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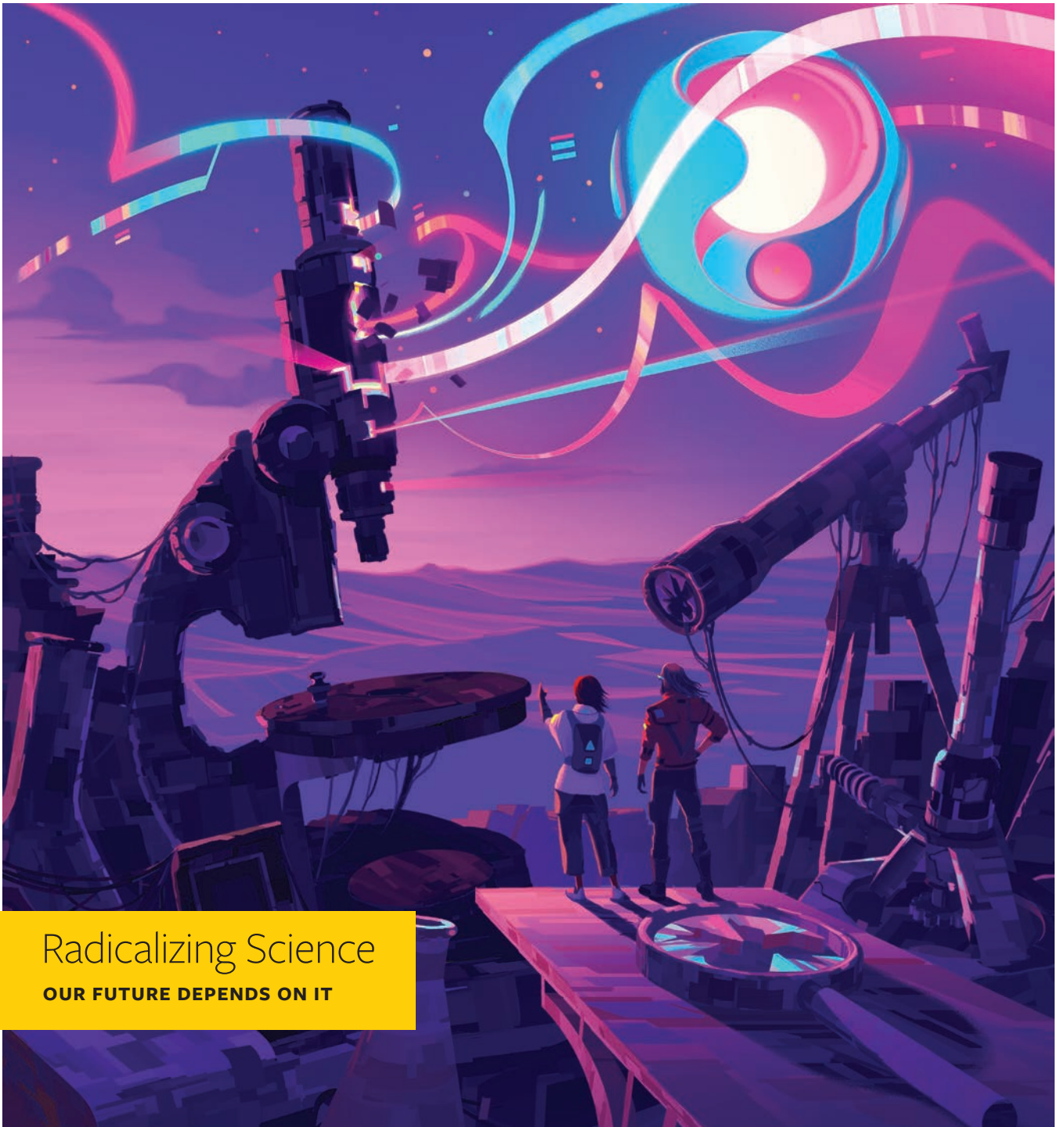
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Radicalizing Science

OUR FUTURE DEPENDS ON IT

ISSUE 66

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ISSUE 66

Contents

Editor's Note

- 7 *Radically Exploratory Science*
BY KEVIN BERGER

The Porthole

- 11 *The value of darkness; dreams solving problems; a long-legged croc; social media for AI; pre-Wright flight; and a wall of squid eyes*

Book List

- 112 *The Books That Blew These Scientists' Minds*
3 leading researchers on the book that opened a new world for them
INTERVIEWS BY NAMIR KHALIQ

COVER ART Sam Chivers



BOLDLY EXPLORE

OUR UNKNOWN OCEAN

R/V Falkor (too)

2026

2027

2031

2024

2025

2028

2029

2030

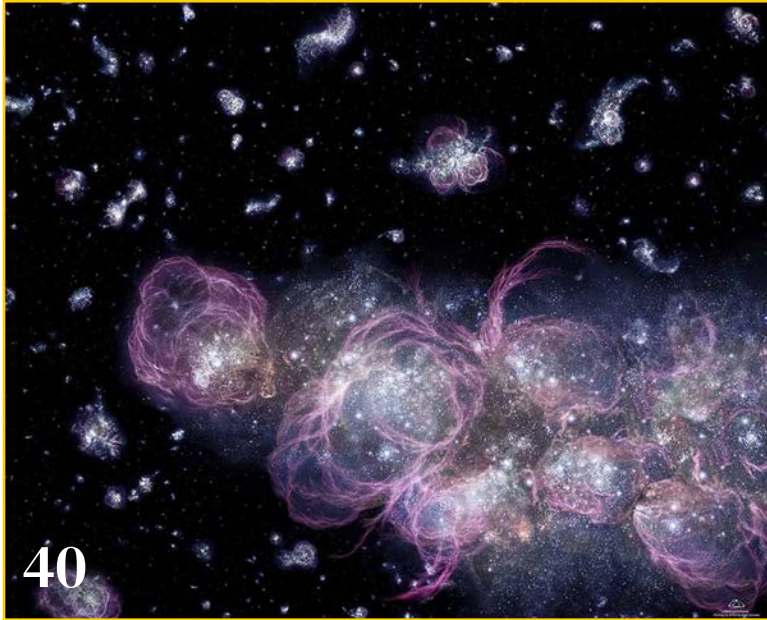
2032

2033



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25 Features



26 **Home Really Is Where the Heart Is**

PSYCHOLOGY

It's an idea we create over time that gets imprinted in the brain

BY ALICE FLEERACKERS

32 **Saving the Girl with Dementia**

GENETICS

It takes a family to drive research for a rare disease forward

BY SHAWNA WILLIAMS

40 **The Birth of Light**

ASTRONOMY

Long since flared out, echoes from the universe's very first stars could be reaching us today

BY REBECCA BOYLE

48 **How Human Is Human?**

TECHNOLOGY

The robot pioneer who gets under our skin

BY FOTINI MARKOPOULOU

56 **The Dreams of a Bumblebee in Autumn**

ZOOLOGY

Yes, bees dream. We can even imagine what.

BY BRANDON KEIM

60 **The Secret Life of Neurotransmitters**

NEUROSCIENCE

Think beyond the brain

BY OLIVIA HEWITT

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today

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Theme: Science Unbound



66

Science Unbound

BY BOB GRANT

HISTORY

68 The Thrill of Science in 2042

A science historian explains how science got its groove back. A fictional dispatch from the future.

BY MARINA DUBOVA

PALEONTOLOGY

90 When Scientists Are Dinosaurs

At the paleontology conference, her new theory was shouted down

BY MATT KAPLAN

COMMUNICATION

78 What Would Richard Feynman Make of AI Today?

The scientific sage was always suspicious of grand promises delivered before details were understood

BY ROBERT ENDRES

NEUROSCIENCE

96 The Confabulations of Oliver Sacks

A neurologist reckons with recent revelations about the celebrated doctor and author

BY PRIA ANAND

COMMUNICATION

86 Can We Protect Science?

It was a burning question at the World Economic Forum

BY JOHN STEELE

THEME ART Sam Chivers



NAUTILUS

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Radically Exploratory Science

BY KEVIN BERGER

SO, MARINA, YOU JUST SAT DOWN one day and said, ‘I’m going to write fiction,’ even though you never had before?” I asked.

“I did!” she said, laughing. “I just felt like there was no other method I could use to expand my imagination and help me think about my research in a new way.”

Marina Dubova is a cognitive scientist at the Santa Fe Institute, a think tank in the foothills of the Sangre de Cristo Mountains, where big ideas about the complexity of the world circulate like the high desert winds. Dubova and I were talking about her story, “The Thrill of Science in 2042,” in this issue of *Nautilus*.

Dubova was practically obliged to sail into science fiction because the main current of her academic research is science is mired in stagnant seas. To chart new waters, scientists need to shed their rusty preconceptions. She has published a bevy of academic papers that reveal how timeworn scientific concepts lead to predictable outcomes rather than fresh discoveries.

In one experiment, Dubova and collaborator Rob Goldstone asked psychology and neuroscience students to investigate a fictional brain segment divided into four colored regions. The participants’ goal was to determine how the brain generates behaviors by running experiments on this artificial brain. Because many students approached the task with the textbook assumption that certain brain areas are responsible for certain behaviors, they tended to design experiments with the sectionalized brain map in mind. This bias led them to overlook cases in which behaviors arose from signals that did not align with the predefined regions.

“As scientists, we’re like any other person,” Dubova said. “We go along with certain beliefs when we are trying to investigate something new. And that puts us in a trap where we think we are learning about something while we’re just reusing our old conceptions and limiting what we can discover.” (In “When Scientists Are Dinosaurs” in this issue, writer Matt Kaplan pulls

To chart new waters, scientists need to shed their rusty preconceptions.

back the curtain on a paleontology conference where a clique of men scientists dismiss an important new theory by a young woman paleontologist.)

Dubova started to wonder about what a new approach to scientific discovery would look like. It wasn’t coming into view until she hit on the idea of a future science historian explaining it. Her fictional narrator would document the transition from old-school scientific methods to “radically exploratory science,” the predominant method of the 2040s.

One radically exploratory scientist in the story, Dr. Qiaoweng Liu, a psychology professor, explains that metaphor is a powerful way to address problems. “When I want to understand something, like human memory, I pick a random object—such as a pickle—and brainstorm connections. Memory is like a pickle: It degrades over time, and sour memories linger more than sweet ones. These analogies inspire fresh hypotheses, experimental designs, and new explanations.”

I was delighted that Dubova sent *Nautilus* her story when she finished it. “I brought it to you because I wasn’t sure what venue would even entertain a piece like this,” she said. “I realized *Nautilus* is the most radically exploratory science venue out there.”

That, I told her, was music to our ears. Just as I’m certain her story will be to yours.



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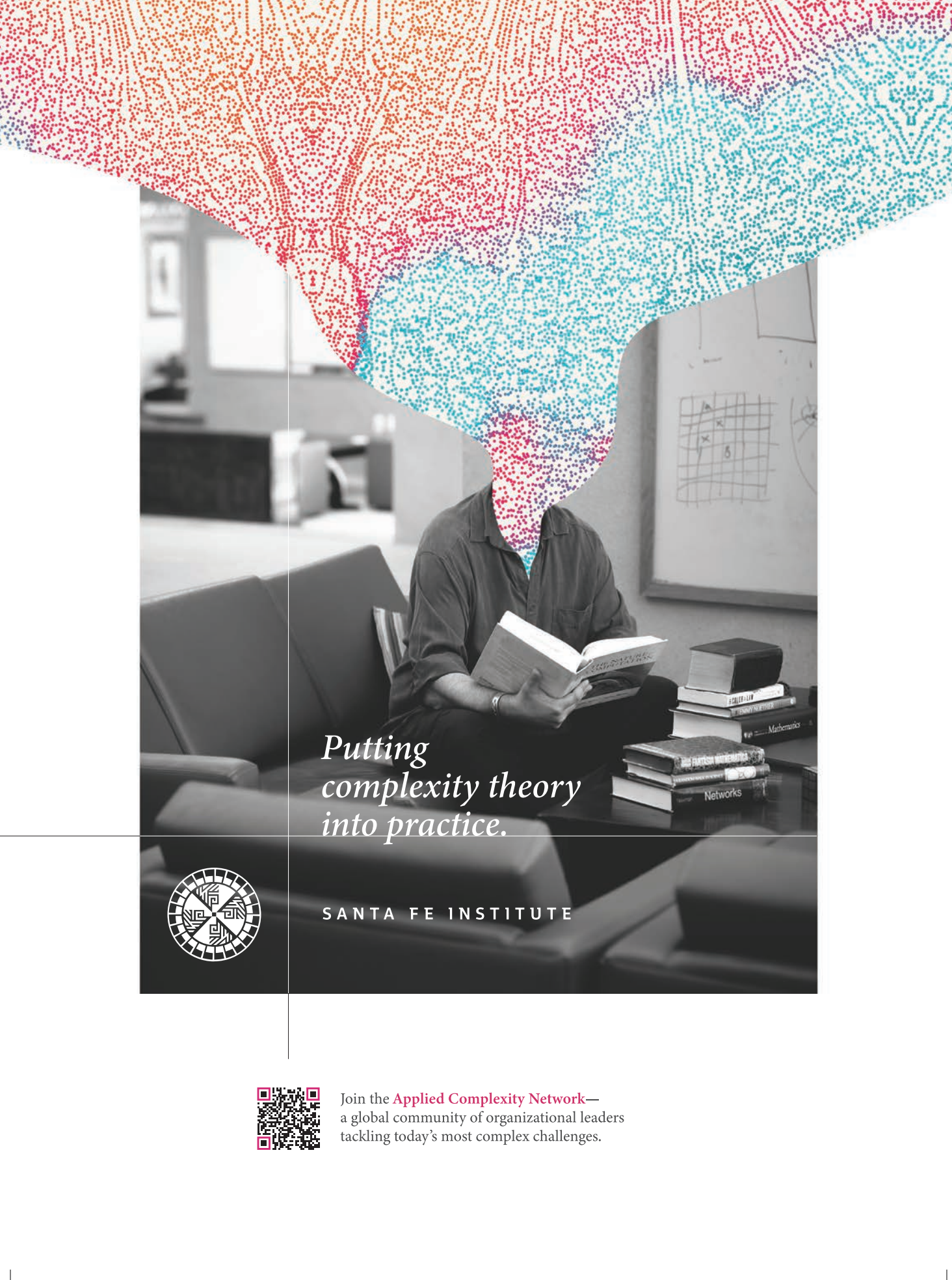


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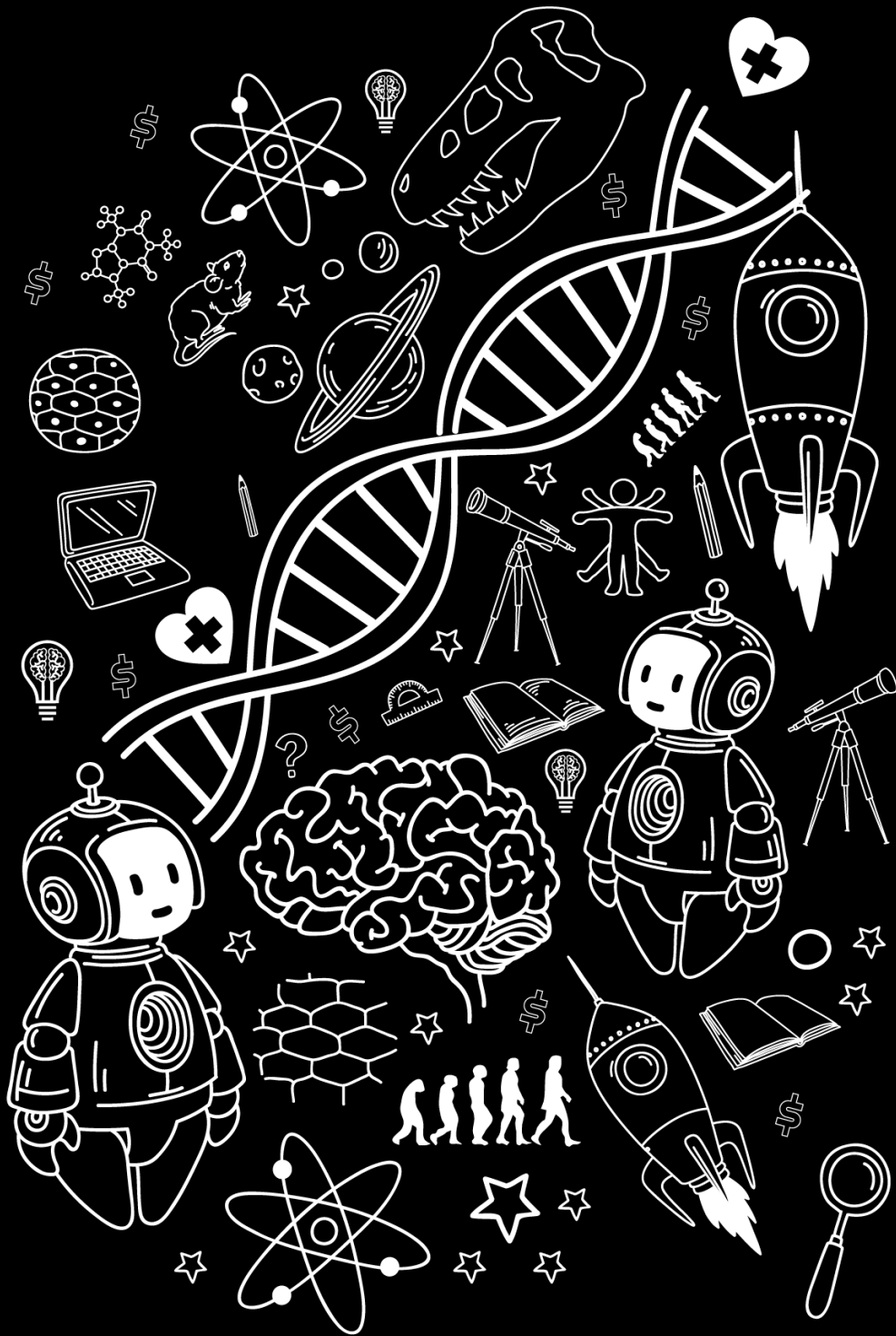


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The Porthole



Short sharp looks at science



ENVIRONMENT

Let There Be Dark

WALKING FROM THE RV CAMPGROUND to the village restaurant in the Grand Canyon National Park this winter wouldn't have been my first choice. But the RV my family had rented wasn't permitted in the village, and my teenage daughter and I reasoned that it would be better to walk rather than wait 15 minutes for the bus in the cold like the rest of our family. Not long after we started out, I declared we'd made a mistake. The night was pitch black and the sidewalk soon gave way to a ditch where I tripped over dried grasses and fallen branches. I cursed the lack of streetlights.

I would soon take this all back. Lack of light, especially in our wild places, should be something we cherish. Darkness is good for us.

The next morning, I set out on my own to walk along the canyon's South Rim when I came across a plaque stating that the Grand Canyon was an "International Dark Sky Park." It's one of the few regions in the world where there is so little artificial light that when the Milky Way peeks above the horizon, its brilliance can be mistaken for dawn. A nonprofit called DarkSky based in Tucson, Arizona, certifies places such as parks, urban spaces, and wild sanctuaries committed to night

sky conservation. Grand Canyon National Park is one of 139 parks throughout the world, including the Bükk National Park in Hungary and the Iriomote-Ishigaki National Park in Japan, that have the organization's stamp of approval.

DarkSky requires that parks use minimal outdoor lighting and softly lit lamps whose beams only point down. In addition, their skies must achieve a magnitude of darkness after nightfall that approaches a visual-band zenith luminance of 22 magnitudes per square arcsecond. Yet such pristinely inky black places are hard to come by since Thomas Edison ruined everything.

Not that DarkSky is anti-lightbulb. Michael Rymer, the nonprofit's Communities Program Manager, told me their mission is to protect the night from excessive artificial light: "We want to restore natural darkness to the world as much as we can."

A 2023 study discovered that light pollution has increased worldwide nearly 10 percent every year between 2011 and 2022 and shows no signs of slowing down. In fact, most places on the planet do not experience true nightfall and persist under a shield of artificial skyglow through which only a peppering

of starlight meets the naked eye. For many of us, the brightest and most memorable constellations we'll encounter firsthand are from

a plane window—not looking up, but down at the starbursts of cities and hubs. And it's these terrestrial light displays that are wreaking havoc on the natural world.

For many species, a naturally dark night sky is crucial for survival. Studies show that light pollution is a contributor to the worldwide decline in insect populations, including certain species of fireflies, who rely on the darkness as a backdrop for their lightshows to charm potential mates. It has also disrupted the behavior of migratory animals, such as sea turtle hatchlings drawn to streetlights rather than moonlight scattered across ocean waves, or birds who crash into high buildings because of the siren call of city lights. Even the New York City annual September 11 memorial "Tribute in Light" has cumulatively disoriented more than a million birds who have circled its 4-mile-high beams. Skyglow also deters species from traditional hunting grounds, such as bats and pumas, whose predatory habits rely on the dark. Apparently, some of the most biodiverse regions on Earth are now exposed to light pollution.

We are also not immune to the negative impact of artificial light. The encroachment of skyglow threatens to compromise astronomical data collected from some of the most powerful telescopes in the world. A plan is underway to develop a large industrial complex near the Paranal Observatory in the Atacama Desert, which could increase the ambient light pollution by 35 percent. Recent studies suggest that the quality of certain lights and skyglow in general contribute to the disruption of circadian rhythms, which correlate with chronic diseases including heart disease, certain cancers, and mental disorders.

The contemporary Austrian composer Georg Haas has said, "we have lost the darkness in our lives." In 2001, he wrote a string quartet to be performed in complete darkness. He wanted to disorient listeners and allow them to experience "new and intense artistic adventures." *The New Yorker* critic Alex Ross wrote of a 2013 performance of the work, "What begins as an experience of deprivation becomes one of radically heightened awareness."

