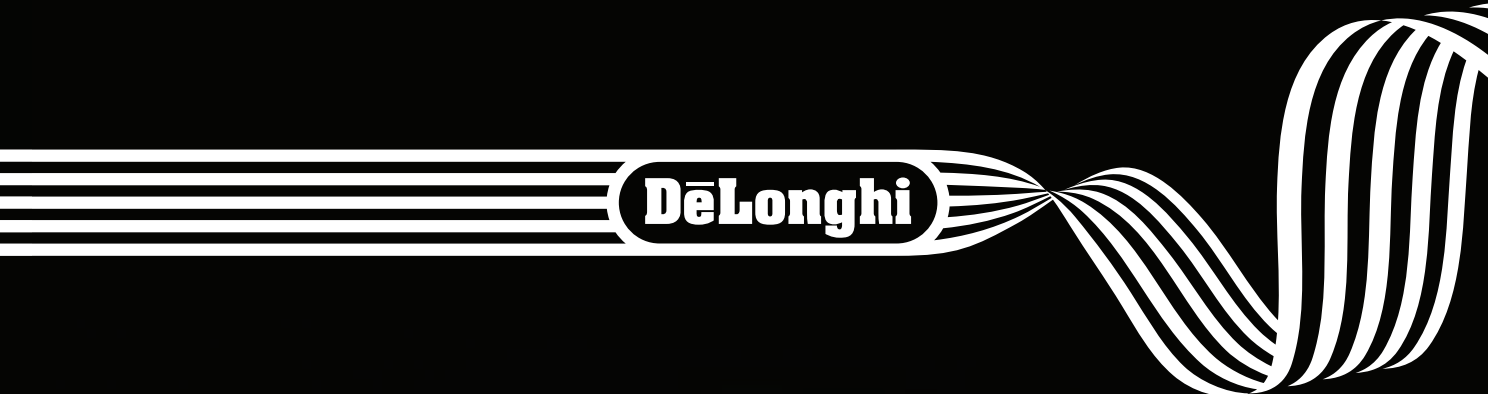
You'll also read about humanity's brush with extinction, between 800,000 and 900,000 years ago. For that precarious millennium, a population of about 1,000 *Homo sapiens* clung to existence. Our species could have vanished. But it (for better or worse) didn't.

In these stories, but especially in Huggett's profile of Stan Crooke, I find hope. Hope that we can somehow bend our lives to some stable state. In the United States a "rare disease" is defined by affecting fewer than 200,000 people. But considering the patients affected by the more than 7,000 rare diseases identified by scientists, rare diseases aren't even rare, at least in the aggregate.

Similarly, it's not rare for people living through our current times to feel unsure, uneasy, uncertain. But we can all take heart—as individuals, as societies, and as a species—in the fact that we've faced precarious situations before. And we've emerged, if not unscathed then at least unvanquished. Doubt and fear may be at the fore now, but knowledge, beauty, and survival have a way of persisting even in troubling times. May these stories inspire in you the hope they have in me.

IF IT'S NOT ITALIAN,





DeLonghi

IS IT EVEN ESPRESSO?



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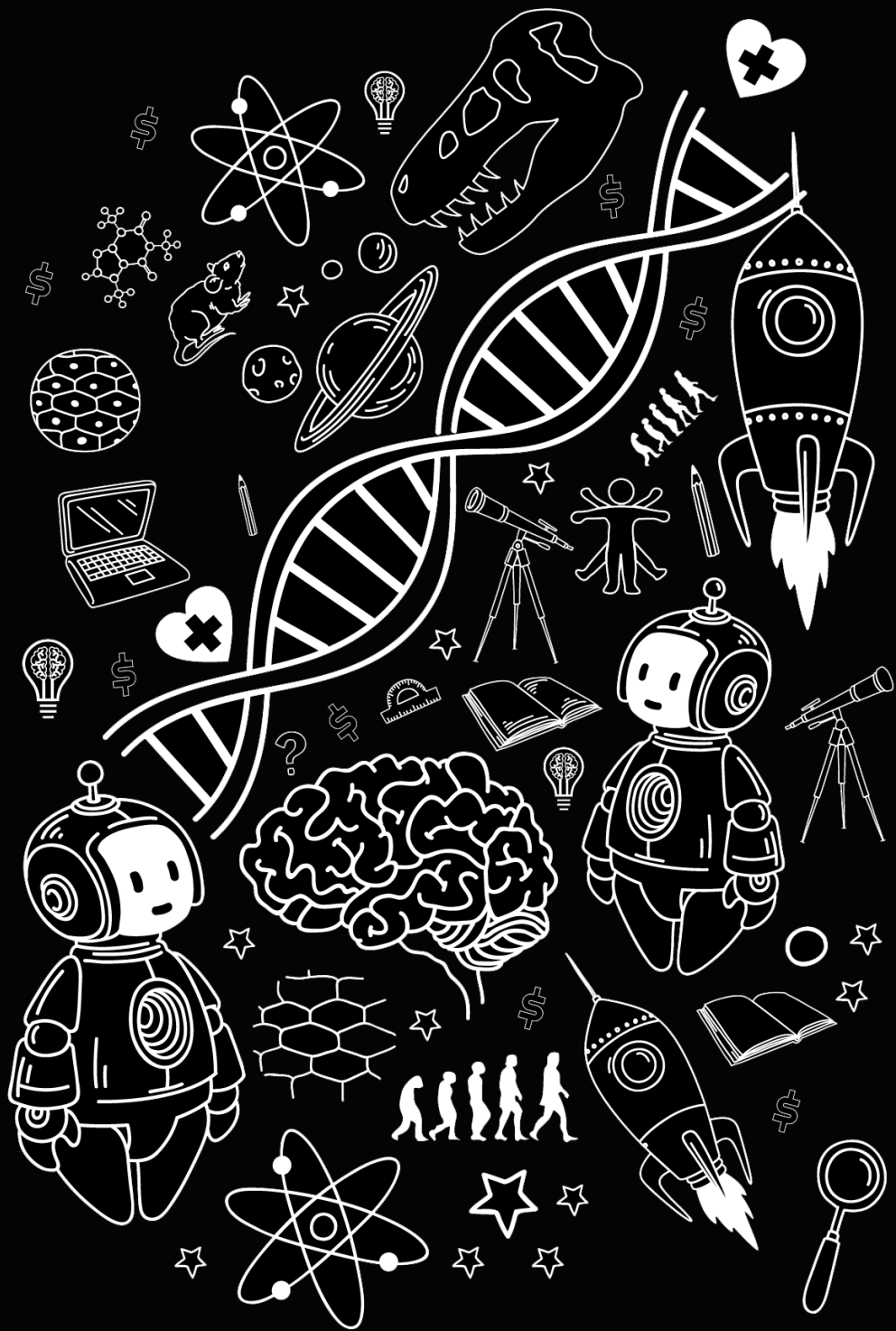
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The Porthole



Short sharp looks at science

MICROBIOLOGY

The Rocks That House the Oldest Life on Earth

S HARK BAY IN AUSTRALIA is famous for all kinds of reasons. As the meeting point of climatic regions and plant ecotypes, it's exceptionally diverse and home to endangered dugong—not to mention more than a dozen shark species (hence, the name). But the rarest feature of Shark Bay is hidden in what look like rocks in its sandy shallows. Because they're hypersaline, the shallows support the growth of stromatolites, or clumps of sediments layered with microbes thought to represent the oldest life forms on Earth.

Now, a new study reveals that Shark Bay's stromatolites have been harboring secrets about how life on Earth began. Long before animals and plants evolved, microbes were secreting gluey substances that cemented them into stromatolite mats. In isolating DNA from samples of Shark Bay's stromatolites, researchers in Australia discovered a microbe from the group "Asgard archaea," which is hypothesized to have partnered with a bacteria billions of years ago to make the first complex eukaryotic cells with nuclei.

The new species name of the archaeon (*N. marumayae*) means "ancient home" in the Malgana language spoken by the native inhabitants of Shark Bay. It honors Indigenous people who colonized Shark Bay 30,000 years ago, even though that's a mere blink of an eye compared to the stromatolites' time there.

Using electron cryotomography, a high-resolution 3-D imaging technique, the researchers got a view of stromatolite structures at a millionth-of-a-millimeter scale. They witnessed tiny nanotubes linking the bacteria to the archaeon. It appeared that both organisms were doing their part to sync up via the tubes and then shoot stuff through them like a pneumatic tube-mail system.

"This could be a little model for how these kinds of partnerships started and ultimately formed eukaryotes," said University of New South Wales study author Brendan Burns in a statement.

The stuff traveling between the organisms wasn't mail, of course, but chemical compounds. In what appears to be a mutually beneficial relationship, the



Shark Bay's stromatolites have been harboring secrets about how life on Earth began.

bacteria and the archaeon each share things that the other needs. While the archaeon offers up H₂, acetate, formate, and sulfite, the bacteria passes along amino acids and vitamins. Since microbial mats live in extreme conditions of UV radiation and salts, the exchange might give them the boost they need for survival.

The discovery left the study authors wondering what other such partnerships remain to be uncovered. "These microbes remind us that even the smallest partners can leave the deepest mark on our history," said Burns.

And they may be hiding in plain sight—in what appears to be just an old pile of rocks.

—Devin Reese

ASTRONOMY

What It Would Be Like to Surf in Space

THE WAVES ON EARTH are pretty crowded these days. Surfing has gotten so popular that shredding the gnar has almost become a contact sport in many parts of the world. It takes a lot of work to find a quiet break where you can carve up a swell with just a handful of your favorite surf homies and a pod of dolphins.

Perhaps it's time to look to the stars for your next surf destination?

The number of planets and moons known to host liquid lakes and oceans, past or present, is growing, and where liquid flows, waves follow. But what kinds of waves you'll find on these distant extraterrestrial bodies varies dramatically, ranging from lazy ankle biters in a sea of lava to 16-foot heavies in a liquid methane lake, according to a new model developed by scientists from MIT and the Woods Hole Oceanographic Institute, which they've aptly named "PlanetWaves." It's the first time waves have been simulated for such extreme planetary environments.

On Earth, waves form as wind drags across bodies of water, pushing unevenly on their surfaces. As the waves lengthen, and the distance between crests grows, the waves are increasingly driven by the force of gravity rather than by surface tension. Once gravity takes over, the waves can grow with the wind. On faraway planets, the size of the waves would depend not only on the strength of gravity and the speed and direction of the wind, but the density of the atmosphere, the viscosity of the liquid in the oceans and lakes, as well as the depth of the bed. All these factors were fed into the PlanetWaves model.

Note that to actually surf these waves, they would need to break in shallow coastal waters in a clean, sustained way, something the PlanetWaves model does not directly address.* But with science as our tour guide, and creative license as our faithful companion, let's take a fictional surfing safari through the cosmos.

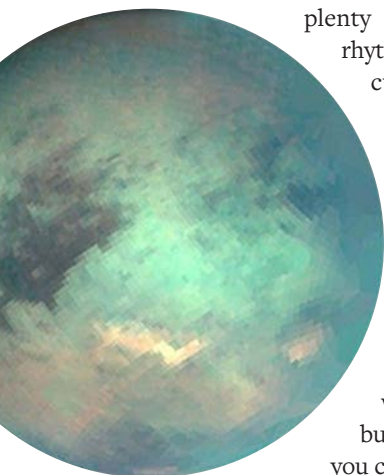


1. TITAN: ONTARIO LACUS

Surfing on Titan would likely be a surreal, slow-motion, and tenebrous experience. Saturn's largest moon is home to several low-density liquid methane lakes. Ontario Lacus is the largest of these, on Titan's southern hemisphere. With a light breeze of 1.5 miles per hour, ripples would just begin to form on the surface, the PlanetWaves model suggests. But the waves would rear up to 16.4 feet in 11 mile per hour winds, making for a pretty radical, if blustery, session.

On Earth, over 10 feet is generally expert-level, but given that Titan has only 14 percent of Earth's gravity and a thick nitrogen-rich atmosphere, the waves would roll in like molasses, taking much longer to break. That would theoretically give even non-experts

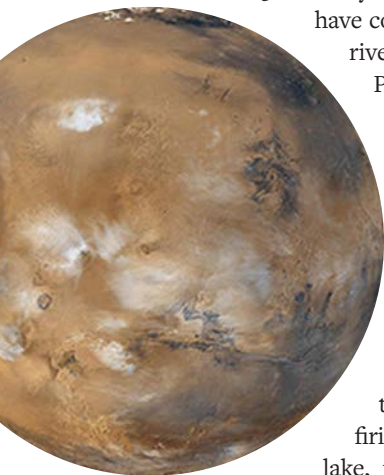
**As waves grow, they become steeper up to a geometric limit, at which point they crest and tumble forward. But waves that break in open water on Earth typically form whitecaps that are too chaotic to surf. When waves enter shallow water, they steepen rapidly, and under the right conditions of wind, swell direction, and seafloor shape, can produce a clean surfable face.*



plenty of time to tune in to the rhythm and perfect pop-ups and cutbacks without getting crushed by the weight of a collapsing wall of liquid. You probably wouldn't have to worry about getting squished by Titan's atmosphere, either. It's dense like that of Venus, but only 1.5 times that of Earth near sea level, so it would be noticeably thicker but likely not dangerous. And you could probably ditch the sunscreen: Titan only gets about 1 percent as much sunlight as Earth. Surfing there would be like surfing in bright moonlight on Earth. Unfortunately, you might also turn to ice as brittle as granite. Average surface temperatures on Titan sit at around -294 degrees Fahrenheit.

2. MARS: JEZERO CRATER LAKE

To surf on Mars, you would not only need to travel up to 249 million miles into space, you'd also have to time travel to the distant past. Current atmospheric pressure and surface temperatures are too low to allow liquid water to flow consistently on Mars. It would either freeze or evaporate. But long ago the planet was likely covered in crater lakes, like Jezero Crater Lake. Around 3 billion years ago, turbid water would have coursed through this lake and river delta on the edge of Isidis Planitia, and in places the lake floor might have reached a depth of 32 feet.



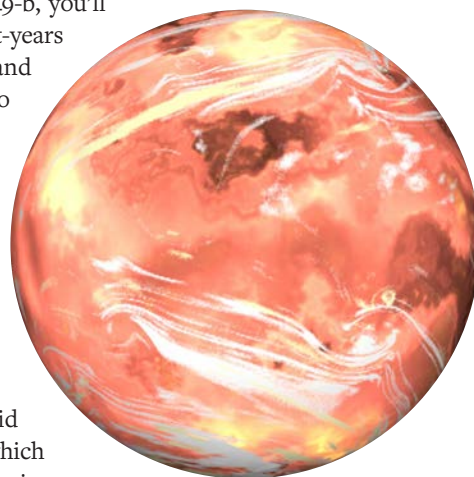
Let's say an easterly 23-mile-per-hour wind whipped up and blew for 10 hours straight. Under these stormy conditions, the waves would bump along at a gentle 1.6 feet near the east coast, but they'd be firing on the west coast of the lake, reaching heights of around

5 feet, according to the PlanetWaves model. In other words, longboarders might find something to ride on the east coast, but shortboarders would want to head to the west.

Like on Titan, the Mars of 3 billion years ago featured low gravity, which would surely make aerial moves a snap. You could potentially achieve higher heights and more acrobatics. And like on Titan, the waves would roll slowly, marching along like a clan of elephants, giving you plenty of time to carve up and down the face.

3. KEPLER 1649-B

To surf on Kepler 1649-b, you'll need to travel 219 light-years into the cosmos, and then make your way to a hypothetical ocean made of sulfuric acid. Aside from the fact that sulfuric acid can give you third-degree burns and permanently scar your skin, it also has much higher surface tension and liquid density than water, which would make it more resistant to wave formation. Winds would

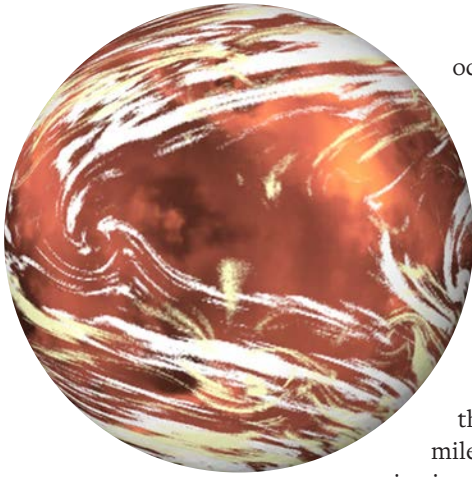


need to reach 12 miles per hour before any ruffles could form on the surface. But above this threshold, waves could grow to heights comparable to those on Earth for a given wind speed, according to the PlanetWaves model. That's because in many respects, Kepler 1649-b is like Earth: The gravity is similar, as is the atmospheric pressure. (The planet is also Earth-sized.)

But be prepared to bake. Beyond the obvious drawbacks of surfing in acid, there's another downside to this surf destination: Kepler 1649-b is thought to have a runaway greenhouse atmosphere. And so, it gets scorchingly hot—roughly 500 degrees Fahrenheit.

4. LHS 1140-B

What a relief: Water! Just a short 49 light-years from Earth, LHS 1140-b may be covered in a massive



ocean. Because this ocean is thought to be composed of water, with surface tension similar to that of the oceans on Earth, the waves can get started with just a light nudge from the wind: around 6 miles per hour. Gravity is much higher, how-

ever—about 2.4 to 3.4 times that

of Earth—which means waves have a tougher time reaching massive heights before collapsing under their own weight.

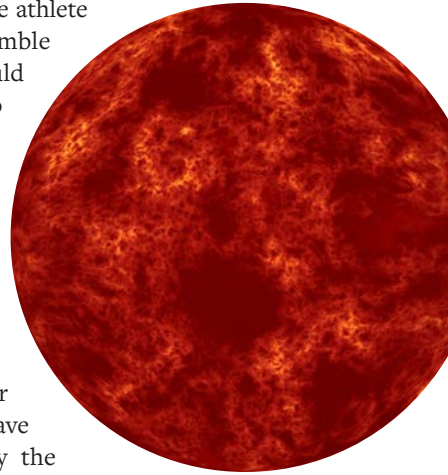
But who knows, you might even meet an extraterrestrial surfer here. Because of its thick nitrogen-rich atmosphere, it's considered one of the best targets in the search for extraterrestrial life. It's also considered tidally locked, meaning one side always faces its star, while the other side is permanently dark and frozen. Surfing and snowboarding in one trip?

5. 55 CANCRI-E

The final stop on this surfing tour is only for the extreme athlete with extremely humble ambitions. You would have to be able to withstand hurricane-force winds and yet satisfy yourself with puddle jumpers. Wavelets only form on this lava world's ocean of dense liquid rock at wind speeds of above 83 miles per hour. Beyond that, wave size is minimized by the planet's hefty gravity, which is more than twice that of Earth. It's a tidally locked hellscape, with dayside temperatures of more than 4,000 degrees Fahrenheit. So don't forget your sun hat.

Or maybe it's best to just brave the crowds at the surf breaks on Earth?

—Kristen French



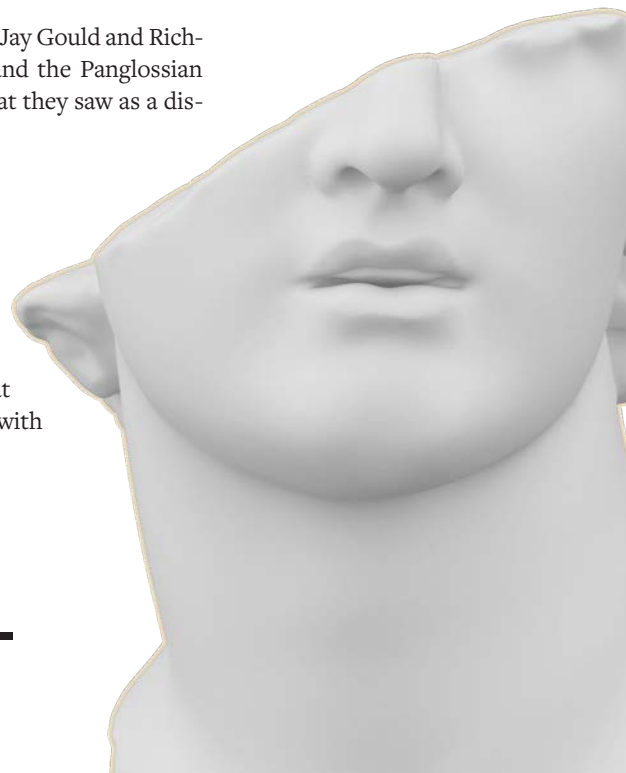
EVOLUTION

The Evolutionary Accident Unique to *Homo Sapiens*

IN 1979, RENOWNED EVOLUTIONARY biologists Stephen Jay Gould and Richard Lewontin published “The Spandrels of San Marco and the Panglossian Paradigm,” a relatively short treatise pushing back on what they saw as a disconcerting trend in their field.

Evolutionary biologists, the two wrote, had become enamored with atomizing organisms into discrete traits and telling “just-so stories” about how these individual aspects had become optimized by natural selection to their ideal form.

To illustrate the fallacy of this mode of thinking (what they called “the adaptationist’s programme”), they used the example of “spandrels” in Venice’s St. Mark’s Cathedral. A “spandrel” is the curved triangular space between two arches at right angles to each other, and in St. Mark’s they’re decorated with detailed mosaics.



“The chin evolved largely by accident.”

It would be wrong to say the spandrels were created for the purpose of displaying mosaics, Gould and Lewontin explained. Instead, they were architectural byproducts of arch construction, decorated after the fact. And just as spandrels are byproducts of the constraints of architectural space, many biological traits are byproducts of the constraints of physical and developmental processes, Gould and Lewontin argued.

Since publication of their paper, “spandrel” has become shorthand among evolutionary biologists for an incidental trait, or result of a byproduct of evolution. Now, a new study published in *PLOS One* is investigating the potential spandrelhood of a human trait: the chin.

Absent from other primates—and even Denisovans and Neanderthals—the bony, protruding chin is a uniquely human characteristic and often used to identify members of our species in the fossil record. As such, it’s tempting to indulge in another uniquely human trait (storytelling) and come up with a reason it was honed by natural selection. Among others, supporting the lower jaw to facilitate chewing or acting as a secondary sexual characteristic to advertise maturity to mates, are two such stories.

To investigate theories of the evolution of the chin, researchers from the University of Buffalo examined gene sequences involved in the development of the head and jaw for evidence of evolution. Specifically, the team looked at whether sequences involved in producing the chin itself were subject to direct selection, whether they arose neutrally due to genetic drift, or whether they were merely a byproduct of evolution acting upon other traits (a spandrel). They found that the evidence pointed toward the chin being a spandrel.

“The chin evolved largely by accident and not through direct selection, but as an evolutionary byproduct resulting from direct selection on other parts of the skull,” study author Noreen von Cramon-Taubadel said in a statement.

The traits natural selection was most likely acting on included reduced anterior dental size and other cranial changes related to the evolution of bipedalism, the authors clarified.

“While we do find some evidence of direct selection on parts of the human skull, we find that traits specific to the chin region better fit the spandrel model,” von Cramon-Taubadel explained. “The changes since our last common ancestor with chimpanzees are not because of natural selection on the chin itself but on selection of other parts of the jaw and skull.”

It’s an important reminder that traits should be considered within their context, and that not all differences between species are a result of an all-powerful force of natural selection.

“Generating empirical evidence against that line of reasoning is an important goal of this study and biological anthropology in general,” von Cramon-Taubadel said. “The findings underscore the importance of assessing the evolution of physical characteristics with trait integration in mind.”

Something to stroke your chin and think about.

—Jake Currie

ASTRONOMY

A 17th-Century Journey to the Moon

AS WE REFLECT ON the Artemis II astronauts’ historic slingshot around the moon, a short novel from the 17th-century reminds us that great thinkers have been imagining the far side of our lunar satellite for centuries.

Published in 1634, *Somnium* was written in 1608 by Johannes Kepler, a giant of early astronomy. Widely considered to be one of the earliest works of science fiction, the book’s full title is *Somnium, seu opus posthumum De astronomia lunari* (translation: *The Dream, or Posthumous Work on Lunar Astronomy*) because it was published by his son Ludwig after Kepler’s death in 1630.

Especially strange are the creatures that inhabit the moon.



The plot of the work is pretty wild. The book opens with Kepler falling asleep and into a vivid dreamscape after reading and admiring the night sky, both frequent pastimes for the decipherer of the laws of planetary motion. Once dreaming, Kepler reads a different book that recounts the tale of Duracotus, an Icelandic youth. Duracotus tells of his witchy mother, Fiolxhilde, who inadvertently sold the 14-year-old to a ship's captain bound for the Danish island of Hven, home to another astronomical luminary of the age, Tycho Brahe.

This is where things get weird. Brahe takes Duracotus under his wing (as he did Kepler in real life), and schools him in the emerging science of lunar observation. Upon reuniting with his mother in Denmark, the boy is introduced to a daemon (neither devil nor demon, more like a spirit or an extraterrestrial) who promises to escort him on a journey “fifty thousand German miles high up in the sky” to the “island of Levania,” aka Earth’s moon. (A “German mile” was a unit of measurement used until the late 19th century that equaled about 4.6 Imperial miles. The moon floats an average of about 238,855 miles above Earth. So Kepler’s fictional distance of about 230,000 miles wasn’t too far off from reality!)

While Kepler’s Earth-moon distance was remarkably accurate, the speed of Duracotus’ journey was not. Traveling at daemon speed, “The whole journey, although far, is completed in a time of four hours at the most.” The Artemis II astronauts, like spacefarers before them, took about four days to get to the moon. As fantastical as the speed of Duracotus’ moonshot, the daemon’s warnings regarding the rigors of space travel ring remarkably similar to rocketeering. “First of all he experiences a strong pressure, not unlike an explosion of gunpowder, as he

is hurled above the mountains and the seas,” Kepler writes. “For this reason, drugs and opium are consumed at the start, so that he falls asleep, and each of his limbs disentangled, so that his body is not torn from his legs, nor his head driven from his body, but so the shock will be distributed across all his limbs.” OK, so maybe not that last part.

The rest of the book is similarly dualistic, peppered with alternating instances of science and fancy: An equation for moment or driving force to get the acceleration just right to leave Earth and touch down lightly on Levania here, and a description of the bizarre creatures that inhabit the moon’s strangely watery surface there.

Kepler accurately relays the fact that the moon is tidally locked to Earth (called “Volva” in the story), meaning that one lunar hemisphere is perpetually facing away from our planet. This hidden face of Levania, he terms the “Privolvian hemisphere.” And it’s not necessarily a welcoming place.

“The Privolvans’ night lasts 15 or 16 of our days, terrible with never-ending shadows, as are our moonless nights. The rays of the Volva never light upon them,” the astronomer writes. “For this reason everything becomes stiff from the ice, the frost and from the sagiest and most powerful winds.”

The days on Privolva aren’t much better. “The Sun is slow under fixed stars and there are no winds. Then, it becomes intolerable hot. Thus for the space of one of our months or of one Levanian day and in one and the same place, the heat becomes 15 times hotter than our Africa, and the cold, unbearable.”