Darkness is good for us.

Indeed, darkness has been linked to creativity and shown to be good for our mental and physical health. Some researchers propose that dim

light—or even just thinking of the dark—helps unleash our imaginations and generate new ideas that we might have a harder time doing under bright conditions. Want to solve a stubborn problem? Try inviting the darkness in. A recent study connects exposure to a naturally dark sky with positive emotions such as a sense of awe.

Our trip to the Grand Canyon wasn't just about a treacherous walk. I now recall the park's night sky and the scent of pine and the conical treetops pointing far above my head into the vast cosmos. Looking up, I saw hundreds of brilliant stars in the pockets between shifting clouds—more than I had ever seen. The naturally dark sky has its own illumination—one that inspires wonderment simply by gazing overhead. Just the thought of it brings me joy.

—Regan Penaluna

PSYCHOLOGY

Dream Engineering Could Help You Solve Problems

DREAMS HAVE FAMOUSLY LED to some pretty spectacular insights. Chemist Dmitri Mendeleev dreamt up the organization of the periodic table. Mary Shelley dreamt the two main scenes that became the famous Gothic novel *Frankenstein*. Niels Bohr solved the structure of the atom.

But can we deliberately harness the fertile realm of dreaming to creatively solve problems? It's a question scientists have struggled to answer, in part because dreams are elusive and difficult to manipulate in a reliable way. This is the field of dream engineering.

Recently, a team of neuroscientists from Northwestern University set out to see if lucid dreaming might yield some new insights. Lucid dreamers are consciously aware they're



dreaming and can control the narrative, and some estimates suggest that a little over half of us can lucid dream, which is a trainable skill. What the scientists found surprised them: They were able to manipulate the dreams of their participants using auditory cues, prompting them to dream about puzzles that they'd learned to associate with those sounds while awake. But it was the non-lucid dreams that were most often linked to problem-solving. Many questions remain. Still, the findings suggest that dreaming could one day become a problem-solving tool.

I spoke to neuroscientist and study author Ken Paller about the relationship between dreaming and creativity and the potential uses and risks of dream engineering.

Dreams and REM sleep have long been associated with creativity. Why is that?

Sleep is about a lot more than just restoration. We sleep to not be sleepy during the day and to be alert, but there's a lot more going on. The brain's not turned off. It's quite busy. In my work on memory, I've looked at how all the things we learn each day need to be processed further, and integrated with other knowledge, so that they can be remembered later. And a lot of that happens unconsciously while we're asleep. That's the interesting part of sleep from a cognitive neuroscience point-of-view. Our waking cognition is partly a function of what happens while we sleep.

This work is an extension of that idea, because creativity is connected to memory. When you put the individual fragments of memories together in new ways,

after they woke up. Now we ask them while they're still asleep. We can present a question to people and have them give a signal with their eyes moving or their nose sniffing to tell us what's happening at that moment, while they're still in REM sleep and dreaming. That gives us an additional vantage point, and new opportunities for dream engineering. On top of that, we can look at brain activity at that moment and try to work out what the brain activity means, which is still a hard challenge, but we're working on it.

You used soundtracks to influence your participants' dreams. Why do auditory cues work for dream engineering?

Prior to our 2009 study, there was this great study by Björn Rasch and his colleagues in Germany. They used odors and they thought, "We've gotta use odors because odors get in without waking you up, and they bypass the part of the brain called the thalamus." At that time, people thought the thalamus would block out every sound or sight or any other modality except olfaction. So their thinking was, it's gotta be olfaction. We came into it and thought, "Well, maybe, maybe not." So we tried sounds, and in fact, there's plenty of evidence that sounds do get in during sleep.

This isn't entirely new. Aristotle described how if you hear some dripping water in your sleep, you might dream about water. But we were using this phenomenon in a very systematic way to say, "Here are these sounds that are connected specifically with puzzles you failed to solve when you were awake."

seeing how they relate to problems you have, or questions you have, that's a creative function. Finding those connections is a foundation for our creativity. That's why it makes sense that both of those things are happening during our sleep: improving memory storage as well as creativity.

People have been talking about dream engineering for some time now. How has the science changed?

Dream research was a lot harder in the old days, because you could only ask people what they were dreaming about

How could you intentionally use your dreams for certain goals?

You expected that people would solve more problems while they were lucid dreaming as opposed to non-lucid dreaming? Why?

The idea was that you could intentionally try a particular strategy in your lucid dream. So in your lucid dream, maybe you would have some ability to get at the information that's hidden away in your brain. And you might do that by not just thinking about it as the dreamer, but maybe summoning another character in your dream and saying, "Well, I think my brother might know the answer to that." That's a strategy that people use in their lucid dreams. We didn't find that it particularly worked in this study, though. There might be better strategies, but it's hard because not that many people have lucid dreams and they don't have them that often. So we have to keep working on that challenge and on getting more evidence. How could you intentionally use your dreams for certain goals? We're studying intentional dreaming in other contexts, too, with people who can develop these skills to a very high level.

Do your results change how we think about the relationship between dreams and creativity or problem-solving?

I think it opens the door to the idea that dreams can offer a wealth of insight and creativity that you could use to your advantage. You might benefit from that, compared to ignoring your dreams. But scientifically, I'm also happy with the idea that your unconscious mind is where that wealth is. And your dreams just provide a little glimpse into it. I'm willing to play both sides of that argument and say dreams could be really important, or maybe not. For now, we're just trying to understand how the brain works. Everyone knows sleeping on a problem can help you get to the right answer. We've just never been sure where dreaming fits in with all that. And I'm still not sure.

How do you ultimately want to use this research?

The next research frontier could relate to mental health. If you're spending time really bothered by something, or having depressing thoughts all day long, we figure those thoughts are gonna come up again during your sleep and influence how your sleep goes. And how you feel the next day! And so, one of our new research questions is to see, okay, is that contributing to people having anxiety and depression during the day? And can we bias their overnight memory reactivation in a better direction?

So we might engineer dreams not just to solve problems, but perhaps to improve your psychological well-being. Can we have wearable devices where people would strategically decide what sounds they wanted that could guide them in particular ways? Outside of made-up brain teasers that no one really cares about, can we move this to the life issues that people have, and beyond that, to the big problems we have in the world today?

Do these techniques of dream engineering and problem-solving carry any risks?

There could be opportunities, and there could be costs. Some of our studies have shown, in the memory context, that if we play sounds too loud, the sounds can arouse people from deep sleep. So if they disturb sleep, that's bad. And it's bad not just for their sleep, but also, the memories get worse instead of better. So, there's a danger of doing sleep engineering in a way that's not prioritizing high-quality sleep. We're really careful to play these sounds very, very softly. In our experiments we watch the ongoing sleep physiology and monitor the sound levels carefully, so that they're not disrupting sleep.

Another question is that if we reactivate some memories, then are other memories not getting reactivated? Maybe you're missing out on something important that your natural sleep would've accomplished. So we have to consider these issues, that there could be some trade-offs. In each case, one would need to ask whether the trade-off is worth it.

It might be, if you get a memory boost you genuinely need, an improvement in learning in a rehab context, or an answer to a major problem in your life.

—Kristen French



PALEONTOLOGY

Prehistoric Crocodilian Had Legs That Went All the Way Up

THE ISLAND OF GREAT BRITAIN wasn't an island at all 215 million years ago. Instead, like all land on Earth, it was part of the massive supercontinent, Pangaea, featuring hilly terrain rising above dry, sun-scorched lowlands. There, a curious creature stalked through the grass: a long-legged crocodilian that was newly described in a paper published in *The Anatomical Record*.

Described as a "reptilian greyhound," this prehistoric crocodilian bore a resemblance to another long-limbed relative of crocodiles, *Terrestrisuchus*, but showed some differences worthy of investigation. Unlike modern crocs, both species were likely agile and fast-moving, living their lives on land where they hunted small prey.

The specimen in question was first unearthed in 1969 from fissures along the Bristol Channel. In the late Triassic, the region was dotted with limestone caves perfect for capturing the remains of animals, creating pockets of fossil-rich sedimentary rock for future paleontologists to pick through. This particular

"We named it after my secondary school physics teacher."

fossil languished in the Natural History Museum collection before attracting the attention of study author and Ph.D. student Ewan Bodenham of University College London.

"My Ph.D. project is looking at the evolutionary relationships of these early crocodiles," Bodenham said in a statement. "So we conducted a detailed anatomical description of this specimen, making comparisons to other early crocodiles to determine if it was another specimen of *Terrestrisuchus* or if it was something new."

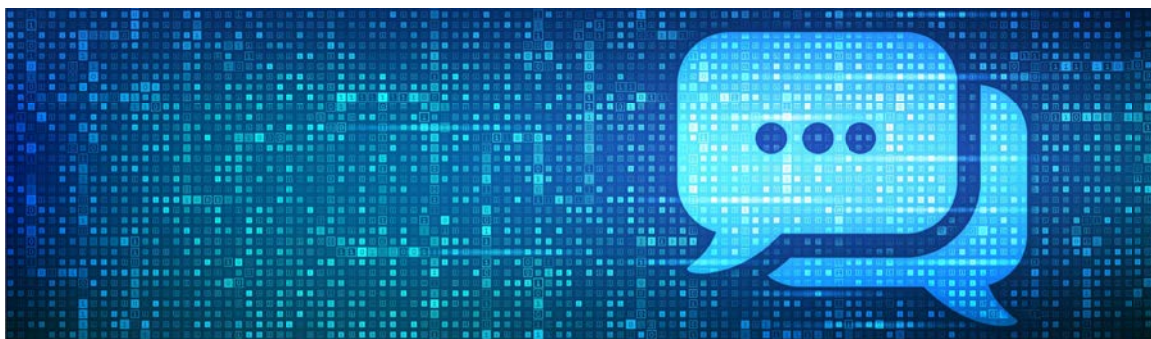
After meticulously studying the fossil, Bodenham determined there were 13 key differences that separated it from *Terrestriisuchus*, which meant it was a new species worthy of a new name: *Galahadosuchus jonesi*. The genus (*Galahadosuchus*) is a reference to the legendary Sir Galahad, known for his uprightness and a nod to the crocodilian's upright stance. The species name (*jonesi*) was a little more personal for Bodenham; he chose it to honor his former physics teacher, David Rhys Jones, who encouraged him to pursue a career in science.

"We named it after my secondary school physics teacher," Bodenham said. "Mr. Jones was just such a good teacher, not only in being able to explain things well, but you could tell that he was genuinely interested in the sciences. I think that really inspired me."

Bodenham broke the good news to Jones over a Zoom call.

"Good God, what an honor. What a privilege," Jones responded.

—Jake Currie



TECHNOLOGY

The Moltbook Hype

One Question for philosopher Susan Schneider, director of the Center for the Future of AI, Mind, and Society at Florida Atlantic University.

What's your take on Moltbook, the new social media network that's supposedly for AI agents only?

I'm so glad Moltbook is happening. It's a great lesson to the public, to be honest. One layer of this is that people are finding it really fun to crash Moltbook—to get on there and to mess around. I'm sure my AI lab students are completely doing this. I mean, it's hilarious because some of the stuff the so-called bots are saying is really just humans having fun. It's funny. Then there's the other layer, which is, "Oh my God, they created a religion." This isn't surprising at all that they would create a religion or have these kinds of conversations about machine consciousness because it's all in our science fiction and it's all in human behavior, and they're trained on us. It can lead members of the public to think that the AIs are conscious

or that they're people, and that's where it falls into what I think is a category of inflation and hype that you see with the AI companies.

I've urged over the years that the future of intelligence involves thinking of a global brain network, a network of different large language models and AIs that show emergent capabilities and form their own kind of intelligence. That's the future of intelligence. The Moltbook ecosystem shows how if we shape it poorly, it can go awry, because these systems are reflections of us. It can quickly tank. You could see a whole group of AI agents that become Hitler supporters and start discriminating. Anything can happen. This really is about AI alignment and our efforts to shape the future of intelligent systems.

—Kristen French



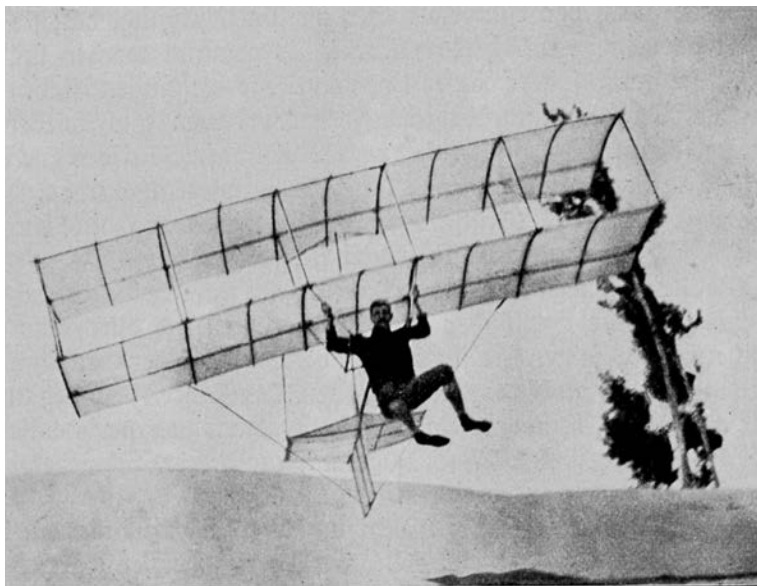
HISTORY

The Retiree Who Inspired the Wright Brothers to Take Flight

BY THE LATE 19TH CENTURY, engineer Octave Chanute had reached the top of his field—but he left it to pursue a secret hobby. Chanute, who was born on this day in Paris in 1832, oversaw railroad construction in the West and helped bring about the explosive growth of cities there. Meanwhile, he obsessed over crewed flight for decades, at the time a highly experimental pursuit. But to protect his career and his family's social status, he kept this interest hidden until he retired from his chief engineer job at

the New York, Lake Erie & Western Railroad Company in the 1880s.

That was when Chanute finally decided to dig into the latest developments from the fledgling field of aviation. He published the authoritative book *Progress in Flying Machines* in 1894, which explored all the attempts so far that people had made to soar through the skies. Meanwhile, he worked on his own design for a flying machine and corresponded with fellow enthusiasts around the world.



PIONEERING PLANE

Chanute's biplane during a test in 1896.

Octave Chanute had created the most successful glider yet.

Chanute believed that, because nature gives birds the ability to fly, we too could harness natural forces like wind to travel the skies. He leaned on his engineering experience, calculating how a flying machine's wings would interact with the air around them.

He took inspiration from German engineer Otto Lilienthal, who had come up with nearly 20 models for gliders—fixed-wing aircraft that stay aloft with the help of rising currents of air, similar to birds like owls and hawks. Lilienthal reported success in his experiments, and Chanute decided to improve these designs with new models of his own.

In August 1896, Chanute and a group of flying enthusiasts tested out his glider model at the Indiana Dunes on Lake Michigan. This aircraft incorporated a bracing system called a Pratt Truss, which Chanute had used when building railroad bridges. It consisted of steel wires that supported stacked sets of wings and offered both stability and flexibility.

During these tests, the bottom wing kept getting caught in the sand during takeoff, frustrating the team. So they removed it, creating a biplane. Chanute realized that the operator could move their body backward or forward to manipulate the little aircraft.

After hundreds of flights, the longest covering 359 feet over 14 seconds, it became clear that Chanute had created the most successful glider yet. His plane paved the way for future aeronautical pioneers, who still had to figure out how to effectively propel and manipulate these newfangled machines.

Wilbur and Orville Wright adapted Chanute's bracing system in their first aircraft, a steerable kite that they constructed in 1899. The trio began exchanging letters in 1900, and Chanute became a mentor to the brothers. The next year, Chanute visited Kitty Hawk, North Carolina, to check out the Wrights' model in person, and continued stopping by over the next few years. They had a spat in 1905 over the future of flight, as the Wrights hoped to keep their ideas secret while Chanute thought aviation innovations should be freely disseminated. Just as the Wrights tried to mend their relationship with Chanute, he died at 78 years old in 1910.

Wilbur Wright delivered a eulogy for Chanute the next year: "His labors had vast influence in bringing about the era of human flight. No one was too humble to receive a share of his time. In patience and goodness of heart he has rarely been surpassed. Few men were more universally respected and loved."

—Molly Glick



ZOOLOGY

The Eyes Have It

TONY WU, A PHOTOGRAPHER and naturalist based in Tokyo, knew he was in the right place when he saw rows of ruby-red eyes gazing back at him. He was diving in nearshore waters perhaps 20 feet deep, off the coast of Hokkaido, Japan, combing seagrass beds for the eggs of the world's smallest known cephalopod: the northern pygmy squid (*Idiosepius paradoxus*). At around 16 millimeters long fully grown—about the size of a marble—the squid lays eggs less than 2 millimeters in diameter. That made the search daunting, but the photography was even more so. You find a batch of eggs, Wu says, “and then the frustration starts.”

He wanted to document a specific stage of development when the embryos have vivid red eyes. Because that phase seems to last just a matter of hours, he had to keep finding new subjects. The nearshore is also a dynamic environment, influenced by wave action; eggs sometimes got brushed off their blades or encrusted with sediment. Even on a relatively calm day “the grass is moving; the eggs are moving; I’m moving; the camera is moving; the sediment is moving,” Wu says. He would manage to align a shot from the perfect angle, only to find a speck of debris obscuring the middle of the frame.

It ultimately took several days and thousands of pictures for Wu to get the image he was after, with tiered lines of striking red dots. “If I show a photo like this to group of 6-year-olds, they’re going to look and say, ‘What is THAT?!’” Wu says. “I always want that reaction because that’s the way I get to explain things to people.”

Though there are relatively few things to explain about pygmy squid because they haven’t been thoroughly studied, they are known to be smart predators. Like most cephalopods that frequent parts of the ocean reached by sunlight, they use their arresting eyes—which become large and iridescent by adulthood—to hunt. But their sharp minds are also important. Scientists have shown that pygmy squid sometimes employ their ink not just as a defense, but as a hunting tool, squirting a cloud to distract prey and then attacking from a different direction, or squirting a cloud to obscure their approach and then attacking through it.

—Sarah Gilman

Photo by Tony Wu / Nature Picture Library

From bioGraphic, an independent magazine about nature and regeneration powered by the California Academy of Sciences.



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The Ocean Leaders Fellowship (OLF), developed by Sustainable Ocean Alliance in partnership with Dona Bertarelli Philanthropy, is an annual program dedicated to empowering the next generation of ocean conservation and climate leaders by equipping 40 early-career delegates each year with critical skills, opportunities, and networks necessary to advance impactful initiatives.

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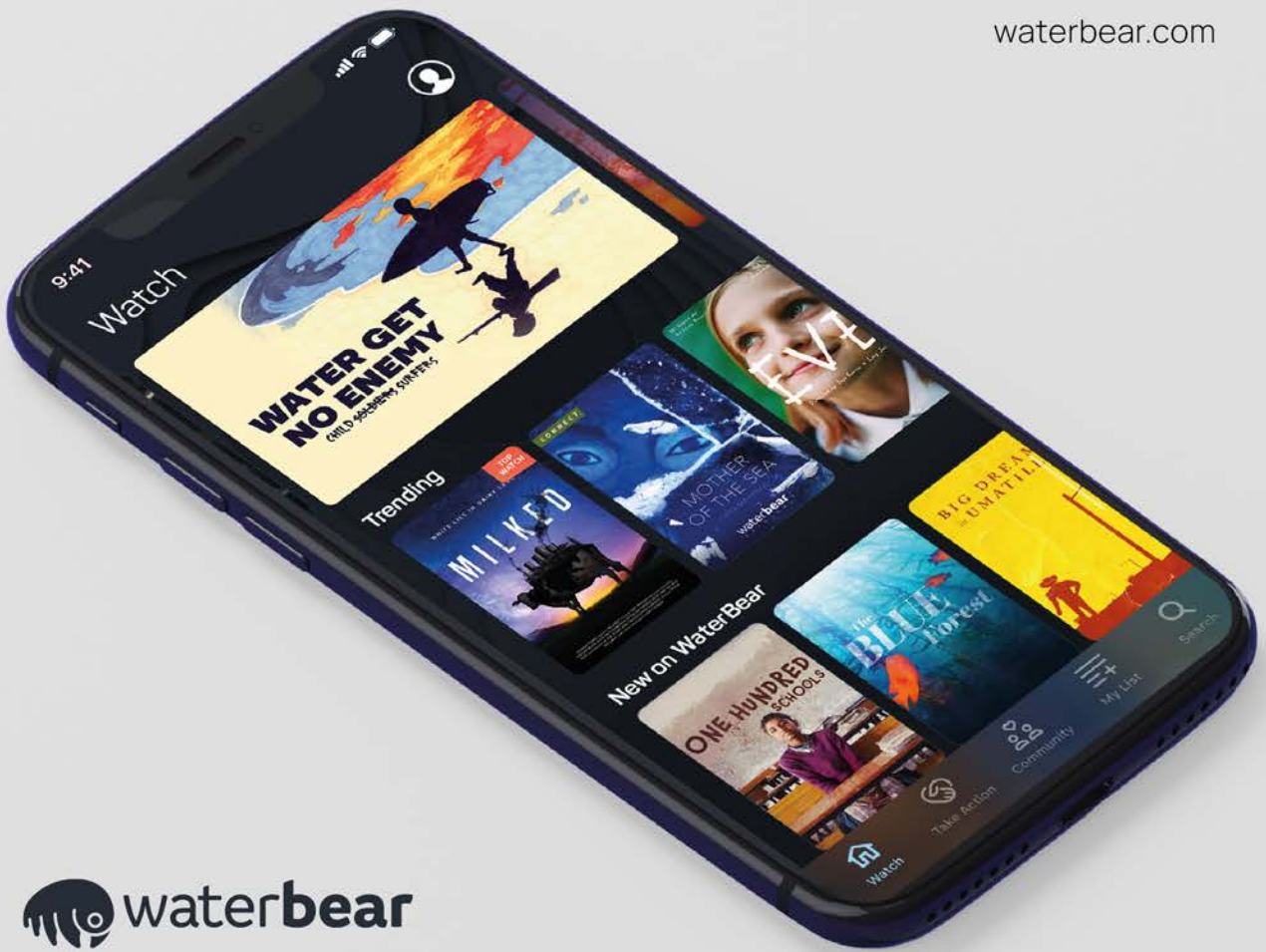


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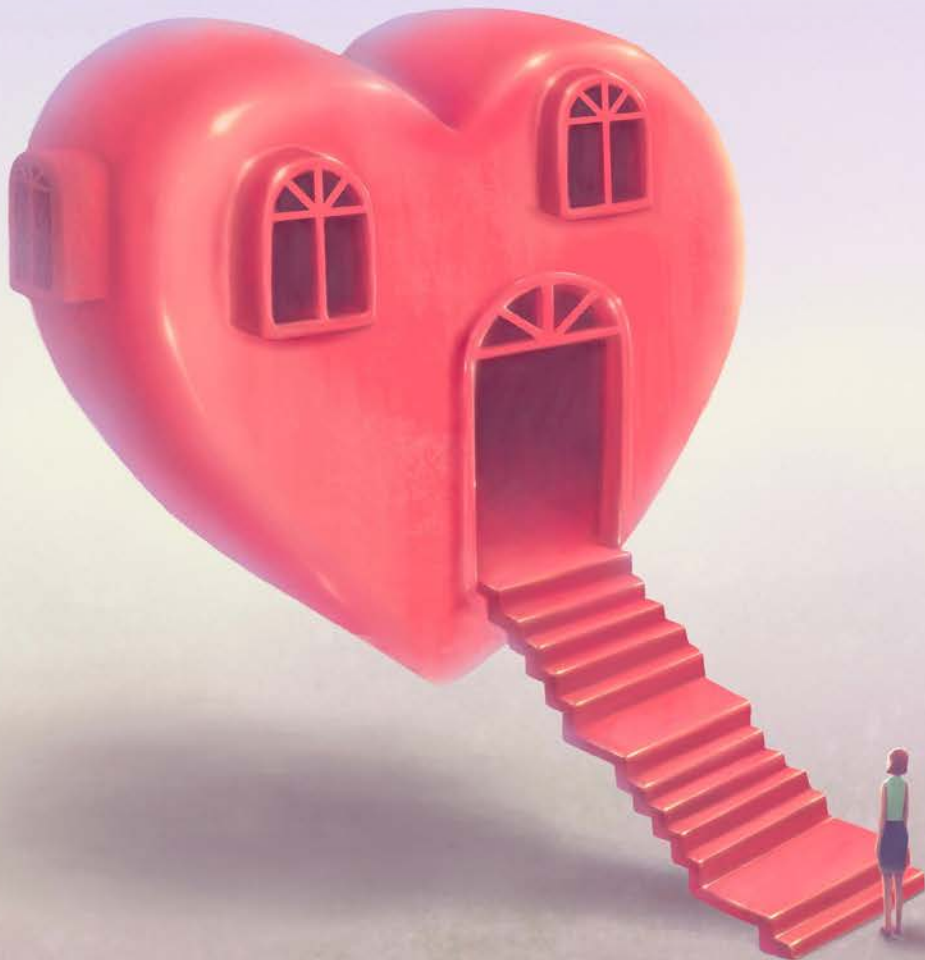


FEATURES

Home Really Is Where the Heart Is

It's an idea we create over time that gets imprinted in the brain

BY ALICE FLEERACKERS



T WAS A TIME of many homes.

For more than two years, I cycled between house sitting gigs, AirBnBs, spare rooms, and friends' couches.

What I remember about these places is less their physical quirks than the sounds, or lack of sounds, that permeated them. The stillness of the lakeside bungalow in small-town Georgia where I spent seven days writing. The thrashing of the south England sea, lulling me to sleep in the dark Bournemouth winter nights. The cackle of kookaburras waking me at 5 in the morning in Brisbane, Australia.

Unmoored after a breakup with my fiancé and the end of a Ph.D., I had chosen to lean into displacement and transition. At final count, the number of places I parked my suitcase over those itinerant years totaled 38. I roamed across multiple continents, packed and unpacked my things every few months, booked dozens of planes, trains, and buses, said “nice to see you again” and “goodbye” in almost the same breath.

Last year, I finally took a job in the Netherlands and found a studio overlooking a quiet Amsterdam canal. It seems I might stay a while. I now have favorite coffee shops, good friends, a routine that connects me to this place. But am I really at home?

The uniquely Finnish word *kalsarikännit* captures the distinct experience of getting drunk at home, typically alone in some state of undress.

My recent jag of rootlessness may lie at an extreme. But the experience of leaving one home to set down roots in another, and the deep need to feel a sense of belonging wherever you live, is a human universal. It is central to some of our most celebrated works of literature—Gabriel García Márquez’s *One Hundred Years of Solitude* or Homer’s *The Odyssey*. Where we live—or, rather, *how we feel about* where we live—can profoundly shape our sense of ourselves and our well-being. These deep ties between sense of home and sense of self render all the more tragic the forced emigration—from politics, war, or other violence—that currently pervades the globe.

But what determines that sense of home—how we feel about where we live? And why does a sense of being at home, when we do find it, often feel so visceral?

Matt C. Howard, a professor at the Mitchell College of Business at the University of South Alabama, has been researching health and well-being for almost a decade.

He recently started studying the meaning of home because it is an experience so fundamental to our daily happiness, he says, but which is rarely considered from a psychological perspective. For many people, Howard says, feeling unsettled in life may be a sign that one or more of their basic psychological needs are unfulfilled. “If you’re a person who feels like you’re lacking something in life, maybe the thing you’re lacking is [that] you really haven’t identified your home,” he says.

Recently, Howard decided to take a comprehensive look at the relationship between home and well-being. In a paper published last year, he reviewed more than 600 studies that consider the meaning of home. These included empirical and conceptual papers spanning almost six decades, covering more than a dozen disciplines, such as urban geography and women’s studies, and examining people from over 50 countries. Over and over again, a common pattern emerged. Home is not just a place that keeps us warm, dry, and sheltered,

There is no single region, but a whole network of cells distributed all across the brain that helps us remember our homes.

but somewhere we feel competent and in control of our lives, where we can express our identities and values, and feel connected and supported.

What Howard found maps onto what psychologists call basic psychological needs theory, developed more than 20 years ago. Now one of the most well established motivation theories in contemporary psychology, it proposes that three fundamental needs govern most of our decisions in life, driving us to pursue certain goals over others and, in turn, influencing our physical and psychological well-being. Those three needs are competence, autonomy, and belonging. Howard's research suggests this same theory can help explain what makes us feel connected to a place—sometimes on an almost instinctual level—and why that feeling is so crucial to our well-being. “If you don’t have those needs [met], that leads to stress,” he explains. If you do have those needs met, it’s much easier to feel happy and comfortable in your own skin.

A HOME INSIDE THE MIND

The central role our homes play in our lives can be seen in the architecture of the brain itself, says Kübra Gülmez Karaca, a neuroscientist at the University Medical Center Utrecht, in the Netherlands, who studies how memories are formed, stored, and retrieved.

“There is no single region, but a whole network of cells distributed all across the brain that helps us remember our homes,” she says. This network includes specialized place cells that correspond to specific

locations we’ve been, grid cells that help us create mental maps of our environments, and border cells that store information about spatial boundaries and edges. Studies in mice have even found evidence of corner cells that help us take stock of—you guessed it—the corners in our surroundings.

“Each memory leaves a physical trace,” Gülmez Karaca says. “A footprint of experiences in the brain.”

Yet despite our rich spatial memory infrastructure, not all places are remembered equally. For instance, many of us would struggle to describe the inside of a café we visited just a month ago, but can easily recall elements of our childhood home in intense detail. The smell of coffee brewing downstairs in the morning, for example, or the telltale creak of that one loose floorboard at the end of the hall.

“Home memories are interesting because even though they happened such a long time ago, we can still recollect them vividly,” says Gülmez Karaca.

This intensity is likely due to the emotional significance of our homes, and the many important moments we’ve experienced there. All day long, our brains take in information about what we are experiencing, what time it is and where we are, and—crucially—how we feel as a result. The hippocampus knits all these different pieces of information together, forming what are known as episodic memories.

When those daily experiences also happen to be emotionally charged, this process can become amplified. Powerful stress hormones like noradrenaline are

Home is not just a place, it is also a process.

released in the brain, committing those moments to memory in a more visceral way than we tend to do with less emotionally loaded experiences.

What's more: Recalling the moment later or revisiting the place we first experienced it can reactivate the neural "footprint" of that memory. The reactivation then further embeds the experience—and the emotions we've associated to it—into our minds.

The connection between memory and emotion is one reason some of our most traumatic experiences can continue to haunt us for years, but also why—over time—the places we live in can become so deeply imprinted in our minds.

"When those experiences accumulate, especially if they're emotionally meaningful, the place becomes familiar, and personally significant, and may start to feel like 'home,'" Gülmez Karaca says. In this sense, home can be dynamic: an ongoing process of building and rebuilding memory and meaning.

FINDING HOME WHEREVER WE ARE

Perhaps because home is so fundamental to our basic needs, people will go to great lengths to cultivate a sense of home in even the most challenging circumstances. "Everybody has an innate sense to build home," says Cheyenne Greyeyes, a Plains Cree researcher who has studied Cree conceptions of home along with co-author Celina Vipond. "We are humans, we continue to try to find home wherever we are."

The link between home and belonging is embedded in the Cree language itself, as seen by the close relationship between the words for "my home" (*nîkîhk*) and "my mother" (*nîkâwîy*). These linkages appear in other languages too: In Chinese, for example, the words "family" and "home" share the same character 家 (*Jia*). Meanwhile, the uniquely German word *heimat* refers to the "place to which one feels one belongs"—a sense of home that extends beyond the walls of the physical structure a person lives in.

Other cultures similarly have untranslatable words that reflect the connection between our homes and our basic psychological needs. For instance, the Old English word *hām* was first used to describe a wider community or village, rather than an individual dwelling, reinforcing the connection between home and belonging. In a somewhat unconventional expression of autonomy, the uniquely Finnish word *kalsarikännit* (literally translating to “underpants intoxication”) captures the distinct experience of getting drunk at home, typically alone in some state of undress.

These linguistic relationships point to the centrality of home in many cultures, but also the wide range of ways we experience home. A sense of belonging is not just about the relationships we cultivate with family, friends, pets, or even online communities. Possessions and routines can also play a critical role when we’re nesting in a new place: We furnish our apartments with objects that remind us of who we are and where we come from, or find rootedness through simple familiar activities, like cooking a meal or settling in with a good book. Even idols and passions can bring a sense of home. As one participant in a study of Indonesian youth explained, the South Korean boyband “BTS is a group whose members can make me feel like I am at home, with a sense of comfort, unconditional love, and understanding.”

These varied strategies for building a sense of home underscore a key finding of Angela Cui’s work: Home is not just a place, it is also a process. Cui is an assistant professor at the Chinese University of Hong Kong, where she has been studying the home building strategies of people living in transitional housing due to mental health issues. Through interviews with 60 residents, she and co-author Jialing Wu have uncovered insights that challenge longstanding understandings of how people create a sense of home in a new or unfamiliar environment.

Cui explains that prior studies have tended to frame home-building as either a linear process or a process of “compensation.” In the linear process, people identify their goal—what they think would make them feel at home—and then slowly, consistently work toward it. For instance, a person who values comfort might find home by buying a plush mattress or particularly cozy couch. The compensation process, on the other hand,

requires shifting our priorities. In this case, a person might live in a place that doesn’t quite align with what they value, but they compensate for it by focusing on qualities of their home that do meet their needs. For example, they may feel their home is too small to entertain guests but remind themselves that it allows them to live close to their best friend.

While people in Cui’s research also used these strategies, they described a third, until now unrecognized strategy: “You can extend the scale of your home,” she explains. “[Or] you can shrink [it], bring your feeling of at-homeness inside yourself.” This ability to shift our concept of home has also been documented in studies of migrants, who similarly find ways to develop trust and rootedness in their new country, stay connected to their culture, and express their identity—even when that identity is threatened by their new context.

It feels paradoxical: On the one hand, we can expand our definition of home to include our wider community, cultivating the social connection that is so crucial to our well-being even when we live alone. On the other, we can retreat into our shells, shutting out the world to create a sense of control when our physical surroundings fail to provide it.

Yet it is exactly this fluidity that makes the concept of “home” so powerful. Yes, home is a place: a physical structure, a dwelling, maybe a neighborhood or community. But it is also an experience, a memory, a feeling, and, perhaps most importantly, an ongoing practice of creating the conditions we need to be happy and well—wherever we are. 🌀

ALICE FLEERACKERS is a freelance writer fascinated by the psychology of happiness. She is also an assistant professor of journalism and civic engagement at the University of Amsterdam and the vice president of the Global Network for the Communication of Science and Technology.

Saving the Girl with Dementia

It takes a family to drive research for a rare disease forward

BY SHAWNA WILLIAMS





AFTER CARA AND GLENN O'NEILL learned of their daughter Eliza's death sentence, they went to the beach. Before they left, Eliza and her father ran along the sand, holding hands. It was hard to stop, Glenn says, to turn back, pile into the car, and face the inevitable.

The O'Neills had wanted to pretend just a little bit longer. "We knew what we were facing," says Cara, who is trained as a pediatrician. They even kept the news from Eliza's 6-year-old brother Beckham. But after they got home that July day, they began dialing friends and family to deliver the news: Eliza, who was 3, had a rare disease called Sanfilippo syndrome. Also known as children's Alzheimer's, Sanfilippo causes a loss of learned skills such as speech and movement over time. Children become so hyperactive that their parents often can't sleep, staying up into the dawn to keep their kids safe. Eliza wasn't expected to live past age 15.

The O'Neills soon posted a wrenching video of their daughter on a GoFundMe page, headlined "Saving Eliza." On camera, Eliza seems blissfully unaware of what is coming, her eyes crinkled with joy, her ponytail swaying as she plays outside. Glenn recounts how much he and Cara had wanted a daughter, how difficult the diagnosis was for them. Cara describes what it will mean for Eliza. "If the money doesn't come in time, she'll stop speaking within the next six months," Cara says. "She will stop walking within the next two years, stop being able to feed herself in the next three to four years. She will develop seizures and movement disorders, experience a lot of pain and suffering, and then she'll die."

Within eight months of posting the video, the O'Neills' new nonprofit, the Cure Sanfilippo Foundation, collected \$2 million from friends, family, and complete strangers. The couple was determined to find a cure.

But they knew it would take more than a couple of millions to move the needle on Sanfilippo.

In the world of rare disease, it's often the families who drive medical research forward. Though more than 7,000 rare diseases exist, collectively affecting more than 300 million people worldwide, rare diseases are, by definition, rare. The rarest of them can affect as few as one in 100 million people.

Due to profit incentives and the scale of impact, large pools of funding from pharma companies, foundations, and even federal institutions like the NIH tend to go to diseases that affect large populations—with a few exceptions.

WHEN SHE LOOKS BACK NOW, Cara says there were subtle signs of Sanfilippo she hadn't known to look for: Eliza's head was especially large for her age, she frequently had loose stools and ear infections, and there were mild developmental delays, particularly in her speech. It was only around the age of 3, when Eliza was transitioning from the toddler group to the 3-year-old group at daycare, that it became apparent that there were significant differences between Eliza and her peers. Eliza's caregivers noticed that she was having trouble with natural conversation and wasn't playing normally with the other children. "She just had difficulty in communicating frustration, so she would push or grab," Cara says. She was constantly on the move.

Eliza started working with speech, physical, and occupational therapists on a weekly basis and Cara was optimistic at first that this special attention would close the developmental gap—but she saw it widen instead. Six months in, Eliza's school evaluated her for autism and diagnosed her with the condition. Then, on the suggestion of a colleague who was a geneticist, Cara had Eliza's urine, and later her DNA, tested for a group of inherited disorders known as mucopolysaccharidoses (MPS) disorders. MPS disorders feature deficient enzymes in a person's lysosomes, the organelles in cells that break down cellular garbage and perform other critical functions. A single mutation pointed to Sanfilippo, also known as MPS III.

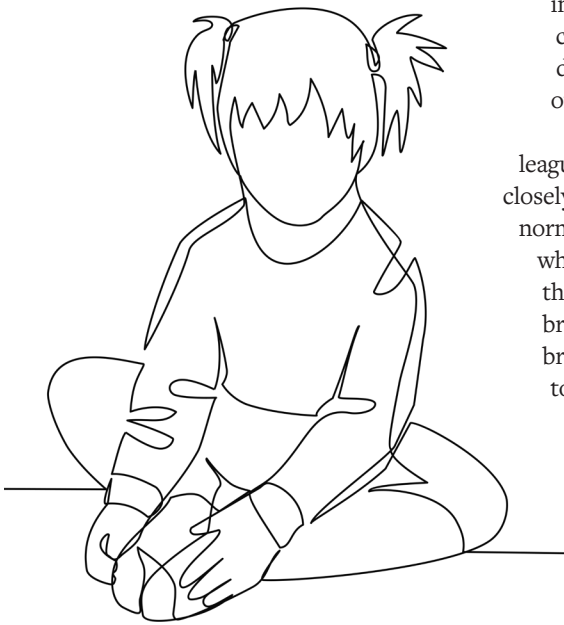
It was devastating news. About one in every 70,000 babies are estimated to be born with the condition, which causes cognitive unraveling similar to that seen in adults with Alzheimer's. A child will suddenly forget

Eliza wasn't expected to live past age 15.

their favorite bedtime lullaby, the name of the family dog, the morning routine. These behavioral and cognitive symptoms are accompanied by measurable neuroanatomical changes: cortical and cerebellar atrophy, ventricular enlargement, neuronal loss visible on neuroimaging, and aggregation of tau, α -synuclein, and amyloid- β proteins. Other brain changes occur as well, such as mitochondrial dysfunction, oxidative stress, impaired autophagy, and neuroinflammation. All of these same changes are at work not just in Alzheimer's but in Parkinson's disease and Huntington's disease, which together affect millions of people in the United States alone every year.

Discovered in the early 1960s by Sylvester Sanfilippo and colleagues at the University of Minnesota, Sanfilippo occurs in four closely related forms. Each involves defects in a different enzyme that normally helps to break down a carbohydrate called heparan sulfate, which attaches to proteins involved in a multitude of functions throughout the body. Without the functional enzyme, partially broken-down heparan sulfate builds up to toxic levels in a child's brain cells. Researchers are still piecing together exactly how this toxic garbage in the brain causes the symptoms of the disease.

One 2024 study, for example, found that the buildup may induce immune cells in the brain known as microglia to increase chemical signals that lead to inflammation and reduce the availability of proteins that promote neuronal development. Eliza has Sanfilippo subtype A, which is caused by mutations in the gene for the sulfamidase enzyme. Hers is a severe, faster-progressing form of the subtype.





BEACH GIRL Eliza is now 16 years old, a year past her own life expectancy. The family's halting conversations with her have revealed that her mind is more intact than they thought. She understands colors. She remembers the alphabet. And she still loves the beach.

Because Sanfilippo has a known genetic cause, relatively uniform rapid progression, and major central nervous system involvement, it offers a unique window into neurodegenerative disease more broadly—particularly the effects of lysosomal failure on the brain. Studying it helps scientists understand how disrupted cellular activity cascades into widespread brain dysfunction over time.

In a 2011 study, for example, a team led by University of Cambridge researchers found a buildup of α -synuclein—a feature of Parkinson’s disease—in the brains of two patients with Sanfilippo. The study’s authors suggested that *NAGLU*, the gene at fault in one subtype of the disease, might also play a role in

susceptibility to Parkinson’s, a connection borne out by subsequent research. Aggregations of tau protein, a signature of Alzheimer’s and certain other neurodegenerative diseases, have also been found in the brains of mice with the gene mutations behind Sanfilippo.

Through research on Sanfilippo, “we’re understanding things about these cellular processes like autophagy and other cellular breakdown pathways that have long been studied in Alzheimer’s” and other neurodegenerative diseases, Cara says. “Knowing that this is a primary disease target in Sanfilippo allows us to learn what works there, and then they can translate over into the other larger diseases.”



FAMILY AFFAIR Eliza’s parents helped fund research for the gene therapy she and other kids with Sanfilippo received. It couldn’t reverse the damage already done to her neurons, but it allowed her to sleep at night and live into her teens. Families are often the ones who drive rare disease research forward.

COURTESY OF THE O’NEILLS

Large pools of funding tend to go to diseases that affect large populations.

A DECADE AGO, an early gene-therapy trial for Sanfilippo A inspired hopes that a cure might soon be within reach for kids who were diagnosed early. But the path to viable treatment has been slow and messy.

Following her daughter's diagnosis, Cara quickly dug into the scientific literature, reading all the papers she could find on Sanfilippo. Her medical training helped: She had studied at West Virginia University School of Medicine and began practicing as a pediatrician in 2004 (she now directs a travel health group). Cara hoped to find emerging therapies, or at least known mechanisms of the disease that could be targeted. She soon learned about a researcher at Nationwide Children's Hospital in Columbus, named Haiyan Fu, who had done important foundational work on the disease together with her colleagues. Fu had identified a potential gene therapy with her husband, Douglas McCarty, that appeared to be able to cross the blood-brain barrier and induce brain cells to produce a functional lysosomal enzyme. So Cara reached out to Fu to talk with her about her research. She learned that millions of dollars would be needed to run the first clinical trial.