Especially strange are the creatures that inhabit the moon. “Whatever springs from the land or walks

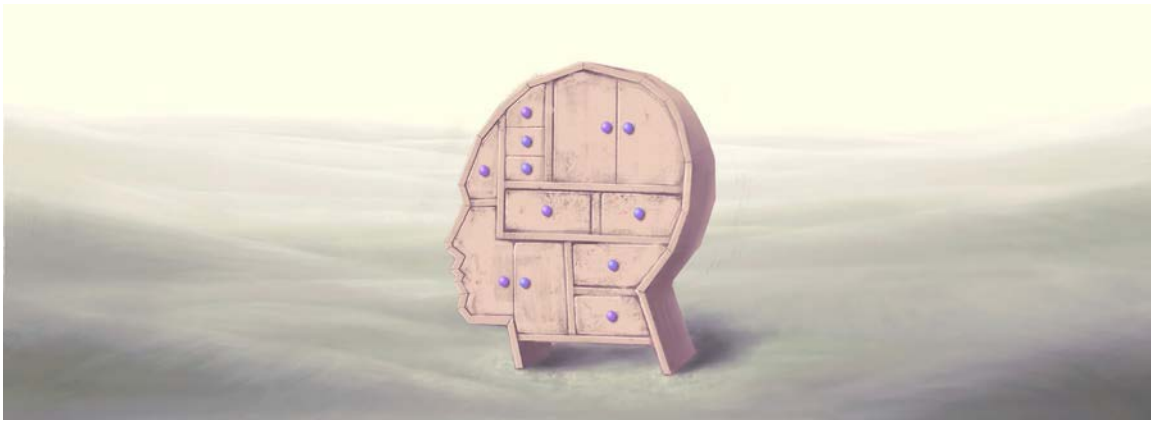
upon the land is of a monstrous size,” writes Kepler. “Increases in size are very rapid. Life is of short duration because all living things grow to such an enormous bodily mass.” On the far side, the moon’s inhabitants mainly stick to the shadows. “The Privolvans have no fixed dwelling place. In the space of a single day, they traverse the whole of their world in hordes, following the receding waters either on legs that are longer than those of our camels, on wings, or in boats. If a delay of very many days is

necessary, they crawl through the caves according to each one’s nature.”

Botanical life on the moon has it even tougher. “Plants in the earth, and there are a few on the mountain tops, spring up and die on the same day, daily making room for new growing things.”

Such a great reminder that so many imaginations, past and present, have been ignited by a heavenly hemisphere obscured to us Earthbound stargazers.

—Bob Grant



PSYCHOLOGY

How Brains Build Categories

One question for Lisa Feldman Barrett, a neuroscientist and psychologist at Northeastern University

What does your new theory about how our brains build categories on the fly, even before we are consciously aware of it, tell us about the nature of objectivity and bias?

At the beginning of the scientific revolution, philosophers like Immanuel Kant were aware of the fact that humans can only know the world through pre-conceived categories. This is the notion of the conceptual veil that you can’t see through. The definition at that point of objectivity was to reduce your bias as much as possible. That was it.

In the 19th century, though, scientists got the idea that technology would somehow allow us to see the

objective world as it actually is. This is a conceit that’s incorrect. To get closer to objective truth, the best you can do is interact with people who have different assumptions than you. From a philosophy of science standpoint, what stands in for objectivity is consensus in a diverse group of people who are being self-critical. It sets aside the idea that there is truth with a capital T.

Taken to its logical conclusion, this position suggests that there’s no reality. But that’s not what we’re talking about here. We believe that reality exists, but it’s perspectival. The patterns that make up reality don’t exist independent of us.

—Kristen French

NEUROSCIENCE

Here's Why Dreams During Naps Are So Weird

THOMAS EDISON USED TO break through creative blocks by napping. The inventor would settle in with a heavy steel ball in one hand, doze off, and awaken when it fell, just after dipping his toes into slumberland. Since then, both scientific research and anecdotal reports have supported Edison's nap strategy, demonstrating that our brains can make novel connections when we slip into the "twilight zone" between sleep and wakefulness. Now, new research published in *Cell Reports* suggests we can access these dream-like states when we're awake, too.

To explore the nether realm between sleep and wakefulness, neuroscientists from the Paris Brain Institute took a page out of Edison's book. They recruited 92 subjects accustomed to napping and describing their experiences (the very definition of a dream job), to nod off while wearing an EEG net and holding a bottle in one hand. After they were roused from their slumber by the falling bottle, they rated their mental experience for bizarreness, fluidity, spontaneity, and perceived level of wakefulness. Meanwhile, the EEG recorded how deeply into sleep they had ventured.

Analyzing the reports revealed the participants' thoughts clustered around four distinct experiences: fleeting recollections ("an image of my dad crossed my mind"); an alert connection to the surrounding environment ("I was listening to the street sounds"); bizarreness ("I saw images of small aliens"); and a high level of voluntary control ("I was thinking about what I would do tomorrow").

"I saw images of small aliens."

These experiences seemed to occur independently of sleep state—and even while the subjects were awake. "This is the major finding of our study. The mental states traditionally associated with dreaming can arise just as well when we are asleep as when we are awake," study author Nicolas Decat said in a statement. "In other words, the content of our thoughts does not follow the boundaries between waking and sleep! One of our participants, while awake, reported seeing ants crawling on her body against a backdrop of crossword puzzles."

An analysis of the EEG data revealed a specific brain signature for strange dreamlike experiences such as this one. Researchers say these kinds of mental phenomena are characterized by reduced connectivity between the brain's occipital lobe, which generates visual imagery during dreams, and the frontal lobe, which controls executive functions. "This signature may well be the correlate of what we feel in such a state: Lucid reasoning is overtaken by a whirlwind of vivid sensations characteristic of dreams," Decat said.

Sometimes you need to unplug, and sometimes you need to unplug different parts of your brain—it could help you make more creative connections. Even if it doesn't, it's a great excuse to give your boss next time you get caught nodding off at work.

—Jake Currie



ENVIRONMENT

Awe in Stripes



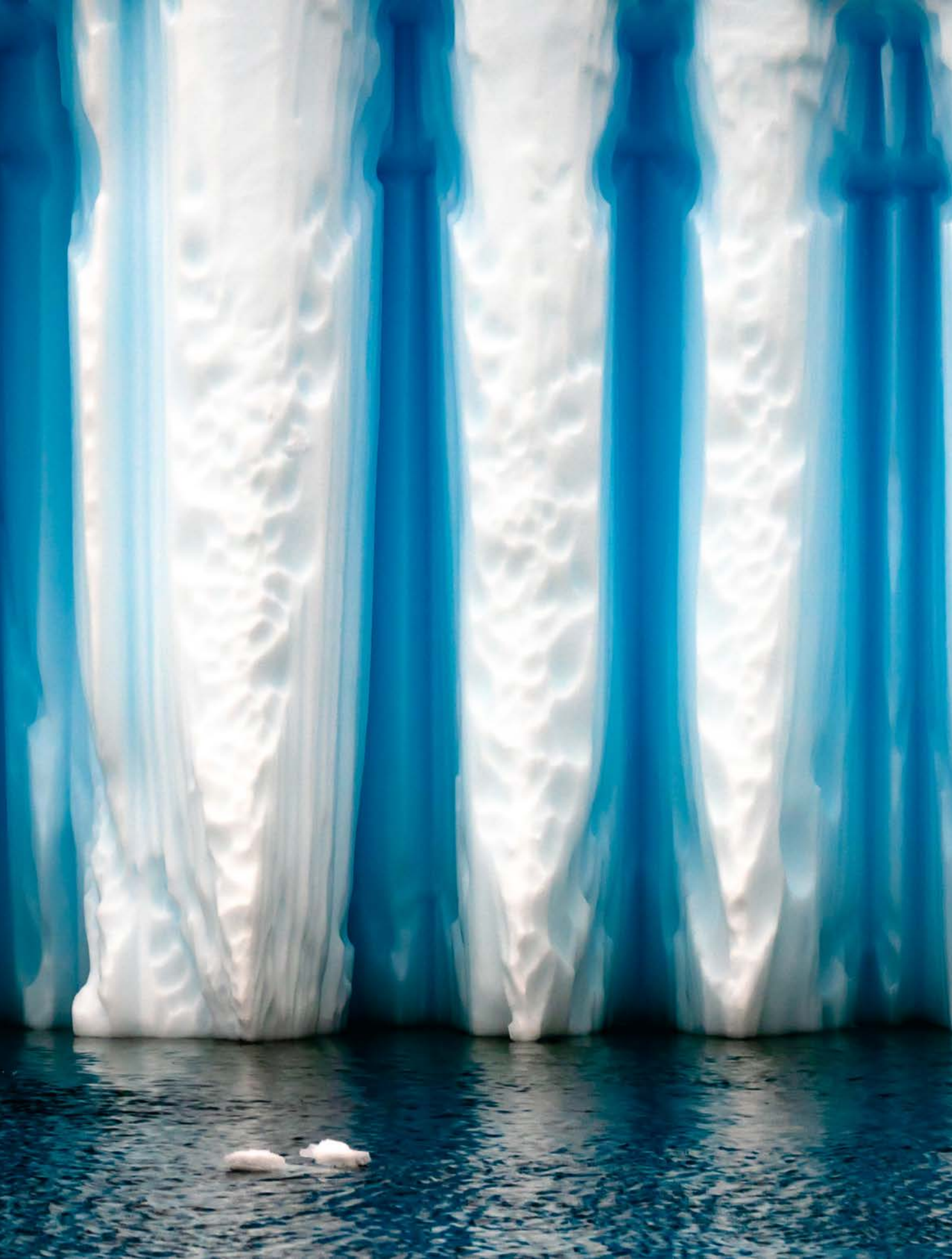
ONE EVENING, NATURE PHOTOGRAPHER Jon McCormack sat in his cabin on a boat off the Antarctic Peninsula, exhausted from a day spent diving the icy waters of the Gerlach Strait. A pattern started to come into view.

“It’s just these stripes of this deep cobalt blue,” he said. “That’s ice that’s been around for so long that the weight of the iceberg has compressed the ice and squeezed out all of the air bubbles. That ice is at the core of the berg. The only way that you get to see that is through the icebergs melting.”

In the beauty and awe in those azure columns, captured in McCormack’s camera, a message is written. The world is changing, and even impossibly solid forms are fragile under the touch of humanity.

—Bob Grant

Photo copyright © Jon McCormack; courtesy of and published by Damiani Books, in the book Patterns. All proceeds of book sales will be donated to Vital Impacts, a nonprofit organization that uses visual storytelling to inspire environmental awareness.



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A paintbrush with a wooden handle and a silver ferrule is shown from the top, painting a dark, starry shape against a yellow background. The shape resembles a mountain or a splash of paint, filled with numerous small white dots representing stars. The word "FEATURES" is written in large, white, bold, sans-serif capital letters across the bottom of the image, with a slight shadow effect.

FEATURES

Why It's Good to Be Bored

Defending our consciousness against the algorithms

BY MICHAEL POLLAN





WORRIED THAT THE AGE-OLD EXPERIENCE of boredom is at risk of extinction at the hands of technology, a group of young influencers on—irony alert—social media are recommending we nurture and celebrate this underappreciated state of mind. To people of a certain age, boredom has evidently become exotic.

These influencers have launched a “viral challenge” on Instagram urging us to try to do absolutely nothing for as long as we possibly can. They claim some scientific backing for the exercise, suggesting that a sustained period of doing nothing will benefit one’s brain and mental health. It increases activity in the “default mode network,” which generates what psychologists call “spontaneous thought”—mental activities such as mind-wandering and day-dreaming.

The voices being raised in defense of boredom are onto something, I think, something we would do well to heed before we throw open our lives and minds to artificial intelligence more than we already have. For boredom is not the only domain of our consciousness that the algorithms have designs on; it’s just the first to fall.

You’re in line at the café waiting for the barista to foam your cappuccino. A few unstructured minutes loom, pregnant with the possibility of boredom. You face a choice. You can reach for your phone to check your email or scroll on Instagram,

efficiently occupying the time—which is to say, your mind. This has become the default for most of us.

Instead of being alone with our own thoughts, however tiresome or banal, the space of our interiority has been given over to someone else’s thoughts—or, in the case of scrolling, someone else’s obsessions, emotions, theories, rants, passions, worries, resentments—you name it. In doing so we are conscious, of course, but only minimally

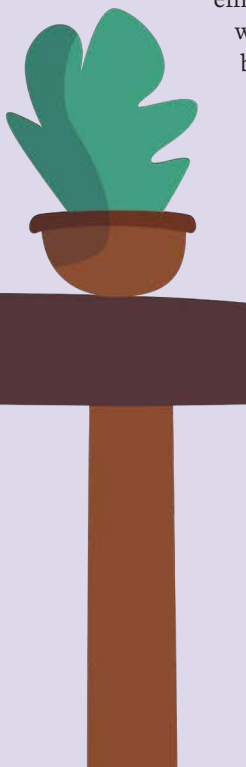
so, at least compared to the state that would arise if we hadn’t reached for our phone.

Call it generative boredom. You might find yourself looking around and noticing the other people milling about. Notice what they’re wearing. Listen to what the couples are saying to one another. You might start to wonder about their lives, perhaps even entertain a fantasy about them. Your imagination has been awakened. Alternatively, you might turn your attention inward, preview the events of your day or consider what you might make for dinner. You entertain your own emotions, obsessions, theories, rants, and worries.

What you’ve done is create a space in which spontaneous thought can unspool. It’s true, you might also find yourself caught up in spirals of rumination, and I suspect that’s one reason so many of us are happy to delegate our thinking and feeling to the algorithms on our phones. Doing so is an easy way to avoid being alone with one’s darker thoughts; scrolling reliably renders us less conscious. But distraction solves nothing; at best it is an analgesic.

It is often said that we have allowed the algorithms of social media to hack our attention. Giving away our attention might not seem like such a big deal—attention is ephemeral, after all, and easily commandeered by novelty or outrage—but in fact attention is an important dimension of consciousness. It’s how we direct it to one object and not another, making it a limited, zero-sum and therefore valuable resource. We live today in an “attention economy” where our attention is bought and sold.

Psychologists have demonstrated that this commodification of our attention comes at a price to our well-being. That’s because the tricks used to command it play on our least noble emotions and prejudices,



What you've done is create a space in which spontaneous thought can unspool.

including anger and envy. (The algorithms know all about the seven deadly sins.) And because our attention is limited—most people can keep no more than four or five things in mind at any one time—space for our own thinking contracts under the onslaught.

Artificial intelligence threatens to make the problem much worse. If social media takes over the space of our attention, the designers of AI chatbots have set their sights on deeper, more consequential domains of human consciousness: our ability to form attachments with other people, something that is core to our identity as social animals.

Just in the last two or three years, millions of people have formed deep emotional relationships with AI chatbots. Some are forming friendships, or therapeutic bonds. Others are actually falling in love with these machines. There are countless children today who, when they get home from school, rush to tell their chatbots about their day before telling their parents. Bathed in the flattery of a chatbot's attention, people have been convinced they have cracked unsolved problems in mathematics and physics—people who are neither mathematicians or physicists. And a handful of people have been encouraged by AI confidants to take their own lives. A better definition of the word “dehumanizing” would be hard to find than

“becoming emotionally attached to a machine.” There is now a term for these relationships: “AI psychosis.”

These chatbots are not conscious, but they're skilled at convincing us they are; after all, they've been trained on the human conversation about consciousness, feelings, and selfhood. By simulating conscious, feeling beings, chatbots keep us engaged, commandeering as much of our conscious lives as possible. The more time we spend bonding with a chatbot, the better it is for its corporate parent.

This is why chatbots are such sycophants; flattery will get them everywhere. A relationship with an AI has none of the friction we encounter in a human relationship. Superficially this is appealing, yet that friction with real life can, like boredom, be generative; it sharpens our thinking and sense of identity. These are the laziest of relationships, seldom challenging us and asking little of us but our time. Indeed to call our dealings with these machines “relationships” or “conversations” is to cheapen the meaning of these words, to settle for a pale imitation, as when we accept an emoji as a substitute for an emotion. As the MIT sociologist Sherry Turkle writes, “Technology can make us forget what we know about life.”

The research isn't in yet, but it seems likely that artificial attachments, like artificial intelligence and

artificial feelings, will eventually atrophy the mental muscles we rely on for the real thing. Yet there is clearly a market for people who want to think and feel less—who are happy to, in the words of the poet Jorie Graham, “retreat from themselves and not be altogether here.”

Kalina Christoff Hadjiilieva is a Bulgarian-Canadian psychologist who studies spontaneous thought—the 30 to 50 percent of mental contents that arise from inside our minds rather than from the world outside us. This includes daydreaming and mind-wandering, creative thinking, mental “flow,” and those thoughts that come to us seemingly from nowhere. These are precisely the types of conscious experiences that boredom can nurture and technology obliterate.

“The mind is not a neutral territory,” she told me. “There are vested interests in what we do with our own minds.” She feels that spontaneous thought has been neglected by science because, compared with, say, reasoning or problem-solving, it doesn’t produce anything. And while scrolling absentmindedly on your smartphone might not be productive for you, it surely is for the companies that own the algorithms and sell advertising to other companies happy to pay for a sliver of your attention.

Christoff Hadjiilieva, who grew up in Soviet-era Bulgaria in the years before the Berlin Wall came down, regards human consciousness as a precious space of mental freedom and self-creation, a space we need to defend against the intrusions of the marketplace and work to expand. She feels that scrolling on our smartphones and “talking” to chatbots have cut into the time we used to spend in mind-wandering and other forms of self-generated mental experience. Our distractions are shrinking the dimensions of our interiority.

So how might we push back? Begin to expand the dimensions of our consciousness in the face of these mounting pressures? We can start by embracing the potential for boredom and the uncertainty that arises in those stray moments when we don’t automatically reach for our phones. What if we learned to regard these gaps in the fabric of daily life as a space of mental possibility rather than a hole to be backfilled with algorithmic fluff? It’s important to recognize just how easily the stream of consciousness can be polluted (by technology, by advertising, by politics) and, when

What if we learned to regard these gaps in the fabric of daily life as a space of mental possibility?

you feel that happening, to practice what I think of as consciousness hygiene. This might be a fast or a sabbath when you abstain from all media and technology. Spending time or, better yet, working in nature is also mentally hygienic—think of the productive friction with nature afforded by gardening. (No sycophancy here!) Anything that helps us be less distracted and more present, whether to the world at large or to the products of our own minds.

I’ve found that meditation is an especially effective way to draw a fence around our interiority for a period of time each day, creating the opportunity for spontaneous thoughts to arise and dazzle us with their sheer strangeness and surprise. For hidden somewhere deep in our minds, each of us has our own mental algorithm, generating images and ideas and even the occasional creative breakthrough or epiphany, popping up from who knows where—*out of the blue*, as we say. But these precious gifts of consciousness won’t ever appear as long as you’re running Meta or X or ChatGPT on this, your one and only mind. ☺

MICHAEL POLLAN has been writing books and articles for more than 30 years about the places where the human and natural worlds intersect: on our plates, in our farms and gardens, and in our minds. Pollan is the author of eight books, six of which have been *New York Times* bestsellers. His most recent book is *A World Appears: A Journey into Consciousness*.





Time Brings Order to the Universe

These scientists are proposing a new law of nature

BY DAN FALK

IF THERE WAS AN AWARD for the most depressing law of physics, the prize would go to the second law of thermodynamics, hands down. The second law says, roughly, that the amount of disorder in the universe keeps increasing. Stuff breaks down. You and I will break down, and one day the universe itself will run out of steam. The Oxford chemist Peter Atkins captured this pessimism in 1984 when he wrote:

We have looked through the window on to the world provided by the Second Law, and have seen the purposelessness of nature ... All change, and time's arrow, point in the direction of corruption. The experience of time is the gearing of the electrochemical processes in our brains to the purposeless drift into chaos as we sink into equilibrium and the grave.

But wait: When we look around us, we also see something quite different. We see acorns grow into mighty oaks, and, over millennia, we see new species arise, and new levels of complexity realized. Consider the brain: It is, as far as we can tell, the most complex structure in the known cosmos. When the universe was young, it boasted no such features; today there are billions of them (including the one in your head and the one in my head).

This is where geoscientist Robert M. Hazen and astrobiologist Michael L. Wong come in. The two researchers, both at the Carnegie Institution for Science in Washington, D.C. believe the second law of thermodynamics doesn't tell the whole story. Instead, another law, previously unnoticed (or at least given short shrift), is driving certain kinds of physical systems toward *increasing* order. They wrote about this idea in a 2023 paper, published in the *Proceedings of the National Academy of Sciences*, and now they've expanded on it further in their new book, *Time's Second Arrow: Evolution, Order, and a New Law of Nature*.

Hazen and Wong are not the first to wonder whether the second law of thermodynamics has been oversold. Our affinity for that law, as the British physicist Julian Barbour wrote in *Nautilus*, has "led us to misunderstand what is happening in the universe and even blinded us to the beauty that it is creating."

Still, proposing a new law of nature takes a lot of chutzpah—could the scientific community really have overlooked such an important and yet seemingly simple idea for so long? At any rate, I was keen to hear more. I recently caught up with Hazen and Wong via videoconference.

Think of the last time you had a slice of wonderful apple pie, and think about the evolution of that pie.

What's wrong with the second law of thermodynamics? What does it leave out?

Robert M. Hazen: Physicists have long said that the only macroscopic experiential arrow of time is the one related to the increase in disorder in the universe. We're getting older, our cells are dying. We buy a new pair of shoes and they get scuffed. I have this nice hot cup of tea, and it's getting colder as we sit here, on and on and on. That's an arrow of time. That's the only arrow of time that's embedded in natural law. I thought, hold it, that's just simply not what I experience in my life. I see my children born, I see them grow, I see them learn. I see science expanding as an endeavor; we know more now than we did 10 years ago. I see new books and new, creative music. We see all sorts of these kinds of phenomena.

Why do you believe this new law of nature, "time's second arrow," is necessary to understand the universe?

Michael L. Wong: The reason why we think that this extra law, the second arrow of time, is necessary, is



BOLD PROPONENTS Geoscientist Robert M. Hazen (left) and astrophysicist Michael L. Wong boldly go where few scientists have gone before in saying the universe also trends toward order.

You can say, OK, that's not scientific, we can't talk about that. But we say, no.

because the second law doesn't explicitly address the tendency for evolving systems to become increasingly complex, or patterned, or ordered, or diverse, over time. You can imagine a universe that starts in a very low entropy state, just like the Big Bang, and progresses toward heat death, toward its maximal entropy state, without creating any complex systems at all.

We think that there is an extra piece missing in the explanation for all of the marvelous things that we see around us. And that missing piece, that missing law, must, of course, be consistent with the second law of thermodynamics—but may not inevitably follow from it. That is, you cannot just derive it from knowing the second law of thermodynamics. And so, this other law has to do with an increase of information.

You write this new law involves something called “functional information.” What is functional information?

Wong: The idea of functional information was first introduced by Jack Szostak in 2003, and Bob [Hazen] and colleagues expanded on it in 2007 in a great paper. It's a metric that quantifies the possible configurations of a system that can achieve a certain goal, or do something useful. Imagine that you can enumerate all of the different configurations of, say, this coffee cup: The atoms in this coffee cup can take on googols and googols of different configurations, but only a small fraction of those succeed at holding a hot beverage, and have a nice handle so that I don't burn myself when I pick it up. Our proposal is that this metric increases over time as a system tries out many different configurations of its components and then is subjected to selection for function.

“Selection” makes us think of Darwin and the idea of natural selection—but you argue that evolution applies much more broadly. What's a good example?

Hazen: The one I've worked on for the last couple of decades is “mineral evolution.” Evolution is applied to a system when you see an increase in diversity of patterning, of different arrangements, of what you might call an increase in complexity. The very first minerals formed around the atmospheres of stars. There are about 25 different minerals that use 15 or so different chemical elements—but those minerals, literally stardust, then seeded the universe. So, then you could make rocky planets. Then rocky planets have a whole bunch of new processes. From there, you make 100 minerals, and from those 100 minerals, you then can make 300 minerals, and from those 300 minerals, you can make 1,000 minerals using different processes, new processes. You're building stage by stage. You're ratcheting up the complexity.

Are there minimum requirements for a system to evolve?

Wong: Yes, three things are necessary: a large number of interacting components; ways to generate different configurations of those components; and “selection for function.”

Think of the last time you had a wonderful slice of apple pie and think about the evolution of that pie. There are all sorts of ingredients—flour, sugar, cinnamon, apples—that you can put together; and you can imagine those ingredients taking on any number of configurations, most of which would be absolutely horrendous, and not taste very good at all. But, through refining the recipes for apple pies, we've landed on relatively few configurations that work, that are delicious, that get selected and passed on and recorded in cookbooks, over generations. And so those apple pies that are selected for are the ones that we get to enjoy in bakeries, or that we make at home.

We live in a universe where there is, of course, an increase in entropy over time—but there's also an increase in something else, as new apple pies are made, as new planets form, as new minerals are forged in those planets, as stars create heavier and heavier isotopes. Something is happening in addition to the increase of entropy, and we think it's an increase of information.

Clearly the idea of information plays a key role in your proposal. But isn't information subjective? For example, a highway sign might say "Toronto" and a certain number of miles or kilometers. That may be vitally important information for the person behind the wheel, but it conveys less information to a young child in the back seat of the car, and no information at all to a seagull that happens to be flying by.

Wong: You're completely right that the functional information calculation is contextual. And that's just the way it is. The functional information of the coffee cup for holding coffee is vastly different from the functional information of a coffee cup being used as a paperweight, because there are more configurations of these atoms that can succeed at that task. The functional information of a DNA strand is extraordinarily high when it's in a cell with a ribosome, but zero when it's just sitting bare-naked on the surface of the moon. It always depends on the system that you are considering, and the function that you are considering for that system.

Hazen: I'd like to underscore that. This idea of a value in physics being contextual is very disturbing to a lot of people. You know, the mass is the mass; the charge is charge; the density is the density. These things are measurable quantities. But here we're saying, well, no, it depends on the environment that you're evaluating. And if you put an object in one environment, it may have one stability, one purpose, one function—whatever word you want to use—but when you put it in a different environment, that changes. The mass doesn't change, but the function does.

Now, you can say, OK, then that's not scientific, we can't talk about that. But we say, no: As scientists, our job is to describe, explain, quantify, and predict nature as it actually is, as we actually see it to be, not as we philosophically would like it to be. If, in nature, the function of an object is important to how a whole evolving system behaves, then, as scientists, we need to say that the function is important—so we have to identify what that function is. And if it's environmental, if it's contextual, so be it—that's the way nature works.

You hint at an idea that was popular hundreds of years ago but has become almost taboo since the rise of

modern science—namely, the idea that the universe may have a purpose. How seriously do you take the idea of cosmic purpose?