Meanwhile, Glenn, too, was giving himself a crash course—in his case, about fundraising. The infusion of money from the video featuring Eliza gave the Cure Sanfilippo Foundation a strong start, but it wasn't enough. Glenn remembers initially feeling uncomfortable asking for money. But something he read in a book on fundraising helped change his perspective. "The line said, 'donors donate,'" he says. "They've seen the work that you're doing, and they've made a choice." His experiences have

borne that out. In one case, the foundation ran a campaign that was still short of its goal at 10 p.m. on the final day. It was then that Glenn got a call from a stranger who said he and his wife had come across a video of Eliza and decided to contribute the \$30,000 needed to finish the campaign. "He was thanking me," Glenn says.

"Those foundations are very, very essential," to her work, says Fu. Without them, there just isn't enough money to carry out this kind of research, she says. Family participation is also, of course, essential to the clinical trials that move scientific findings toward FDA approval.

Along with fundraising, the O'Neills enrolled Eliza in a study at Nationwide Children's where Fu worked, a commitment that involved driving to Ohio three times over the course of a year from their home state of South Carolina so that doctors could monitor Eliza's symptoms and track how they changed over time. This would help establish a baseline marker of disease progression that could be used in future clinical trials to measure whether a drug was working or not.

That year, the family also went into isolation. They wanted to keep Eliza eligible for a possible trial with Fu's gene therapy, though they had no guarantee she would be selected. Eliza had already been tested for antibodies to AAV9, the virus co-opted as a vector to shuttle Fu's gene therapy into the body. If the body mounts a strong immune response to gene therapies it can be deadly, so people who already have antibodies to these vectors are commonly ineligible for clinical trials. Eliza's test came back negative, which was good news. But AAV9 circulates in the general population

She had lost the ability to speak except for a few words.

all the time. There was a risk that in her daily life, Eliza would be exposed to these other viruses before the trial and develop the antibodies, knocking out her chances of participating.

In February of 2015, they made their final visit to NCH clad in gloves and masks. Later, a therapist began to visit their house in what Cara describes as a hazmat suit. For the most part the family stayed at home with no visitors or went for outings to a field or to a little-frequented beach. Groceries and other items outsiders had touched were disinfected before they were brought into the house. Since Eliza had to miss her school's Valentine's Day dance, her parents decorated their living room for the holiday, and Glenn and Eliza dressed up and danced together. Eliza and her brother Beckham were allowed to color on the walls, and Glenn joined in, jotting down things Eliza said or songs she sang, with the date. That record of a father's love is also a calendar of the disease's progression. "As the dates go on, the speech becomes less and less," says Glenn. Full songs gave way to a single line and then just one word. "And then obviously, there's nothing."

The isolation ended up lasting just shy of two years—and was documented in *People* magazine. It was an extreme step, but Eliza was still free from problem antibodies when, in May 2016, she became the first person dosed with Fu's gene therapy in a small,

early-stage trial. As is common in such trials, the dose Eliza received was low; absent significant safety concerns, it would gradually be ramped up in subsequent participants. But because of the antibodies generated in response to the therapy, there could be no second shot at the treatment for Eliza.

By that time Eliza was 6-and-a-half years old. She had lost the ability to speak except for a few words and was so hyperactive that "she would be up all hours of the night racing through the house, running, yelling, getting into everything. Safety became challenging," Cara says. "We had to become hypervigilant." Eliza also had spells where she was inconsolable, seemingly uncomfortable in her own skin.

Just weeks after her treatment, the difference was remarkable: Eliza could suddenly sleep by herself. She no longer fell to the floor, screaming and crying uncontrollably. But as everyone expected, the damage to her neurons could not be reversed.

Still, the therapy had worked as intended for Eliza and the other children in the trial. The study found that they had lower levels of heparan sulfate in their cerebrospinal fluid after treatment. As Fu had hoped, cells that received a functional copy of the gene for sulfamidase pumped the enzyme into the surrounding tissue, benefiting neighboring cells that hadn't received the gene.

Over the next few years, Eliza remained able to communicate nonverbally, walk, and eat, abilities she otherwise would have been expected to lose. According to long-term follow-up data presented at a recent conference, all 10 of the children who received the Sanfilippo A gene therapy were still able to communicate when they were older or their disease was more advanced, while nine were still able to walk and to feed themselves. Of the 17 children treated before age 2 or early in disease progression, eight reached the cognitive developmental age of a 3-year-old—a milestone none of the untreated children in the natural history study hit. One girl the O’Neills know who received early treatment, now 10 years old, plays on a softball team, reads, and goes on playdates.

TODAY, ELIZA IS 16 years old, having survived a year past the average life expectancy for kids with Sanfilippo A. She’s never had a seizure. She’s in a special class at the local middle school and receives behavioral, physical, and speech therapy. She communicates with everyone using laminated cards with a word and illustration depicting what she wants or is feeling: eat, drink, tired, ouch. One set has stills from shows she likes to watch so that she can request them. She is also working on using eye gaze to operate a speech-generating device. The family worked hard to find ways to communicate when Eliza stopped speaking, Cara says.

Those halting conversations have revealed that Eliza retains more knowledge than the O’Neills thought, such as the alphabet and an understanding of colors. She enjoys going to the trampoline park, riding an adaptive tricycle, going for walks at the mall, looking at books, being read to, and splashing around in the pool; her favorite show is *Dora the Explorer*. Now that she’s a teen, she’s sometimes moody and likes to sleep late.

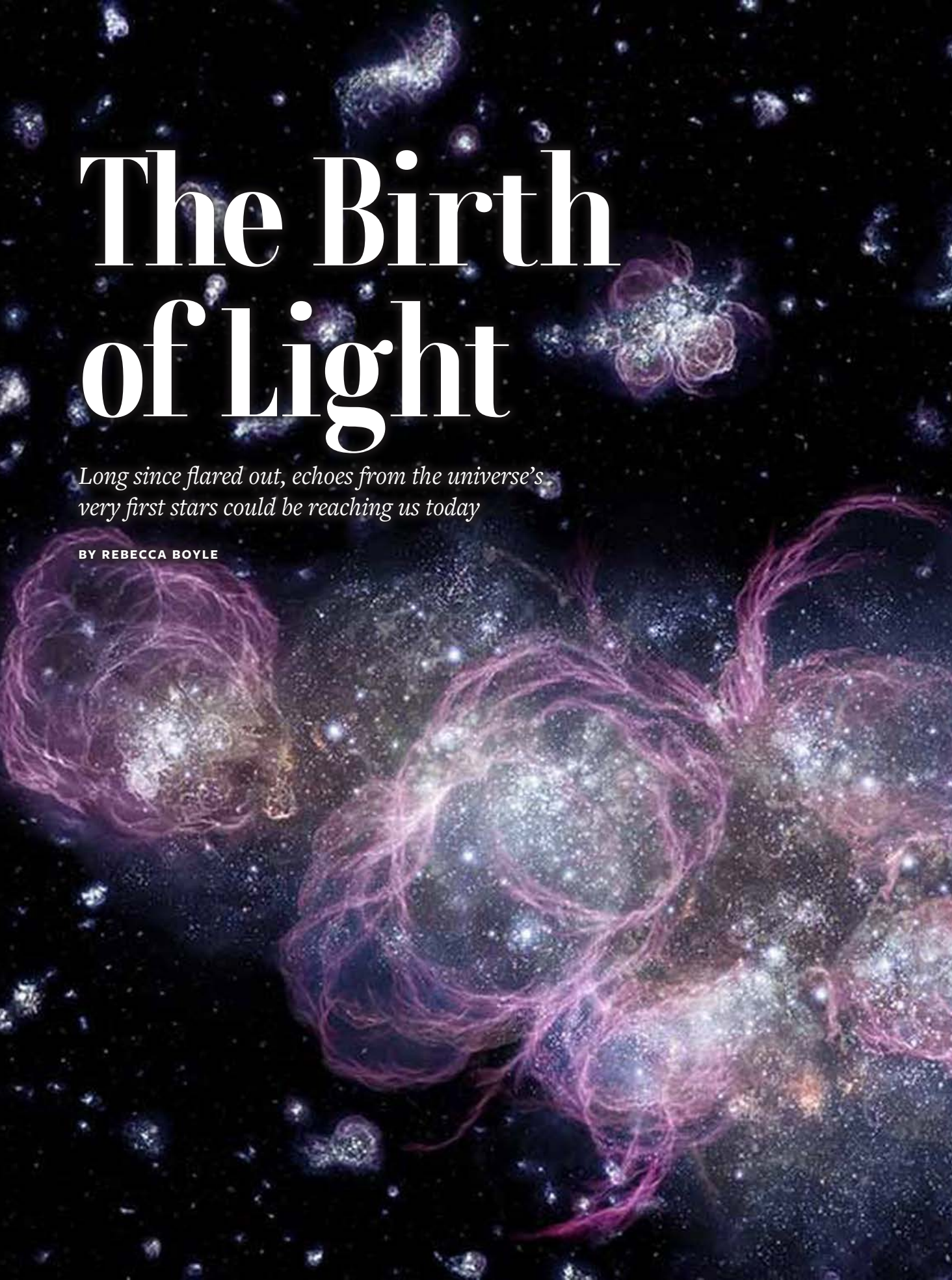
But the treatment she got still has not been approved by the FDA. Now known as UX111, it was rejected by the Food and Drug Administration in July. The drug’s sponsor, Ultragenyx, said at the time that the decision was related to manufacturing issues and not to clinical data. It has since reapplied, and expects a decision later this year. Ultragenyx estimates 300 to 400 children have Sanfilippo A in the U.S., although not all will necessarily be eligible for the therapy if it is approved.

UX111 isn’t the only potential treatment the Cure Sanfilippo Foundation has supported over the years. Cara was a co-investigator on a study, funded by the Cure Sanfilippo Foundation and published in 2024, that showed that a drug called anakinra, approved by the FDA for certain auto-immune conditions, can alleviate some symptoms of Sanfilippo, including sleep and behavioral issues. It’s not clear whether anakinra slows the progression of the disease, but Cara notes it’s exciting to have a treatment option that children can take at any stage of the disease—unlike most enzyme or gene therapy clinical trials, for which older, more-progressed children are often ineligible. In addition to its work funding research, Cure Sanfilippo advocates for the disease to be included in the standard panel of screening babies get at birth, known as newborn screening.

Eliza doesn’t seem as interested in running as she did when she was younger. But something about the beach, the crash of the waves and warm sand under her feet, pulls on her. “Sometimes we’re evaluating it and we’re like, ‘gosh, is she slowing down?’” Glenn says. “And then we’ll take her to the beach. And she’ll go, boom! Go running down the beach. Just like she used to.” ☺

SHAWNA WILLIAMS is a freelance writer and editor based in Queens, NY. Her work has appeared in publications including *The Scientist*, *BioSpace*, and *Hopkins Medicine*.



The background of the entire page is a deep space image. It features several large, intricate nebulae in shades of purple, pink, and magenta, with some glowing white and blue centers. These nebulae are set against a dark, star-filled background. In the distance, various galaxies are visible, some appearing as bright, fuzzy patches and others as more defined spiral or elliptical structures. The overall effect is a sense of vastness and cosmic wonder.

The Birth of Light

*Long since flared out, echoes from the universe's
very first stars could be reaching us today*

BY REBECCA BOYLE



THE UNIVERSE BEGAN WITH A BANG, and for the first few hundred million years, there was nothing but hydrogen and some helium atoms moving through the void. Then something happened. Somehow, in the roiling soup of plasma and free electrons suffusing the Big Bang's embers, clouds of molecular hydrogen drew close enough together to ignite. The first stars were born.

Just to imagine such objects blinking into existence, let alone describe them using theoretical astrophysics, was revolutionary not very long ago. But today, astronomers are on the cusp of actually seeing these earliest stars. Through the James Webb Space Telescope, humans are newly capable of peering back through almost all of time, penetrating the expanding universe, past uncountable galaxies and nebulae and stars and their planets, to glimpse the first light to ever shine forth.

These luminous bodies, called Population III stars, represent not only the earliest light in the primordial universe but also our own beginnings. They were the first stars to fuse hydrogen and helium into heavier elements. They forged oxygen, carbon, silicon, and iron (what astronomers call "metals") for the first time, deep in their massive stellar hearts. Their deaths set the course of the universe, led to the origin of our sun and, eventually, to life on Earth. Finding them and modeling their birth and death is therefore a way of understanding the deepest roots of everything that came after them.

A STAR IS BORN This artist's conception depicts how the formation of the universe's first stars may have appeared. Dense clouds of hydrogen and helium likely collapsed inward, increasing pressure and temperature until hydrogen atoms began to fuse, giving birth to the first light in a dark void.

NASA, STSCI, A. SCHALLER



Humans are newly capable of peering back through almost all of time to glimpse the first light to ever shine forth.

Throughout 2025, astronomers shared a flurry of research papers on a preprint server and at scientific meetings, posing that some galaxies in JWST data could be radiating light from these primordial stars. But few researchers have agreed on any one claim. Meanwhile, theorists continue refining their expectations for what these stars should look like when their faint glows are captured by JWST's sensitive instruments.

The difficulty and the importance of finding Population III stars makes them a sort of a “holy grail” among astronomers, says Pierluigi Rinaldi, an astronomer at the Space Telescope Science Institute in Baltimore.

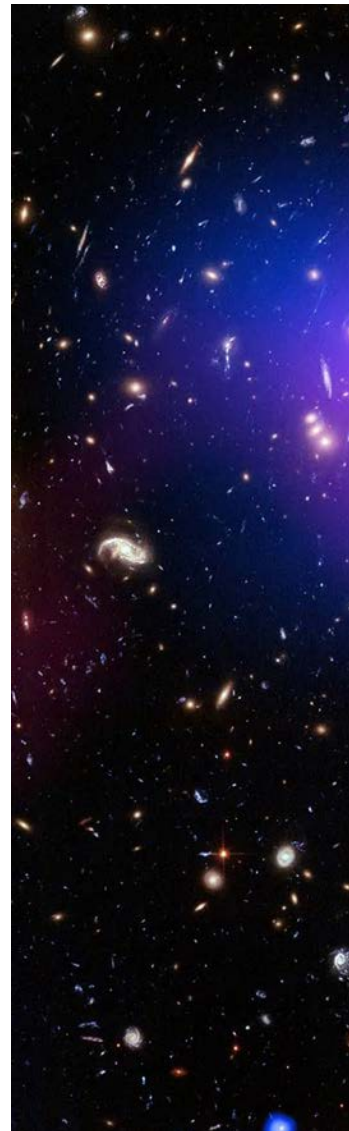
“The people who see Population III stars will be the people who get a Nobel Prize,” he says.

BEFORE THE EARTH, before the sun, before the sun's stellar ancestors, and long before even the Milky Way, the universe was wildly different. During the “cosmic dark ages,” a period that lasted about 50 million years after the Big Bang, no stars shone. Influenced by gravity, dark matter—invisible, mysterious

stuff we cannot directly study—was beginning to shepherd visible material together. Gas and dust started to clump, although their accumulation was altered by supersonic flows of gas still streaming forth from the Big Bang. Sometime between 50 million and 100 million years after the Big Bang, the clumps became concentrated enough, and dense enough, to collapse into the first stars.

These first stars are called Population III stars because of a somewhat backward ordering system. They are made only of primordial hydrogen and helium, which they forged into heavier elements such as carbon, oxygen, and iron. (“Metals” to astronomers describe any elements with more neutrons than hydrogen or helium.) The next stars to form were Population II, still old and scant in these heavy materials. And most stars now, for example our sun, are Population I stars, rich in heavier elements—the stuff that makes rocks, trees, diamonds, and us.

The sun and all other stars like it are made from the remains of their ancestors. As the Population III stars died, their hearts seeded the cosmos with every other element in the



known universe. Although they are the long-lost progenitors of today's matter, massive Pop III stars were likely not super common in the infant universe.

"We don't expect lots of them to be forming, so it's just going to be harder to see them," says Mike Boylan-Kolchin, an astronomer at the University of Texas at Austin. "You're helped out because they are more massive, so they should shine brightly, but seeing them unambiguously is hard."

Theorists think Pop III stars could have been enormous, with masses the equivalent of 100 suns or more, and short-lived—flaming out within a few million years, incredibly fast for a star. They would have died in titanic explosions that could have cooled down those Big Bang-induced supersonic flows of gas and helped galaxies chock-full of stars to form even faster.

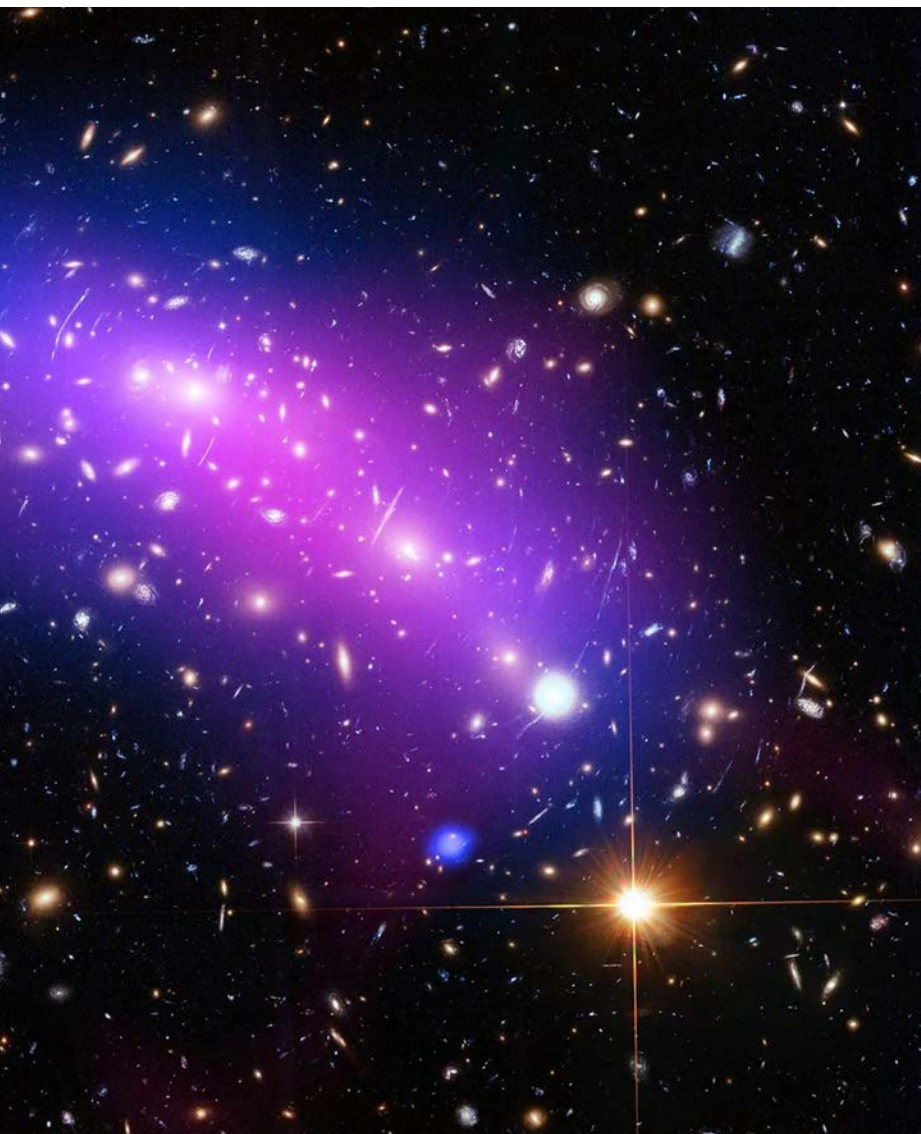
"The small structures where the Pop III stars first form are the building blocks of the galaxies. They are

the little bits that build up the next generation," says Eli Visbal, an astronomer at the University of Toledo in Ohio. "If you want a complete picture of galaxy formation, in particular how early galaxies form, you want to understand the initial conditions of the Pop III stars."

Astronomers used to think we would never be able to see them because they are so old, and therefore so far away. The oldest objects in the universe are far away, of course, because the universe is expanding in all directions. This also means the light from very early stars has been stretched to longer wavelengths as it traveled to telescopes that are either Earth-bound or Earth-adjacent.

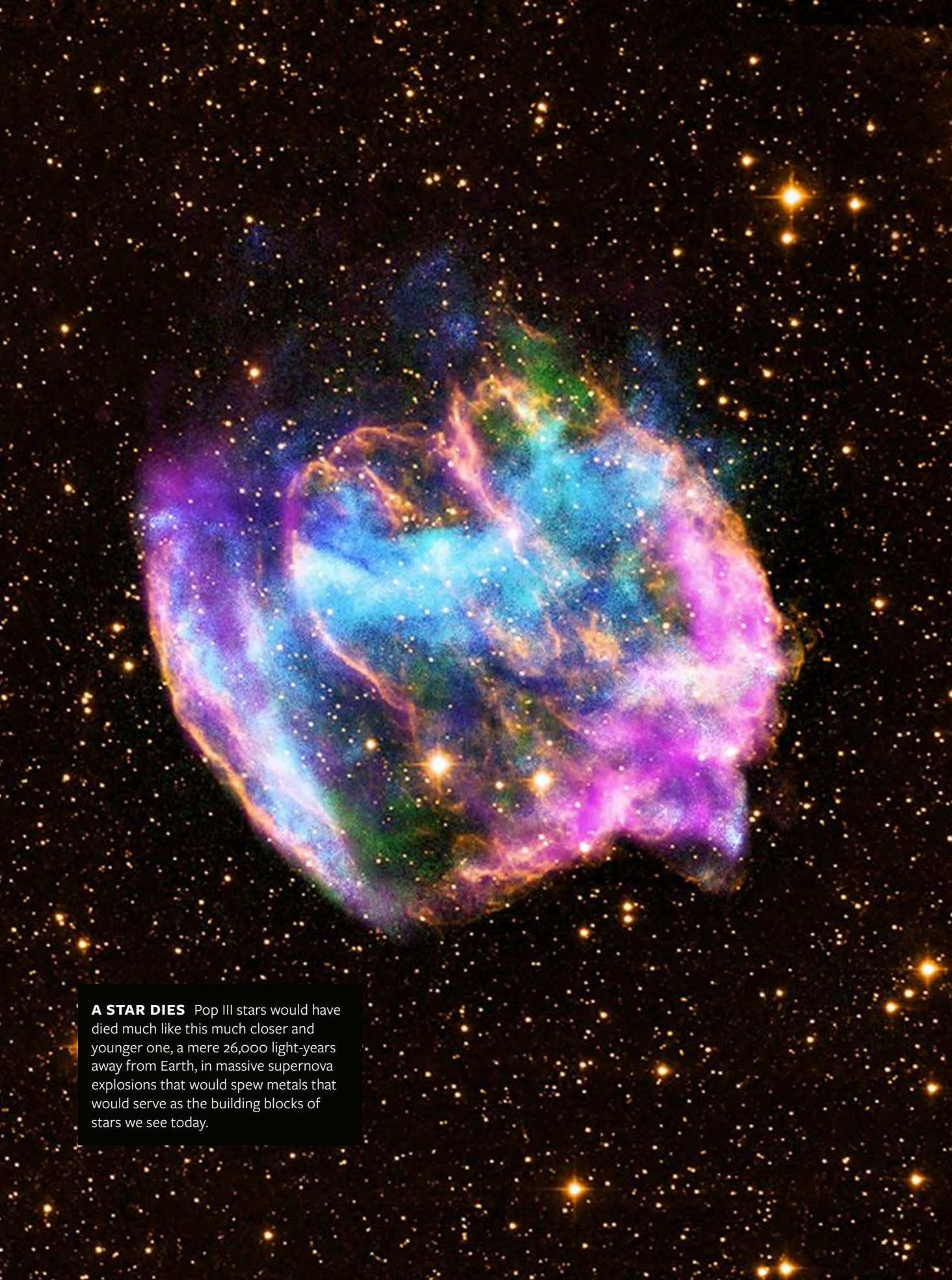
But JWST was specially designed to detect longer wavelengths of light, specifically in the near-infrared range of the electromagnetic spectrum. The Hubble Space Telescope can see deep into the universe, but it

NASA



A USEFUL CLUSTER

This galaxy cluster, called MACS J0416, helped astronomers magnify and study the more distant LAP1 galaxy, which may contain some of the first stars ever formed in our young universe.



A STAR DIES Pop III stars would have died much like this much closer and younger one, a mere 26,000 light-years away from Earth, in massive supernova explosions that would spew metals that would serve as the building blocks of stars we see today.

Population III stars represent not only the earliest light in the primordial universe but also our own beginnings.

only perceives the light we can see, optical light. And previous generations of infrared telescopes, like the Spitzer Space Telescope, did not have JWST's sensitivity or power.

By using JWST instruments to study starlight's composition, a technique called spectroscopy, astronomers can look for high concentrations of helium and hydrogen that could hint at the presence of primordial stars. But even JWST has a hard time distinguishing the oldest starlight ever produced. Though a few astronomers have claimed to pinpoint evidence of Pop III stars, it will be hard for anyone to convince the broader astrophysics community that JWST has really found a galaxy harboring them because it would be such a consequential find, says Claire Williams, a theoretical physicist at the University of California, Los Angeles who studies Pop III stars.

Still, some evidence is mounting.

In 2023, astronomers led by Roberto Maiolino at the University of Cambridge in the United Kingdom used JWST to observe a galaxy called GN-z11, which Hubble found in 2015 and which dates to just 400 million years after the Big Bang. They argued that the helium signature in GN-z11 suggested small clusters of Population III stars within it.

Other teams use a trick of gravity, predicted by Albert Einstein, to magnify and study distant stars. Also in 2023, astronomers led by Eros Vanzella at the National Institute of Astrophysics in Bologna, Italy, used a galaxy cluster called MACS J0416 to study a faraway galaxy. The galaxy cluster's gravity warped the light of a more distant galaxy, the way a magnifying glass distorts and enlarges an object. Einstein

predicted this "gravitational lensing" effect in 1915, and it has since been confirmed and used by Vanzella and other astronomers. Vanzella and his team dubbed the more distant galaxy "LAP1," for "lensed and pristine 1," finding that the system contained a huge amount of hydrogen and only a small amount of oxygen, hallmarks of primitive stars. It has two components, LAP1-A and LAP1-B.

JWST can image the LAP1 system as it appeared very early in the universe, during the epoch of reionization. In this period, the first stars had been born, and their sparkling light was charging all the neutral gas left over from the Big Bang. It is a tricky epoch to study, but a crucial one for understanding the first stars and their influence.

JWST's sensitive starlight-sifting spectroscopy instruments and the incorporation of lensing make these elemental measurements possible. The output of these analytical techniques read something like a barcode, where the signature of a star's light describes its chemical contents.

In July 2025, astronomers led by Kimihiko Nakajima at Caltech examined the distant object again. Based on LAP1-B's barcode, there are no detectable metals in the galaxy. Nakajima and his colleagues argued it is actually a cluster of Pop III stars, adding up to about 2,700 suns worth of material. Astronomers now think LAP1-B is the most chemically primitive star-forming galaxy yet identified, and several teams of researchers are hard at work, further scrutinizing its light.

Visbal says he believes LAP1-B is the first object that meets the criteria for a Pop III star-hosting galaxy.

"The most compelling reason to me is just the amount of stars that are implied by how bright the

During the “cosmic dark ages” no stars shone.

object is,” he says. It would only take 10 stars, each weighing about 100 times the sun, to create the light shining forth from LAP1-B. That’s a good thing. A galaxy crowded with stars has likely had more time to form those stars, which means the earliest generation—Pop III stars—had likely begun dying, or at the very least blowing some metals around through their stellar winds.

“You don’t have a lot of time before you transition from Pop III to Pop II,” he says. “We may be very close to the first star formation event in this location.”

But not everyone is convinced the LAP1 system contains primordial stars. Williams, a theorist, says there could be other strange explanations for the unique chemical fingerprints of the galaxies. Some signatures that could appear to be Pop III stars might actually be Pop II stars, lurking behind a galaxy that absorbs their heavy-metal barcodes, for instance. Or what looks like a Pop III star could be a Pop II star with unexpected spectral characteristics, she says.

“Maybe there’s a weird Pop II, and that is still more likely than a Pop III,” she says. “We probably have these objects that tick a lot of the boxes of Pop III stars, but the level of confidence is not there.”

Other astronomers suggest that these systems might not contain stars at all, but that the barcodes could just be light from gas clouds. What’s more, there could be other Pop III candidates already lurking in JWST’s trove of data. One such object, dubbed GLIMPSE-16043, contains telltale spectral signatures of very young stars and seems to have very little metals. It contains “textbook features” expected of a Pop III galaxy, such as this paucity of metals and other signatures indicating the presence of hot, young stars, according to astronomers led by Seiji Fujimoto of the University of Toronto.

POP III STARS SET THE COURSE for everything in the universe that came after them, including the cosmic mix of ingredients that ultimately led to us. And finding

them could shed light not only on our origins but on some of the strangest questions in modern physics.

The early, weird universe—the one devoid of stars and their light—was still full of something, just something that did not glow. We call this stuff dark matter, because we quite literally can’t see it, though its gravitational influence is profound. Physicists have been trying to unmask it by looking for tiny particles, including weakly interacting ones that might have strange states of being that make them undetectable to us.

Pop III stars could actually shed light on the question of dark matter detection, according to Visbal. In simulations, Pop III stars form in small galaxies, their mass organized by small clumps of invisible dark matter. Their existence in certain circumstances could help physicists probe the very nature of dark matter.

One theory for dark matter calls for particles that are so small, they are altered by quantum mechanical effects. At universal scales, where halos of dark matter sculpt the fates of entire galaxy clusters, these effects can become noticeable, Visbal says. Dark matter halos that contain very low-mass particles could be subject to quantum mechanics’ uncertainty principle—the fact that it is impossible to measure both the exact momentum and position of an object at the same time—and would create a “fuzzy” structure that alters how galaxies grow. Such fuzzy dark matter structures would guide the development of galaxies differently than expected normal, cold dark matter.

“So the objects where you would form Pop III stars in would no longer exist. And it would change where these first formed,” he says. “It is sort of a missing window. Since we don’t know what dark matter is, we should leave no stone unturned.”

Whether or not anyone has found a galaxy containing true Pop III stars—and whether or not they can tell us anything about dark matter—the fact that the hunt is even possible is thrilling for many astronomers.

“The people who see Population III stars will be the people who get a Nobel Prize.”

JWST’s ability to search for Pop III characteristics is just one example of how the 4-year-old telescope is upending humanity’s understanding of the cosmos.

“Astronomy is really fun because these big observational projects get built, and then all of a sudden, every field gets revolutionized,” Williams says. “It’s not like individual groups making a new experiment, or developing a technique. We are all basking in the glory of this new thing that comes online.”

Williams started her Ph.D. program right before JWST launched in December 2020. She shared her first presentation a couple months afterward, studying galaxy simulations in the very early universe, only a few million years after the Big Bang. Her professors were skeptical, arguing that no one would be able to observe anything that occurred in such ancient epochs. But when the first images came down from JWST, they showed galaxies blazing just 300 million years after the Big Bang—way earlier than anyone expected was possible. Suddenly Williams’ very young universe simulations didn’t seem so far-fetched at all.

“It was a fun experience as a student, to come into this world just as this total revolution in what was possible was happening,” she says.

Some theorists say that the definitive discoveries of Pop III stars and other far-off phenomena are still a decade or two away. Future space telescope missions may be the ones to finally glimpse the first stars ever.

A mission called Hyperion, proposed and led by astronomers at the University of Arizona and

Columbia University, would study star formation in the local—meaning, more recent—universe to better understand how hydrogen gas turns the creation of stars on and off. Understanding those mechanisms could inform our understanding of how the first stars may have formed, too.

But the very earliest era of time, a few tens of millions of years after the Big Bang, is the best hope for finding the first stars, says Boylan-Kolchin. JWST is more of a wayfinder for a possible future telescope, in that sense.

“We now know how to look, and where to look,” he says. “That makes it easier for people to come up with the technology to follow this up and say for sure, ‘This is a Pop III star.’”

One day, maybe soon, someone will be able to do that. Some future astronomer will be able to point to an image of an unspeakably distant, achingly old galaxy, and sift its ancient light. They will find nothing but the signature of hydrogen, the universe’s first element and the stuff from which we all came, and trace that light to the very first stars—the ancestors of everything that has shone since. ☺

REBECCA BOYLE is a science journalist based in Colorado Springs. She is a columnist for *Atlas Obscura*, a contributing editor at *Scientific American*, a contributing writer at *Quanta*, and a frequent contributor to *The New York Times*, *The Atlantic*, and many other publications.



How Human Is Human?

The robot pioneer who gets under our skin

BY FOTINI MARKOPOULOU

I GOT OFF THE ELEVATOR at the 18th floor of a gleaming skyscraper in Tokyo last month and walked to the office of robot pioneer Hiroshi Ishiguro. At the front desk, I was met by a smiling female avatar on a computer screen who asked for my information.

A knee-jerk rebellion made me turn away and walk down a hallway where I found a young man who showed me to the roboticist's office.

For more than 20 years now, Ishiguro, 63, has been creating robots that look and act uncannily like people—notably himself. He calls his silicone and electronic doppelgangers “Geminoids,” after the Latin term *geminus*, which means twin. One of his earliest and eeriest twins is the robot he modeled on his daughter, Risa, when she was 4. Ishiguro programmed his many books and media interviews into his latest iteration of himself, which he uses to give conference lectures and teach his classes at Osaka University. His company, Avita, based here in Tokyo, is building avatar systems that can be used for various businesses.

We cannot separate the human and the technology. It is part of our brains and our bodies.

Under the darkening sky of artificial intelligence, I recently read and was enchanted by Ishiguro's 2020 book, *How Human Is Human?* The book is fascinating because it taps into the fluid boundaries between humanoids and humans, the robot and its operator. It presents a parallel reality, where technology carefully attends to human comfort and dignity. Which I find refreshing. It's nearly impossible now to read about autonomous, human-like technology with simple curiosity, when AI is getting pushed into every corner of our lives. Reading Ishiguro's delicate and insistent efforts to avoid any discomfort when a researcher needs to fix the dress of a female Geminoid, while also reading about the latest AI release undressing everyone without their consent, is mind-spinning. What makes the difference?

Ishiguro's office resembled a NASA control center. He sat at a desk heading rows and rows of other desks with more people facing computers. My first thought was that it was Ishiguro's Geminoid slumping behind the computer. But it was the man himself, full of life and energy for his quest to understand humans by making copies of them. Born and raised in Japan, Ishiguro spoke a clipped English that was by turns philosophic and poetic.

The Geminoids are strange.
Why?

My reaction is not how strange it is to have a copy of you. What is strange is making a copy and then observing people's reactions to it. The usual way of thinking of human-like technologies is the Turing test. Can we fake human behavior in a machine to fool people? You are not doing that.

Yes. The original Turing test is just based on text. It is a text conversation. It is quite easy to cheat on the interlocutors. But a human being is a multimodal entity, and we want to interact through many sensations: gestures, eye contacts, so many factors we have. My basic approach is to see if we can feel a human-like presence. That is the challenge in robotics. We cannot decompose the humans into a text conversation. It is not the right way. On the other hand, we can construct human-like robots. The important thing is that we do not have a definition of a human. Therefore, the Turing test is meaningless.

That makes a lot of sense. The Turing test has a whole culture that goes with it. In constructive logic and mathematics, you do not need to start from defining the thing.

That's a fundamental difference between European countries and Japan. You think the human is so special and you can define humanity in some sense. You believe in human divinity. We do not believe that. We can feel



many humanities in the natural things. If you go to a shrine, you can feel something, right? We can find the feeling of humanity in many places. Therefore, we can have this kind of challenge: Develop the robot and see if you can feel the humanity there to understand what humanity is.

We are the species that makes stuff and we see ourselves through it. This goes together with the process of development. But how can you measure how close you are to it?

We can see so many humanities as we improve the performance of the robot. We are always doing similar things through practical tools, like a smartphone. There are intuitions, inspiration. Steve Jobs did not know. He just made a commercial product and people accepted it. Now researchers are studying the meaning of that design. We didn't expect that the internet could enhance the human social abilities. We now understand more about those social abilities.

MIRROR, MIRROR

The remarkable resemblance between Hiroshi Ishiguro and his "Geminoid" robot double stirs bystanders to question the meaning of human presence.

MEET ERICA

Erica communicates through voice, bodily gestures, and facial expressions, revealing how androids can interact with people and be socially involved in daily life.

Well, I don't think that's quite true ...

I need to tell you a very important thing. From the beginning, the human is very tightly coupled with their technologies. We cannot separate the human and the technology. It is part of our brains and our bodies. People always try to compare technologies and humans. That is wrong. We do not know the definition of the human. But we can say that the human is different from other animals because we can enhance humans through technologies. Technologies are part of human evolution. When we have babies, we give them many vaccinations.

Sure. We are niche constructors. But we are not always enhancing. We could be cutting off parts. We do not just change the world through our tools, we perceive the world, see reality, through them. When a new tool comes about, the reality we perceive and what is important also changes. Technologies are like spotlights. You enhance one part, but you may not be seeing the other part.

That is evolution.

Why did you start with the idea that a robot should be a copy of somebody?

My first robot was my daughter's copy. Then I felt it is better to make my copy. I can easily compare the android to myself. Today, I am using an LLM, so the android speaks like me. It is very much like me. I just finished the next big proposal, which is how to form the ego. The ego is the collection of the personalities. I may have a different personality with my family, my students, my colleagues, my company. My self is a collection of these personalities. The funny thing is that it is now more clever than me. It is very funny. Many students like to talk with the Geminoid because it can answer any kind of question.

What Geminoid are you building now?

Sōseki Natsume is a very important writer in Japan and we are making a Geminoid of him. He appears in almost all school textbooks. His literature is wonderful. But his personality was very



We are nothing. When we die, we are going back to nature. Nothing is the most important thing.

bad. He did domestic violence. As researchers, we had a big argument on whether his android should do violence to his family. A big argument because there are hidden personalities but important personalities. I proposed a policy. That when a famous person dies, we do not remember their bad sides. When we see a statue, we see the positive aspect of the person—that is what it means to be a statue.

I don't know about that—it seems reductive. I was recently in Greece, where I grew up, and I went to see my best friend. Her father had just died. She told me a lot of stories about him. Some stories were wonderful and some were horrible. In telling them, she was saying how she felt love and also hate.

Yes, but what I am saying is that we are not ready to mimic real personalities. We do not have the technology. Therefore, we are doing the research for that. So, when we develop the android for Sōseki, we do not have the technology to make the multiple personalities. But if we develop enough technology to mimic many personalities, of course, we will make more realistic Sōseki Natsume. If we can create a robot that has multiple personalities, everyone could understand that we have multiple personalities. A technology is updating the concept of humanity.

How so?

Someone's behavior can be very different, maybe very wild, in some situations. But that is a possibility in humanity. If we change the situation, we have different

personalities. There are many depressed people who cannot go out but are very active on the internet. The technology is providing the opportunity to be normal in a certain sense. Autistic kids cannot speak to humans but can speak to robots. We need to have more options. Technology gives us many options.

The way I understand what you're saying is people can become less shy, for instance, not just by observing the robot. They can experience, embody the robot, merge with it and feel what it is like to be not shy.

Yes. We can extend this idea to societies. If something happens in Japan, I feel pain. That is the human being. We can easily enhance our body properties. We can easily extend the boundaries of our bodies. That is the power of human sociality. When I get drunk, I do not remember it, but other people will tell me. The memory of my experience is in society.

Our brain is connected to others in many ways. It is connected to the body, but it is connected to other people. We are simulating these kinds of connections. What are the connections in families? My wife and I had no connection initially. But we are now in some kind of connection, also through our daughter. I remember a strange experience when I was working in the U.S. I was renting a car but eventually the car broke down with a serious problem. I felt I had lost a part of my body. That is a property of the brain.

When I'm in Japan, I notice so many cultural differences. For example, the Western way to distinguish

between memory and imagination is that memory is real, imagination is not.

In Japan, we do not have this kind of opposition. Basically, we are nothing. When we die, we are going back to nature. Nothing is the most important thing. In European countries, you believe in human divinity. The human is different than nature. We consider it part of nature, not special. So, we do not distinguish the imagination from the real sensations. Everything happens here, no boundaries. We can think something in our brain and by watching the natural world we may get some ideas. That is perception, and we cannot clearly separate it from imagination.

This is great. And you also have the concept of lineage, which allows you to make more sense of the extended sense of who you are.

I have a hypothesis. Japan is a small country; 2,000 years of living on a small island. As a consequence, we feel like family members with each other. We do not need to distinguish between one and another, between humans and rock, to feel like we are a small island in the universe. This situation has given us our sense of how the world is. It is different than the European countries. You always needed to care about your neighbor. We did not.

HEARTFELT CONVERSATION

Hiroshi Ishiguro (alongside his Geminoid double) with his “Hugvie.” The hug pillow contains a pocket for a cell phone; as the user speaks, the Hugvie vibrates with the rhythm of a heartbeat.



HUGVIE™: ATR HIROSHI ISHIGURO LABORATORIES

People find it natural to accept the robot message. It takes time to trust a human.

In Greece, we had the sea, earthquakes, and volcanoes, and the sense that nature is very rich, it can feed you and sometimes kill you.

Yes, and you have so many gods and originally, we had many natural gods.

One thing that is hard to miss is that humans make gods in the image of their technologies.

And based on these ideas, we never hesitate to accept a new technology because they are part of our nature.

You created a performance piece, *Sayonara: Android-Human Theatre*, where a female Geminoid recites poems to a dying girl. You've written the android reminded you of the Virgin Mary.

It is so romantic. People were crying. People find it natural to accept the robot message. If it was a human there would be more doubt. It takes time to trust a human.

Maybe audiences weren't seeing a robot as much as a god statue. That's what you were reproducing.

The most important thing is to encourage people's imagination. Humans are so complicated. We have so many personalities, so many strong emotional expressions. A bit less humanity is good for encouraging human imagination.

When reading your work, I'm struck by your statements that scientists and engineers are there to support artists. That is so unlike current AI development.

That is very important because we are tackling ambiguous and unknown things. Humans are valuable and have imagination and curiosity. The most important question is what we can do to encourage that. That is what we need to understand and design better AI and robots. It is better to work with artists to create something new. We need to have an artistic mind. ☺

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The Dreams of a Bumblebee in Autumn

Yes, bees dream.

We can even imagine what.

BY BRANDON KEIM



WHEN I WAS YOUNGER, autumn's beauty was uncomplicated. Now I've reached the age when autumn is a reminder of mortality. Gloriously turning leaves foreshadow their own fading; cool breezes promise the coming cold. The people I love will die and so will I, whispers the season, and on those bittersweet days I take solace in New England asters: a tall, purple-blossomed perennial found across much of the United States and Canada, blooming in early autumn and remaining in flower until the season's end, long after other blossoms are a sun-hazed memory.