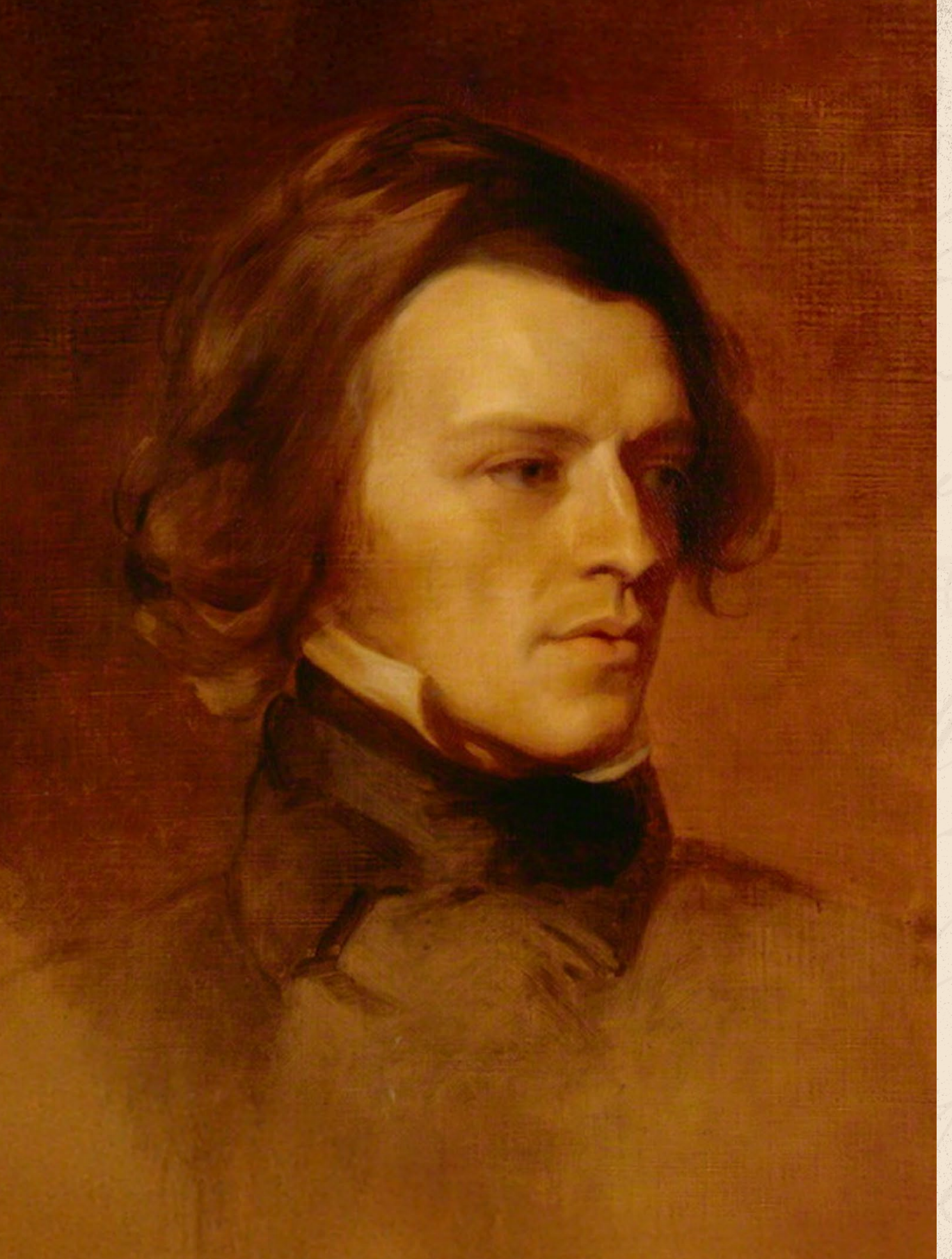
Hazen: Yes, I have thought about this. And you know, without gravity, we wouldn't have stars; we wouldn't have the periodic table of the elements. Without gravity, we wouldn't have planets, and without planets, we wouldn't have life, and we wouldn't be sitting here talking about these profound ideas. So is the purpose of gravity, life? Is the purpose of gravity, stars and planets? Is the purpose of gravity, the periodic table of the elements? And we would say, no, gravity is just a mechanistic description of how the universe works. By the same token, what we're describing is simply a mechanism. It's a selection mechanism that goes on without any direction, without any purpose, without any end point in mind. It's just that each step is a step that ratchets up functional information.

This is a book of big ideas. Will you be disappointed if it doesn't make a big splash?

Wong: If it turns out to be fruitful, then wonderful. If it doesn't, that's OK too, because hopefully it is a stepping stone to whatever is next, whatever is better, whatever functions in an even greater way to help us understand the marvelous, evolving cosmos of ours.

Hazen: I fully agree with what Mike said. I don't really care whether we're right or wrong. I hope we've said something interesting. I hope that others can think about it, learn from it, and come up with better ideas. Our book is by no means an end point. But if it's a beginning point, then we've really accomplished something, and that would be very exciting for me. ☺

DAN FALK is a science journalist based in Toronto. His books include *The Science of Shakespeare* and *In Search of Time*.



A Poet of Science Who Shook Faith in God

Biographer Richard Holmes reveals how Tennyson predated Darwin and speaks to us today

BY KEVIN BERGER

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HEN RICHARD HOLMES was a fellow at Trinity College, Cambridge, in 2001, researching the surprising affinity among Romantic poets and scientists, he often walked by a giant white marble statue of Alfred Lord Tennyson, looking imposing and, well, irrelevant. Tennyson was the Victorian poet born after the wild Romantics, vaguely remembered by English senior citizens who had to memorize “The Charge of the Light Brigade” in school. “When can their glory fade?/O the wild charge they made!”

“With his long beard, Tennyson looked monolithic, like he had nothing to do with anything,” Holmes said to me recently, from his home in Norfolk, England. “Life had passed on.”

Being the natural-born biographer he was—Holmes had written vivid books about the poets Shelley and Coleridge—he began to wonder about the young man beneath the beard. Who was Tennyson before he became England’s stodgy poet laureate? Holmes seemed to recall that Tennyson was tutored by another one of the marble statues in the chapel, William Whewell, a Cambridge don of science, who in the first decades of the 1800s published works on astronomy, physics, mineralogy, and philosophy. Perhaps science lurked in Tennyson’s background.

Holmes filed away the thought as he went on to write his 2008 book about the Romantic poets and scientists, *The Age of Wonder*, a brilliant corrective to the “two-cultures” trope that 19th-century science cut the heart out of humanity and the humanities. The era’s radical poets—Byron, Shelley, Coleridge—read deeply in the burgeoning sciences of astronomy, chemistry, and electricity. The scientific revelations supercharged their poetry and amplified the natural world and the cosmos with astonishing beauty and terror.

The poets palled around with scientists like gregarious chemist Humphry Davy, whose experiments with dosing himself and volunteers with nitrous oxide, formed a blueprint for anesthesia. Getting high on the gas was an “unmingled pleasure,” Coleridge said, echoing Xanadu, with its “stately pleasure dome,” in his poem “Kubla Khan.”

In London taverns with Coleridge and essayist Charles Lamb, anarchist philosopher William Godwin and his wife Mary Wollstonecraft, Davy loved to hold forth on the like-

minded mission of science and art. The genius of Newton and Shakespeare are not remote in character, Davy would say. “Imagination, as well as the reason, is necessary to perfection in the philosophic mind.”

Holmes spoke with infectious enthusiasm for his subjects, as if they were old friends.

“One of the most interesting exchanges that Coleridge and Davy had was on the idea of pain,” he told me. “What is the function of pain, particularly in animal life? What is it doing? Why was it put there? They would frame it in terms of, ‘Why did God put pain into this system?’ This was the kind of metaphysical discussion they often had.”

WHO ARE YOU?

While biographer Richard Holmes was a fellow at the University of Cambridge, he would walk by this statue of Alfred Lord Tennyson. He began to wonder if he could chip away the image of the ancient Victorian bard and expose the young poet beneath.

VYSOTSKY / WIKIMEDIA COMMONS



As a kaleidoscope of images from astronomy, chemistry, and geology, Romantic poetry was the first popular science.

Crossing the wires of science and poetry sparked a dangerous new awareness. Through the eyepieces of the new telescopes, illuminating the vastness of space, Earth suddenly looked insignificant. Fossils of extinct species, uncovered in rock layers that had to be hundreds of thousands of years old, gave lie to the Bible story that God created all creatures great and small in six days. Religion was losing its hold on truth.

The complex feelings caused by the new revelations can't be understated. Nature wasn't as people had been told—it was more extraordinary! The Romantic poets captured the vertigo of a worldview caving in, and a new one evolving. And their poems were widely read. As a kaleidoscope of images from astronomy, chemistry, and geology, Romantic poetry was the first popular science.

After *The Age of Wonder* was published, Holmes wrote about the adventures and scientific discoveries (the layered spheres of Earth's climate system) of the first hot-air ballooners, and candid reflections on his experiences as a biographer, the Frankenstein art of bringing the dead alive. But he knew the story of science and poetry couldn't have ended with the Romantics and began to think about the next chapter. He didn't have to think long. His curiosity about Tennyson returned. He decided to chip away the marble statue and meet the real man underneath.

Tennyson was born in 1809, the same year as Charles Darwin and Edgar Allan Poe. He came of age in a chaotic family of 11 in the country parish of Somersby in England. His father was the parish's highly educated rector who carried a chip on his shoulder for being left out of his family inheritance for being “rude and ungovernable” as a kid.

To escape his father's drunken rages, Tennyson journeyed to the seaside town of Mablethorpe and strolled along the windy dunes and beaches on the North Sea. “I come again,” he wrote in a poem: “Gray sand-banks, and pale sunsets, dreary wind, Dim shores, dense rains, and heavy-clouded sea.” Not the cheeriest of chaps, that Tennyson.

At Cambridge, Tennyson often hid behind his sullen self. At the same time, Holmes would write, the budding poet was “strange, energetic, independent, and subtly engaged with contemporary questions” arising from the daring science offending the Christians in his midst. Tennyson read through works on astronomy, geology, and the incipient science of evolution with his mind ablaze.

Holmes grew up farther south in Kent County. In his early teens, following his own wandering spirit, he and his older sister rode their bikes a couple hundred miles north to camp on the dunes along the North Sea beaches. Holmes hadn't returned for decades when in

Tennyson's relevance today is not so much about science itself, but what science does to the imagination.

2020, deep into his research on Tennyson, with England under lockdown during the dreary Covid days, he had the freeing idea to make like the poet and return to the gray sand banks and wander under pale sunsets himself.

"The North Sea coast is quite fierce, and always meant rather a lot to me," Holmes said. "It was wonderful returning there. I felt Tennyson's childhood excitement as my own. Coming back to the atmosphere of that wild North Sea coast was quite another level of inspiration. It was like returning to my old idea to go and walk in the footsteps of people to write about them."

Holmes' reference is to his 1985 book *Footsteps*, which trailblazed a new model for the literary biography as autobiography, and travel writing too. Holmes' own life and passions emerge as he traces the footsteps of his young idols, including Robert Louis Stevenson, Wollstonecraft, and publicly flamboyant Romantic French poet Gerard de Nerval, best known (if at all), for walking through the gardens of Paris with a lobster on a leash.

After his drives to the North Sea coast in 2020, Holmes felt a newfound closeness to Tennyson. Discovering Tennyson's engagement with science deepened the connection. Through Tennyson's eyes, Holmes thought, he could portray the social earthquake of science in the Victorian era—and take readers with him. Which he has done beautifully in *The Boundless Deep*:

Young Tennyson, Science, and the Crisis of Belief, published earlier this year.

Tennyson is an ideal lens on the insurrections of science because his brooding nature made him so incredibly sensitive. His father's violent outbursts not only cracked apart the family—two of Tennyson's siblings were confined to a mental asylum—but Tennyson's faith.

"Because of the nature of what we'd now call a dysfunctional family," Holmes said, "Tennyson, despite his golden education, became a kind of permanent outsider. That allowed him to take on board all these rather frightening things about science, to educate himself and write about them."

If Tennyson was a saturnine fellow by nature, he sunk even deeper into his tenebrous self when his closest friend, Arthur Hallam, died of a stroke at age 22. Tennyson and Hallam trekked across the mountains and villages of Europe together, sharing the kind of conversations that you can only have once in your life, the kind that liberates you from yourself, allowing you to feel what love is.

Hallam's death haunted Tennyson nearly every waking and sleeping hour. For 16 years, from 1833 to 1849, he wrote about his friend, a "fragmented graveyard," Holmes writes. In total, Tennyson wrote 131 cantos, published together as "In Memoriam."

The intensely autobiographical work opens with one elegy of pain after another. But gradually a transformation takes place. Hallam's death leads Tennyson to

consider “death in general, and the meaning of ‘Extinction’ throughout nature.” These reflections stemmed from his reading in science.

One work that had a profound influence on Tennyson was *Principles of Geology* by Charles Lyell. In it, Tennyson read, “Amidst the vicissitude of the earth’s surface, species cannot be immortal, but must perish, one after another, like the individuals which compose them. There is no possibility of escaping from this conclusion ... None of the works of a mortal being can be eternal.”

“It’s difficult to appreciate today what a bewildering impact this would have had back then,” Holmes said. “Here was evidence that individual animals, creatures, had become extinct. From that came the logical idea that mankind itself was destined to become extinct.”

In his epic mourning for his beloved friend, Tennyson transformed Lyell’s science into mourning for the cruelty of nature, a decade before Darwin published *On the Origin of Species*. Before Tennyson or anyone could have read Darwin, Holmes explained, Tennyson captured “the metaphysical crisis that Darwinism and the actual theory of evolution would subsequently produce throughout society.” In fact, Tennyson penned one of the most famous lines about nature—“red in tooth and claw”—often mistaken for something Darwin wrote. A stanza of “In Memoriam” goes like this:

Who trusted God was love indeed
And love Creation’s final law—
Tho’ Nature, red in tooth and claw
With ravine, shriek’d against his creed

Tennyson uses “ravine” in its Victorian sense of rapine or plundering; in other words, God’s love is fine and all, but no match for nature’s violence.

“That phrase, ‘red in tooth and claw with ravine,’ would have struck Tennyson’s original readers with horror,” Holmes said. And not just readers in elitist academies. “In Memoriam” was published in May of 1850; by the end of that year, it had sold 60,000 copies. That number, unheard of for a book of poetry today, made “In Memoriam” the talk of English towns.

Many biographies and books of criticism have been written about Tennyson since the poet’s death in 1892. What’s exceptional about *The Boundless Deep* is how

modern that Holmes makes Tennyson feel. In one of his youthful conversations with Hallam, Holmes writes, Tennyson told “a story about a Brahmin destroying a microscope because it showed animals killing each other in a drop of water. He and Hallam agreed that this was a ‘significant’ kind of unscientific response: ‘as if we could destroy facts by *refusing to see them*.’”

Tennyson’s relevance today “is not so much about science itself, but what science does to the human imagination,” Holmes said. “That was Tennyson’s subject. Science shares things that we can’t face but have to face. We still undergo the same emotions today. Science can haunt and depress. But it can also expand and excite.”

In a poem Tennyson began in the 1830s, “The Palace of Art,” he imagines a woman astronomer describing what she sees through a telescope.

Brushes of fire, hazy gleams,
Clusters and beds of worlds, and bee-like swarms
Of suns, and starry streams.

Edwin Hubble, the 20th-century astronomer who established that galaxies exist far beyond our own, planting awe in humanity’s conception of the universe, wrote, “Our stellar system is a swarm of stars isolated in space. It drifts through the universe as a swarm of bees drift through the summer air.”

“I don’t know if Hubble read Tennyson,” Holmes said. “But isn’t the image of the universe as a swarm of bees wonderful?” Yes, it is.

In *The Boundless Deep*, Holmes has done what science does. He has stripped away myths calcified in culture to expose what’s real. Tennyson is not the stodgy marble statue anchored in the Trinity Chapel at the University of Cambridge. He was and is a magnificent voice of humanity and the universe, ringing out today. ☺

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



Precarious

BY KEVIN BERGER

The enlightenment driven away
The habit-forming pain,
Mismanagement and grief:
We must suffer them all again.

POET W.H. AUDEN WROTE those lines in 1939, dourly marking the start of World War II and its violent spread across Europe. We may not be in a world war today, but wars are ongoing in too many parts of the world. And authoritarians here and there have driven away enlightenment.

Life now feels so precarious. How can we ignore it? That's the thought we expanded into the theme of this special section. Where does science take us? The answers underscore the fragility of life—all the way down to the subatomic, where everything is up in the air.

Listen to this. On September 1, 1939, Hitler invaded Poland, Niels Bohr introduced nuclear fission, and Robert Oppenheimer described a star collapsing to a black hole. The world beneath our feet came undone in a single day.

Earth is never stable. Magma is a perpetual wave beneath volcanic Iceland. Coral reefs have tipped over the edge of survival. At one time in our evolution, our ancestors made it through a population bottleneck on the winds of chance.

Oh, and this. Our oceans are now being overrun by cephalopods like squid, octopuses, even nautilus. The last time that happened on Earth it signaled a mass extinction of animals was under way and there was no turning back.

As we say, life is precarious. But you know what? On the edge, life has real beauty and meaning. You will find both in our Precarious articles. 🌀

ILLUSTRATION BY KATHERINE STREETER



The Most Precarious Day in the Universe

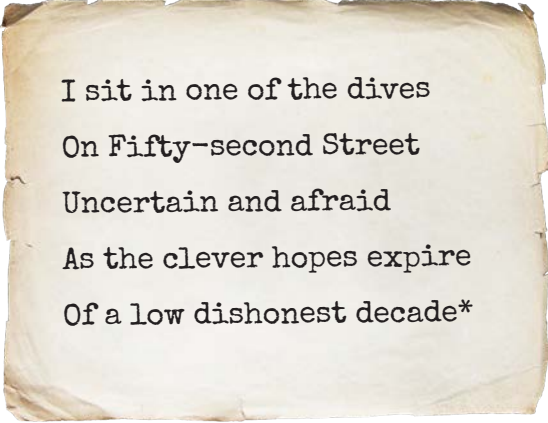
On the same day the world descended into war, physicists saw reality itself unraveling

BY AMANDA GEFTER

S

SEPTEMBER 1, 1939.

W. H. Auden wandered into the Dizzy Club in midtown Manhattan and sat down at the bar. Amid jazz rhythms and stiff drinks, the poet tried to find balance in a world that, from a false equilibrium, had tipped.



I sit in one of the dives
On Fifty-second Street
Uncertain and afraid
As the clever hopes expire
Of a low dishonest decade*

* These and the following lines of poetry are selections from W.H. Auden's poem, "September 1, 1939."

ILLUSTRATION BY KATHERINE STREETER

Hitler had just invaded Poland, and the world, for the second time, was falling into war.

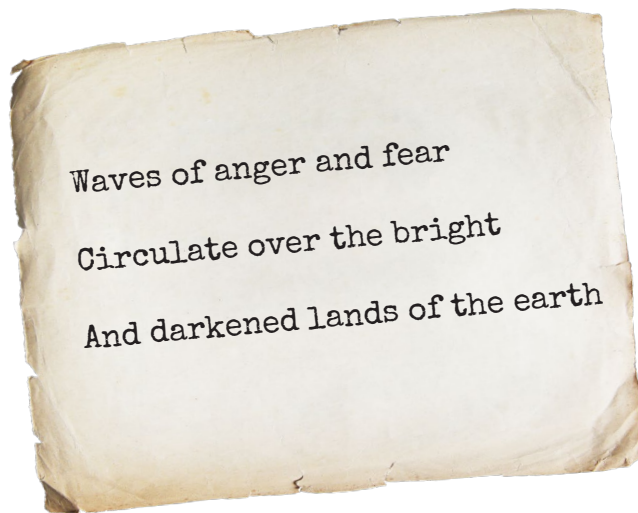
On the same day, the science journal *Physical Review* published its 56th volume, containing two papers that, together, could unravel the universe.

In one, Robert Oppenheimer and Hartland Snyder gave the first description of a star collapsing to a black hole. In the other, Niels Bohr and John Archibald Wheeler showed

how an atomic nucleus can split, releasing a horrific energy.

The continuity of spacetime on the largest scales, the stability of matter on the smallest, and the human world smack in the middle: They all teetered at once.

It was a date that formed its own singularity. If the precariousness of human affairs had once been offset by the solidity of physics, it was suddenly precarious all the way down.



Everyone thought the collapse would stop. Albert Einstein, Karl Schwarzschild, every physicist who'd ever thought about ultra dense objects contracting under their own gravity, they figured it would stop eventually. Knock a vase off a table and it lands on the floor; it doesn't just fall forever. There had to be some ground beneath our feet. But in their paper "On Continued Gravitational Contraction," Oppenheimer and Snyder proved otherwise.

When an ordinary star is shining, it's thanks to a perfect balance between the outward pressure of nuclear fusion and the inward squeeze of gravity. That balance is the star. But when it runs out of fuel—when there's no more hydrogen to fuse into helium,

no more helium to fuse into carbon and oxygen—the outward pressure goes slack and gravity takes over.

For a medium-sized star (eight times the mass of our sun or less), the outer shell is ejected into space while the inner core collapses, its material squeezed denser and denser until ... it stops. There's a ground.

The laws of quantum physics prevent electrons from occupying the same state. As they're crammed closer and closer, their momenta are forced to diverge, creating enough outward pressure to halt the crush of gravity. Like evenly matched arm wrestlers, they're caught in a deadlock. We call it a white dwarf—a dense, blue-white ember glowing faintly in the sky.

But say the star is bigger, or the white dwarf steals some mass from a companion star. Then, the electron pressure isn't enough. The star keeps collapsing, its density rising. The electrons are crushed into the nuclei; they combine with protons to form neutrons. Gravity tries to squeeze those neutrons together into the same quantum state, so their momenta spike wildly, creating a new pressure that catches the fall. There's a floor beneath the floor. This new equilibrium is a neutron star.

But if the star was even more massive—if, say, it started out 20 times the mass of the sun—the neutron pressure won't hold. And what then?

"If the mass of the original star were sufficiently small," Oppenheimer and Hartland wrote in their September 1 paper, "or if enough of the star could be blown from the surface by radiation, or lost directly in radiation, or if the angular momentum of the star were great enough to split it into small fragments, then the remaining matter could form a stable static distribution ... We consider the case where this cannot happen."

The case, that is, where there is no floor.

Using Einstein's equations, Oppenheimer and Snyder showed that the buckling star

would shrink, eventually reaching the size of its "gravitational radius"—what we'd now call its event horizon—the boundary at which gravity grows so strong, and the geometry of spacetime so warped, that light ends up running in place; every path outward leads right back in.

To an observer watching from a distance, wavelengths of light would appear increasingly stretched and time increasingly slow as the star shrinks. It's Zeno's collapse: The infalling matter takes forever to approach the horizon and never makes it across. The horizon looks like a floor, but it's only relative. Switch to the perspective of the infalling matter and there is no horizon. There's just the world still collapsing, and gravity, having eaten everything else it could find, eats itself. No counterforces can be summoned. Reality is out of options. In the space of a second, all contracts to a point, and then nothing.

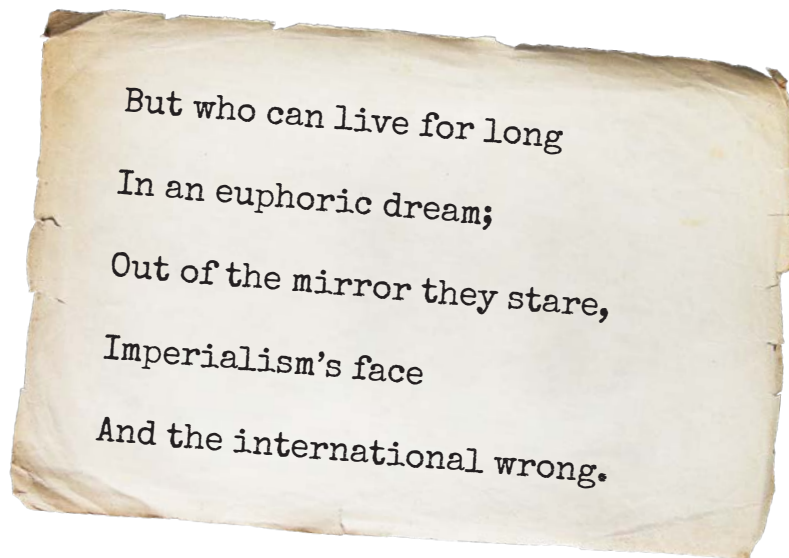
Oppenheimer and Snyder themselves hung onto a shred of hope. The formation of the singularity—the end of space and time and world—was so unnerving they were convinced they were wrong. That they'd left out "some essential physical fact which would really smooth the singularity out."



At 4 o'clock that September 1 morning, at the central post office in Danzig, the phone lines went dead. Wedged into the Polish Corridor, Danzig was a semi-autonomous city, but the Poles ran the railways and the mail. Forty-five minutes after the Germans cut the phone lines, the first shots rang out over the Baltic Sea. Volunteers rushed to defend the building: Konrad Gunderski, combat engineer and Army Reserve Sublieutenant; Jan Michon, director of the post office; 51 Polish employees; plus the building caretaker, his wife, and their 10-year-old daughter, Erwina. They stockpiled machine guns,

assorted rifles, and hand grenades as the Nazis approached.

In Warsaw, air raid sirens sounded over the city. Commuters poured from street cars and took shelter in the nearest buildings. Police officers hurried stray pedestrians inside. In Pilsudaski Square, a family of farmers ditched their horse-drawn cart and ran for cover. All was silent. A light rain fell over the empty streets—over buses, cars, and trams abandoned in the middle of the road. Then one of the farmers ran back out, attached a feed bag to his horse's muzzle, and quickly ducked back inside.



But who can live for long
In an euphoric dream;
Out of the mirror they stare,
Imperialism's face
And the international wrong.

Atomic nuclei were supposed to be stable. Sure, you could bombard them and they'd emit a particle or two, like chips off stones, but the stones remained. Then chemists hit a uranium atom with some neutrons and ended up with barium—an element so far down the periodic table it made no sense. As if the uranium nucleus had snapped in half. No one knew how that could happen. But in

their September 1, 1939 paper, "The Mechanism of Nuclear Fission," Bohr and Wheeler showed that the nucleus is less like stone and more like water. "In the present article," they wrote, "there is developed a detailed treatment of the mechanism of the fission process and accompanying effects, based on the comparison between the nucleus and a liquid drop."

In a nucleus—made up of protons and neutrons—the repulsive electrostatic force between the positively charged protons exerts an outward pressure, threatening to blow the whole thing apart, while the nuclear force, which attracts at close range, holds it all together. In certain heavy isotopes—like uranium-235, or plutonium-239—the configuration of protons and neutrons sits right at the edge of stability. Hit it with a neutron and the whole thing deforms, like a liquid drop stretched from the faucet. In their paper, Bohr and Wheeler worked through calculations showing the various stages of deformation—how it oscillates and elongates and tries to hang on.

Sometimes a nucleus can take the hit and recover. It can absorb the neutron, deform, then shake off the extra energy by emitting a gamma ray; the neutron finds a place in the nucleus, which settles into stability as a heavier isotope. Sometimes it'll spit the neutron back out or convert a neutron into a proton or teeter in metastability before it finds a new ground state.

But sometimes, Bohr and Wheeler showed, there's a point of no return. The neutron deforms the liquid drop just enough that it can't recover. It elongates and pinches in the middle; groups of protons and neutrons huddle at either end, the nuclear force barely holding it all together, like the surface tension that keeps the drop hanging from the faucet, ready to drip.

Bohr didn't like the word "fission." ("What's the verb?" he asked Wheeler. "You can't say a nucleus 'fishes.'") But there's no stopping it now. The nuclear force, which only works at close range, can't span the shape, while the electrostatic repulsion crosses the full distance and sends the two halves bursting apart. "By the division of the nucleus," Bohr and Wheeler wrote, "a very large amount of energy will be set free."

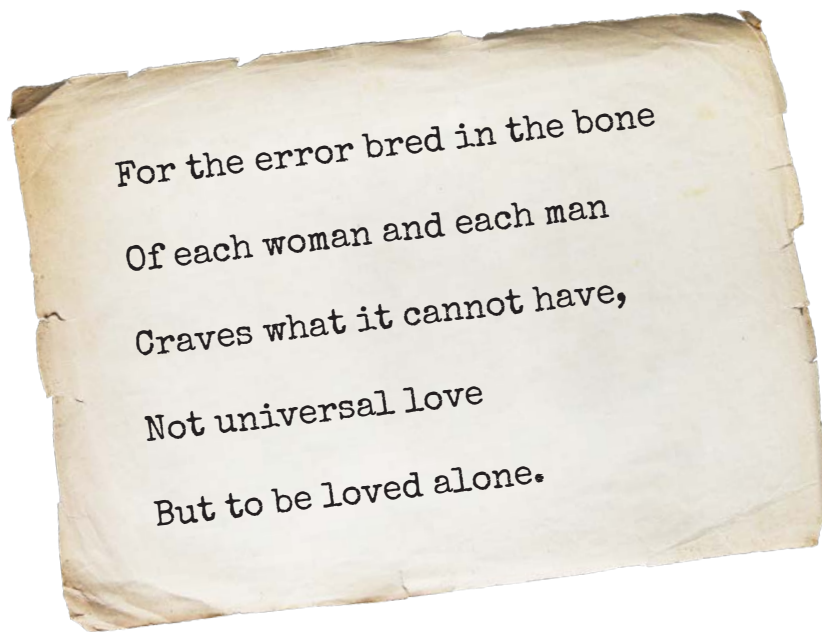
But the result of fission isn't just energy. It's also more neutrons. Place the dominoes just so, and you could start a chain reaction.

Lost in a haunted wood,
Children afraid of the night
Who have never been happy or good.



The children of London stood in line at every train station in the city, one hand clutching their mother's, the other a gas mask. Telephone service was cut off between the United States and Europe. The British banks moved their money to mansions in the countryside. A blackout was enforced; traffic lights were covered with slitted cardboard discs. At the London Zoo, 40 venomous snakes and a handful of black widow spiders were euthanized to prevent their escape

in the chaos. Three thousand taxi drivers joined the fire service; trailer pumps were fitted to their cabs. In Manchester, 3,600 pregnant women were evacuated. (News-papers reported that the men left behind were forced to cook their own breakfasts.) In Cairo, jewels from King Tutankhamun's sarcophagus were packed in bomb-proof cellars. In Paris, the last piece of stained glass was removed from the Church of Saint-Denis de la Chapelle and carefully stashed away.



And more happened. In Heath, Massachusetts, Norma Behr was presented with a basket of flowers in honor of her 24 years of service at the New England Telephone Company. In New Bedford, sewer workers recovered Daisy Fleming's lost pocketbook. A Great Dane in Beaver

Falls, Pennsylvania gave blood to save the life of a Boston terrier named Tiny. In Cleveland, Ohio, hundreds of children attended a marsh-mallow toast. And at noon in Berlin, with the sound of gunshots in the distance, a crowd spotted a flock of storks and cheered.

Defenceless under the night
 Our world in stupor lies;
 Yet, dotted everywhere,
 Ironic points of light

In life, in the universe, there are tipping points. Points of no return. Sometimes you fall and something catches you, and sometimes you just keep falling. We want to believe that things are stable to their core, like the fixed stars in the firmament, when it's all always on the brink, the forces of nature pushing everything to extremes, to the places where they break. And it's only because there are nodes along the way—objects that are really eyes in the storm—where the forces momentarily cancel out, or hold each other at bay, that spacetime and structure and society persist, at least for a little while, until something pushes

them off balance again and one force or another is set loose with no brakes. This triggers the chain reaction: the compounding effects of neutrons on neutrons, gravity on gravity, fear on fear, power on power. When that happens, there's no going back. There's only some new equilibrium if we're lucky.

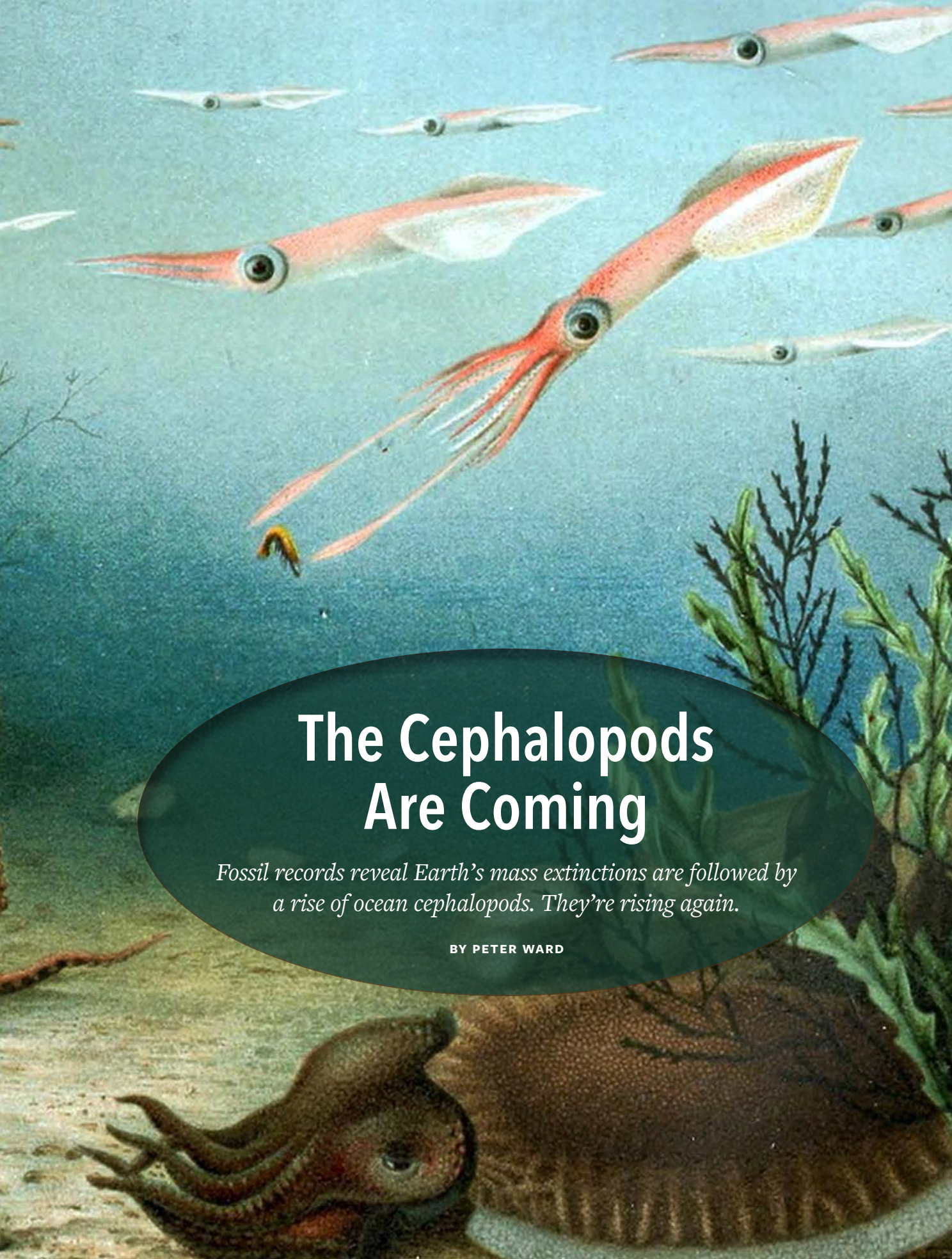
But here may be the essential fact that Oppenheimer and Snyder feared they'd left out. Stars and atoms succumb to the forces of nature. But you and I are forces of nature. We can push back and try to bend the world to some stable state before it gets away from us.

May I, composed like them
 Of Eros and of dust,
 Beleaguered by the same
 Negation and despair,
 Show an affirming flame.

AMANDA GEFTER is a science writer and the author of *Trespassing on Einstein's Lawn*.



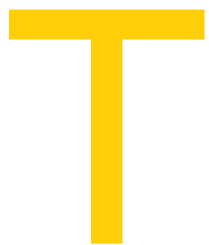




The Cephalopods Are Coming

Fossil records reveal Earth's mass extinctions are followed by a rise of ocean cephalopods. They're rising again.

BY PETER WARD



THE QUIANT SEASIDE VILLAGE of Lyme Regis is precariously perched between rugged black cliffs in southwestern England. It sits astride one of the most famous fossil sites in the world. On an autumn day several years ago, I left behind the crowded streets of souvenir shops selling fossils and T-shirts. I walked along the cliffs and over the ribbed rocks underlying the beach, stepping across one of the most devastating mass extinctions of the geological record.

The fossils beneath the village represent the end of the Triassic geological period. Around 200 million years ago, great gouts of deep Earth material welled out of volcanoes. As it flowed across land and sea bottom, it decanted enormous volumes of carbon dioxide. Mixed with the late Triassic atmosphere, it caused global temperatures to skyrocket.

But it was not heat alone that stressed the world into one of the greatest mass extinctions in Earth history. The warming planet reduced the temperature differential between polar and equatorial regions. A consequence was a slowing of the important ocean currents called Thermohaline Circulation Currents. These are the drivers of oxygenating the oceans. When they slow and then halt, mass extinction follows. The living Triassic world, home to early dinosaurs, invertebrates, strange plants, and so much else, became a death world—on land, in the sea, in the skies.

As I walked along the rocky beaches northwest of the town itself, I traversed from the youngest strata of the Triassic period to the oldest of the Jurassic period. The strata changed from being largely devoid of fossils to becoming packed with them. These fossils were almost exclusively cephalopod fossils, including the remains of nautiluses, squids, and belemnites, squid-like animals with an internal skeleton. This is where the area's fabled 19th-century paleontologist, Mary Anning, made some of the most important finds of her life. They included the complete, if flattened skeletons of early Jurassic period

As a paleontologist who studies mass extinctions, I see signs of that story today.

ichthyosaurs, or “fish lizards,” among many other treasures that she extracted from these strata with the primitive, brute force equipment available in her time.

But far more commonly than the marine reptiles, which now adorn so many museum walls, are the fossils that were used as the

title of the 2020, nearly totally imaginary movie *Ammonite*. The movie was focused on the supposed romantic affair between Anning and geologist Charlotte Murchison, as they grubbed fossils out of the Jurassic coastline. One of the few aspects that rang true was the abundance of the ammonites discovered by Anning and Murchison.

Ammonites are gorgeous white spirals that look like the externally shelled nautiluses, except with far more styles. Where the nautilus fossils had smooth exterior shells looking very much like those of the modern day, the ammonites were more rococo. They had ribs, spines, indented lines along the shell in all manner of designs. Most importantly, the ammonites had respiration systems capable of surviving extremely low oxygen levels just as the nautilus does today.

Like the dinosaurs in the earliest Jurassic period, ammonites evolved the ability to live in a superheated world. Some lived just above the sea bottom, some in mid-water, some at the surface. Some simply floated and might have spun like pinwheels in waves; others were flat, compressed, and surely awesome and rapid swimmers. Their only competition in the earliest

Jurassic probably came from their own kind. Gone were their 200-year-long nemeses: bony and cartilaginous fish, suffocated by the ocean's lack of oxygen.

More than 40 species of ammonites existed in the early Jurassic of Europe. Add in the squids and nautilus, and there were probably at least 100 species of cephalopods living in the shallow warm waters in the 2 to 5 million years after the Triassic mass extinction. It was a marine biology unlike anything humans have ever witnessed.

Today, the Lyme Regis fossils tell us a clear story: The survivors of the Triassic mass extinction were the seedstock of a great cephalopod flourishing.

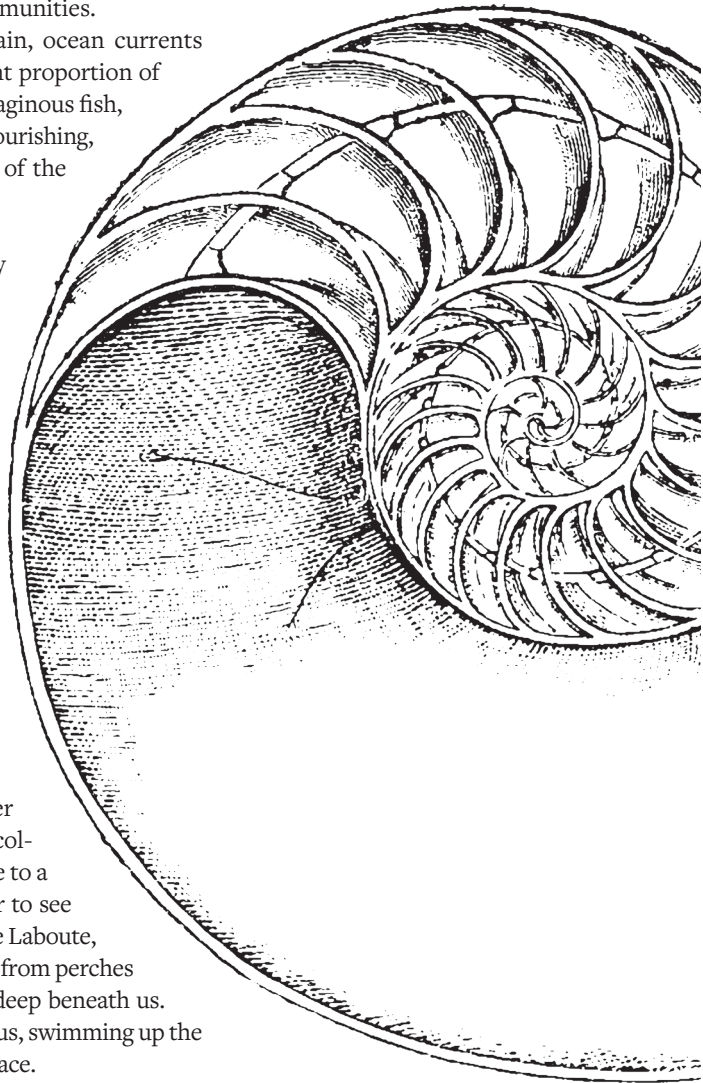
As a paleontologist who has studied cephalopods and mass extinctions for more than five decades now, I see signs of that story today, similar in ways both familiar and horrifying. It is as if our world is like the one at the end of the Triassic. Signs point toward a mass extinction, the sixth in the geological time of animals, that is either completed or heading toward finality in our ocean communities.

Once again, we are in a warming world; once again, ocean currents that supply oxygen are slowing; once again, a significant proportion of marine predators, such as the predatory bony and cartilaginous fish, are disappearing. And once again, the cephalopods are flourishing, blooming like weeds, as they fill the ecological niches of the ocean animals around them being wiped out.

I BEGAN TO STUDY the living nautilus, morphologically as close to an ammonite as we will ever get, as a graduate student in 1975. The living nautilus is the great survivor. As good as the ammonites were at surviving a mass extinction caused by low oxygen oceans, they ran out of luck due to the great asteroid collision of 66 million years ago. Yet the catastrophe spared one of the common fossils found at Lyme Regis—an enormous nautiloid species that looks remarkably like those still living today in the tropical Pacific Ocean and parts of the Indian Ocean.

At age 25, I took my first diving trip to the waters of the tropical Pacific, including New Caledonia, a giant island that parallels the Great Barrier Reef of Australia, and Papua New Guinea, which has the highest diversity of nautilus.

I arrived in Noumea, New Caledonia, with the fervor of the young and the skills of a professional salvage diver and dive instructor, both of which I had been earlier in college. It's one of few places on Earth where nautilus rise to a depth shallow enough for human divers with scuba gear to see them—but only at night. My French diving partner, Pierre Laboute, and I would sit on the edge of the barrier reef in the dark, from perches about 60 feet deep, and with our dive lights probe the deep beneath us. Several times each dive, our lights would pick up a nautilus, swimming up the vertical wall from its 1,000-foot deep, daytime resting place.



JURASSIC BEACH

A walk along the rocky shore at Lyme Regis, England, with its visible cephalopod fossils, is a step back into deep time.



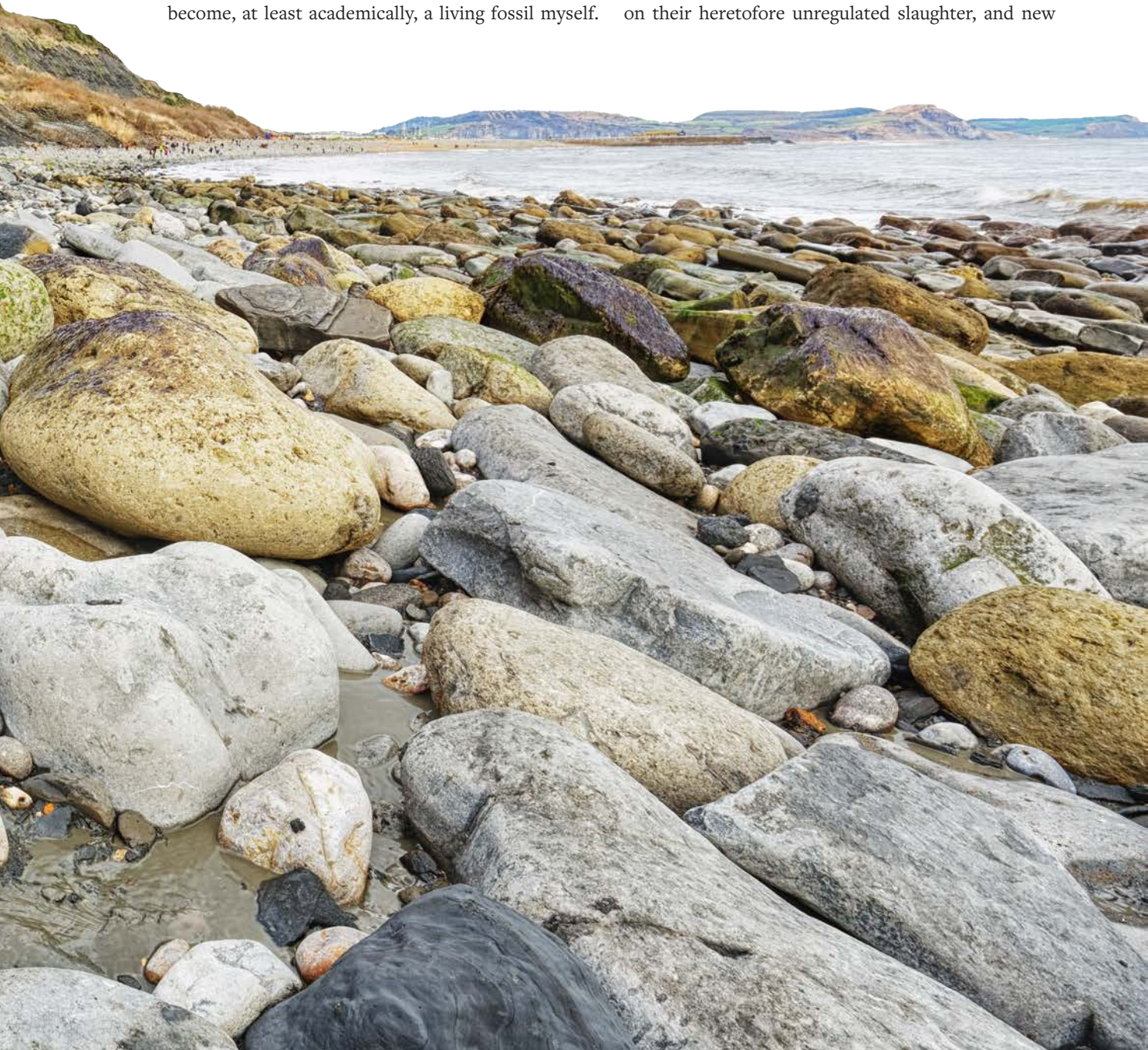
I have returned to the South Pacific many times to observe the living nautilus and its underwater environment. This includes the waters and coral reefs surrounding Australia, the Philippines, Palau, Vanuatu, New Caledonia, Samoa, and Fiji. My colleague Bruce Saunders and I discovered a second nautiloid genus, *Allonautilus*, which we formally named in 1997, and is known today as *Allonautilus* Ward & Saunders.

In December 2025, 50 years after my first trip, I was back again. I was not quite as spry as I was a half century ago, but still able to gear up with old, but well-maintained dive equipment and underwater cameras, and enter the world of these living fossils, having become, at least academically, a living fossil myself.

What we observed was a remarkable replay of the early Jurassic—the cephalopods taking over niches once dominated by fish.

We saw cephalopods taking over at all sites save those still being actively fished for nautiluses. Even that, though, is not a clear-cut story.

For a century, nautiluses have been hunted for their meat and beautiful spiral shell. In fact, since 2010, my trips to the South Pacific had been funded to research the threats of extinction to nautiluses. And today in places where nautiluses are still hunted, such as the Philippines and Indonesia, they do face extinction. This, despite the 2017 passage of international controls on their heretofore unregulated slaughter, and new





ORIGINAL SURVIVOR

Ammonites, fossilized here, thrived during a mass extinction because they got by on extremely low levels of oxygen.

rules against trading their shells—rules informed by census counts based on my groups' deep water camera work.

Of the many sites we visited over the years, the Philippines were the saddest. As far back as my first trip there, in 1987, local fishermen told me that the nautilus had been totally fished out of the area's Tanon Strait. In the 2010s, as we began to document the Philippine populations at other regions than Tanon, our deep-water cameras, which filmed at 1,000-foot depths, showed only the occasional nautilus. Thousands had been caught and sent to Europe and America, with the fishermen receiving \$1 a shell. We discovered that as many

as 500,000 nautilus shells (or parts of their shells) had been imported into the United States alone in the first decade of the 21st century.

The nautilus alone among cephalopods lives a relatively long life. It takes them up to 15 or 20 years to reach full size. So, the killing of that many nautiluses in such a short time would seemingly have a catastrophic effect on the living species. But that hasn't been the case.

At island nations other than the Philippines, such as Fiji, Palau, and Papua New Guinea, as well as off the Great Barrier Reef of Australia, we found that the laws that banned or regulated the nautilus trade worked. Genetic analyses, using samples provided from our

I was chased out of the water on numerous occasions by aggressive grey reef sharks.

trips, discovered three new species. And this is probably only the tip of the nautilus diversity iceberg. We have discovered that every island group separated by deep water seems to have its own endemic nautilus species.

And yet, while the nautilus has been spared in countries with legal protections, the fish consumed by humans are not.

“WHERE ARE THE SHARKS?”

Last December, as I was following a pair of bobbing nautilus with my underwater camera, this was my persistent thought.

During my work in these same waters in the 1980s and '90s, diving was hazardous. I was literally chased out of the water on numerous occasions by aggressive grey reef sharks, even the small ones. Now I saw no sharks at all. My colleagues and I also found that few to no fish, such as Conger eels and snapper, were caught in our nautilus traps, something that invariably occurred in the 1980s. Our underwater video cameras, over the course of 300 hours gathered in the past five years, showed fewer fish than we had ever seen before. But showed many, many more octopus, squid, and nautilus. And we weren't the only ones seeing it.

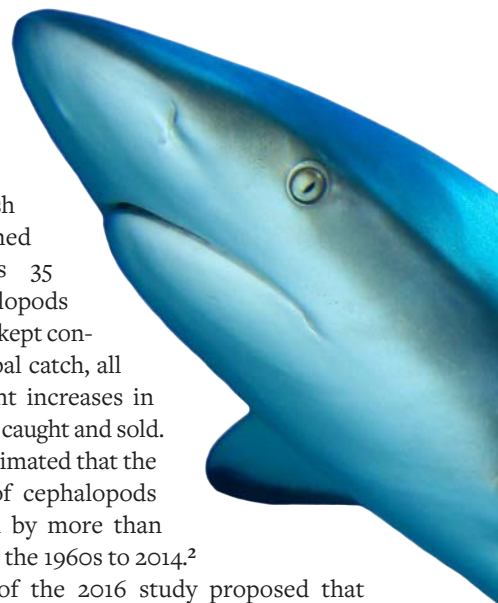
In 2016, a team of fisheries biologists from the University of Adelaide, in Australia, published a paper that looked at the global catch of cephalopods from the world's oceans from the early 1950s onward.¹ The scientists were astonished at their results. They found that the catch of cephalopods was showing just the opposite of the known catch of human-food fish.

While the global yield of caught fish tonnage was steadily dropping, the catch of cephalopods was going up. And it was among virtually every kind of

cephalopod, from the fast-moving squids to the bottom-dwelling cuttlefish to the eight-armed octopus. Across 35 species of cephalopods that have records kept concerning their global catch, all showed significant increases in the tonnage being caught and sold. Another study estimated that the yearly tonnage of cephalopods caught increased by more than 400 percent from the 1960s to 2014.²

The authors of the 2016 study proposed that human-caused warming of the oceans allowed cephalopods to grow faster than fish they might compete with. But they also stated the vast increase of cephalopods relative to fish populations was related to “the global depletion of fish stocks, together with the potential release of cephalopods from predation and competition pressure.”

Indeed, cephalopods and fish have been both competitors and predators on each other for 450 million years. Remove one, and the other is affected. Generally, it's the fish that triumph. The bite scars we found on many nautilus shells that we observed in the 1980s tells us that early in nautilus' lives, predation by sharks and other fish were the most significant cause of mortality. Plus, sharks and bony fish compete for food with the nautilus, which are not predators. They are scavengers. Dead fish or other carrion are their prized food,



but they swim slowly once the scent is detected, and in a big-fish-and-shark-filled world, by the time they get to that dead tuna or snapper, it has already been eaten by the fast-swimming fish.

Now, the tables are turned. That alone is an augury.

In the ocean's Mesophotic Zone, the depth with little light, from around 320 feet to 1,600 feet, we saw cephalopods thriving. Paleontologists call this the "Recovery Zone." After a mass extinction, it's where the survivors mostly dwell and compete for oxygen and food. It is the cradle of future marine life. It's where the cephalopods have an evolutionary advantage.

As a group, they are one of the fastest known "evolvers." They have short lifespans, about six months to two years, and natural selection works quickly to reward survival to new genes that increase population numbers. They reach sexual maturity at full size after only one to two years since hatching. They also have short reproductive cycles, which produces many more generations over the same period than fish can accomplish. This is how they win the evolution race: outgrow, out-reproduce, and out-evolve.

Nothing stokes the evolutionary fires of new species formation like the slaughter of the incumbents. The bigger the body count, the faster the refilling of community positions in many environments. And that's what we now see in the recovery zone.

The removal of so many large fish has enabled cephalopod populations to thrive. Sharks, in fact, are among the most significant victims of overfishing. A 2021 article in the journal *Current Biology* stated that "overfishing" of sharks is driving one third of all species to imminent extinction.³ Add in a warming ocean (which favors cephalopods) with diminishing oxygen (which favors cephalopods), and you see why the cephalopods are flourishing.

DEEP DIVE

Author Peter Ward releases a nautilus with a transmitter to track its movements and behaviors near the Great Barrier Reef in the Coral Sea.



The great extinctions of the past did not include the asteroid of humanity.

It's not just us scientists who are witnessing the sea change. In 2025, fishermen along England's southern coast, not far from the fossil beds of Lyme Regis, pulled up their nets and traps not with the Dover sole, crabs, or lobsters they were expecting. Instead, they were filled with cephalopods, notably octopus and squid. Steve Simpson, a professor of marine biology at the University of Bristol, told *The New York Times* that "climate change is a likely driver" of the population boom. "We are right on the northern limit of the octopus species range, but our waters are getting warmer, so our little island of Great Britain is becoming increasingly favorable for octopuses' populations."

This is undoubtedly correct. But a more thorough hypothesis is that the removal of so many fish stocks allowed the octopus populations to thrive and increase in size. The global fisheries industry is akin to the global petroleum industry. It produces a product of importance to humanity. But leaves humans to contend with its deep environmental gouge in Earth.

AS SCIENTISTS, WE CAN'T SAY for certain the current rise of cephalopods represents the early phase of a new mass extinction in our oceans. But there are certainly signs for Cassandra to see.

For one, this is what a mass extinction does. There is no sudden death, not even after the Chicxulub asteroid hit the Yucatan peninsula 66 million years ago. Extinction still took a few decades. The extinction ending the Triassic period took a minimum of 1 million years to consummate its slaughter, based on our knowledge of rock dating, from the first evidence of darkening strata in the Late Triassic, to the appearance of those thin, dark rocks of the Lyme Regis shore and seaside cliffs.

As time intervals go, this cephalopod survey, measured in decades, is so short compared to the vastness of geological time as to be so ephemeral. But the great

extinctions of the past did not include the asteroid of humanity. They did not include very determined humans in vast armadas of fishing boats, factory ships quickly processing the catch, or innumerable stores in Asia where hundreds of shark fins hang in the windows for sale.

If we continue to fill the atmosphere with carbon dioxide in volumes that match the volcanoes and lavas that tended the Triassic, creating a reduction in high latitude polar regions without similar temperature increase in the tropics (what is happening now), and if we cause the critical ocean currents to slow or cease by 2050, and studies predict we are, then in all probability we are headed toward the sixth mass extinction.⁴ The cephalopods are coming.

Calamari, anyone? 🐙

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For Every Patient Their Own Drug

Patients with exceedingly rare genetic diseases fall through the cracks of the medical system. This doctor is designing drugs for them, one at a time.

BY BRADY HUGGETT

THE FIRST TIME STAN CROOKE helped treat a terminal cancer patient was in 1969—or maybe 1970. The 81-year-old physician and pioneering drug designer can't quite remember the year. He has, after all, worked with many patients with seemingly incurable diseases over his long career. But in this case, he certainly remembers the feel of it.

Crooke was a third-year student at Baylor College of Medicine at the time, his Ph.D. already behind him, and a young man had been referred to the hematology-oncology unit with an abdominal mass.