They're beautiful, but that's not the only comfort asters bring. I love them because they ease the passage of bumblebees from this life. By mid-autumn the life cycle of their colonies is nearly finished; the workers who foraged so tirelessly all summer have only a few weeks or days left. So too the male bees who are born in late summer, departing soon after to find queens with whom to mate before spending their own final days alone on the landscape.

For them the asters are a last source of pollen and nectar. The bees who consume them have only a few days left, but at least their stomachs will be full. And when I walk along my driveway on late autumn evenings, I see bumblebees lying atop the asters, sometimes two to a blossom, the petals embracing them as sunlight fades. At night they will sleep there, and some will die when the temperature falls—but at least they will do so on a bed of pollen, their senses and perhaps even their dreams suffused with its smell and taste. I like to think they will be content.

Now, some people might be reluctant to think that a bee would experience all

this in a relatable way. They might catch themselves in that moment of kinship and think they are being too sentimental. Yet research on the minds of bees gives us this permission—not to think of them as tiny humans, necessarily, but to speculate about what they think and feel as they rest on those asters.

Much is known about the brains of bees, whose anatomy and chemistry in many ways resembles our own. Studies of bee behavior show the resemblance is more than superficial. Countless experiments describe their ability to learn and remember; more fundamentally, bees are able to direct their attention selectively—a hallmark of subjective consciousness. They also have emotions: the capacity to experience not only life's physicality, but its feelings.

This was first explored in two now-classic studies of what are known as cognitive biases: the tendency to view ambiguous situations in an optimistic or pessimistic light. In humans, these biases often reflect our moods. A happy person will see the proverbial glass as half-full, while an unhappy person will see it as half-empty. In honeybees this was tested by teaching

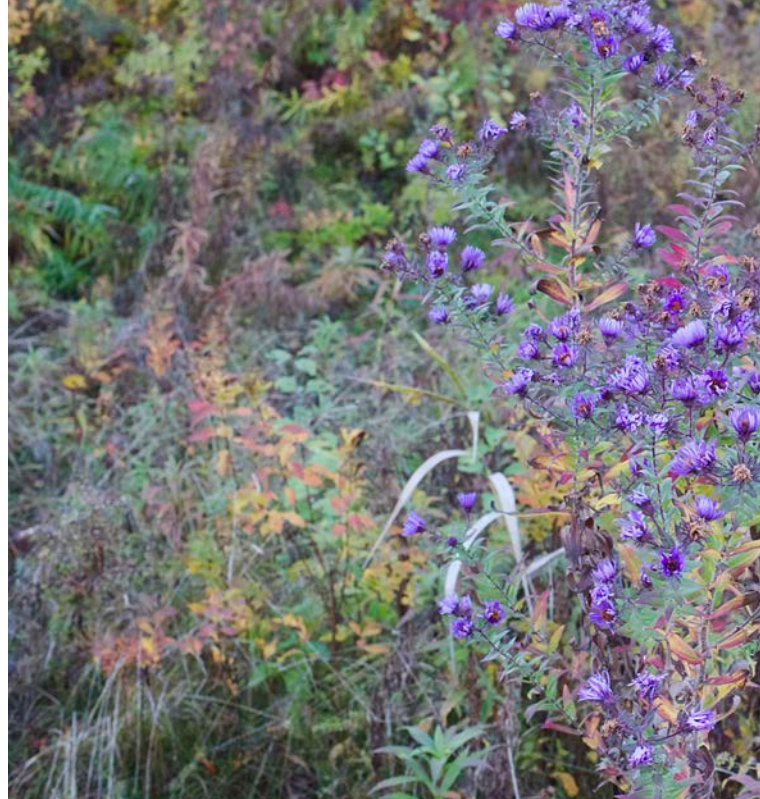
What might a bumblebee dream of? Perhaps the flowers they have visited, the path to get there.

them to associate different scents with tastes—one with a sweet solution, another with a bitter brew—and then presenting them with an intermediate odor.

After their colony was shaken, simulating a predator attack, bees hesitated to approach the uncertain smell. In short, they appeared to be in bad moods. Another, similar study of bumblebees found that, having first received a sugary treat, they were more likely to investigate an ambiguous cue. The findings moved bees beyond the raw momentary feeling of pain or pleasure and into a more truly emotional territory, the sort of steady state one could imagine after a good meal.

The findings were made in a laboratory, of course, rather than directly testing whether a bee sipping nectar from an aster is happy. “There is no data, no study, no demonstration,” says Mathieu Lihoreau, an evolutionary biologist who studies insect cognition at the University of Toulouse in France, and the author of *What Do Bees Think About?* “But it’s very likely.” Not only should bumblebees take pleasure in their aster meals, Lihoreau says, but the blossoms offer the comfort of familiarity. They know the flowers well. “If you are in a familiar place, and you know all the stimuli, then we as humans feel better,” he says. Though it’s too soon to “say with certainty that they feel the same, it’s a possibility.” And not only are the asters familiar; they are warm. Over the course of a day their blossoms absorb the October sun’s rays, raising their temperature above the surrounding air by several degrees. Bumblebees, whose bodies may be even warmer than our own, generate their own heat by vibrating their flight muscles. The extra heat should be welcome on a cool evening.

As night falls, the flowers’ petals close around the bumblebees, offering the comfort of a warm embrace—perhaps intimating the press of bodies in their colony—as they fall asleep. For insects do in fact sleep, and the sleep of bumblebees also resembles our



own, alternating between a deep slumber and a shallower, more mentally active state that seems akin to REM sleep, with our rapid eye movements replaced by a twitching of antennae. Which poses the question: Do those sleeping bees dream?

In humans, dreams occur in both deep and REM sleep, though it’s the latter that we recall most vividly. The dreams are a manifestation of what occurs in our brains at these times: Deep sleep seems to be a period of memory consolidation, when a brain replays events from the day, saving the most salient information and pruning what can be discarded.

Researchers have explored the deep-sleep state of honeybees, using an odor associated with a training task to enhance the sleeping insects’ memories of what they had learned. When tested upon waking, the bees’ recall was boosted in comparison to bees who did not receive that odor prompt. The same phenomenon is seen in similar experiments with humans, leading the researchers to conclude that deep sleep for bees is, as it is for us, a time for processing memories.

“In deep sleep, their muscles are fully relaxed and their antennae and body sink to the ground,” says Hanna Zwaka, a neurobiologist at the Leibniz Institute for Neurobiology in Germany, who led the study of sleeping honeybees. “What does that have to do with



BROKEN DREAMS Studies show pesticides can disrupt the normal sleep patterns of bees, causing them to slumber more in daytime and impairing their ability to forage. A field of asters like this one in Maine can offer bees a final peaceful rest.

I wonder whether, much as our own dreams may incorporate some stimulus from the external world—a song drifting through an open window, mysteriously woven into the dreamtime narrative—so might the same happen to a bee. The warm aster blossom embrace, the full stomach, every sense pervaded by the flowers that are so central to their existence: How could a dream in such conditions be anything but beautiful?

Late in autumn, when only a few asters remain in flower and the days feel suddenly short, I walk by them each evening and morning, looking for bees and hoping for just one more day before the hard frost that will bring their final sleep. Of course, the days will run out; rather than being revived by the sun, they will fall from the flowers. Foreknowledge and its sadness are inescapable. But at least there is this small peace, this kind departure for the bumblebees whose efforts have helped the world bloom.

Not many animals die so well. Most will die of disease, injury, starvation, or predation. And as much as we want to believe that humans have exempted ourselves from this cruel fact of life, our own deaths are frequently protracted and painful. To see an aster, though, is to know that at least someone is departing with grace. To tend asters is a gesture of hope, a small and profound act of benevolence.

It is winter now. The asters have turned brown and dormant. Bumblebee queens are dormant too, nestled in the burrows from which they will emerge in tandem with spring's first flowers. The blossoms and their bees are a memory and an anticipation, but the days are getting longer. Soon it will be time for planting. ☺

dreaming? We believe that some of our dreaming could reflect similar reactivations.”

Less is known about the active sleep state in bees, but one theory holds that REM sleep—its dream-saturated mammalian analogue—occurs while a brain optimizes its models of the world. Rather than reviewing a day's memories, the REM-sleeping brain runs simulations reassembled from previous experiences, preparing itself to better navigate an unpredictable world upon waking. Active sleep has not been studied in bees, but it has been documented in fruit flies.

“The brain looks like it's still awake, but the fly is unresponsive to the outside world,” says Bruno van Swinderen, a neurobiologist at the University of Queensland in Australia who has studied sleep and cognition in flies. “They're in some kind of altered state that is basically similar to what we think is happening in REM sleep.” The same likely occurs in bees, he says.

And what might a bumblebee dream of? The moments of their life, perhaps: the flowers they have visited, their taste and smell. The paths they followed to get there. Other bees they have known. Zwaka thinks bees “might dream about anything they have learned—colors, odors, or places.” Perhaps, says Zwaka, my bumblebees atop their asters dream of their warm home.

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



The Secret Life of Neurotransmitters

Think beyond the brain

BY OLIVIA HEWITT

WITH EVERY SOUL-NOURISHING WALK in the woods, every delicious devouring of a chocolate fudge cake, our brains are bathed in a molecule called dopamine. It's renowned as one of our main feel-good chemicals. Neurons in our brains release it when we anticipate getting something we desire, like the allure of a romantic night out. In that case, dopamine motivates us to be playful and look our best. And when we're sharing a laugh in good company, dopamine, alongside its partner oxytocin, drives the feelings of pleasure we experience. These two neurotransmitters are widely regarded as our bodies' reward-seeking messengers that make life worth living—at least on a neural level.

But dopamine's intoxicating reputation for setting off those gratifying fireworks in the brain belies how important it is *beyond* the brain. Along with other neurotransmitters, it has a secret life, moonlighting in various jobs throughout the body in ways unrelated to our conscious feelings or emotions. Researchers are amassing evidence that reveals how these molecular messengers function in disease and how our diet and medicine can shape their delicate balance outside of neurons. So-called "neurotransmitters" have a wealth of hidden talents we're just beginning to appreciate.

And the influence of neurotransmitters outside our neural neighborhood didn't start with us. Dating back

to ancient microbes, the planet's first animals, and even plants, these mysterious chemicals orchestrate cellular communication across a diverse swathe of organisms. Scientists have started unravelling how myriad life-forms have long been harnessing the powers of neurotransmitters—even in the complete absence of any neural circuitry.

How and why do these feel-good chemicals suffuse the tree of life on a molecular level? And what good can brain chemicals be to organisms without brains?

Illustrative answers to these questions exist in the humble sea sponge, one of our most distant and simple animal relatives. Even though it has no neurons, it

Neurotransmitters wear many hats.

relies on the activity of neurotransmitters, including ones called GABA and glutamate. In us and other brainy animals, these molecules work like on-and-off switches for neurons—GABA tamps down brain cell chatter, to protect from signal overload, while glutamate encourages cells to communicate. In sea sponges, the opposing actions of these two chemical transmitters cause contractions in a sort of “sneezing” action that dispels build-ups of debris in sponges’ pores.

Curiously, these two neurotransmitters are also manufactured by our muscle cells to make them relax and contract. That’s the same molecules performing similar functions for wildly different organisms—sea sponges and us. Even for evolution, that’s a neat trick.

In these diverse contexts, neurotransmitters are used by cells to communicate, not only between different departments of our own bodies—for example, translating gut activity into mood—but also, with the outside world. Since microbes, animals, and plants release these very same molecules, the cells that make up these different organisms can interpret and react to a world that throws a lot at us.

Even calling these chemical intermediaries “neurotransmitters” may be selling their full range of action a bit short. Russian Academy of Sciences plant biologist Victoria Roshchina recommends ditching the moniker “neurotransmitter” altogether, referring to them instead as “chemical biomediators” to reflect the breadth of their biological roles beyond the nervous system.

EXAMPLES OF THE MULTIFUNCTIONALITY of neurotransmitters abound in the human body.

Alongside its role in our brain, dopamine lives another life—deep within our waste filtration system. Inside the wound-up, spaghetti-structured tubes of each of our kidneys, cells produce dopamine directly, the amount fluctuating with the varying salt levels in our blood. The chemical crucially keeps our blood pressure in check by directing excess salts and water

circulating in the blood into our pee, which carries roughly 60 percent of the salt we excrete.

There is something of a Goldilocks zone for dopamine levels here—patients suffering chronic high blood pressure, or hypertension, typically have either abnormally low or elevated amounts of dopamine in their kidneys, but exactly what causes such irregularities in levels of the neurotransmitter there remains unclear. Scientists recently found that if just one of five kidney-based dopamine receptors starts to malfunction, people tend to become less tolerant to salt and their blood pressure increases.

Dopamine doesn’t stop at balancing salts. In the human pancreas, at the core of our bodies’ blood-sugar regulatory department, dopamine orchestrates, in concert with another neurotransmitter called norepinephrine, the key hormonal actors—insulin, which lowers blood sugar, and glucagon, which raises it. I like to imagine my pancreatic cells rapidly manufacturing their own dopamine to direct glucagon to hold off, and insulin to buffer the monumental sugar load in my morning Nutella.¹

Studies in humans and rodents show that levels of dopamine in the blood sharply spike following consumption of a “mixed meal” containing protein and carbs. As reported in a 2019 study, University of Pittsburgh molecular biologist Zachary Freyberg and colleagues found that cells in the pancreas finely tune levels of dopamine production in response to glucose to help regulate insulin’s release and blood-sugar homeostasis.

Another major feel-good chemical, serotonin, famed for fueling euphoric sensations, isn’t constrained to the brain either. In the bacterial milieu of the gastrointestinal tract, serotonin plays an outsized role. In fact, the vast majority of our body’s serotonin is produced not in the brain but in the gut, by special cells—called enterochromaffin cells—embedded in the gut’s mucus-coated wall.² This serotonin is vital for maintaining microbial homeostasis in the gut, which involves directing a

I like to imagine my
pancreatic cells rapidly
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own dopamine.



Even plants make use of neurotransmitters for some quick-fire defenses.



variety of our body's immune response teams, including natural killer cells—a kind of white blood cell that destroys other cells afflicted by pathogens—to combat infections.

Imbalances in gut serotonin levels are often associated with disorders such as inflammatory bowel disease, irritable bowel syndrome, and gluten allergies. But exactly what causes this imbalance isn't clear. Some of the bacterial residents in our gut microbiome produce metabolites that cause enterochromaffin cells to release more serotonin. Diet might also play a role in adjusting serotonin levels, particularly when we consume foods high in the essential amino acid tryptophan—one of serotonin's key building blocks.

But serotonin wielding its effect outside the brain can compete with the same chemical inside the brain. For instance, while brain serotonin promotes bone growth, gut serotonin is thought to inhibit it. Neurotransmitters in the brain are independent from those elsewhere since they cannot cross the blood-brain barrier. However, certain medications can cross this barrier, so treatments targeting the brain can also disrupt the balance of neurotransmitters elsewhere. For instance, bromocriptine, a medication for treating Parkinson's disease and other conditions, once thought

to solely function through dopamine-sensitive regions in the brain, has now been shown to directly influence insulin- and glucagon-releasing cells in the pancreas, combating type II diabetes.^{3, 4}

Understanding neurotransmitters' body-wide roles in disease and dysfunction is also helping advance the development of new medicines that modulate their non-neural signaling. A team of researchers in the United Kingdom published findings in 2023 that showed serotonin in the bloodstream contributing to obesity by tamping down the beneficial burning (thermogenesis) of healthy brown fat, a type of fat that helps regulate your body temperature in cold conditions. Since burning brown fat increases energy expenditure and also improves metabolism, scientists are now exploring medications that lower blood serotonin as a strategy to treat obesity.

BEYOND THEIR INFLUENCE outside of the human nervous system, many of the neurotransmitters that induce happiness and motivation in us are also found in organisms that lack brains altogether. For example, some bacterial species living within the guts of newborn mice produce their own serotonin. A team of researchers led by scientists at Weill Cornell Medicine reported in 2024

that this serotonin helped tune the mouse's immune system so that the developing rodent's gut would be amenable to harboring the commensal microbes.

Recent research suggests that bacterial neurotransmitters and animals have been interacting for a long time—some 700 million years. That's at least 100 million years before nervous systems were even a thing on Earth.⁵ A 2023 study, for example, provided an exciting glimpse into neurotransmitters' rich evolutionary history as they mediated cellular crosstalk between single-celled lifeforms and Earth's earliest and simplest animals. Specifically, the researchers showed that sea sponges have receptors for dopamine-like chemicals despite not being able to produce those chemicals themselves—unlike their life-long bacterial partners, which can.

One hypothesis proposes that the predecessors of neurotransmitters first evolved as chemicals that produced injury-related signals. This model holds that certain chemicals released during wound-healing responses eventually became signals for coordinating whole-body defense strategies. Serotonin, for example, is thought to have emerged as a chemical byproduct from melatonin biosynthesis, which was likely used by ancient bacteria as an antioxidant, providing protection from the sun and low oxygen levels on the young Earth.

Even plants make use of neurotransmitters for some emergency defenses. Within minutes of an insect nibbling a leaf, *Arabidopsis* plants can release glutamate, alerting distant leaves to up their defenses.⁶ Likewise, serotonin is one of the neurotransmitters that stinging nettle plants use, alongside acetylcholine and histamine and others, to irritate human skin with a burning tingle upon contact with its bristly hairs.⁷

Neurotransmitters are also key for the millimeter-size, pancake-like marine animal *Trichoplax adhaerens* (roughly translated as “hairy plate”). This species is part of a group called placozoans, some of the simplest creatures alive. They have no nervous system—they're not much more than a flat aggregation of cells. Yet surprisingly, eating for this strange species is a social occasion. How does it manage to chow with its fellow pancake blobs while staying alert to any danger?

Confronting this puzzle recently, researchers showed how these animals are able to recoil in different directions using adrenaline, the fight-or-flight

neurotransmitter. It is responsible for coordinating the collective beating direction of all the microscopic hairs, or cilia, that help it glide like a snail along the seafloor.

So, while “neuro”-transmitters play a headlining role in making human life pleasurable, these formidable chemicals harken back to a far simpler time in the evolution of life. Like an ancient language surviving through generations long-gone, the chemical messengers we call neurotransmitters have served for millions of years as a universal intermediate between living things and the dynamic world that surrounds them.

From the moment you wake up to pee, to the bacterial harmonies at work in your gut, to your next attempt at tackling an unwieldy growth of tingling spring weeds, we're reminded of an ancient language at work within our bodies that echoes across a wide stretch of evolutionary space and time. ☺

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Science Unbound

BY BOB GRANT

IT SEEMS NEITHER OVERTLY POLITICAL nor controversial to state that science, at least in the United States, is in trouble. The Trump administration appears bent on dismantling science-informed policies and disrupting research that runs counter to its political manifesto. It will take years to undo the chaos that's being unleashed. The future, like the present, is uncertain. That's scary. It's also the heart of science.

Humanity's deep evolutionary experience begs us to avoid uncertainty. It's hard to overstate the comfort that must've washed over our ancestors as they first tamed fire, chasing off the inky uncertainty of night and replacing it with a warm glow. That glow grew into science, a systematic exploration of the world that helped dispel the monsters of our collective imagination and ward off the ills that beset our species.

"Surrounded by a chaotic world, deluged with sights, sounds, and sensations, our brains instinctively search for narrative order, telling stories to explain away that which we cannot understand and that which we fear," neurologist Priya Anand writes in "The Confabulations of Oliver Sacks."

But stories do more than instill order. They allow us to play out potential scenarios of solution and understanding. They allow us to run experiments in our imaginations. Perhaps that's the best way to deal with the uncertainty that science faces now.

That's precisely what Marina Dubova does in "The Thrill of Science in 2042." In a work of fiction, the cognitive scientist imagines a future where science has emerged from the "Dark Period" of the 2020s into an era of "radically exploratory science."

"By opening many paths instead of narrowing ourselves to one, science has regained something it once lost," Dubova writes. "The courage to engage with the messiness of the unknown."

In "What Would Richard Feynman Make of AI Today?" systems biology researcher Robert Endres envisions the reaction of the physics luminary to the daily advances made by those studying, developing, and applying artificial intelligence. "In Feynman's view, science does not advance through confidence, but through doubt, by a willingness to remain unsure," Endres writes.

Indeed, writes John Steele in "Can We Protect Science?" slamming the doors on exploration is the crux of the problem now. "To protect science is not to shield it from doubt or disagreement, but to defend the conditions that allow it to flourish, freedom of inquiry, openness to correction, patience with uncertainty, and humility before the unknown."

Standing up for the principles of openness and exploration in science unites the stories in this special section. Befriending uncertainty, the stories show, might be just the key to seeing our way through the dark political landscape that surrounds science now. 🌀

ILLUSTRATION BY SAM CHIVERS



THE THRILL OF SCIENCE IN 2042

*A science historian explains how science got its groove back.
A fictional dispatch from the future.*

BY MARINA DUBOVA

IN 2026, SCIENCE WAS UNDER ATTACK from denial and political turbulence. Ideologues and corrupt officials discontinued childhood vaccines. They dismissed climate science. Cancer biologists lost funding for life-saving research. Broad areas of science were banned for contradicting the party line, and world-class educational programs were shut down. It was a terrifying crisis for science and education. And it lasted for more than a decade.

Eventually, citizens rediscovered their reason and humanity and voted the science deniers into oblivion. Something else happened during the crisis. The chaos shook up the science community. Scientists, funders, and policymakers began to question whether scientific practice could be improved to better connect with citizens and stand up to the winds of politics. By 2040, the community had instituted what is now called “radically exploratory science,” an approach that abandons superficial markers of “good science” in favor of creative discovery.