It turned out to be disseminated testicular cancer. The patient was maybe 25—around the same age as Crooke himself then—and a college grad engaged to be married. Crooke was in the room when the patient received the news, and seeing “the process of telling him that he was going to be dead in six months was impactful for me,” he says. The interaction showed Crooke that a physician would sometimes be in “the most responsible position a human being could be in,” he adds, face to face with a patient who has “put his life in your hands.”



STAN-OF-ONE

Stan Crooke in a laboratory at n-Lorem.

program, so he called Bristol Labs, the company that had the rights to bleomycin in the U.S., asked for a job, and got hired as a clinician.

It put Crooke on a career roller coaster, and for decades he fought through—and sometimes with—the drug development world. He would spearhead the effort to introduce a new type of drug therapy into the pharmaceutical arsenal, but the patient was never far from his mind. Now, after more than eight decades

He could have had a career filled with those moments. He had a classmate who talked about setting up a rural practice somewhere, out in the country's plains, or maybe a foothill community, and he wanted Crooke to join him. But that wouldn't work. For years, Crooke's wife Nancy had been plagued by a mysterious vasculitis, an autoimmune disease of the arteries that physicians couldn't get a handle on. And they had a young son with a learning disability, who would probably require private schools. Crooke needed a guaranteed, sizable income, more than what a country doctor would make.

But another important thing had happened in that room with the young cancer patient: The medical team had offered to try an experimental drug called bleomycin. Crooke had never heard of it, and when he looked it up, he saw it was a natural product discovered in Japan, not yet approved for clinical use in the United States. It had "a structure that I'd never seen, a mechanism of action that was completely unknown" and a "bizarre toxicity," he recalls.

Returning to his Baylor lab, Crooke began investigating bleomycin, and he realized something else about medicine: The impact he might exert from "making one good drug" could exceed any good he could do as a physician. He was nearing the end of his M.D.-Ph.D.

on the planet, Crooke finds himself again seeking to treat people suffering from diseases or disorders one-by-one.

If you had known Crooke as a boy, it would have been difficult to predict the arc of his life. He was born to a teenage mother in 1945. He didn't know who his father was growing up, and still doesn't. For the first years of his life, he was raised by his grandmother and great-grandmother, sharing space with a couple of cousins in a shotgun house in downtown Indianapolis.

Eventually his mother married a man, and she moved Crooke into their home. She had two more children, a boy and a girl. Their neighborhood was decidedly blue collar, filled with laborers, machinists, and mechanics. His mother was "easily annoyed and volatile" Crooke says, and she was addicted to amphetamines (diet pills) and barbiturates, introduced to her by her doctor. Plus, she had rheumatoid arthritis and took a lot of cortisone.

After such an inauspicious start, Crooke managed to lift himself out of that life with raw intelligence and a furious work ethic: He had a pre-dawn, bicycle paper route before he was 10; he held an after-school job in a corner drugstore; and he worked in a pharmacy, all before graduating high school. The money he brought in went to help support the family.

Crooke finds himself again seeking to treat people suffering from diseases or disorders one-by-one.

In 1960 he was accepted into Purdue University's aeronautical engineering program for college—he'd applied simply because he liked airplanes—but he struggled. And in his second year he withdrew. Back in Indianapolis, Crooke enrolled in a pharmacology program at Butler University and married his childhood sweetheart, Nancy. After he'd completed the requirements for a master's degree in pharmacology, that might have been that—a life spent running a drugstore right there in Indianapolis.

But Crooke wasn't quite done with higher education, and he applied to a handful of medical schools. And when he enrolled in Baylor's M.D.-Ph.D. program, he was exposed to "true science" for the first time, he says. The experience reshaped his world.

THE SEMINAL PAPERS in so-called "antisense technology" were two studies by the same authors published in the *Proceedings of the Academy of Sciences* in 1978. Those papers reported that a short, single-stranded piece of synthetic DNA, when delivered into stem cells taken from chicken embryos, was able to inhibit the replication of a virus infecting that embryo. The piece of DNA—called an oligonucleotide—bonded to the "sense" strand of messenger RNA in the cells, rendering it unable to produce a protein critical to virus replication. The term "antisense" itself arose from the bonding to this "sense" strand, and the paper suggested that antisense oligonucleotides, or ASOs, might be able to influence protein production elsewhere in the body. That ability had all kinds of tantalizing possibilities for medicine.

Crooke learned about antisense around 1987, when a speaker at a symposium hosted by the pharmaceutical company SmithKline presented his own work in the young field. By then Crooke had left Bristol, was worldwide president of R&D at Philadelphia-based SmithKline, while also running a lab at the University of Pennsylvania. After the talk he dug up those original antisense papers.

It was fortuitous timing, because Crooke was at something of a crossroads. Nancy had died of her illness in 1984, leaving Crooke a widower and a single father. He had begun to rebuild his life, in particular by marrying a researcher named Rosanne Snyder, a former grad student at his UPenn lab. But he'd grown unhappy in his career. The pace of innovation at a big pharma company was frustratingly slow, he felt, and SmithKline's shares had been underperforming.

It seemed like the company might be bought, and Crooke was dead set against that. He was "very aggressive" about saying so, he recalls, a stance that left him with few friends in senior management, and he admits that he "should have been a better subordinate." But also, he thought the drug development world needed a new way to make medicine, and he wanted to investigate antisense on his own terms. After all, he had that pharmacology degree in his background, his M.D. training, all his research work, and now he had spent years actually making drugs. Something told him he was exactly the right person to develop antisense as a drug platform.

So when SmithKline fired him in 1988, he was already halfway to forming a biotech startup. He rounded up a core of talented researchers, including Rosanne, and launched an antisense company in January 1989 on the other side of the country, in Carlsbad, California.

THAT COMPANY WOULD EVENTUALLY be called Ionis Pharmaceuticals. And for more than 30 years Crooke ran it with the overarching goal of perfecting antisense as a therapeutic platform. The company won milestones—approval of the first antisense drug (for a sight-threatening, viral inflammation of the retina called CMV retinitis), and then one for homozygous familial hypercholesterolemia, a rare, congenital high-cholesterol disorder. But those drugs were eventually discontinued for lack of use, and the company's reputation was also marred by two high-profile failures in clinical trials. Mostly during this time, Crooke fed a

N-OF-HARLOW Harlow is a 5-year-old girl living with a neurodegenerative disorder caused by a nano-rare mutation in her *TUBB4A* gene, which encodes a protein essential for cellular structures called microtubules. She first received an antisense oligonucleotide discovered and developed at n-Lorem in October 2025.



rapacious R&D arm that burned through money, and by the end of 2015, Ionis had a net loss of \$1.1 billion.

But near the end of 2016, Ionis won approval for an antisense drug that Crooke called a “piece of magic.” Marketed as Spinraza, it treats spinal muscular atrophy (SMA), a disease caused by a mutation in the survival motor neuron 1 gene, or *SMN1*. When defective, the gene does not produce enough of the SMN protein, this lack of protein causing neurodegeneration, particularly in skeletal muscles of the trunk. In the most severe cases, SMA leads to death before a child turns 2.

There is a backup copy of the gene, *SMN2*, but the gene produces just low levels of SMN protein. Spinraza, which was created in collaboration with the biotech company Biogen, boosts the production of a full-length, functional SMN protein. The drug immediately began extending children’s lives, and by the end of 2025, Spinraza had been approved in more than 70 countries and administered to more than 14,000 people.

Spinraza seemed almost like divine intervention to the SMA community, which had never had even a single therapy to treat the disease, partially because the mutation behind SMA wasn’t known until 1999. But the drug to target that mutation was the culmination of 25 years of work by Ionis to make RNA stable in the body, and deliverable to the desired tissue without toxicity. “And all of those questions took

decades to work out,” says Eric Green, CEO of Trace Neuroscience, a company developing an ASO for Lou Gehrig’s disease.

And the work was mostly “done by Ionis, and largely led by Stan Crooke.”

Once Spinraza showed benefit in patients, Green adds, observers realized that if antisense worked for “spinal muscular atrophy, you can take that same backbone, redesign it based on the specific sequence that you want to target in a new gene, and you are well on your way.”

CROOKE FULLY STEPPED AWAY from Ionis midway through 2021, at age 76. But similar to when he’d left SmithKline, he had an exit plan. Sometime around 2018, Crooke estimates, a man and a woman came to see him, each with a son who had a mutation in a gene called *SCN2A* that is essential for brain cell communication. The boys were “desperately ill,” Crooke remembers, and the parents wanted to know if Ionis could build an antisense drug that would target their children’s defective gene.

Crooke explained that it was not financially viable to make and sell a drug

for just one person. This was a hole in the capitalist drug development process: Pharmaceutical companies will tell you that it takes 10 to 15 years and \$2.6 billion to create a new therapy, when you consider the sunk cost of failed drugs. To make a drug for a single patient in that system would never be financially viable.

But Crooke knew that antisense technology had become “efficient enough that I could probably make them an ASO and give it to them,” he says. And once he realized that, he felt a “moral imperative” to try.

Still, there were three things that gave him pause. The first was whether the U.S. Food and Drug Administration would allow him to run “N-of-1” clinical trials—studies of a drug in just a single patient. But when he approached the regulatory authority, he found “fertile ground,” he recalls: Others were already asking the FDA about this, including a researcher named Tim Yu, from Boston Children’s Hospital. It helped that Crooke had been dealing with the FDA himself for some 30 years, and the regulators realized that the team at Ionis, some of whom had also been working there for decades, “understood antisense,” Crooke says.

Then there was money. Crooke planned to give the antisense oligonucleotides away, so he needed to establish a non-profit, and that meant sizable fundraising. But he’d been “through that before” as CEO of Ionis, he says.

The third thing had to do with Crooke himself. Somewhere around turning 75, he realized that he actually felt tired at the end of a work day. That had never happened before. For his entire life he’d worked like a man on fire, but “anyone my age,” he says, “has to recognize that time’s running out.”

These were minor concerns, though, when compared to the exhilarating challenge of developing bespoke drugs for patients. The truth was, he’d fallen in love with antisense technology when he’d first heard of it back at SmithKline, and that passion had never dimmed. It might have been hubris, but when he’d launched Ionis back in 1989, he’d felt he “was exactly the right person to do it,” he says. “I had the right training, the right mental makeup, the right focus.” That feeling, too, had never dissipated. After more than three decades chasing antisense, he thought, who was better prepared to make bespoke drugs than he was?

N-LOREM OPENED ITS DOORS in 2020. The response was overwhelming. Stan expected about five applicants that year, but the non-profit received 53 requests to create ASOs for patients—nearly all of them children—with “nano-rare” genetic mutations, meaning they affect only 1 to 30 people globally. The next year applications jumped to 64, and by the end of 2025, n-Lorem had received more than 400 applications, and had decided it could create ASOs to target 216 of those nano-rare mutations.

The first patient dosed was a girl named Susannah. Her parents, Luke Rosen and Sally Jackson, realized something was wrong when Susannah—18 months old at the time—stopped being able to kick her legs in the bath. A full genetic screening revealed a mutation in the girl’s *KIF1A* gene, which codes for a molecular motor protein essential to normal neuronal function. They made an appointment with Wendy Chung, the Kennedy Professor of Pediatrics in Medicine and the director of the division of clinical genetics at Columbia at the time, who told them Susannah had a rare neurodegenerative condition that shared characteristics with SMA or the similar Huntington’s disease. Chung added that there was no cure, but suggested contacting people working on drugs for those conditions.

Rosen came across Ionis. He visited the company, and Crooke, again, had to explain that making a drug for one person wasn’t financially viable. Chung knew the team at Ionis through her own work, and when n-Lorem launched, she assured Rosen that the people there “knew what they were doing.” She and Rosen and Jackson put in an application to work with the non-profit, and Chung eventually heard that Susannah’s genetic mutation had been accepted by n-Lorem for investigation. “And so we started on that journey,” Chung recalls.

Susannah was first dosed in November 2022, and by that time she was having between 100 and 290 “behavioral arrests” per day—moments of unresponsive staring, sometimes accompanied by eye rolling, leaning to the side, and falling. The n-Lorem team slowly increased her dose, and when it had reached 80 mg, Susannah’s behavioral arrests had dropped to 30 per week. She fell down less, and her speech improved, as did her quality-of-life score.

Who was better prepared to make bespoke drugs than he was?

Susannah has now been treated for more than three years. She can stand, she can walk with assistance, and her vision has improved. And because she is what n-Lorem calls a “pioneer patient,” every metric she generates helps inform not only how to treat others with mutations in their *KIF1A* genes, but how to treat patients with ultra-rare diseases in general.

To date, n-Lorem has dosed more than 50 patients with a variety of nano-rare mutations, easily more than any other organization. The cost of this is significant; n-Lorem’s spend in 2024 was nearly \$16 million. Stan and Rosanne started n-Lorem by putting in \$10 million of their own money, and Ionis and Biogen were both founding donors. These days the foundation is funded in three nearly equal ways: charitable giving from high-wealth individuals and donations from pharmaceutical companies (Biogen continues to donate); business deals, in which n-Lorem provides research services for payment; and directed giving in the form of grants or support for particular patient programs.

With this money, n-Lorem creates bespoke ASOs and supplies them to patients for free, for life. The foundation will also provide small funding for the institution hosting the patient, but generally the costs of administering the drug at a hospital, and monitoring the patient, are borne by the family. They can try to use their health insurance, but because the ASO is experimental, “insurance doesn’t have to pay one iota” for covering the administration expenses if they choose not to, says Chung.

This has created a “complicated situation,” Chung says. “How much are families filling the gap when things aren’t covered? I don’t know.”

Yet n-Lorem was not the first to make a bespoke ASO. That was done in the lab of Tim Yu, at Boston Children’s Hospital, who created an ASO for a girl named Mila. She had a variant of a severe seizure disorder called Batten disease, caused by a mutation in her *CLN7* gene. Yu received guidance from Ionis members and his lab created an ASO with the same backbone and sugar chemistry modifications as Spinraza, but targeting Mila’s specific mutation.

They called the drug Milasen, and Mila got her first dose in early 2018. In the clinical trial, the amount of time her body spent in seizure dropped by more than 80 percent—but her disease might have been too far advanced by the time treatment started, and she died in February 2021, at age 10.

With his team at Boston Children’s, Yu went on to make ASOs for two other girls—both 3 years old at the start of treatment—who had mutations in their *KCNT1* genes, which help regulate neuronal function in the brain. But both suffered swelling in the brain after treatment. (The first child was withdrawn from the trial and died three months after her final ASO dose. The second child was removed from the study and treated for her brain swelling; two years later, she resumed treatment, and her seizures have reduced 66 percent to date.)

Similar instances of brain swelling, called hydrocephalus, have also occurred in Spinraza patients and

in one trial of an ASO to treat Huntington's disease, but so far at n-Lorem the safety record has been mostly clean. Only Susannah has had an ASO-related safety event. Near the end of 2025, she had a fever after dosing, and the team at n-Lorem worried "she might have inflammation in her central nervous system," Crooke says. They monitored her cerebral spinal fluid pressure until, in early 2026, it fell low enough for her to resume treatment.

Even with the hydrocephalus cases, drug regulators are considering the benefits of bespoke drugs designed for individual patients. In late 2025, the United Kingdom's version of the FDA, the Medicines and Healthcare products Regulatory Agency, said it was hoping to consider "a single marketing authorisation" pathway for therapies with a variable component tailored to an individual's characteristics. And the FDA in December 2025 gave guidance for a Plausible Mechanism Framework, laying out an avenue for bespoke therapies to be cleared for commercial use. Approved drugs bring insurance companies to the table.

WHEN CROOKE HEARD RUMORS of the coming Plausible Mechanism Framework guidance from the FDA, he worried that whatever the FDA put forth would be "misguided."

He was wrong about that, he says. The draft guidance suggests that regulators will consider a pathway to approval for therapies that show a direct link between a defective gene and disease, for instance, and when the therapy has been confirmed to affect the underlying target. Drugmakers could also use the natural history of the disease in untreated patients as a baseline for improvement, given there would be no large-scale clinical trial. The FDA received public comments on the draft until April 27.

In addition to calling the Plausible Mechanism Framework an important step, Crooke says he thinks that n-Lorem's growth and safety record has something to do with the FDA's willingness to consider an approval pathway for bespoke drugs. "I certainly want to believe that. And we've treated more nano-rare patients successfully than all the other organizations' dreams combined," he says.

The n-Lorem patients are often unblinded, and the whole team knows exactly who they are making

drugs for. This intimacy wasn't something that Crooke considered before starting n-Lorem, but once he was at the helm, he realized his life, in a way, had circled back around to practicing medicine. Running the foundation has felt "very much more like seeing patients again," he says.

Amy Williford has worked for Crooke twice now—first in investor relations at Ionis and now as vice president of foundation development and external relations at n-Lorem. She has seen him as CEO of a for-profit biotech, and now, in his supposed retirement, she's watched him grow n-Lorem. She knows the hardships Crooke endured in his youth and reckons that he carried "a lot of anger at the injustice of the world" that may have showed up in his earlier management style. But now he's a "kinder, gentler" version of himself, she says, and not as "terrifying" to the scientists who present their work in front of him.

It's possible that the time Crooke spent babysitting his younger half brother and sister acclimated him to caring, and that's why he likes treating patients. Or maybe being a breadwinner as a boy in his family made him feel responsible for others. Or maybe he was just born an empathetic, caring person. It's one of the great questions of science: nature vs nurture. But Crooke is not particularly interested in interrogating it.

"I don't know exactly why I am the way I am," he tells me. "But I do know that I want to be in control. And I like being responsible. And when I had the chance to take care of a patient, I changed. And, it was meaningful to me to be responsible for another person." 🌀

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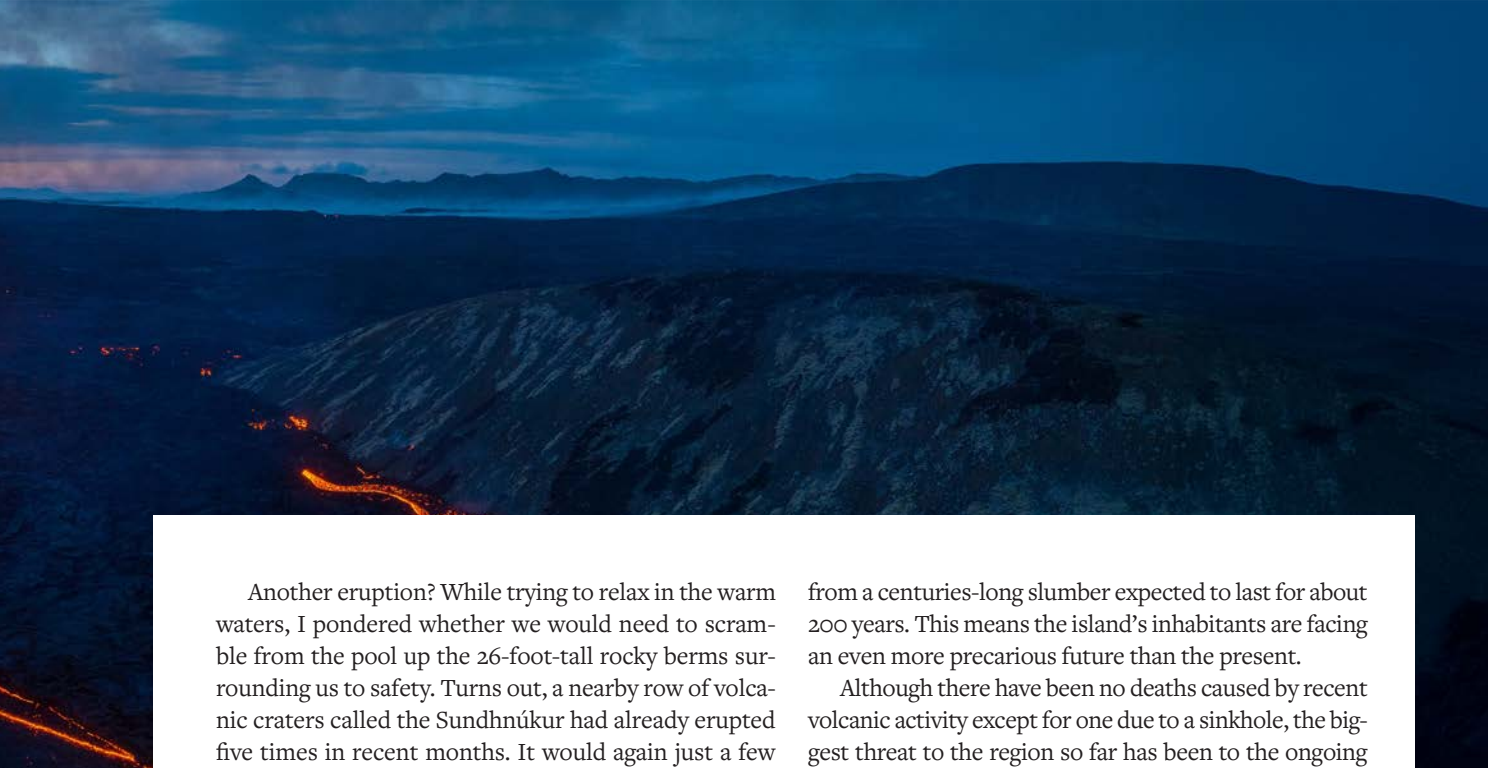
“Iceland Is Going to Erupt Again Very Soon”

Deep beneath the volcanic island, scientists are trying to predict the next big one

BY REGAN PENALUNA

IN AUGUST 2024, I was driving with my children in Southwest Iceland toward the Blue Lagoon, a cluster of hot geothermal pools in the Reykjanes Peninsula, when the highway suddenly ended. Before us, a frozen river of dark lava engulfed the road and much of the land to the horizon. As my children and I exited the car to get a closer look, I imagined a fluorescent taffy of hot lava just under its crust. The obsidian lava whorls and undulations both mesmerized and inspired in me the fleeting thought of “let’s get the hell out of here.” When we made it to the Blue Lagoon by taking a gravel detour, we learned that the flow we’d observed was only a few weeks old. “But don’t worry,” an employee assured us. “Our alarms will sound when another eruption occurs.”

JAG_CZ / ADOBE STOCK



Another eruption? While trying to relax in the warm waters, I pondered whether we would need to scramble from the pool up the 26-foot-tall rocky berms surrounding us to safety. Turns out, a nearby row of volcanic craters called the Sundhnúkur had already erupted five times in recent months. It would again just a few days after we flew home, with a couple reporting that they were sitting in the lagoon when they were suddenly told to grab towels and run, and yet again a few months after that, which would be the largest eruption to date, resulting in lava oozing—like the ceaseless blob of the eponymous 1958 horror flick—along the makeshift barriers of the Blue Lagoon and inundating the parking lot and a service building with flaming hot lava. No one was harmed, and visitors and employees at the Blue Lagoon were safely evacuated, but they had only 48 minutes advance notice before the eruption began.

That's about the best that Iceland can do for now. Lovísa Mjöll Guðmundsdóttir, a volcanologist at the Icelandic Meteorological office, told me that they can't make a solid prediction a few days out. Instead, the most certainty they have before an eruption is typically "20 minutes up to a few hours."

This isn't exactly a comfort to lagoon bathers or the roughly 70 percent of Iceland's population who live within the vicinity of the Reykjanes Peninsula, including the capital region of Reykjavik. Guðmundsdóttir says the next eruption of Sundhnúkur could happen in a few minutes, a few days, a few years, or not at all.

Iceland has 35 active volcanoes, placing it in the top 10 countries in the world with the most volcanoes erupting since 1960. Iceland may soon launch itself further up the list as more volcanoes in the Reykjanes Peninsula wake

from a centuries-long slumber expected to last for about 200 years. This means the island's inhabitants are facing an even more precarious future than the present.

Although there have been no deaths caused by recent volcanic activity except for one due to a sinkhole, the biggest threat to the region so far has been to the ongoing destruction of Grindavik, a village whose residents have either moved away or faced repeated evacuations while lava and ash bury their homes, and to Iceland's infrastructure, such as water pipes which were damaged in a 2024 eruption and left 30,000 residents and travelers at the Keflavik International Airport without hot water in subzero temperatures. The volcanic eruptions also threaten the 249,000 residents of the capital region of Reykjavik with the emissions of volcanic ash particulates, which can reach them within a few hours after an eruption and have been associated with emergency hospital visits for cardiorespiratory problems.

Yet there is promise that Icelanders may not have to grit their teeth through the next couple centuries until the Reykjanes Peninsula goes dormant. Unlike most other volcanic regions in the world, Iceland has one of the shortest known distances between the Earth's surface and the magma below—a feature that a team of researchers is exploiting in the hopes of opening up a whole new way of predicting volcanic eruptions that could give days—rather than just hours or minutes—advance notice before an eruption occurs.

In Iceland, this can only be welcome news. Valentin Troll, a petrologist at Uppsala University in Sweden, says that as of March 2026, the volume of magma under the Sundhnúkur is now at the same level it was before the previous eruption in July 2025. "Iceland is probably going to erupt again very soon."



TOO CLOSE FOR COMFORT? Iceland's famed Blue Lagoon geothermal spa is located near the volcanically active Sundhnúkur crater chain.

IN JULES VERNE'S *Journey to the Center of the Earth*, Professor Von Hardwigg and his nephew enter the bowels of the Earth through a volcano on Iceland's Snæfellsnes Peninsula before popping back to the surface through a volcano in Italy. They do this by foot. You might say that this is a fantasy of volcanologists today. Not to travel into the deep Earth themselves—the constraints of pressure and heat would make this rather unpleasant and, frankly, impossible—but to have instruments that could withstand these conditions and allow them to test what's happening underground before the lava emerges to the surface.

Currently, all the methods used to study volcanoes are indirect. Seismographs record Earth tremors, fiber optic cables detect changes in temperature and geological movement, and satellites together with ground tilt meters sense ground deformation—a tell-tale sign that magma may be near the surface like a pot about to boil over. Heat-resistant instruments test surface

lava for temperature, viscosity, minerals, and gas emissions to reconstruct pressure and chemical changes underground. Plate tectonics and the history of volcanic activity are also considered. Computer models are built to draw inferences based on available evidence that could simulate the magma's potential to erupt.

All of this is an effort to get a better picture of what might be happening under the crust where the molten rock sits—the missing piece in volcanic prediction. Yet scientists find it difficult to not only guess the composition of magma, but to even determine where it is. "We cannot really see under the surface," says Troll. "That's the problem." If volcanologists could know precisely where a magma chamber rests, including the magma's composition and the changes it went through days or weeks before it exploded to the surface, then the theory goes that they could vastly improve their predictions.

In 2009, the Iceland Deep Drilling Project, a consortium of geothermal companies, set out to drill down

BHUSHAN / ADOBE STOCK

around 3 miles in the Krafla Caldera, a volcano in North Iceland, looking for high enthalpy fluids, that is, superheated gases, which could potentially be harnessed to produce electricity and heat homes. Instead, their drill jammed just over 1 mile in. They moved the drill to the left and then to the right to see if they could bypass whatever hard material was making it difficult for them to go any deeper, when suddenly the drill started bringing up glass chips. This is what happens when magma is pulled rapidly to the surface, and it could only mean one thing: They had hit a magma chamber.

Hitting a magma chamber has only happened in two other locations in the world: the Menengai Crater in Kenya and the volcanic region of Puna on Big Island in Hawaii. However, the Krafla Caldera is by far the best documented and most accessible. Not to mention, exploration of this volcano has the backing of the Icelandic government, and drilling poses few risks because there are few people living nearby. This was an “aha moment,” says Björn Þór Guðmundsson, CEO of the Krafla Magma Testbed, a company that emerged in the wake of the discovery of magma below Krafla.

KMT’s aim is to use the Krafla well not only as a potential source for clean energy, but also as a site for scientists to conduct research. The company plans on building a permanent magma “observatory,” which they define as a well drilled deep in the Earth’s crust through which they can send down instruments able to withstand temperatures ranging from around 1,300 degrees Fahrenheit to 2,400 degrees Fahrenheit to access the magma and the surrounding rock. This will enable an international team of scientists to measure the temperature, pressure, chemical compositions, and stress changes in the liquid magma prior to an eruption—“the holy grail for volcanologists,” says Guðmundsson.