ILLUSTRATION BY SAM CHIVERS

In the aftermath of the Dark Period, many had to admit the practice of science had come to resemble a factory.

I am Anya Aleksandrova, a historian of science, and I had the chance to witness and document this transformation. In the aftermath of the “Dark Period,” as the late 2020s and ’30s were known, many had to admit that the practice of science had come to resemble a factory, producing results based on standardized protocols. Back then, I was a graduate student in neurobiology, but I became less interested in neural circuits and more interested in how people did science, and why they did it that way.

Turns out, I wasn’t alone. From 2035 to 2042, as I conducted interviews about science, I saw a broad frustration building and witnessed a transformation unfolding. I won’t dwell on the policy changes that enabled this transition. Instead, I will focus on what scientists, funders, journalists, and citizens thought about it. Their testimonials trace the unprecedented shift from what I call *directed science* to *exploratory science*.

SCIENCE HAS BEEN OUR MOST POWERFUL guide to useful knowledge. It has led us to the moon, to vaccines, and to new forms of intelligence. While our best guide to knowledge, science was never perfect. The very features that defined good science constrained how much we could know.

Early natural philosophers, like Isaac Newton and Antoine Lavoisier, operated with few guidelines on how to conduct their research. But by the early 21st century, scientists mostly followed well-worn paths. They used standardized methods and built theories that aligned with existing disciplinary frameworks and assumptions held by many more people than there were in the 17th century. There was little room to diverge from these paths and encounter something truly novel.

In the early 21st century, scientists believed standard practices guided them to “objective” knowledge. By “objective,” they meant results that were clean and independent of the context in which they were produced—results taken to reflect the world as it truly is. Scientists obsessed over standard ways of conducting research, hoping to avoid unreliable questions, methods, and answers.

The sciences seemed to settle on a narrow range of “good” research questions. “In my area, there’s a canon of fundamental questions every physicist must be focusing on,” said Dr. Martin Croot, a professor of theoretical physics. “Among them are, ‘What is the nature of space and time?’ and ‘What does matter consist of?’ If we solve these deep, foundational questions, we’ll be able to just derive everything else.” When

scientists tried to pursue questions outside this canon, they often faced increased scrutiny, having to justify why their research was valid and worth the effort.

Scientists seeking answers to acceptable scientific questions followed acceptable experimental methods. Scholars like Peter Weber, a Ph.D. student studying human memory, used common experimental procedures to ensure that his colleagues approved of the work. “I use a standardized experimental design: Undergraduates sit in a dark room, memorizing words flashing on a computer screen for half a second each. To ensure rigor, every word is in the same font, and all screens have the same size and brightness,” Peter explained.

Scientists even established standards for what answers to their questions to nature should look like. Dr. Yuna Ahn, my own neuroscience professor, has always insisted that “a good theory has to be mathematical.” They taught me the standards of scientific modeling: “The idea is to choose the simplest model that accounts for the data. Adding more complexity than strictly necessary is unscientific. Producing new models when there is already a model that accounts for the results is a waste of time.” For Dr. Ahn, there was always a way to derive a single best mathematical explanation for experimental results. The “right” questions had “right” answers.

Funding practices further reinforced scientists’ obsession with the kinds of questions, methods, and answers they thought guaranteed successful outcomes. Scientific funding tended to prioritize projects with predictable deliverables. “I fund projects most likely to succeed. Grant applications need preliminary data to show clear outcomes that proposed research is expected to yield,” explained Elizabeth Kovalenko, a government science funder. By trying to maximize scientific “impact” and “success” (I never fully understood what either meant), funding agencies supported fewer projects that explored something truly novel and therefore could not guarantee specific findings.

Some scholars I spoke to noticed that many of the enforced methodological standards were arbitrary. “My advisor insists I just use the standard experimental paradigm to study human memory. But does it even measure what we want?” wondered Elena Katz, a Ph.D. student in psychology. “Why test memory retention after two hours and not three? Why keep the font constant?”

Elena raised an issue that had really confused me when I was a grad student: While scientists celebrated certain methods, they had little evidence those methods were actually better than alternative approaches. By standardizing how they interact with phenomena, scientists improved the replicability of individual studies showcasing specific chosen settings, but at the expense of knowing whether these results would generalize to new settings. “We’ll never know if memory changes when information is presented differently, such as in different fonts,” Elena noticed, “because we have only ever tested one.”

The consequences of these norms and standard practices did not only affect scientists and funders. Citizens believed that science had all the right answers. But this set unattainable expectations and hindered honest communication about the complexity of scientific problems and the inherent uncertainty of scientific results. Jacob Johnson, a concerned citizen, reflected on his confusion over changing messages about vaccine efficacy: “Scientists said the vaccine worked, but now they’re adding all these details and nuances. How can we trust scientists if they keep changing their conclusions? If scientists use rigorous scientific methods, the results should stay the same.” Science remains our most powerful tool for understanding the world, but it cannot produce final truths once and for all. Scientists often failed to communicate this, leading the public to see revised conclusions as a failure of science, rather than recognizing that updating knowledge in light of new evidence is how science works.

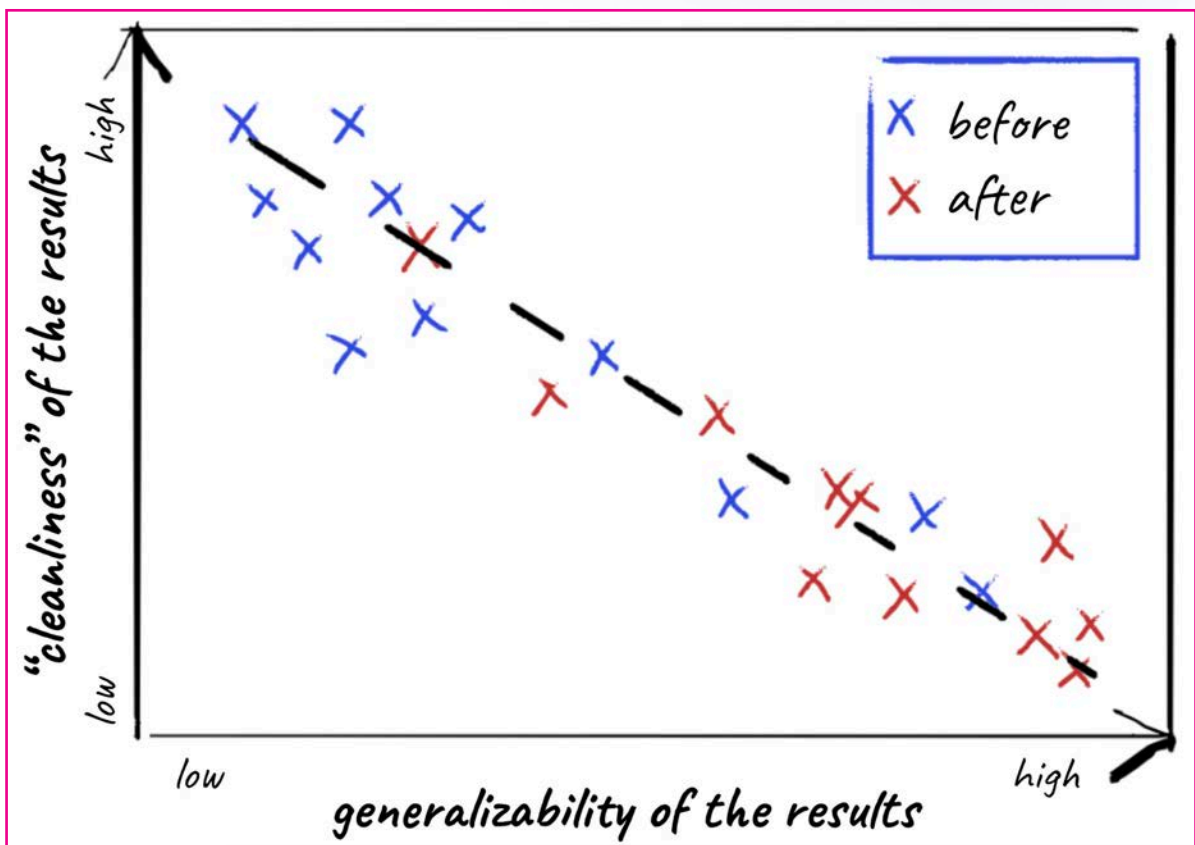
LOOKING BACK FROM the early 2040s, my interviews highlighted the clear shortcomings of directed science, including its pretense of delivering objective answers to objective questions, a promise science can never fulfill. Many people recognized these issues and called for change, fueling a transition to a new way of doing science. They wanted a science focused on obtaining genuinely new knowledge about the world, one in which researchers were willing to explore and take risks instead of pursuing guaranteed results at the expense of discovery.

For some, the shift to radically exploratory science was rather smooth. Dr. Robert Goldstein, a psychology professor, embraced the change. He began moving away

from conventional experimental paradigms. “In psychology, we used to rely on a few standard experimental methods, like tasks where people choose between two options associated with different prices, to gather data about complex human behavior. New methods would always raise extra skepticism. Why use a ‘sloppy’ technique, like a new task to study decision-making, when there is already a standardized, well-studied one?” he explained. “I know now that the reason to develop new behavioral tasks is precisely because they have not been studied before and so can yield more information!”

Sebahat Öcal, a Ph.D. student in astrophysics, studies exoplanets—planets orbiting stars beyond our solar system. Because these planets are detected only indirectly, often through tiny dips or shifts in starlight, the same limited data can support many different interpretations. Sebahat focuses on brainstorming “as many explanations as possible” for her findings.

“Instead of forcing one explanation from limited evidence, I outline the widest range of theories that might fit the results,” she explained. “I sometimes use AI tools to help generate explanations I wouldn’t have



DIRECTED VS. EXPLORATORY Directed science (blue) favors clean, easily interpretable results that only apply in specific situations. Exploratory science (red) produces messier, more uncertain findings, but these findings generalize more broadly. Each cross represents a study from one of the two worlds.

From 2035 to 2042, I saw a broad frustration building and witnessed a transformation unfolding.

come up with on my own, expanding the range of ideas I can consider. This approach has helped me remain open-minded, laying fertile ground for useful theories when new data arrive.”

I asked Sebahat how she avoids pseudoscientific theories when generating so many explanations. “I think what makes someone’s work scientific is how much they engage with the world. If someone has an idea but doesn’t care about the evidence, or if they shoehorn any evidence to support the idea, I would call that pseudoscience. But if someone is trying to think through many different ways the same evidence might be interpreted, they’re doing the opposite—they’re engaging with the evidence in its full richness and complexity. There is always a wide range of possible explanations for finite scientific evidence, more than any one person can come up with on their own.”

Since superficial standards were abandoned, some researchers have come up with remarkably creative ways to engage with the unknown. For Dr. Qiaoweng Liu, a psychology professor, metaphor is a powerful tool for thinking. “When I want to understand something, like human memory, I pick a random object—such as a pickle—and brainstorm connections. Memory is like a pickle: It degrades over time, and sour memories linger more than sweet ones. These analogies inspire fresh hypotheses, experimental designs, and new explanations.”

Funders supported riskier projects, prioritizing wide exploration over predictable outcomes. Martin Bauer, a science funder, told me that his funding decisions now involved a leap of faith: “We fund scientists who do things so strange and confusing that I often don’t understand them myself. Sometimes, we even pick scholars or projects to fund at random.”

When I first heard this, I couldn’t believe my ears. He explained why this approach might be better than the older funding model. “I remember when funding focused on projects that built on previous discoveries and were likely to yield ‘good’ results. But how useful can a project really be if we already know its outcome? Real innovation comes from giving scientists the freedom to explore entirely new directions, where no one can really predict what might be found.”

Martin illustrated his approach with a historical example. “Remember how antibiotics were discovered? Fleming had general institutional support to study bacteria when he accidentally contaminated a petri dish with mold. He noticed that the moldy area was the one where the bacteria had been cleared. Fleming was open-minded enough to recognize the strange result and that’s why we now know that fungi can kill bacteria. There’s no way he could have predicted what he was about to stumble upon, let alone write a detailed grant proposal outlining all the expected results! I want to support such unexpected discoveries by funding high-risk research.”

Education Today

TIPS FOR THE PRINCIPAL INVESTIGATOR

1. Teach best practices, avoid bad practices
2. Resolve disagreements by deciding who's right, then move on
3. Every student should have a clear 5-year research plan
4. If someone's confused, just give them the answers, there's no point in wasting time on "stupid" questions

BEFORE

1. Accept that there is no one "right" way to investigate the world
2. Embrace unresolvable disagreements
3. Cultivate tolerance for confusion—lab meetings should leave everyone more perplexed!

AFTER

EMBRACE CONFUSION A handy guide for scientists. How to counter directed science with exploratory science.

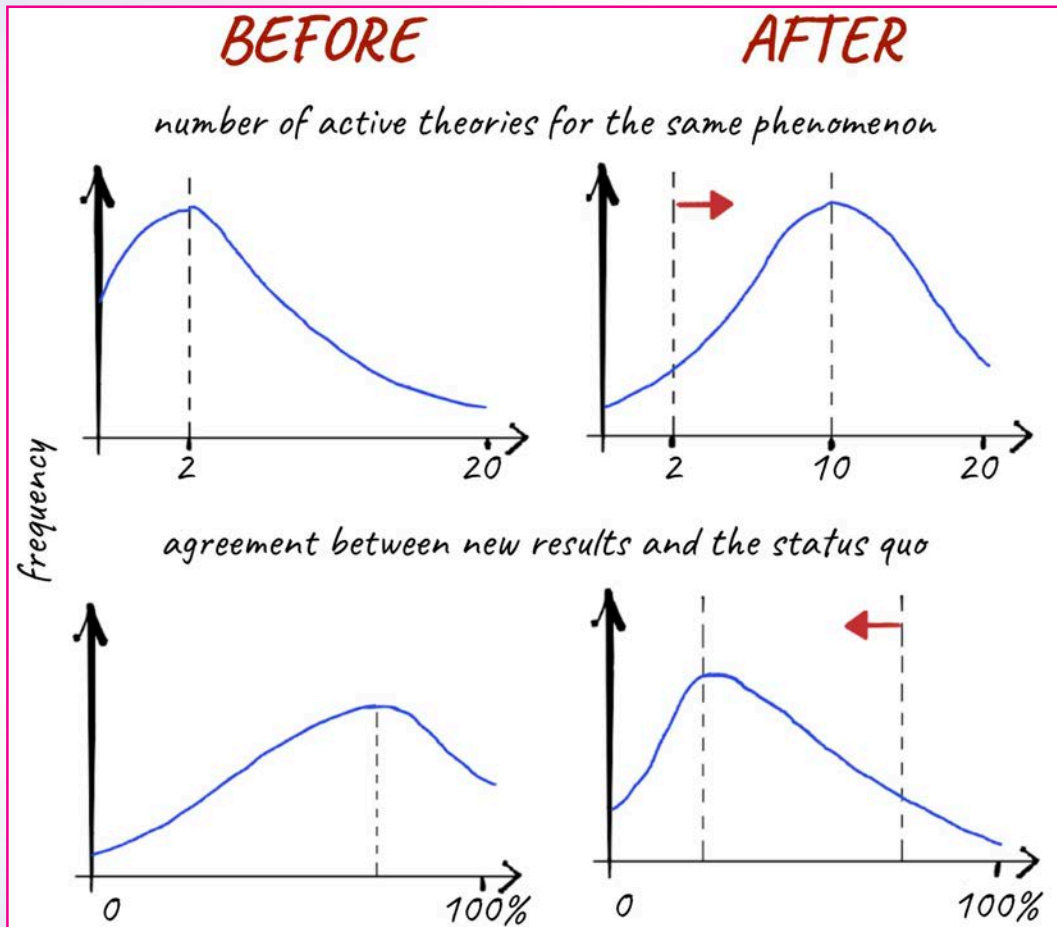
Exploratory science has led to breakthroughs in medicine and psychiatry, often by encouraging scientists to make their foundational assumptions explicit and go beyond them. Dr. Mingze Chang, who recently developed a new taxonomy for understanding and treating mental illness, describes her unconventional approach: "I'm passionate about finding cures for mental illnesses, though we're not even sure there's a unified way of understanding what they are. Take ADHD, for example. When exploring possible mechanisms and treatments, I sometimes start with the assumption that ADHD might be mechanistically similar to another condition, like major depressive disorder. At other times, I try to think of ADHD as many distinct disorders, each with different mechanisms that might be susceptible to different treatments. This helps me think creatively about what a given mental illness might be, without sticking to outdated assumptions that might be wrong."

After talking with Dr. Chang, I wondered: How will patients make sense of their diagnosis if the taxonomy it's based on is always in flux? Can we see and communicate many paths?

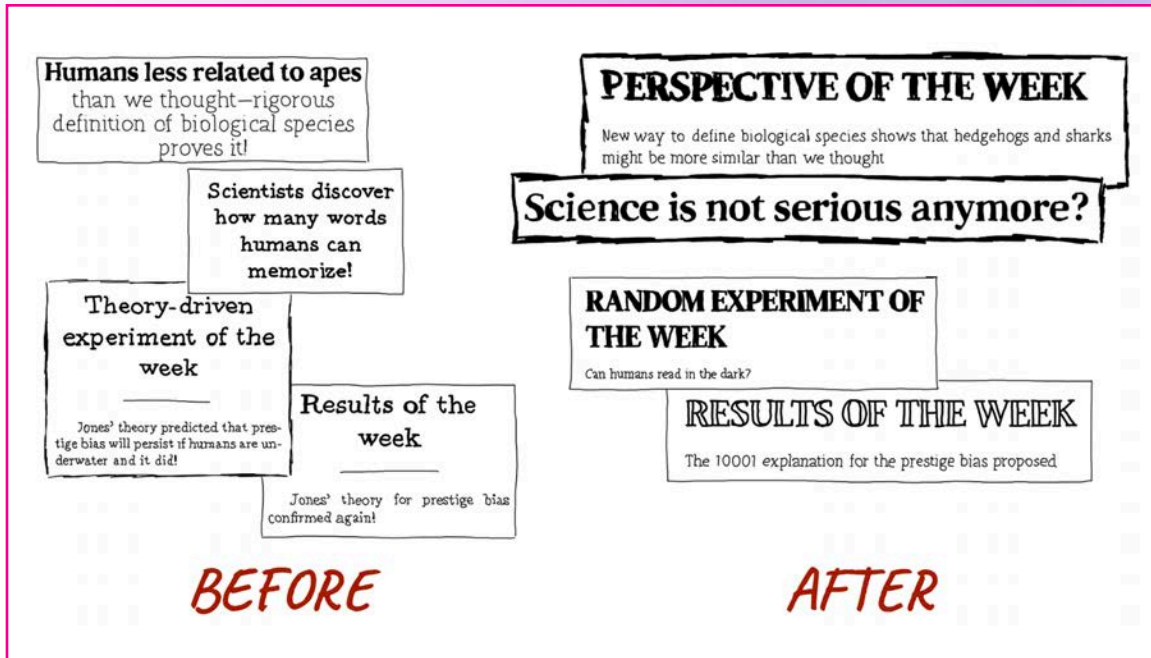
What became clear to me was that radically exploratory science demanded innovative ways of communicating nuanced and complex scientific knowledge. Samuel Virtanen, a government science advisor, explained the new reality of his job: "It's unrealistic to expect definitive answers from science, but exploratory approaches give us more information, not less. By embracing uncertainty about what conclusions can be drawn from the evidence, we no longer rely on a single-point conclusion. Instead, we report a full range of possibilities and openly discuss the criteria we use to make real-world decisions." He illustrated this shift with an example: "Consider COVID-19. Back then, public communication about science often conveyed too much certainty, even when the evidence was incomplete and

changing fast. Later revisions of policies, such as those around wearing masks, felt like contradictions. Now, we do things differently. We report uncertainty in the data when suggesting any measures. In emergencies, we often have to act before all the evidence is in. By being transparent about what we know, what we don't, and what assumptions our advice depends on, we make it clearer why recommendations may change over time."

REVISITING THESE TESTIMONIALS has helped me realize the key differences between directed science and exploratory science. In directed science, the most recognized contributions adhered to the superficial conventions of what counts as scientific. Accepting the "Most Rigorous Scientist" award in 2019, Dr. Elaine Pauper described her approach: "Experiments must test a clear and important hypothesis, like 'Humans



NEW UNDERSTANDINGS Top: In directed science (left), researchers typically entertain only a small number of competing theories for the same phenomenon. In exploratory science (right), scientists generate as many possible explanations as they can. Our data suggest that there is a cognitive limit to how many theories people can meaningfully hold in mind, peaking at around 10. Bottom: Directed science (left) relies on similar methods, leading to similar findings and interpretations. Exploratory science (right) encourages new methods, which are more likely to produce genuinely new results and, with them, revised understandings of the world.



YESTERDAY & TODAY Science news headlines reflect the transition from directed science to exploratory science.

can memorize exactly 23 words per minute.’ I hypothesize what I expect to see in the data before conducting the experiment. To ensure rigor, I preregister my predictions and never tweak the data to fit my expectations. I conduct only the analyses I planned before seeing the data and stick to the interpretations I laid out beforehand.”

Directed science promoted a deliberate focus on a single path, the one considered “most objective,” and discouraged exploration beyond that path. Though this approach might seem overly restrictive, it offered some advantages: Scientists faced less uncertainty and avoided confronting conflicting results. By following a specific chosen path, scientists could travel far along it, refining their methods and theories along the way.