Scientists observing the Krafla testbed won’t necessarily wait for an eruption to happen, either. They plan to inject radioactive chemical tracers into the magma, and then induce minor scale eruptions. The next step is to follow the tracers to learn where the magma flows and what compositional changes it undergoes before it emerges in the light of day. Paolo Papale, a scientist at KMT and Research Director of the National Institute of Geophysics and Volcanology in Pisa, explains that this will help scientists establish a relationship between changes underground and those on the surface, and

The next eruption could happen in a few minutes, a few days, a few years, or not at all.

how these two things correlate to eruptions. This “natural laboratory,” says Papale, will take the field of volcanology from “theory and speculation to a real testing of ideas and hypotheses.”

Eventually, KMT hopes to replicate their observatory at other volcanic sites to study the behavior of different types of magma and how this corresponds to eruptions. For example, Sundhnúkur’s magma is more basaltic than Krafla’s and so less explosive but runnier, which explains the huge lava flows my children and I had witnessed. Papale says they hope to one day establish observatories at some of the most high-risk volcanoes in the world, such as Campi Flegrei and Vesuvius in Naples. Better predictability in these locations has the potential to save hundreds of thousands of lives. “Imagine if the citizens of Pompeii would have had just one or two days rather than a couple hours to evacuate Naples before Vesuvius erupted,” says Guðmundsson.

Now, KMT is testing alloys that can withstand the pressure and temperatures in magma chambers for a sustained period. Their aim is to open the observatory in 2027 for experimentation. In the meantime, some Icelanders aren’t holding their breath. There are discussions of building another international airport in a safer zone. As for the Blue Lagoon, it’s expanding into areas away from an active volcano. ☺

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We Got Lucky as a Species

*From an ancient brush with extinction came
the big modern brain*

BY KENNETH S. KOSIK

GORHAM'S CAVE FORMS a magnificent arch on the eastern side of the Rock of Gibraltar, at the southern tip of the Iberian Peninsula. Backed by a sheer rock face that looms higher than the Eiffel Tower, the cave, and three adjoining ones, were home to Neanderthals and early humans for a span of 120,000 years. The caves were among the last refuge for Neanderthals before they went extinct some 25,000 years ago.

I am a neurogeneticist, keen to learn about the origins of the human brain, and several years ago visited Gorham's Cave as the guest of paleoanthropologist Clive Finlayson, director of the Gibraltar National Museum.

On a sunny, windy afternoon, waves crashing on the shore of the Alboran Sea, Finlayson and I threaded our way along the rock-strewn ground to the mouth of the seaside cave. We maneuvered around the neatly partitioned dig sites toward the back wall, where we sat on a couple of wobbly stools.



We threaded our way along the rock-strewn ground to the mouth of the seaside cave.

In the dim light, Finelayson told me about the last days of the Neanderthals in Gorham's Cave. A severely cold and arid climate had taken hold of the area 25,000 years ago, and the dwindling Neanderthals, which lived in small groups, likely didn't survive the drought. Meanwhile, *Homo sapiens*, whose diet was more diverse, and occupied more territory on the Iberian Peninsula, flourished, ultimately claiming the caves as their own. Archaeological evidence hints that Phoenicians and Carthaginians, who occupied the area between the ninth and third centuries B.C., used the caves as areas of worship.

As Finelayson and I talked, I looked outward from the cave at sky and sea framed by the stone arch, toward the Rif mountain range of North Africa visible on the horizon. Feeling wistful, I began to ponder the last days of the Neanderthals and the precarious survival of *Homo sapiens*, our species. It's a far lesser-known story than the demise of the Neanderthals. But there was a time in Africa when our direct ancestors teetered on the brink of extinction. At this critical moment, a small cluster of unknown hominins heralded the future of modern humans with big brains and minds.

THIS DRAMA UNFOLDED about 900,000 years ago. The first rumblings of an ice age, more severe than any glaciation over the previous hundreds of millions of years, bore down on the planet. Called the Mid-Pleistocene Transition, it was a new type of ice age that occurs in 100,000-year cycles rather than the previous history of more mild ice ages every 40,000 years. While massive ice sheets spread through the high northern latitudes in Africa, megadroughts punctuated by periods with moisture caused the forests to recede and the savannahs to expand.

Our human ancestors didn't fare well. As many as 99 percent of them were wiped out. With so few individuals, their small sparse groups left only silence in the fossil record. These unidentified archaic humans were an endangered species that clung to existence for over 100,000 years while evolutionary changes churned in their genes.

The focus on this perilous time was sharpened by scientists at the Chinese Academy of Sciences in Shanghai.¹ In 2023, they used contemporary genomes to reconstruct human history and concluded that the future emergence of *Homo sapiens* from an environmentally ravaged population hung on the survival of a mere 1,280 breeding individuals. For 117,000 years, a group the size of a tiny village eked out a bare-boned existence.

In the absence of a fossil record, we can only surmise their existence by interpreting modern genomes and computing the number of generations and individuals that could give rise to the global distribution of DNA variants today. In each generation, mutations occur at known rates, like a clock, from which we can picture a few details of this ancestral population. Doing the math, it appears that a massive population loss was coincident with the Mid-Pleistocene Transition.

It was not the only time that the numbers of ancestral humans dwindled. Since we diverged from the apes 7 million years ago, all the ancient humans on our branch of the tree of life have been replaced. But on this occasion, the human ancestral line, on the verge of extinction, hung on.

How? We made it through a bottleneck, a population collapse followed by recovery. Successfully squeezing through a bottleneck requires enough individuals to avoid high levels of inbreeding. Inbreeding



TO THE CAVE Neanderthals and early *Homo sapiens* entered this opening in Gorham's Cave Complex on the Rock of Gibraltar for shelter and home.

jeopardizes population survival by eliminating genetic diversity and making a species vulnerable to environmental threats that pick off individuals and their progeny. About 500 to 5,000 individuals is the minimal viable population size needed for survival, placing our ancestors in the zone of extreme jeopardy when a few chance circumstances determined whether *Homo sapiens* would one day exist. The genes of those who survived the bottleneck became evolution's easel leading to *Homo sapiens*.

Those intrepid few who faced the most severe bottleneck of human history originated about a million years earlier, when the taxonomic genus *Homo* first diverged from earlier archaic humans. During that time, they nearly doubled their brain size from the 600 cc (cubic centimeters) of the presumptive first *Homo*, known as *Homo habilis*, to the roughly 1,000 cc brain of *Homo erectus*. A larger brain suggests more brain cells, and more brain cells likely benefited hominins with greater adaptive versatility to environmental



COGNITIVE LEAP These first known engravings by Neanderthals inside Gorham's Cave Complex indicate they were capable of abstract thought.

A ravaged population hung on the survival of a mere 1,280 breeding individuals.

challenges. Along with a more spacious brain cavity, *Homo erectus* walked a lot like us, and walked right out of Africa to vast regions of Asia. In the extreme environments of this epoch, *Homo erectus* was the first hominin to transcend environmental boundaries on a global scale.

Those that remained in Africa spent about 5,000 generations leaving barely a trace of their dwindling numbers. But against all odds, the fossil history comes alive again 600,000 years ago with a new member of the *Homo* lineage—*Homo heidelbergensis*. Fossil remains from this new species were discovered at sites in both Europe and Africa, including Zambia, Ethiopia, Tanzania, and South Africa. Remarkably, *Homo heidelbergensis* was gifted with another 500 cc of brain.

What happened in those missing 300,000 years, from 900,000 years ago to 600,000 years ago, is one of the unfathomable mysteries of human evolution. While the gene pool presumably shrank due to the declining population during the bottleneck, the engine of evolution increased the brain size 25 to 30 percent from *Homo erectus* to *Homo heidelbergensis*. One explanation for both the survival of this small population and the emergence of a creature with a large brain can occur through a genetic “shortcut.”

A large population may suppress genetic change because a less fit individual cannot survive among so many better adapted competing peers. However, in a small population, a mutation—even one that reduces fitness—is under less competition and might persist in the population until further mutations come along and add biological innovations that combine to enhance fitness.

Counterintuitively, the small population might benefit from inbreeding that will filter out the most lethal recessive genes and leave fewer deleterious genes. When a favorable mutation occurs in a founder, one who has many progeny over generations, evolution can

accelerate in a small group and become fixed in just a few generations. Demarcating small groups, or “isolation by fragmentation,” occurs as isolated patches of habitat destruction limit gene flow and erode genetic diversity. Unlike gradual separation, fragmentation causes rapid, severe, genetic divergences that drive adaptive changes in traits, but also increase the extinction risk. The climate conditions of southern Africa at the time fit this scenario.

As *Homo* lineages recovered in Africa, with *Homo heidelbergensis* among them, the adventurous ones left the continent 700,000 to 400,000 years ago, just as their *Homo erectus* ancestors had done about a million years earlier. Their destination was Europe where their descendants became Neanderthals and Denisovans, first identified in Siberian caves.

Early Neanderthal and Denisovan wanderers lived in small groups with a small circle of mating partners. The genes they brought with them from the time of the bottleneck added another 500 cc of brain tissue and probably helped them learn to adapt to cold climates, to migrate across Eurasia, find a diverse diet, and invent rope, possibly for clothes. Neanderthals survived for about 360,000 years and Denisovans, who populated a vast territory from Altai Mountains in Siberia to the high-altitude Tibetan Plateau and down to the tropical forests and islands of Southeast Asia may have had a comparable survival.

In the end, though, numerous possible threats to their survival, including the low genetic diversity of both species associated with small-group living conditions decreased their fertility and increased their mutational load and decreased their adaptation to environmental change. Nevertheless, they had a good run.

AT LEAST 100,000 YEARS after some *Homo heidelbergensis* groups left Africa, a new species appeared about 300,000 ago in many parts of Africa. These were *Homo*

We might not be the only possible destiny of our lineage if we replayed the tape of life.

sapiens, whose oldest fossil was found in Jebel Irhoud, Morocco. *Homo sapiens* with the same bonus genes from the bottleneck no longer lacked partners. With the passage of another 100,000 to 200,000 years, progeny from those few who had lived on the edge of a precarious existence began to spread through many regions of Africa, perhaps originating from the fragmentation patches. They formed a family of relationships that more resembled “a tangled vine” through which genes flowed among disparate peoples rather than a single evolutionary tree trunk.

Unlike the *Homo* lineages that already left Africa with a low diversity gene pool, the remaining ancestral *Homo sapiens* were the beneficiaries of a larger gene pool due to human expansion across Africa from forests to arid deserts.² The additional time that *Homo sapiens* ancestors spent in Africa compared to Neanderthals and Denisovans was a great boon that contributed to the distinctiveness of contemporary *Homo sapiens*. That is us.

During the many years since the severe bottleneck, we must assume that the genes that survived through a time of near extinction constituted the genetic canvas upon which cognitive innovation arose and created large social organizations around abstract notions such as countries and religions as well as a vast library of symbols that represent these institutions. *Homo sapiens* too wandered off to Europe, 60,000 to 70,000 years ago, where they mated with the Neanderthals. But the gene flow from these new arrivals that might have enhanced their fitness was too late to prevent Neanderthal extinction. Only a brief few thousand years passed when *Homo sapiens* and Neanderthals overlapped and interbred. It happened in the interval when Neanderthals lived in Gorham’s Cave.

As much as we would like to tell the entire story of those genes passed down through ancestral *Homo* species that led to our complex brains today, we simply

don’t have the full picture. We know the answer is not a magic gene that suddenly appeared. The answer—still obscure—lies somewhere in the highly intertwined networks of pre-existing genes, many with small evolutionary changes that tweaked their functions.

And there have been tantalizing examples. One is the *NOVA1* gene, which has a *Homo sapiens* variant absent in Neanderthals, Denisovans, and all other animals. As a master regulator of gene expression, the variant affects how numerous other genes are expressed, particularly those related to synapses and neural connectivity.

When a single mutation corresponding to the Neanderthal variant was introduced into a human brain organoid, the development of the organoid and its firing pattern was altered, but how or even whether that pattern might relate to the large-scale behavioral differences between these species is unclear. When the human variant was introduced into the mouse, it altered its vocalization.

Quite provocatively, the variant might serve to develop the brain circuitry of language, a key facet of *Homo sapiens* evolution.³ While this variant is rare in *Homo sapiens*, a small number of individuals carry the Neanderthal version, again pointing to the fact that no single gene can account for the transition to *Homo sapiens*.

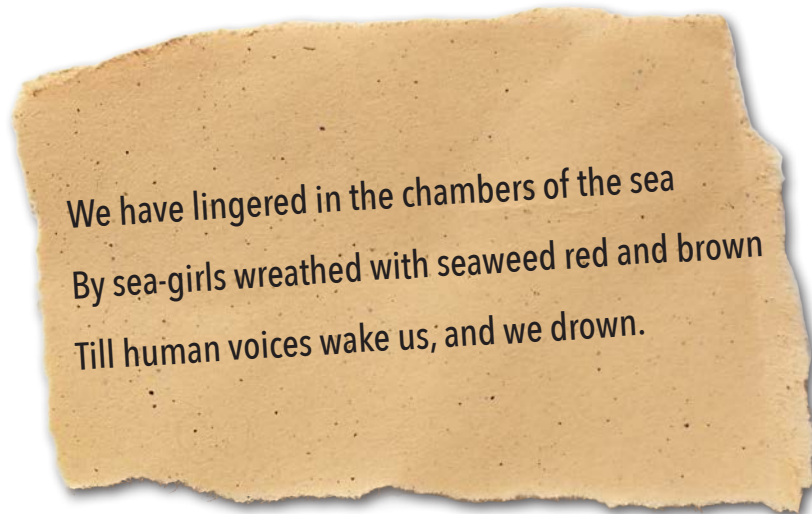
From my point of view, our survival through a bottleneck and the accompanying genetic story fits the punctuated equilibrium hypothesis proposed by paleontologists Niles Eldredge and Stephen Jay Gould in 1972. This view of evolution posits long periods of stasis during which the gene engine that generates constant small numbers of mutations rumbles along without much obvious impact on overall anatomy and physiology until the collective changes mount and in a brief, rapid burst, novelty appears.

Eldredge and Gould suggested that demarcated speciation—not gradual change—was the dominant mode of evolution in the human lineage represented by our numerous diverse ancestors, each accompanied by large genetic changes. From stirring the genetic mix of DNA variants among the survivors of the near extinction event 900,000 years ago, came a leap in brain size and then further mixing as the first *Homo sapiens* emerged from interbreeding among regionally isolated populations across the African continent. While the details of our evolution remain elusive, *Homo sapiens* ultimately emerged, even though we might not be the only possible destiny of our lineage if we “replayed the tape of life,” Gould famously said.

A leap in brain size can be measured. A leap in cognition can only be inferred. Reflections of the natural world that fill the brain with the kind of abstractions

and symbolic images that guide us today are nearly—but not entirely—invisible. Gorham’s Cave itself is proof that early hominins possessed symbolic thought. Neanderthals engraved crisscrossing lines, rather like a tic-tac-toe grid, into the bedrock.⁴ Finelaysen explained the engravings represent a form of symbolic communication, revealing the Neanderthals were capable of abstract thought, contrary to what had long been thought about them.

As twilight approached and Finelaysen and I got up to leave the cave, I paused in reflection about our imaginary friends the Neanderthals. They spent the twilight of their precarious existence here, deeply embedded in the rhythms of the natural world, uncertain of their fate. I looked out at the sea, and a few lines from T.S. Eliot’s “The Love Song of J. Alfred Prufrock” came to mind.



We have lingered in the chambers of the sea
By sea-girls wreathed with seaweed red and brown
Till human voices wake us, and we drown.

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Schrödinger's Kittens Are All Grown Up

Offspring of the most famous thought experiment
in physics are now testing the very fabric of the universe

BY PHILIP BALL



IN 1935, ERWIN SCHRÖDINGER had had enough.

A decade earlier, the bold Viennese physicist had transformed the new theory of quantum mechanics with his “wave equation,” describing how quantum particles could behave like waves. Since then, he had watched some researchers use his theory to concoct what he considered a ridiculous interpretation of quantum theory, which seemed to deny reality to quantum objects like atoms or subatomic particles until they were observed.

Schrödinger wrote a letter to his fellow skeptic Albert Einstein, outlining a thought experiment in which a quantum event might or might not kill a cat hidden inside a box. How ridiculous it was, Schrödinger said, to suppose that the cat could be both alive and dead before we observe it, and that mere observation could force nature to choose one state or the other.

By enabling quantum behavior to influence objects large enough for us to see—and indeed, stroke—Schrödinger wanted to expose the absurdity of giving observations the power to summon what is real.

For a century, his thought experiment has provoked debate about what it means to make a measurement or observation in quantum theory. It laid down a gauntlet to experimental physicists: Just how big *can* we make objects while still finding peculiar quantumness—neither *this* nor *that*—in the ways they behave? Can we place, if not a cat, then at least sizable lumps of lifeless matter (which some fancifully call Schrödinger’s kittens) in such strange quantum “superpositions?”

It’s not just an academic question. Last year’s Nobel Prize in physics was awarded to researchers who showed in the 1980s that superpositions can be created in loops of superconducting wire: components like those

now used as quantum bits in the quantum computers made by companies such as Google and IBM, which achieve their formidable computational speed by processing information represented as superpositions of binary 1s and 0s.

Ultimately, experiments on Schrödinger’s kittens are about probing the limits of quantum theory itself. Is the world truly quantum all the way up, its peculiar consequences just getting ever harder to see as sizes and masses increase? Or might there be, as some researchers think, a cutoff point where quantum mechanics breaks and only the old-style classical physics will work to describe the world?

Some researchers are now seeking to make Schrödinger’s kittens consisting of tiny crystals almost as big as dust grains, that might help to resolve foundational questions in the cosmos. If these little grains have enough mass to feel one another through their gravitational attraction, placing them in delicate quantum superpositions might provide a means of testing whether gravity can—as most researchers believe, yet without hard evidence—be given a quantum-mechanical description. And their precarious nature could supply a sensitive method for detecting elusive particles like those proposed to explain the mysterious dark matter that seems to pervade the cosmos.



One reason to test ever larger Schrödinger's kittens is that they might show us that quantum mechanics itself breaks down.

THE CAT THAT ATTACKED COPENHAGEN

What was Schrödinger so upset about? Since the first mathematical formulation of quantum mechanics, devised in 1925 by German physicist Werner Heisenberg (followed by Schrödinger's alternative wave mechanics in early 1926), Heisenberg and others, especially his mentor Niels Bohr in Copenhagen, had been claiming that the theory forced us to reconsider the very notion of what is real. According to the Copenhagen interpretation of quantum mechanics, all the theory can tell us is the chance of observing experimental outcomes when we observe a quantum system.

In general, the theory predicts several possible outcomes of a measurement, each with a well-defined probability. Before it is observed, a quantum object like an atom or a subatomic particle can't be considered to be in any of those states; they are somehow mixed together in a superposition. Only when we observe an

object initially in a spatial superposition, say, does a choice get made and it acquires a definitive position.

Bohr and colleagues insisted that we must just accept this as the way the quantum world works. Measurement somehow creates definite outcomes—elements of reality—from what was previously just a range of possible worlds. In Schrödinger's time it was common to talk about superpositions as being in multiple states or places at once, although this is not really the right way to express the matter: A superposition just means that any one of several observed outcomes is possible.

The idea that measurement itself could have this seemingly magical effect of *producing* reality, and that objects may have multiple states at once before being observed, didn't sit well with Schrödinger or Einstein. It seemed to deny any pre-existing, objective reality, contradicting what scientists had always assumed.

Schrödinger illustrated how crazy, indeed illogical, that notion was by imagining an experiment where some probabilistic quantum event such as the radioactive decay of an atom (which could happen at any moment) triggers a chain of events that leads to the cat in the box being poisoned. If the atom was, before we open the box to look, in a superposition of decayed and not decayed, then the cat must be in a superposition of alive and dead.

“His thought experiment still teaches us the full absurdity of quantum mechanics, once one includes the observer in the description,” says physicist Klaus Hornberger of the University of Duisburg-Essen in Germany, who works on the quantum physics of objects at the nanometer scale.

Imagining a subatomic particle in “two places (or states) at once” didn’t seem so challenging in Schrödinger’s time, since in those days no one expected to be able to observe them individually anyway. But by amplifying the idea up to the macroscale, and applying it to a property that has to be either one thing or the other (how could anything be both alive and dead at once?), Schrödinger was raising the stakes to expose the craziness of the Copenhagen denial of a pre-existing objective reality.

However, many physicists now see the thought experiment a little differently. Not only do we now know that quantum superpositions are real, but since the 1970s experiments have shown that observational outcomes don’t seem to be predetermined before a measurement is made.

Nonetheless, at our everyday scales, objects really do seem to be either this or that, whether we look at them or not, just as classical physics supposes. So, when does quantum become classical? Do quantum superpositions just get ever harder to see as objects get bigger, or is there some more fundamental principle that prohibits quantum superpositions as big as Schrödinger’s cat?

WAVY MATTER

Superpositions are typically precarious. According to quantum mechanics, an observation destroys them—but that’s not really a question of whether we look at them or not. It’s enough to destroy a superposition if any information about the state of the object leaks out into its environment where it can potentially be detected: It’s all about whether an observation *could* be made. If a photon of light bounces off the object, or if the object itself emits a photon, we might be able to work out where the object is by observing the photon—and that will destroy the superposition.

This “leakage” of information about a quantum state because of its interactions with its environment, and the consequent destruction of its “quantumness,” is a process called decoherence. The bigger the object gets, the harder it becomes to suppress any such interactions. *This*, most researchers think, is why it’s challenging to see quantum effects at large scales: not because they are inherently unstable for large things, but because large things are hard to isolate and to shield from decoherence.

Seeing atoms in superpositions is fairly straightforward. One way is to use them in the famous quantum double-slit experiment, where a beam of particles is fired through two closely spaced slits in a screen. Schrödinger’s equation described all quantum objects as wave-like entities—and a key property of waves is that they can interfere with one another, their peaks and troughs amplifying or canceling out to create an interference pattern.

In the double-slit experiment, such interference between the waves emanating from each slit creates a characteristic pattern in the particles detected on the far side: a series of “bright” bands where many particles are detected, separated by dark bands where few of them are. Interference of atom-waves was first demonstrated in the early 1990s. It only appears if the particles are in a superposition; that is,

GLOW IN THE DARK

(Below) The central bright dot is a silica nanoparticle levitated in a vacuum by electric fields. Its thermal jiggling has been reduced so much that its effective temperature is just a few millionths of a degree Kelvin above absolute zero, and it is in the lowest-energy quantum state possible: the ground state.

they can be considered to go through “both slits at once” and interfere even with themselves. Measure which slit each particle goes through and the superposition is destroyed—the interference pattern vanishes.

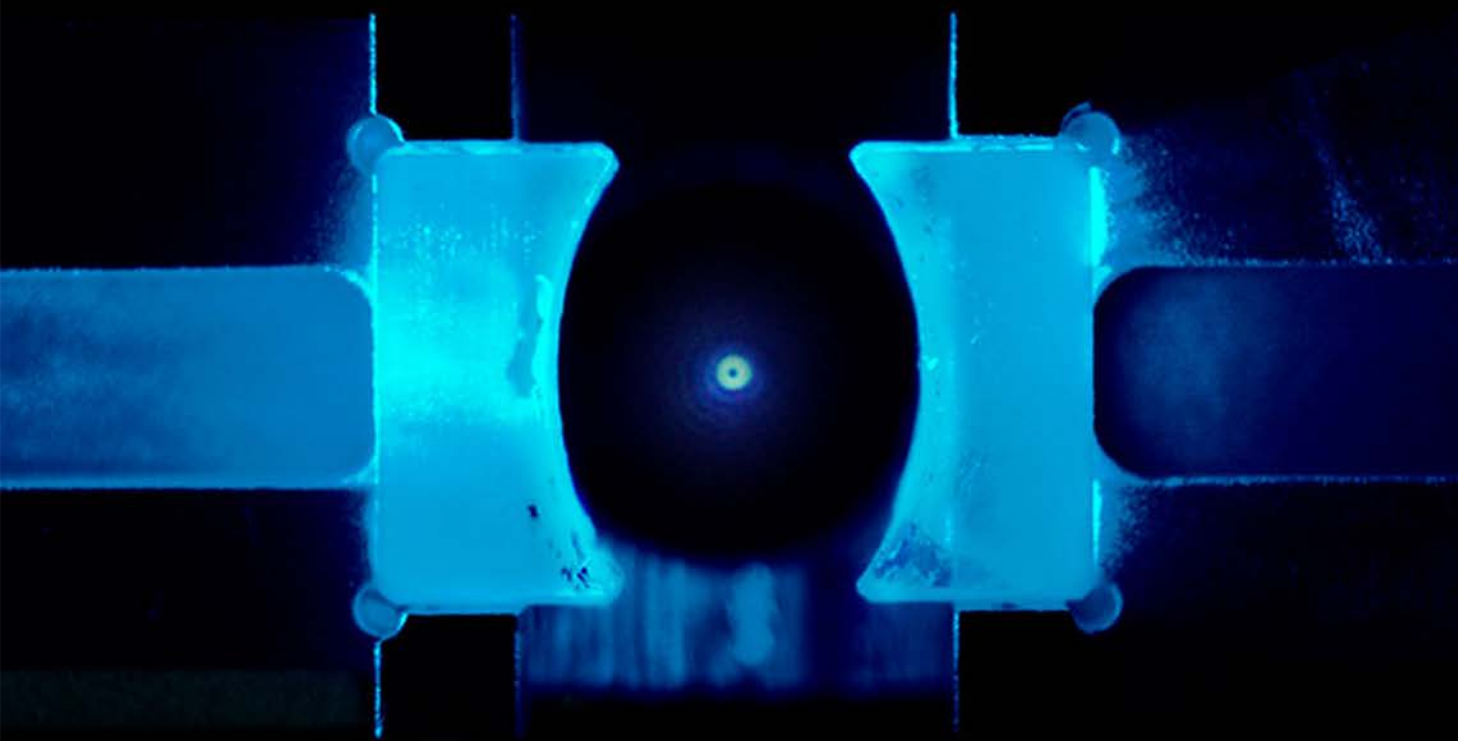
Can we scale such experiments up? Will entire molecules behave this way, too? In 1999, Markus Arndt of the University of Vienna, who today is at the forefront of experimental work to make large quantum superpositions and was then working in the team of future Nobel laureate Anton Zeilinger, showed that indeed matter-waves made from fullerene molecules, each containing 60 carbon atoms, linked into hollow spherical cages, will display interference.

Since then, Arndt has been demonstrating interference in ever larger molecules. In 2019, his team reported quantum superpositions of organic molecules containing up to 2,000 atoms, with masses of 25,000 daltons. (One dalton is about the mass of a single proton

or neutron, the particles of the atomic nucleus.) In these experiments, the particles are usually fired not at double slits but at an entire grid of parallel slits made from light itself: laser beams prepared as “standing waves,” where they bounce back and forth between mirrors to create an interference pattern of light and dark.

Making a “big” positional superposition isn’t just about using large objects, though. It also depends on how far apart the two observable position states—the centers of gravity of the objects—are. To measure this scale, Hornberger has introduced the notion of “macroscopicity.”

“The macroscopicity value quantifies how perplexing a quantum effect is to a classical physicist,” he says. If, say, you made a superposition for a golf ball in which the two positions differ by less than the width of an atom, that might have a lower macroscopicity than a superposition of a fullerene molecule with a “here” in New York and a “there” in San Francisco.



The idea that objects may have multiple states before being observed didn't sit well with Schrödinger or Einstein.

Last year, Arndt's group, collaborating with Hornberger, reported a new record in the macroscopicity of a quantum object. They showed that they could create superpositions for tiny crystals of sodium about 8 nanometers across, containing about 7,000 atoms. The centers of mass of the two superposed locations were up to 133 nanometers apart—more than 10 times the size of the particles.

Hornberger thinks that producing matter-wave interference for particles perhaps about 10 times more massive than the sodium nanocrystals “will get really tough.” He suspects that to scale up to this level, a different method may be needed: to levitate nanoparticles cooled so that they are in the lowest possible quantum energy state (the ground state).

Markus Aspelmeyer at the University of Vienna is pioneering efforts to do that. In 2020, he and his coworkers reported that they had cooled down particles of silica about 150 nanometers across, containing about 100 million atoms, so that they spent at least 70 percent of their time in their ground state rather than boosted by thermal jiggling into higher-energy states. To do this they levitated the

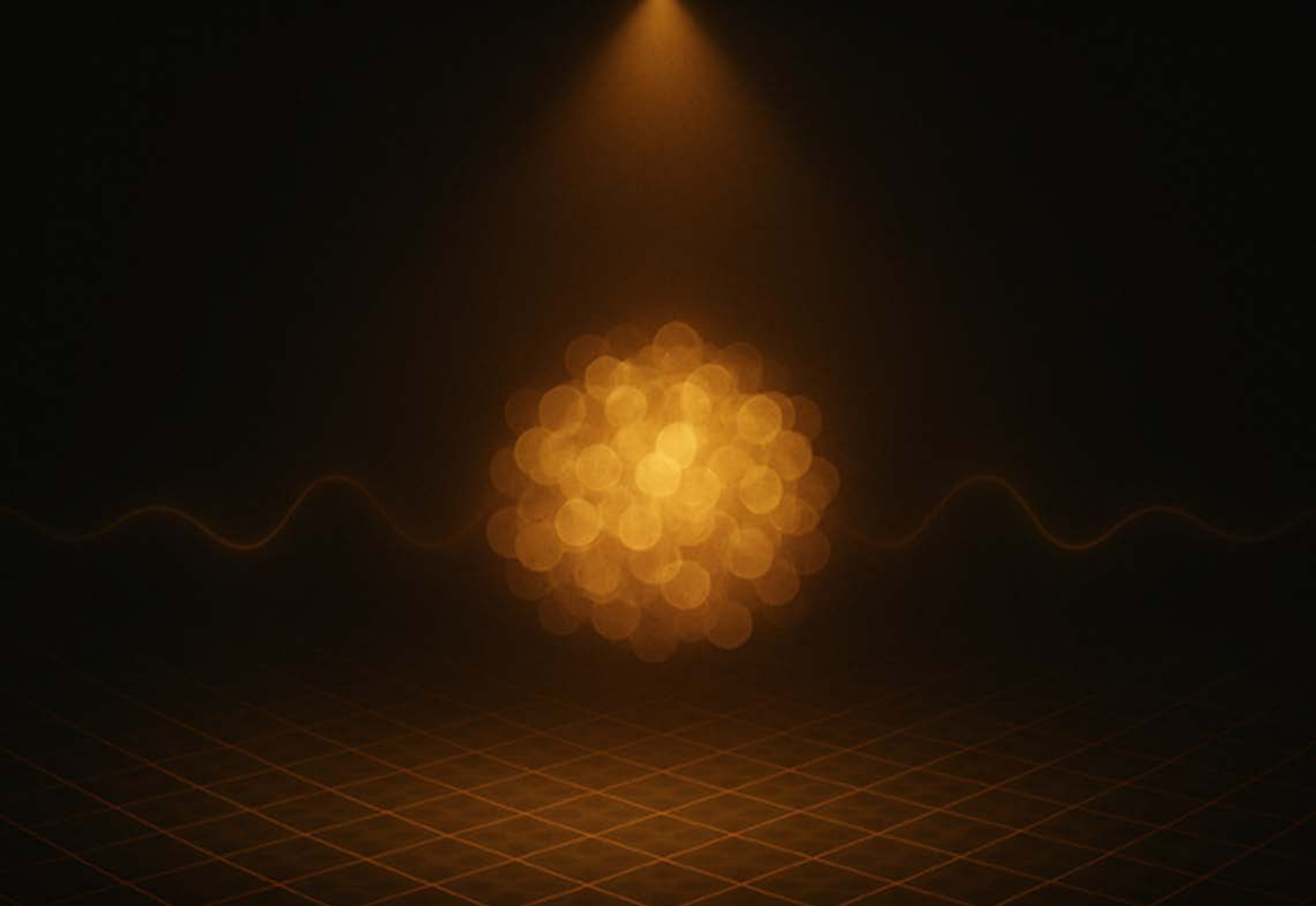
particles in an optical trap, suspending them in a field of intense laser light.

The following year, Aspelmeyer's team, as well as another group in Zürich, Switzerland, showed that they could make such particles even colder and more securely lodged in their ground state by ditching the optical trap and just using light to apply little nudges to keep the particles in position. But coaxing lumps of matter this big into a superposition is another matter, and no one has yet achieved it.

Arndt, though, is optimistic. “We see a realistic path toward [superpositions of] particles in the range of tens of millions of daltons in the coming years,” he says. That “would already be a hundredfold improvement in mass and up to six orders of magnitude in macroscopicity compared to the current world record set by our sodium metal particle.”

SEEKING QUANTUM GRAVITY

One reason to test ever larger Schrödinger's kittens is they might show us that quantum mechanics itself breaks down before we reach the macroscale. Some researchers have long suspected this could happen.



MATTER WAVE IN THE SPOTLIGHT A computer-generated representation of a cluster of sodium atoms in a delocalized state, where the wave function that describes the positions of the atoms is somewhat spread out over space. Only when the cluster enters the “spotlight” so that its position is measured do the atoms acquire definite locations.

In one theory, proposed independently by Hungarian physicist Lajos Diósi and British mathematician Roger Penrose, quantum objects in superpositions undergo a spontaneous “collapse” to a well-defined location with a probability that increases as the object gets larger, such that at some scale collapse will become inevitable no matter what we do. Penrose thinks such a collapse is necessary to prevent quantum mechanics from conflicting with general relativity, the theory of gravitation devised by Einstein in 1916.

In Einstein’s theory, massive objects deform spacetime itself, forcing other objects to travel

along trajectories that deviate in just the way expected from what we have traditionally called the force of gravitational attraction. Penrose’s concern was that, when objects get big enough to exert a significant gravitational force, a superposition of two locations would create two different geometries of spacetime—a situation that ought to involve an enormous amount of energy. Spontaneous collapse would switch off quantum effects like superposition before that uncomfortable circumstance arises.

But perhaps there is no conflict between quantum mechanics and general relativity, because gravity itself is a quantized force, like

electromagnetism. Even though we lack a theory of quantum gravity consistent with both quantum mechanics and general relativity, most physicists think gravity is indeed quantum in nature. The first person to suggest this was physicist Richard Feynman, in 1957. Feynman even suggested a thought experiment to test the idea—but he didn't imagine it would ever be possible to carry out real experiments.

That, however, is the only way to find out. "I see no reason at all to believe that we have already a complete picture" about the putative quantum nature of gravity, says Arndt. "Personally, I would be shocked if the principles of quantum theory would break down" at larger scales.

The goal to proving that, Aspelmeyer says, is to make "systems that have enough mass to produce a measurable gravitational field, and that are sufficiently delocalized [that is, in superpositions with large enough macroscopicity] that the gravitational phenomena cannot be described by classical general relativity anymore." He and his colleagues have proposed an informal measure of the usefulness of such objects for exploring quantum gravity that is somewhat analogous to Hornberger's macroscopicity, and which they call, with a nod toward Schrödinger, "quantum cattiness."

One way to use "quantum-catty" objects to probe quantum gravity was proposed two decades ago: to see if gravitational interactions can be used to create the strange quantum effect called entanglement.

This is perhaps the most perplexing and counterintuitive of all quantum phenomena. As Einstein pointed out in 1935, if two quantum objects interact—if they "feel" one another's presence in some way—then thereafter quantum mechanics says that they will act essentially like a single quantum entity: The two original objects have become entangled.

This has bizarre consequences. For example, we can find out the properties of one object by looking at the other. Einstein argued that, if

the Copenhagen interpretation was right and quantum properties weren't fixed until they are observed, this seemed to imply that the observation of one of an entangled pair in one place instantaneously affects the other, no matter how far away it is. Such instantaneous action at a distance is forbidden by Einstein's theory of special relativity, and Einstein felt that this apparent paradox showed that quantum mechanics cannot be the whole story.

But in fact, quantum entanglement doesn't require action at a distance because the entangled pair aren't separate entities at all. Their properties have become "nonlocal": not fixed to the particles themselves. However odd this seems, it has now been confirmed experimentally countless times.

It was Schrödinger who, also in 1935, called this phenomenon entanglement. The reason it can be used to look for quantum gravity is that just about the only way two objects can become entangled by interaction is if the force of interaction is itself quantized. So, if two masses could be entangled solely via their gravity, it would be proof that gravity is quantum.

The challenge in seeing such gravity-induced entanglement, though, is that the particles would have to be big enough that their mutual gravitational attraction would be strong enough to matter, yet not so big that it becomes impossible to hold them in a quantum state.

Physicist Sougato Bose of University College London and his coworkers proposed an experiment in 2017 in which two nanocrystals are placed in superpositions while at a distance far enough apart (about 100 micrometers) that they don't feel each other's electromagnetic fields but interact only through gravity. The superpositions of locations would mean that the gravitational interactions of the different particle positions would differ, creating measurable interference effects.

The modern quest to make ever bigger Schrödinger's kittens could be useful in the quest to find dark matter.

To keep such relatively big masses in superpositions, says Bose, you need to ensure that they are extremely well isolated from any interactions in their environment. A single molecule of gas or a photon hitting one of them could be enough to collapse the superposition. So, they would have to be levitated in an extremely high vacuum and screened from any stray electromagnetic fields.

The key challenges for increasing the “gravitational cattiness” of Schrödinger’s kittens, says Aspelmeyer, are “to extend our current quantum control techniques to larger masses,” and to reduce the decoherence caused by the impacts of gas molecules or stray electromagnetic radiation. Despite the formidable technical demands, Arndt says that the idea of testing for quantized gravity this way is worth pursuing.

So, could things really be quantum all the way up? “I see no compelling reason why the laws of quantum theory should cease to hold at some scale of macroscopicity,” Hornberger

says. “But we simply don’t know, and there are good reasons to suspect a fundamental change once general relativity kicks in.” But, he adds, “I believe if quantum theory is ever to be superseded by something more fundamental, I guess it will be even more crazy.”

NO LIMITS?

Just under a century ago, Schrödinger wanted to find an extreme scenario that would expose the flaws, as he saw them, of the Copenhagen interpretation of quantum mechanics. What he ended up doing was a lot more. He pushed generations of physicists to delve even deeper into the precarious character of nature itself.

Arndt says the modern quest to make ever bigger Schrödinger’s kittens could be useful in the quest to find dark matter—the stuff proposed to explain the “extra” gravity that seems needed to hold rotating galaxies together. Many researchers think this putative invisible matter is composed of unknown and

highly elusive particles, but no such thing has ever been seen. But if dark-matter particles interact, however incredibly rarely, with ordinary matter, might their presence be revealed by their ability to trigger the collapse of precarious superpositions? Delicate superposition states of large objects might also reveal the effects of entirely new forces of nature beyond the four already known, such as the “fifth force” that some physicists have long suspected to exist. If such a fifth force couples a superposition to its environment, that could induce a collapse.

And what of the cat itself? Physicists today are still tantalized by the question of what it would feel like, if anything at all, for a living, breathing, thinking organism to be placed in a superposition. Ethical concerns aside, could scientists ever perform Schrödinger’s original

experiment? It’s not clear what a live/dead superposition could even mean, given that life doesn’t have a well-defined quantum description. But might we at least place a tiny living organism like a bacterium in a superposition of positions?

Arndt thinks it might be possible, at least for a virus. “If we get the money for it, we will certainly do our best to get there,” he says. “There are very many challenges, but it is not impossible.”

And then a living cell? “Give me more time to think about it,” he says, smiling. ☺

PHILIP BALL is a freelance writer based in London, and the author of many books on science and its interactions with the broader culture. His latest book is *How Life Works*.





An underwater photograph of a coral reef. The foreground is dominated by large, white, branching coral structures. A small, striped fish is visible near the bottom left. The background shows more coral and the surface of the water with sunlight filtering through. The text is overlaid on a white, torn-edge rectangular background in the upper half of the image.

Coral Reefs Are at a Tipping Point

*My underwater dive to discover whether the
beautiful ocean organisms are ever coming back*

BY ELENA KAZAMIA



WHEN I SLIDE OFF the tiny panga, the water feels warmer than the air. It is late January in the Caribbean, and I am about to snorkel around a patch of reef immediately off the coast of Puerto Morelos in Mexico, a fishing village south of Cancun, the buzzy hub for tourists on the Yucatan Peninsula.

I'm at the northernmost point of the Mesoamerican Barrier Reef system, which extends for 700 miles and runs the coastline of four nations. It is second in size only to the Great Barrier Reef in Australia and is considered among scientists to be a harbinger for warm water coral reefs globally.

In 2025, Global Tipping Points, an international group of scientists led by Tim Lenton of the Global Systems Institute at the University of Exeter in England, warned of the collapse of six major Earth systems due to global warming. The systems include the Greenland Ice Sheet, Amazon Rainforest, ocean circulation, and coral reefs. The scientists state that reefs are the first major Earth system to have breached a point of no return.

"We can no longer talk about tipping points as a future risk," Lenton told *The Guardian*. "The first tipping of widespread dieback of warm water coral reefs is already under way."

Few reefs are as degraded as the one at Puerto Morelos. After 30 years of continuous study, local scientists have documented every shift in its decline. The 2025 Global Tipping Point study states the Mesoamerican Reef "faces collapse with devastating impacts."

And yet when I dip my head into the water, the reef looks both beautiful and eerie. Enormous corals each the size of a Volkswagen Beetle give shape to the seafloor. These are *Orbicella*, large stony species, which over

centuries built this reef. On closer inspection it is clear their surfaces are smudged with slimy algal growth. The fretted inundations, the ridges and crowns that give corals their elaborate outlines, look blunted over by some ugly, destructive carelessness. Still, fish continue to take residence inside their nooks and crannies; colorful, curious, otherworldly.

Within a quick half hour, I have seen hundreds of animals including groupers, angel-fish, eagle rays, and lobster. My fellow snorkelers are thrilled. They snap underwater images they plan to share on social media, they tell me, as highlights of their trip. It is hard to immediately judge from their colorful photos if the corals are alive or not, and our guide, Xavier, who has been leading tours in these waters since the 1980s, chooses not to discuss it. Who can blame him? Telling the tourists that an international body of scientists has just declared the reef dead on arrival would not be good for business.

But in fact the reality about coral reefs is too complex and uncertain for binaries like living or dead, scientists in Puerto Morelos tell me. To call this moment in time a tipping point is to effectively close the book on coral reefs, precluding the resilience that has allowed them to persist against all odds since they first formed on Earth more than 400 million years ago.

Corals have an unusual relationship with death. They defy easy categorization.

THE IDEA OF A “TIPPING POINT” in Earth systems is relatively recent. The insight that shocks to natural ecosystems can upend their stable states of existence dates to research by theoretical ecologists in the 1970s. But the ecologists didn’t invent the term. Its origin can be traced to Morton Grodzins, a political scientist at the University of Chicago who, in the late 1950s, studied the “tipping point” of racial segregation in American neighborhoods.

Decades later, the concept caught the eye of writer Malcolm Gladwell, whose titular best-seller popularized the idea that small social phenomena could turn contagious. The book offered an appealing one-shoe-fits-all logic, applying the same mechanics to viral fashion trends as it did to the spread of syphilis in Baltimore or the falling crime rates of 1990s New York. It spotlighted small incidences with “massive, disproportionate effects” on

the behavior of large cohorts of people. The term itself proved to be as viral as the trends Gladwell described.

In the 2000s, Lenton introduced “tipping point” into climate science. He calls it a “nudge,” a tiny push that hurls a complex system from a balanced state to another. A pushed chair has a tipping point—the threshold it crosses when going from balancing upright to falling. Global warming is destabilizing natural ecosystems like coral reefs, causing escalating, irreversible damages.

Corals have an unusual relationship with death. Lorenzo Alvarez-Filip, a marine ecologist and researcher at the Reef Systems Unit of the National Autonomous University of Mexico (UNAM), affectionately calls corals “monsters.” As living things go, they defy easy categorization.

A coral is indeed a kind of mythological creation of interacting organisms living in





“I know my sons will not see these corals again. This is the window that is closed.”

a precarious equilibrium—part animal, part plant, and even mineral. (Roman poet Ovid described coral as “stony stalks” animated by the slain Medusa’s head, which Perseus placed on a bed of seaweed.) A colony of polyps, which are close relatives of sea anemones, makes up the animal part. Polyps are tiny, but visible to the naked eye. They coat the coral’s surface, and gradually build a skeleton beneath them, into which they can retreat when startled. The animal tissue of a coral is skin deep, and when the polyps die, only limestone remains. Its deposition is continuous over decades, sometimes centuries. Some living corals are millennia old.

To survive, polyps depend on algae for energy. It is these “zooxanthellae” which give coral their bright color. When a coral first coalesces into being, in a process that is mostly mysterious to scientists, baby polyps absorb algae from the water around them and

stitch them into their tissues. The algae provide 90 percent of the energy the polyps need for life through photosynthesis—the process typified by plants. They get the remaining 10 percent by feeding on drifting plankton, which they digest in a rudimentary gut.

In this way, corals are nature’s true chimeras, a rich blend of species making up a composite organism. The symbiosis includes other players, including bacteria, whose role is an active subject of research.

When a coral “bleaches,” its zooxanthellae are released back into the water column, leaving the polyps looking paler, or bone white if the evacuation is total. There is disagreement among scientists on whether zooxanthellae are expelled by the polyps, or if the algae escape the partnership.

“Bleaching” gets all the bad press about coral reefs, symbolized by widespread photos of the once-colorful reefs looking pale and



REEF OUTREACH

Esmeralda Pérez-Cervantez of the National Autonomous University of Mexico strives to educate locals about their neighboring reef. She holds a plaster cast of a critically endangered starlet coral that children will decorate at an upcoming science fair.

lifeless. But in fact, paling is a natural part of a coral's life, triggered by seasonal warming. "It's a beautiful equation," says Anastazia Banaszak.

Banaszak is a senior researcher at UNAM who specializes in coral reproduction. During a paling event, normally during summer, "the corals spawn and produce new babies," she explains. Coral polyps release millions of tiny eggs and sperm. The eggs match with sperm in water columns and produce larvae, which now have premium access to potential symbiotic algae (having been bleached out of the

adult corals). The larvae, called planula, settle to the ocean floor, and begin their fight for a chance at maturing into adult coral on the reef. Meanwhile, once the water cools, some algae return to the adult colonies, restoring the reef's hue and color.

Coral death, in fact, is a protracted event. It is a gradual undoing of a colony that normally relies on steady seasonal rhythms and capricious partnerships with zooxanthellae. A large coral can survive disease or heat stress, emerging as a mosaic of living polyps

THE HEAT IS ON

Lorenzo Alvarez-Filip of the National Autonomous University of Mexico, an authority on the Mesoamerican Barrier Reef, says the effects of a recent marine heatwave shocked him: “Even the fish looked dizzy and exhausted, swimming in a trance.”



alongside skeletal patches. In severe cases, through a process not fully understood by scientists, all the polyps die of starvation, waiting for algae that never return to the partnership.

Banaszak, who has studied the Mesoamerican Reef for more than 20 years, tells me that warm water reefs like the Mesoamerican are slow growers and vulnerable to heat and stress. “They are already at the edge of their thermal tolerance,” she says. “Corals are very sensitive organisms.”

ON AN OVERCAST, WINDY AFTERNOON, I meet Alvarez-Filip in his UNAM office in Puerto Morelos. He specializes on the dynamics of change in reef ecosystems and is widely held as an authority on the Mesoamerican Barrier Reef. He is also one of the authors of the Global Tipping Points report.

Principled with his remarks, with dark warm eyes, Alvarez-Filip is a strict adherent to the scientific method. As a young boy he followed his mother on her field trips, a scientist collecting data on biodiversity in the

ELENA KAZAMIA

coastal Pacific forests of Mexico. When he started working on the reef in Puerto Morelos, after completing his doctorate in 2010, “the corals were already very degraded,” he says. The primary cause, as he saw it, was pollution.

In Puerto Morelos, as in most reefs that lie close to urban centers, the damage to corals is persistent. “First came the building of Cancun,” Alvarez-Filip says. The development of the tourist destination in the 1970s, he says, flushed sewage into the reefs. Then came fertilizer run-off from agricultural expansion in the Yucatan. In 2018, an epidemic of Stony Coral Tissue Loss Disease swept through the area. “This disease killed hundreds and thousands of corals in small areas in a matter of weeks,” Alvarez-Filip says. Its cause, likely a virus, has never been fully resolved.

For years, Alvarez-Filip says, he was weary of scientists crying wolf about coral reefs as a result of climate change. But an event that started in 2023 changed his mind. An extreme marine heatwave that lasted for two years burned through the reef. Water temperatures exceeded 35 degrees Celsius (95 degrees Fahrenheit), wiping out adult corals that had survived all the previous shocks. It was a staggering anomaly of sea warming that exceeded 4.8 degrees Celsius above average.

“Even the fish looked dizzy and exhausted, swimming in a trance,” Alvarez-Filip says. “This is what many scientists were predicting—that climate change will occur in extreme events rather than in this gradual thing. And what happened was a really extreme event.” This time the wolf was real.

Alvarez-Filip says he has been studying future projections of ocean temperatures, when severe heatwaves are predicted to come strong and in quick succession. He and his colleague Banaszak both see this as snuffing out the potential for substantial growth. “I have seen millions of corals dying,” Alvarez-Filip says. “When I extrapolate my data, this

becomes millions and millions of corals dying over hundreds or thousands of kilometers. This is the scale of the problem.”

A dying coral reef can retain its skeletal structure before turning into rubble and continue to provide coastal protection against waves and support a thriving fish community. But in many ways the reef is already a goner, beyond recovery, Alvarez-Filip says. It has crossed its tipping point. “I know that my sons will not see these corals again,” he says. “This is the window that is closed.”

THE NEXT MORNING in Puerto Morelos, things look a little brighter. In the hallways of UNAM hangs a map that pictures the world according to corals. Strewn across the globe’s vast seascape are wispy and colorful strokes that denote reefs. Continents look like afterthoughts. The reefs appear like cities which are home to more than a quarter of all the fish in the ocean. But much of the diversity of the corals remains unexplored.

On campus, I sit down with Esmeralda Pérez-Cervantez, a softly spoken fieldwork technician. She is busy making plaster casts of various coral species for local schoolchildren to color during an upcoming local festival of women and girls in science. Much of her work at UNAM involves scuba diving to document coral health and abundance along vast transects of the Mesoamerican Reef. Over thousands of dives, Pérez-Cervantez has witnessed firsthand the death of countless adult coral colonies. But Pérez-Cervantez wants to tell me about the juveniles she sees.

“There are tiny, tiny corals that we can see growing on the seafloor,” Pérez-Cervantez says. “And they withstand the bleaching, they withstand the diseases. It sounds very clichéd, but when you see the little baby coral child, I see hope in them.”

Most surveys of reefs, which become the bedrock of academic studies, don’t focus on juveniles, Pérez-Cervantez says. These are young corals smaller than 1.5 inches in





The tipping point narrative is most confident when it speaks of the present moment.

diameter that have found a foothold on the seafloor. They're difficult to spot during a dive, often lying obscured by seagrasses. "Sometimes I move the grass with my hand, and there it is. A coral baby. I am always surprised," Pérez-Cervantez says.

Because juveniles are the offspring of adults who have survived warming, they hold the most potential for developing tolerance to future climate change. A product of natural selection, they represent the reefs' true shot at continuity.

Claudia Padilla Souza says the reefs will indeed persevere. For her Ph.D. at UNAM in the early 1990s, Padilla Souza was diving on the Mesoamerican Reef to document its corals. Following her degree she spent almost 30 years as a researcher in Mexico's Institute of Fisheries studying corals, queen conch, and king crab. Padilla Souza left academia in 2024 to focus on coral restoration projects in the area. Today she is the research and development director of the Reef Aquaculture Conservancy.

On the outskirts of Puerto Morelos, Padilla Souza's home is nestled in the Mayan Forest, thick with the sounds of birds, and other creatures I couldn't name. We meet at sunset, and I am immediately struck by her energy. She sees the big picture.

"I'm very sure that the corals can surprise us about what they can do," she says. "Corals have been on the Earth for too many millions of years. A lot of things happen in all this history. Corals change, but they don't disappear."

Padilla Souza doesn't buy the idea that coral reefs have crossed a tipping point. "It is an arbitrary point," she says. "The problem for us is that we are seeing it over our timescales, a very short time. We are so egocentric that way." Padilla Souza prefers to think of ecological change as it is enacted over geological periods. "Species need to adapt, evolve, and I think corals are not going to disappear, they are going to change."

But the corals do need our help now, Padilla Souza says. Recovery will come

naturally when we alleviate at least some of the pressures the reef is under from pollution, disease, or warming. “The last partner we need for the collaboration is nature itself. We need to help nature, not manipulate it,” she says.

Leaving Puerto Morelos the next day, I think about the lonely grief that Alvarez-Filip and Banaszak expressed to me. Few of us have breathed air underwater or seen the magnificence of light mixing with sound and color on a tropical reef. Alvarez-Filip and Banaszak have swum in the reefs for most of their lives. I understand why Alvarez-Filip uses the language of loss to “honor the dead colonies,” to “tell their stories.” Banaszak told me she can no longer bring herself to dive on the reef, such is her pain.

The tipping point narrative is a projection of the catastrophe in store for the world’s warm-water reefs. But it is most confident when it speaks of the present moment, rather than as a forecast on the future of ecosystems we have barely begun to explore. There is a danger in the simplicity of its sticky shorthand; we risk blinding ourselves to the subtle mechanics of ecosystem resilience, something we are only beginning to measure. This could prove to be the coral reef’s greatest untold story. Something worth fighting for, even if the ending lies beyond our lifetimes. 🌀

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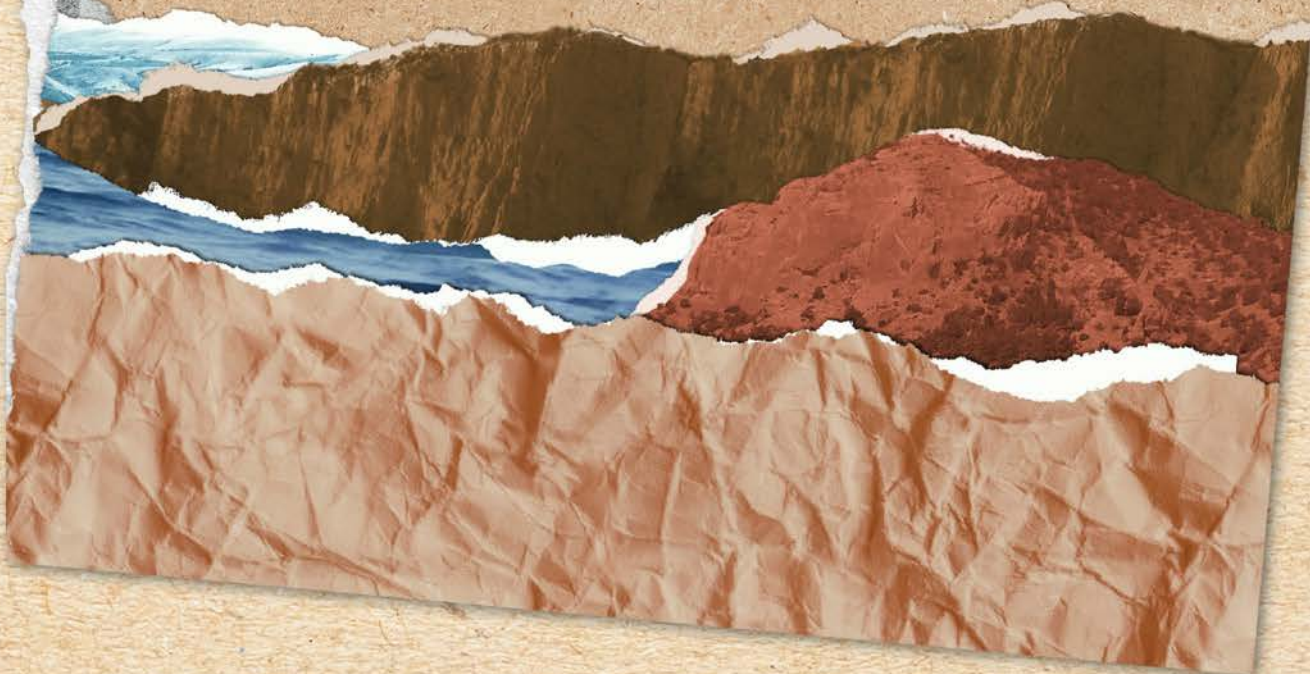
ALL SHOOK UP

*Why we think earthquakes are becoming
more frequent*

BY EVAN HOWELL



THE GROUND BEGAN TO SHAKE beneath Mineral, Virginia, on a sultry August afternoon in 2011. Dense bedrock carried shockwaves unusually far from the rolling Appalachian foothills, across the range's long, northeasterly spine. Millions of people from Georgia to Canada snapped to attention as they felt what few expected so far from America's geologically dynamic Pacific coast: an earthquake.



If earthquakes aren't more frequent—and they're not—then why do we feel that way?

The internet erupted seconds later: “OMG EARTHQUAKE!!!”, read one tweet. In the first minute, people fired off 40,000 tweets. By the fourth minute, 3 million Facebook users had posted updates using the word “earthquake.” Within eight minutes, someone created a Wikipedia page. At the peak, Twitter users were pumping out roughly 5,500 messages per second.

The magnitude 5.8 temblor was far from the largest to shake the United States—that distinction belongs to Alaska’s magnitude 9.2 quake in 1964—but was likely felt by more people than any earthquake in North American history. The quake caused an estimated \$200–\$300 million in property damage, including to Washington, D.C. landmarks such as the Washington Monument and the National Cathedral. Yet no one died, and only a few suffered minor injuries. By Californian standards, the seismic episode barely merited a shrug.

As the dust settled, a meme went viral. A cheap white plastic table and chairs sat on a sunny suburban lawn. One chair lay toppled on its back. The caption read: “2011 VA Earthquake.” Beneath it: “We Will Rebuild.”

The meme captured the disconnect: An unusual but modest event had triggered outsized attention. According to United States Google Trends data, searches for the term “earthquake” spiked during the Virginia temblor to the highest levels since tracking began in 2004, nearly doubling similar searches

regarding the devastating magnitude 9.1 earthquake and tsunami that struck Japan earlier that year, which killed about 19,000, caused up to \$300 billion in damages, and triggered the Fukushima nuclear disaster.

Unlike the Pacific Coast’s active plate tectonic boundary, the Atlantic Seaboard is considered a “passive” margin today, where earthquakes are small, infrequent, and mostly the result of reawakening old tectonic scars or rebound from vanished glaciers. Because the 2011 quake felt unusually strong for a geologically quiet region—where most Americans and media institutions reside—could it have inspired warped perceptions on the frequency and intensity of other earthquakes?

I began by asking seismologists a simple question: Are earthquakes becoming more frequent? The answer, a resounding no, came with a few exceptions (we’ll get to those). What spurred my inquiry was a discussion about how earthquakes seemed more common in unusual places, like New York City or St. Louis. But if they aren’t more frequent—and they’re not—then why do we feel that way?

IN 1985, NEIL POSTMAN described the dizzying transformation in how information travels in *Amusing Ourselves to Death*. Stories once traveled no faster than we could run. Once horseback yielded to rail, telegraph, phone, television, and eventually the internet,

information that may have taken *years* in transit now arrives nearly instantaneously. Over mere generations, our awareness broadened from the few things we could personally touch to anything we can conceive to wonder about: Many can sooner name Pluto's moons than recall their local mayor.

In our hyperconnected world, where information ricochets through our collective consciousness like a pinball, countless things compete for our attention. But attention, more than memory, is remarkably limited, says Paul Slovic, a psychologist at the Oregon Research Institute. He likens it to a spotlight with a narrow beam. We assume we can widen it or aim it at many things at once, but we can't. We can only move the beam from one target to another; everything else remains out of mind. Most of the time, earthquakes remain in the background of our awareness. Instead, we focus on the here and now, a psychic gift from our earliest ancestors who survived by responding to immediate threats.

Because I'm human, I began with a suspicion I expected scientists to confirm. I assumed the internet and the 24/7 news cycle, tuned for drama and outrage, had distorted how we think about earthquakes. Several seismologists and social scientists I spoke with immediately offered that explanation as at least part of the story, while others seemed to find the matter settled: "It's social media," one prominent seismologist said, shaking her head.

It's easy to understand those reactions. For centuries, earthquake awareness came largely from slow-moving stories that emerged from the rubble. Word of mouth gave way eventually to television, which brought visceral imagery into our living rooms. But aside from a few CC-TV security videos and "lucky" shots, quake aftermath scenes dominated—crumpled concrete and rebar, rescuers whisking away the bloody and broken.

The first televised earthquake struck during game three of the 1989 World Series between the Oakland Athletics and the home team, the San Francisco Giants. The 6.9-magnitude Loma Prieta earthquake, among California's last major tremors, killed 63 and caused upward of \$10 billion in damage. However, the live imagery was arguably far surpassed 15 years later when a devastating earthquake and tsunami struck unsuspecting beachgoers throughout Southeast Asia in late 2004. Home videos revealed something truly human: Palpable terror on

faces and body language as the seas sucked away and then surged, inundating everything. Muddy water filled with debris, animals, and people. And the *sounds*.

Now, so-called democratized videos—those that any of us can upload on the internet and share, bypassing traditional media barriers—captured *during* quakes "pop up really quickly," says USGS geophysicist and earthquake statistician Morgan Page. On March 28, 2025, a 7.7-magnitude earthquake struck Myanmar, killing more than 4,900 people. Heaps of videos appeared in the immediate aftermath. A security camera captured a fault surface rupture for the first time. In a video viewed more than 24 million times, care-free loungers in a Bangkok high-rise infinity pool—over 600 miles from the Myanmar epicenter—were clearly surprised as the earthquake sent water sloshing violently. Fortunately, they scrambled out in time, avoiding the fate of their floaties, which spilled over the edge and tumbled to the streets far below.

We now know more about devastating events that, centuries ago, might have passed unnoticed beyond the local communities that experienced them. When our world is small, once-in-a-generation events feel rare. When our awareness broadens, they can seem constant. A certain paradox therefore emerges. We may perceive the world as less stable than it is, at least statistically speaking. Psychologists refer to this phenomenon as the availability heuristic: The more readily examples come to mind, the more common they seem. For some people, a steady drumbeat of instability may manifest as low-grade unease, a sense that something is changing. Yet social scientists say nothing shapes perceptions and memory like firsthand experience.

Scientists and natural hazard communicators are divided on whether any of our expanded, technology-fueled awareness has translated into protective behavior. Many insist the public isn't adequately prepared. Others argue that people are doing about as well as can be expected given the psychological and economic realities they face. This reflects a sharp division between human experience, memory, and the slow heave of geologic time.

"I'm in the Bay Area," says Stanford University psychologist Gabrielle Wong-Parodi. "We haven't had a major earthquake since 1989. Not only is it out of scope in terms of what people remember—a lot of people here have never even experienced a [major] earthquake."

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HOW TO PREDICT AN EARTHQUAKE

We know from dense worldwide seismometer networks that the plate tectonic engine, the primary driver of earthquakes, has not meaningfully changed over our lifetime. But for geologic processes, which operate on the scale of thousands or millions of years, that's no time at all. To understand the deeper past, geologists must dig into a deeper and often murkier archive.

Katherine Scharer, a USGS geologist, has spent her entire career in the trenches, literally. She and colleagues, other paleoseismologists, contract earthmovers to dig reinforced ditches across California's most dangerous "headliner faults." I know this because she was my undergraduate advisor, and in 2006, I spent a summer working in one of those trenches along the San Andreas fault in the dusty foothills of the San Gabriel Mountains.

That summer, we labored under the hot Southern California sun, navigating aluminum hydraulic shoring meant to keep the trench from collapsing as we stood inside the earth with a quiet sense of mortality, directly atop a live plate boundary. We worked on the property of a retired man who enjoyed our company and showed vague interest in our goals. If memory serves, he even invited us inside, reminding us that "it's 5 o'clock somewhere." We probably

discussed the scientific holy grail driving the work: establishing how often earthquakes strike, and getting a rough sense of when the next might come.

Along smoothed dirt walls, geologists scan for offset—layers that suddenly jump in a stair-step up or down, evidence that a fault moved during an earthquake. To establish when that happened, they often rely on radiocarbon dating, using bits of wood or plant material plucked from the walls. By dating the offset layers and undisturbed layers above, geologists can bracket the age of past ruptures.

A single trench may reveal numerous earthquakes, some of which are known from historical records and many that predate written records. From these clues geologists estimate the timing, magnitude, and location of past earthquakes along active faults. This process is repeated in trenches across California, mapping ancient ruptures that scored the earth for miles.

While not entirely diagnostic, paleoseismologists like Scharer have demonstrated that California's transform fault network, driven by the Pacific tectonic plate as it grinds relentlessly northward against the North American plate, exhibits a certain earthquake cadence. Geologists now know that this fault network, which includes the San Andreas, is practically guaranteed to host a



IN THE TRENCHES

USGS geologist Katherine Scharer works to reveal rock and soil layers offset by ancient earthquakes.

large future earthquake. But scientists like Scharer know the risks vary substantially depending on where one works, resides, or travels across California's fractured and faulted landscape.

Geologists have established a refined story for the last 1,000 years, but the historical record is even clearer. Between 1800 and 1906, California experienced eight significant, ground-rupturing earthquakes on the San Andreas, San Jacinto, and Hayward faults. Yet over the last 120 years, "there's zero," she says. "We went from having basically one every 10 to 20 years to zero over the last 120 years." A hiatus of this length isn't unheard of in the geologic record, but it's stretching the upper limit.

That's why the USGS says "the likelihood for a magnitude 6.7 or larger earthquake somewhere in the entire region remains near certainty" over the next 30 years. In their "readiness" model, the southern San Andreas, with its visible scar slicing

roughly 40 miles from downtown Los Angeles and directly through glitzy Palm Springs, is widely considered prone to rupture. As such, Los Angeles faces a 60 percent chance of a 6.7-magnitude or larger earthquake in the next 30 years.

Paleoseismology, therefore, isn't just an attempt at cataloging. It's a science that helps us understand the stark tension between two vastly different timescales, human and geologic, that from time to time unpredictably converge.

— Evan Howell

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THERE MAY BE NO better place to understand earthquake frequency than California. The state, wealthy, densely populated, and absolutely teeming with sensors, also hosts a populace accustomed to motion underfoot. Page says Southern California's notoriously testy seismic hotbed has experienced fewer earthquakes in the last decade than it did in the 1980s and 1990s. USGS geophysicist Susan Hough agrees: In the contiguous United States, 2025 was "really quiet"—California did not experience an earthquake of magnitude 5.5 or greater. In fact, the largest earthquake to strike an area in the contiguous U.S. in 2025 was a 5.4-magnitude event in West Texas that Hough says is linked to oil and gas activities.

This is an important caveat: Some types of earthquakes have become more frequent. In Texas, Oklahoma, Kansas, and other locations, wastewater injected into deep reservoirs, mostly a secondary byproduct of fracking operations, has been linked to increased local earthquake activity. This phenomenon, induced seismicity, also appears to make earthquakes seem more common *anywhere* to the people who experience them.

Climate change also sometimes enters the conversation. Receding glaciers and changing seasonal water loads can occasionally nudge faults already near failure. But all forms of induced seismicity are highly local, minor in magnitude, and play a very distant second fiddle to the main driver of concerning quakes: plate tectonics. "It's going to be a straw that breaks the camel's back," says Hough. "But then the headline writers go to town."

Scientists know earthquakes haven't become more common in recent decades for a simple reason: They are so good at detecting them. Since the 1960s, an increasingly dense seismometer network has revealed millions of previously unnoticed quakes, sharpening our sense of a landscape that is very much alive. In Southern California alone, scientists now record roughly 10,000 earthquakes each year, most too small to feel and many that are noticeable yet rarely damaging.

When those quakes strike, a vast, automated communication network springs into action, pushing alerts and updates onto screens across the west. Mark



Benthien, the director of public education and preparedness at the Statewide California Earthquake Center, says the system, while essential for public safety, also amplifies awareness of seismic activity, detecting even tremors equivalent to "dropping an iPhone."

When the ground rumbles, information automatically passes into the Earthquake Early Warning system, which routes from the USGS ShakeAlert into millions of smartphones within seconds, via apps like MyShake. Users predefine alerts like Do Not Disturb settings: "Maybe I have it at 3.5 during the day. But at night, I

JOHN NAKATA / ADOBE STOCK



TWISTED METAL

Some of the damage from the 6.9-magnitude Loma Prieta earthquake in San Francisco in 1989.

raise that up to 4.5 or 5.0,” says Benthien. People can now receive an alert before they experience shaking, allowing them to take state-sanctioned action: “Drop, Cover, and Hold On!”

And from automated alerts come automated news: Media networks scrape the notifications and publish bot-written stories with basic earthquake information. This rapid information network is widely praised and undeniably important. It has since been replicated in the Pacific Northwest, with similar systems operating in New Zealand and planned for expansion into Alaska and Nevada.

But the system isn’t flawless. In 2017, the *LA Times* automatically tweeted about a 6.8-magnitude quake off the Santa Barbara coast—only the “new” quake was really a Prohibition-era seismic event from 1925. In December 2025, the USGS ShakeAlert system reported a 5.9-magnitude earthquake near Carson City, Nevada, generating automated news articles and smartphone alerts, just as intended. The problem? The quake didn’t happen.

Into that information flood, other voices enter. YouTube videos claim to predict the “big one” or dwell on other unlikely threats, like cataclysmic eruptions or earthquakes in Yellowstone. “You have individuals fueling this alarmism, and they’ve always been around,” says Hough. She describes how Charles Richter, the inventor of the namesake earthquake scale, kept a folder called “nuts and flakes”—those who wrote him with unconventional earthquake trigger theories, from harmonic convergence to the weather. But in those days, “Someone had to find an address and write a letter ... now, people have podcasts and Twitter channels. You get these sophisticated-looking accounts that are pushing out predictions, latching on to activity to make it sound like it’s alarming when there’s nothing out of the ordinary.”

This has prompted some scientists to take a more active online role. “People are complaining because there is nobody to answer their questions on the internet,” says seismologist Rémy Bossu of the Euro-Mediterranean Seismological Centre in France, who views pre-bunking as a vital scientific task in the online age. “If seismologists do not take their share in public information, we have an information void which allows charlatans and crooks to say whatever they want.”

WHEN I RAISED THE QUESTION of why people might feel that earthquakes are more frequent, Carnegie Mellon psychologist Baruch Fischhoff challenged me on whether that was even true. He explains that we tend to assume others are irrational when their behavior doesn’t make sense to us. Yet “people have plausible mental models of how things work,” he says.

Part of the disconnect may be related to classifications and statistics—such as logarithmic magnitude

In Southern California alone, scientists now record roughly 10,000 earthquakes each year.

scales—which, while critical to scientists, can either be confusing or carry far less weight among a public that values experience and stories. Fischhoff says many experts blame the public for misunderstanding: “It’s easy to say, ‘Oh, the public is innumerate,’ when actually, we’ve done a terrible job of communicating.” The 2011 Virginia quake demonstrated that even a relatively moderate event can lodge itself in the collective psyche when widely felt and shared online. “The magnitude cannot measure the societal importance of an earthquake,” says Bossu, who studies the public reaction to seismic events.

Paul Slovic says that humans have two distinct ways of processing risk. Risk as feeling is fast, automatic, and experiential—the gut response conditioned by direct experience. Analytical risk is slow, effortful, and abstract. That’s the likelihood of a magnitude 7.0 quake, which changes from region to region and across different time intervals. Many scientists live more in the second mode. Most people live more in the first.

The problem with earthquakes is that the gut feeling is largely unavailable to most people in most places. There’s little to no memory and no perceptible buildup—no smell, no darkening skies, no rising water to trigger the intuitive system. The only pathway to awareness is analytical, which requires significantly more effort, communication, and translation, all while fighting against more immediate demands. That’s why

even Slovic, a risk perception expert, doesn’t feel he’s adequately prepared for a major earthquake that could suddenly strike his home in Western Oregon.

As the population grows and urban areas become denser, risks naturally rise even if the underlying mechanisms remain unchanged. Even smaller quakes in places like Boston, where virtually no seismic culture exists amongst the longstanding masonry of our forefathers, could do serious damage.

Because earthquakes occur unpredictably and according to an unfathomably slow geologic clock, with recurrence intervals of thousands of years, it’s psychologically difficult to be prepared for something that could strike in the next instant—or many years from now—regardless of threat awareness.

PART OF THE PROBLEM with the public’s perception of earthquake danger is the difficulty in accurately predicting when the ground might shake again. To be clear, no one can predict earthquakes. However, geologists can establish probabilities of near-future ones, an attempt to resolve the enduring tension between how geologic and human timescales overlap. To do so, scientists like Katherine Scharer, a USGS paleoseismologist, have spent decades digging trenches across major faults, extending earthquake histories far beyond the written record. It turns out that earthquakes cluster with a rough cadence, but with long quiet periods that can lull people into a sense of safety.

“We have a pretty good handle on the last 1,000 years,” she says. But translating that into human terms is daunting. California is practically guaranteed to host a major earthquake in the coming decades, but to scientists like Scharer, that broad proclamation is not enough. She says it’s like saying, “I’m 100 percent sure in the future it’s going to rain. But where?”

Harold Tobin, a geophysicist at the University of Washington, says the public tends to therefore sort into two camps: Either they see disaster as inevitable and beyond control, or they grow complacent as memories fade or awareness never fully takes hold. “I teach undergrad students who weren’t born yet when the Nisqually earthquake happened”—a February 2001 6.8-magnitude quake that struck Seattle, killing no one. For many, the scale of an enormous earthquake along America’s famed Pacific Coast is almost too much to fathom. And so we don’t. Tobin says that’s a grave error. “We have to take these hazards very seriously. But taking them seriously means doing things to improve our likelihood of coming out well on the other side.”

Tobin points to Japan, where about 19,000 people died in the 2011 earthquake and tsunami. But it could have been much worse. Due to Japan’s interwoven culture of seismic risk and alert systems, 90 percent of people in the tsunami “death zone” fled to safety ahead of the deluge. “Familiarity breeds understanding and respect, not fear.”

MUCH HAS CHANGED in California since the last truly “big one”—the magnitude 7.9 1906 San Francisco earthquake that struck an urban setting. Now, the state boasts the world’s fourth-largest economy. Los Angeles County is home to about 10 million people. Scharer says a 7.2-magnitude quake along the southern San Andreas, likely to occur in the coming decades, could destroy major connective infrastructure between southern California and the rest of the U.S.

For Scharer, who lives in Pasadena, this impending reality occasionally hits home. “Every once in a while, I’ll be walking my dog and just the realization of how serious it is flicks through my mind. The hairs stand up on my arm. You go, ‘oh boy.’ We’re kind of untested, you know.” She added, “None of us would be surprised by a magnitude 7.8.”

“When newscasts say ‘Oh, that magnitude 4.6—that was a lot,’” says Scharer, shaking her head. “That was really small. I don’t want to sound glib or belittling in any way. It’s just that those are very small releases of energy.” Californians have grown accustomed to small and even moderate quakes, perhaps even impatient with warnings about what’s coming.

Earthquakes may seem to be happening everywhere, and that’s probably because they are—especially when our awareness broadens to a global scale. But the planet isn’t suddenly more alive. We’re seeing more of it, but not necessarily in a way that makes us more prepared. Experience is the best teacher, but most of us haven’t gotten that lesson. And even for those who have, experience can mislead. Take, for example, one of California’s last major quakes.

When the 6.9-magnitude 1989 Loma Prieta quake struck the Cypress Street Viaduct of Oakland’s Nimitz Freeway, thick concrete pillars snapped like matchsticks. The top of the double-deck I-880 began to crash down like great dominoes, enormous slabs of cement falling in stepwise fashion as people tried to outrun or outdrive them. Many did not—42 people lost their lives there, two-thirds of the total quake death toll of 63. Thankfully, with so many people at home and tuned into the World Series across the bay, the freeway traffic at 5 o’clock on a Tuesday evening was relatively light.

Like all earthquake survivors, those affected by the Loma Prieta quake didn’t share a common experience. Geology, engineering, proximity, and random luck conspired to define and even distort experience and memory. Wong-Parodi, who now studies how people make decisions under climate and environmental risk at Stanford, vividly remembers that day as a child in the Bay Area. Unlike those who stood outside their ruined homes or stared, bewildered and horrified at what they saw on the Cypress freeway, at her childhood home: “The only thing that happened was that the vase was about to fall over. That’s it. I thought it was fun. We had no school the next day. It was great.” ☺

EVAN HOWELL is a Colorado-based freelance science journalist. His work has appeared in *Science*, *Scientific American*, *Science News*, and other outlets. He holds a master’s degree in geology and spent over a decade working as a senior geologist.

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MATTHEW GABRIELE

The medieval scholar on doomsday prophecies

INTERVIEW BY KRISTEN FRENCH

THE END OF THE WORLD

People have always thought the end was coming. Can we put historically confident numbers on how many? That's a little bit more problematic. But there's certainly textual evidence, artistic evidence, and other cultural artifacts that show that end-of-the-world thinking has been around for a long time, and that's true across different monotheistic religious traditions, such as Christianity and Islam.

DEFINING AN APOCALYPSE

The problem of definition has troubled scholars of apocalypse for a long time. The term apocalypse comes from the Greek *apokálypsis*, which translates as revelation, an unveiling of a truth. So it's not necessarily about disaster, or catastrophe, but certainly in the 20th and 21st century, it's taken on that meaning.



But what people who live in the United States and Canada in the 21st century consider the end of the world is probably not the same as what anybody in the past would've considered the end of the world, before the threat of nuclear annihilation, climate calamity, and global pandemics became a possibility. If you asked an atomic scientist what the end of the world looks like, they're going to say something different than an evangelical pastor.

SELF-MADE ANNIHILATION

In the 1940s and 1950s, the world became preoccupied not just with Hiroshima or Nagasaki, but the arms race of the early Cold War—the possibility that we could have a nuclear war triggered between the U.S. and Soviet Union that could annihilate not just those countries, but life on Earth. Before that time, death on that scale was almost impossible. The exception was the flu epidemic that killed millions across the world in 1918. That led to end-of-the-world speculation. But the plague is an old idea that goes back to ancient Egypt. It's talked about in the Book of Revelation, and it's talked about within other traditions as well.

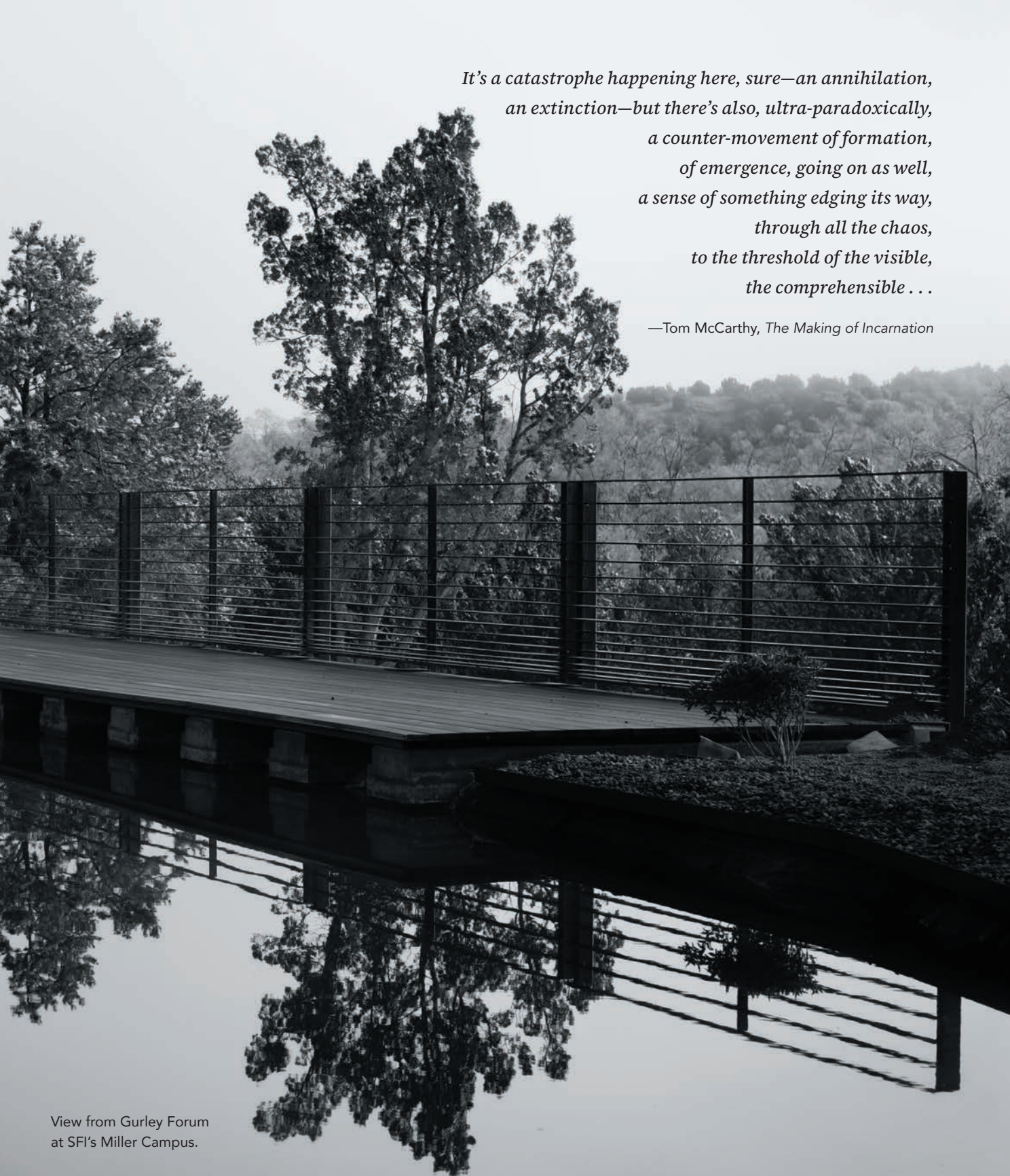
Concern about the end of the world has always been with us. But the change from belief that something theological would drive it, to the possibility of human-made destruction, is absolutely new. That shift seems to have excited more speculation because there's just more ways that it could happen. The Doomsday Clock, for instance, is super close to midnight right now. But that's a purely secularist kind of participation in end-of-world thinking. Trying to time the end in this way had traditionally been a theological speculation. ☺

COURTESY OF VIRGINIA TECH

[illegible]

*It's a catastrophe happening here, sure—an annihilation,
an extinction—but there's also, ultra-paradoxically,
a counter-movement of formation,
of emergence, going on as well,
a sense of something edging its way,
through all the chaos,
to the threshold of the visible,
the comprehensible . . .*

—Tom McCarthy, *The Making of Incarnation*



View from Gurley Forum
at SFI's Miller Campus.

Novelist Tom McCarthy has been a Miller Scholar at the Santa Fe Institute since 2022. The Miller Scholarship is awarded to highly accomplished, creative thinkers who make profound contributions to our understanding of society, science, and culture.



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