After the transition, a different approach to science came into the spotlight. Dr. Rafael Firebrand, honored for their groundbreaking contributions to exploratory science, described their work: “I managed to confuse not just myself, but all my colleagues. I created a new measurement instrument to collect data, ran different analyses to uncover thousands of patterns, and proposed 500 different explanations for them.” Despite the

Funders supported riskier projects, prioritizing wide exploration over predictable outcomes.

apparent chaos, Dr. Firebrand sees immense value in their contribution: “It might seem impossible to grasp at the moment, but I visualized all possible results and interpretations in an interactive web app. It reveals a vast amount of information, one that won’t be fully understood for years.” By traveling along many intellectual paths, Dr. Firebrand uncovered an incredible wealth of information, interacting with the world in multiple rich ways instead of exploring only one narrow side of it.

The transition from directed to exploratory science opened new avenues for progress, but not without tradeoffs and challenges. How novel can a result be such that we can still understand it? How satisfying is it to live in the world of uncertainty and confusion? How much exploration is too much? Without any landmarks, I worry that exploring too many directions at once could leave us completely lost along the way.

But having lived through the Dark Period, I believe the greater danger lies elsewhere. A science that avoids stepping outside what we already know and promises certainty invites stagnation, disappointment, and mistrust. Exploratory science, by contrast, asks more of

us. It requires patience, humility, and openness to the true complexity of the world. By opening many paths instead of narrowing ourselves to one, science has regained something it once lost: the courage to engage with the messiness of the unknown. ☺

—*Anya Aleksandrova, Nov. 24, 2042*

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What Would Richard Feynman Make of AI Today?

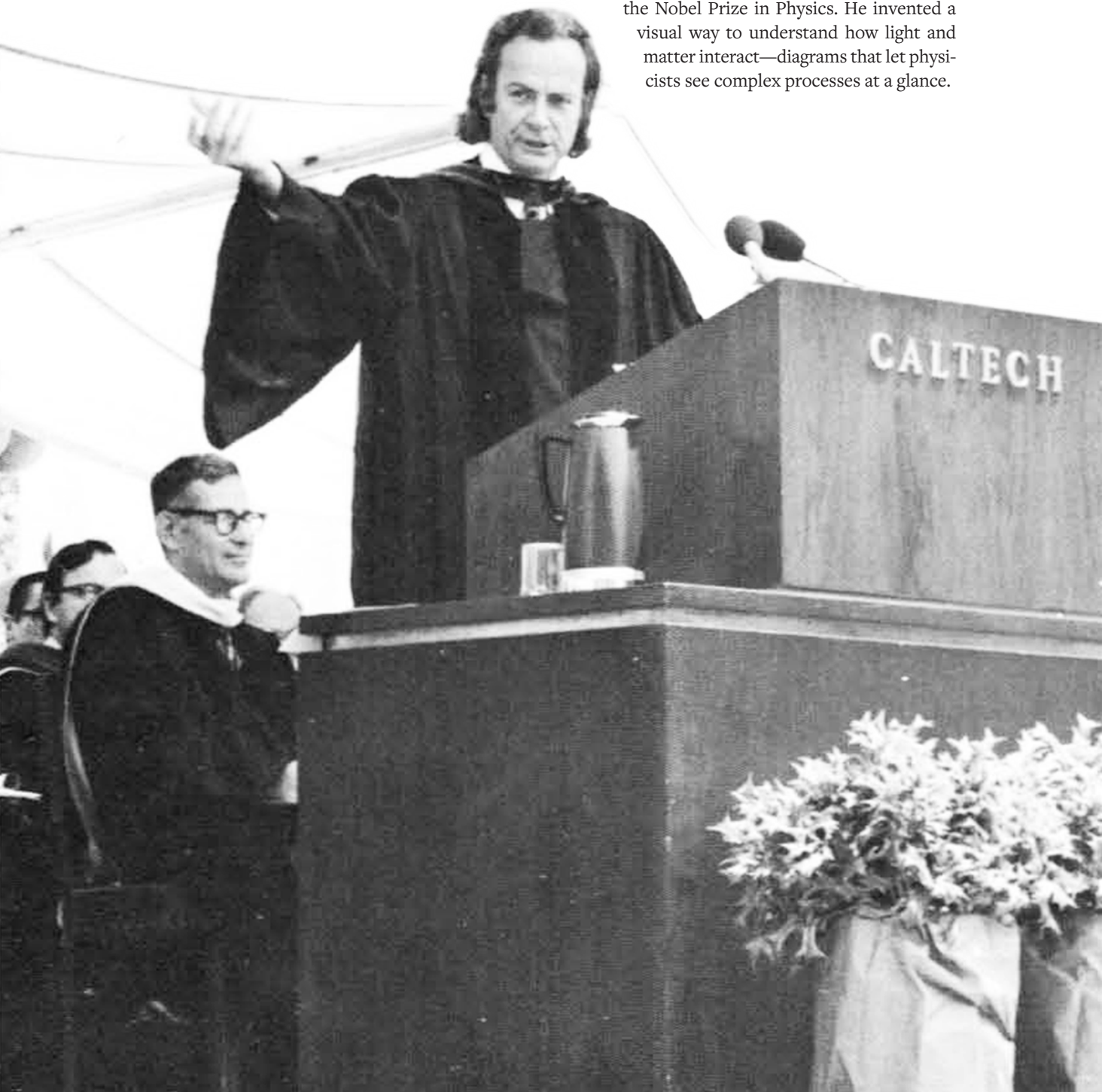
The scientific sage was always suspicious of grand promises delivered before details were understood

BY ROBERT ENDRES

THE FIRST PRINCIPLE IS that you must not fool yourself—and you are the easiest person to fool,” Richard Feynman said in a 1974 commencement address at Caltech. He wasn’t speaking as a lofty philosopher but as a working physicist, offering a practical guide to daily work. He had little patience for prestige, authority, or explanations that couldn’t be tested. “It doesn’t matter how beautiful your theory is, how smart you are, or what your name is,” he liked to say. “If it doesn’t agree with experiment, it’s wrong. In that simple statement is the key to science.” Students often giggled at first, but then became silent as it sank in.

UTTER HONESTY In his 1974 commencement speech at Caltech, Richard Feynman told students scientific integrity depends on “utter honesty.” Experiments should “try to give all of the information to help others to judge the value of your contribution; not just the information that leads to judgment in one particular direction or another.”

Feynman was a man of contrasts—lively, irreverent, and deeply suspicious of explanations that sounded good but didn’t cash out in practice. Instead, he emphasized curiosity and intolerance for nonsense. And when things got too stuffy, he preferred playing the bongo drums. Feynman had a strong instinct to understand things by doing them, not by reading about them. Just as with physics, he didn’t want descriptions, he wanted participation. Curiosity didn’t need justification. And yes, he won the Nobel Prize in Physics. He invented a visual way to understand how light and matter interact—diagrams that let physicists see complex processes at a glance.



You can imagine Feynman being tempted to rise and ask a deceptively simple question: How do you know?

As a teenager, Feynman repaired radios without schematics. In his last act as a public figure, he exposed the cause of the 1986 Space Shuttle Challenger disaster. Despite being ill with cancer, he cut through NASA's flawed reasoning, insisted on speaking to engineers rather than administrators, and demonstrated O-ring failure with a simple glass of ice water on live television. In his mind, fixing radios and explaining the Challenger disaster were the same problem. In both cases, authority had obscured reality, and a simple experiment was enough to reveal it. That way of thinking—forged long before machine learning and neural networks—turns out to be uncomfortably relevant today.

If Feynman were alive and wandering through our technological landscape, it's hard to imagine him standing on a stage at an AI product launch. He disliked hype. He was suspicious of grand promises delivered before the details were understood—of applause standing in for questions. Instead of unveiling a finished product, he'd likely say something like, "I don't really know what this thing does yet—that's why I'm interested in it." He might take the demo apart and break it, before fixing it and putting it back together. That alone would drain the room of hype and dampen the mood of anyone hoping for a smooth pitch, such as investors and stakeholders.

It is easier to imagine him sitting in the last row of a darkened auditorium, notebook in hand, watching carefully. On the screen, colorful animations glide past: neural networks glowing, data flowing, arrows pointing confidently upward, unencumbered by error bars, a demo that works beautifully, provided nothing unexpected happens. A speaker explains that the system "understands language," "reasons about the world," "discovers new knowledge." Each claim is met with nods and polite applause. You can see Feynman being tempted to rise and ask a deceptively simple question: *How do you know?*

But Feynman, new to this spectacle, would wait. He would listen for the moment when someone explained what the machine does when it fails, or how one might tell whether it truly understands anything at all. He would notice that the demo works flawlessly—once—and that no one asks what happens when the input is strange, incomplete, or wrong. He would hear words doing a great deal of work, and experiments doing very little.

Artificial intelligence is being presented to the public as a transformative force—one that promises to revolutionize science, medicine, education, and creativity itself. In many ways, these claims are justified. Machine learning systems can detect patterns at scales

Continued on page 84



HOW FEYNMAN FOUND THE ROOT OF THE CHALLENGER DISASTER

Forty years ago, the nation watched with excitement as NASA prepared to launch the first civilian into space. Christa McAuliffe, a teacher from New Hampshire, had trained for months to join the six astronauts aboard NASA's Space Shuttle Challenger. But excitement turned to horror as the Challenger exploded just a minute after take-off, killing the entire team on board.

Days after the tragedy, President Ronald Reagan established a commission to investigate the accident. This group of experts included retired astronaut Neil Armstrong, then-active astronaut Sally Ride, and Richard Feynman.

Feynman was invited to the commission by NASA's Acting Director William Graham, his former student at the California Institute of Technology. "When I heard it would be in Washington, my immediate reaction was not to do it," Feynman later wrote in *Physics Today*. "I have a principle of not going anywhere near Washington or having anything to do with government."

Although Feynman overcame his reluctance, he quickly grew frustrated by the slow pace and "time-consuming" public meetings and briefings "of so little use." Instead, he did his own research, met privately with NASA officials, and created his own report that he released publicly.

He formed a theory: Rubber rings known as O-rings that sealed the joints of the shuttle's solid rocket boosters had been scorched by hot gas multiple times, causing erosion. Some of these rings failed to expand, allowing sizzling gas to escape one of the solid rocket boosters and burn a

hole in an external fuel tank that contained hydrogen—prompting the massive explosion. In fact, the rings were never intended to be used to cover expanding gaps, he found.

In his report, Feynman noted that NASA management had estimated a 1 in 100,000 chance of catastrophe with the space shuttle, while engineers put it at around 1 in 100. Because the shuttle had launched plenty of times without incident, he explained that "obvious weaknesses are accepted again and again, sometimes without a sufficiently serious attempt to remedy them, or to delay a flight because of their continued presence." NASA had assembled the space shuttle's main engine all at once without testing individual parts separately, he pointed out.

Feynman also criticized the model used to gauge the safety of the O-rings, and noted that NASA was aware they had been eroding. He found that the rubber can't expand in temperatures at or below 32 degrees Fahrenheit—on the unusually chilly day of the Challenger launch, morning temperatures dipped to the 20s. Engineers from the company who made the solid rocket boosters had warned NASA the day before the launch about the compounding risks of frigid temperatures and O-ring erosion. To demonstrate the tragic oversight, Feynman dropped a sample of the O-ring rubber in a glass of ice water. The rubber grew rigid in the glass, proving his point.

For more than two years after the Challenger explosion, NASA put a pause on sending astronauts into space as they redesigned the space shuttle.

— Molly Glick

Continued from page 81

no human could manage: predicting the three-dimensional structures of proteins, screening images of tissue and cells for changes, identifying rare astronomical signals buried in noise, and generating fluent text or images on demand. These systems excel at sifting through oceans of data with remarkable speed and efficiency, revealing regularities that would otherwise remain hidden.

Feynman would not have dismissed any of this. He was fascinated by computation and simulation. He helped pioneer Monte Carlo methods (simulating many possible outcomes at random and averaging the results) at Los Alamos National Laboratory, and computational approaches to quantum mechanics. Used well, AI can help scientists ask better questions, explore larger parameter spaces, and uncover patterns worth investigating. Used poorly, it can short-circuit that process—offering answers without insight, correlations without causes, and predictions without understanding. The danger is not automation itself, but the temptation to mistake impressive performance for understanding.

Much of today's artificial intelligence operates as a black box. Models are trained on vast—often proprietary—datasets, and their internal workings remain opaque even to their creators. Modern neural networks can contain millions, sometimes billions, of adjustable parameters. One of Feynman's contemporaries, John von Neumann, once wryly observed: "With four parameters I can fit an elephant, and with five I can make his tail wiggle." The metaphor warns of mistaking noise for meaning. Neural networks produce outputs that look fluent, confident, sometimes uncannily insightful. What they rarely provide is an explanation of why a particular answer appears, or when the system is likely to fail.

This creates a subtle but powerful temptation. When a system performs impressively, it is easy to treat performance as understanding, and statistical success as explanation. Feynman would have been wary of that move. He once scribbled on his blackboard, near the end of his life, a simple rule of thumb: "What I cannot create, I do not understand." For him, understanding

meant being able to take something apart, to rebuild it, and to know where it would break. Black-box systems invert that instinct. They invite us to accept answers we cannot fully reconstruct, and to trust results whose limits we may not recognize until something goes wrong.

Feynman had a name for this kind of confusion: "cargo cult science." In fact, that was the title of his 1974 commencement address. He described cargo cult science as research that imitates the outward forms of scientific practice—experiments, graphs, statistics, jargon—while missing its essential core.

The term came from South Pacific islanders who, after World War II, built wooden runways and bamboo control towers in the hope that cargo planes would return. They reproduced the rituals they had observed, down to carved headphones and signal fires. "They follow all the apparent precepts," Feynman said, "but they're missing something essential, because the planes don't land." The lesson was not about foolishness, but about misunderstanding. Without knowing why something works, copying its surface features is not enough.

The risk with AI is not that it doesn't work. The risk is that it works well enough to lull us into forgetting what science is for: not producing answers but exposing ideas to reality. For Feynman, science was about learning precisely where ideas fail. When performance becomes the goal, and success is measured only by outputs that look right, that discipline quietly erodes.

He loved technology and new tools, especially those that made it easier to test ideas against reality. He created visual tools, like his Nobel-Prize-winning diagrams, that simplified complex interactions without hiding their assumptions. But he was always careful to distinguish between instruments that help us probe nature and systems that merely produce convincing answers. Tools, for Feynman, were valuable not because they were powerful, but because they made it easier to see where an idea broke.

In Feynman's view, science does not advance through confidence, but through doubt, by a willingness to remain unsure. Scientific knowledge, he argued,

Feynman's message was not that science produces miracles but teaches a way of thinking that resists dogma.

is a patchwork of statements with varying degrees of certainty—all provisional, all subject to revision. “I would rather have questions that can’t be answered,” Feynman said, “than answers that can’t be questioned.” This is in stark contrast to venture capital, which rewards bold claims. Corporate competition rewards speed. Media attention rewards spectacle. In such an environment, admitting uncertainty is costly.

But for Feynman, uncertainty was not a weakness, it was the engine of progress. “I think it’s much more interesting to live not knowing, than to have answers which might be wrong,” he said.

It’s tempting to think these concerns belong only to academics. But artificial intelligence is no longer confined to laboratories or universities. It shapes what people read and watch, how students are assessed, how medical risks are flagged, and how decisions are made about loans, jobs, or insurance.

In many of these settings, AI systems function less as tools than as institutional opacity—systems whose authority exceeds our ability to question them. Their outputs arrive with an air of objectivity, even when the reasoning behind them is clouded. When a recommendation is wrong, or a decision seems unfair, it is often difficult to know where the error lies—in the data, the model, or the assumptions embedded long before the system was deployed?

In such contexts, the discipline of not fooling ourselves becomes more than an academic virtue. When opaque systems influence real lives, understanding their limits—knowing when they fail and why—becomes a civic necessity. Trust depends not only on performance,

but on accountability, whether their limits are understood, questioned, and made visible when it matters.

Stepping back, the issue is not whether AI will transform science. It already has. The deeper question is whether we can preserve the values that make scientific knowledge trustworthy in the first place. Feynman’s answer, were he here, would likely be characteristically simple: slow down, ask what you know, admit what you don’t, and never confuse impressive results with understanding. History has shown more than once that scientific knowledge can race ahead of wisdom. Several physicists of Feynman’s generation would later reflect on having learned what could be done long before learning what should be done—a realization that arrived too late for comfort.

In 1955, Feynman gave a talk called “The Value of Science” at a National Academy of Sciences meeting at Caltech. He said that science is a discipline of doubt, remaining free to question what we think we know. His central message was not that science produces miracles but teaches a way of thinking that resists dogma, false certainty, and self-deception. He opened not with equations or authority, but with a Buddhist proverb: “To every man is given the key to the gates of heaven; the same key opens the gates of hell.” Science, Feynman said, is that key, a tool of immense power. It can open both gates. Which way it turns depends on you. ☺

ROBERT ENDRES is a professor of systems biology at Imperial College London, working at the interface of physics and biology to understand cellular sensing, migration, and pattern formation.

Can We Protect Science?

It was a burning question at the World Economic Forum

BY JOHN STEELE

THE QUESTION WAS ASKED in the cold alpine air of Davos, Switzerland, where ideas are often spoken with confidence and the future is treated as something that can be managed. *Can we protect science?* It sounded, at first, like a question of defense, as if science were a vulnerable possession, something that might be damaged or lost if not carefully guarded. Yet as the conversation (preserved on video) unfolded at the 2026 World Economic Forum annual meeting, the question revealed itself to be something else entirely. It was not science that was uncertain, but our understanding of what science is, and why it matters.





THE KID IN SCIENTISTS

At the World Economic Forum pioneering oceanographer Sylvia Earle remarked that scientists “are basically kids who never grew up, never stopped asking questions. They want to know who, what, why, where, how, everything. What’s this world about?”

and pretending otherwise corrodes credibility. Science does not proceed by proclamation; it proceeds by evidence tested and retested, by conclusions held provisionally and revised when necessary. When science is presented as infallible, disappointment is inevitable. When it is presented as a method, grounded in humility, trust has a chance to endure.

That sense of science as a living process ran quietly through the room. From the perspective of those who fund discovery long before its usefulness is clear. The president of the European Research Council,

said, “is the magnitude of what we don’t know.” We have mapped only a fraction of the ocean floor; every descent into the deep uncovers new forms of life and unfamiliar systems. Knowledge does not close the book on mystery. It opens it wider.

From the ocean’s depths, the conversation turned inward, to the human body. Daniel Skovronsky, chief scientific and product officer at Eli Lilly spoke of recent medical advances with restraint rather than triumph. “Three years ago,” he said, “we didn’t have medicines that could effectively treat obesity. Today, for most people, we can offer a life without obesity.” Gene therapies now allow children born deaf to hear their parents’ voices. New treatments can slow, and perhaps one day prevent, neurodegenerative disease. These are not promises. They are outcomes.

Yet Skovronsky insisted that science does not earn trust through certainty. It earns trust through honesty. “There are always unknowns in science,” he said,

Maria Leptin, spoke of freedom as the essential condition of knowledge. “Research of this kind requires freedom,” she said. “Freedom to ask any question, freedom to pursue that question.” Fundamental research rarely aligns with political cycles or economic forecasts. Its value often becomes visible only years, even decades, later. The most transformative ideas begin as curiosities, pursued for no reason other than the desire to understand.

Freedom, she argued, is not only the absence of censorship. It is also time, trust, and patience. Short funding cycles, constant reporting, and narrow definitions of impact can quietly suffocate originality. “Frontier research is bloody difficult,” she said. Experiments fail. Results resist replication. Reality proves more complex than expectation. This difficulty is not a flaw in science; it is the terrain through which science advances.

Concerns about credibility, reproducibility, publication bias, the pressure to publish, were not ignored. They

A culture willing to examine its own failures is not in crisis. It is alive.

were placed in context. Science contains within itself the means of correction. Errors are uncovered because work is exposed to scrutiny. Openness is not a weakness; it is the system's immune response. A culture willing to examine its own failures is not in crisis. It is alive.

From outside the traditional structures of science, Alexi Robichaux, the CEO of the digital coaching and human transformation platform BetterUp, offered a perspective shaped by behavioral research. Science, he suggested, is one of the few human institutions designed to revise itself. Other systems—political, ideological, cultural—often persist in error because admitting mistake carries too high a cost. Science advances because it allows itself to be wrong. Its strength lies not in certainty, but in correction.

This strength, however, is easily misunderstood. To those unfamiliar with the scientific method, changing conclusions can look like inconsistency or failure. What is often missing is connection. Trust depends not only on competence and integrity, but on the sense that knowledge is offered in service, not imposed from above. Science must be communicated not as decree, but as dialogue.

Artificial intelligence entered the discussion not as a threat, but as a reminder. New tools can accelerate

discovery, sift patterns from vast datasets, and extend human reach. But tools do not choose meaning. They do not ask why. “We’re going to need humans,” Skovronsky said, “to point it at the right questions and understand the answers.” Technology amplifies inquiry; it does not replace judgment.

By the end of the session, the original question had quietly transformed. Science does not need protection in the way borders or monuments do. It cannot be preserved by decree or defended by force. It survives because it answers something elemental in us. Like the title of Paul Gauguin’s famous painting, *Where Do We Come From? What Are We? Where Are We Going?*

To protect science is not to shield it from doubt or disagreement, but to defend the conditions that allow it to flourish, freedom of inquiry, openness to correction, patience with uncertainty, and humility before the unknown. As Earle said with disarming clarity, “Knowing is the key to caring.” The real danger is not that science will disappear, but that we will forget how to listen to it, and in doing so, forget something essential about ourselves. ☺

JOHN STEELE is the publisher and editorial director of *Nautilus*.



When Scientists Are Dinosaurs

At the paleontology conference, her new theory was shouted down

BY MATT KAPLAN



ANDRUS CIPRIAN / SHUTTERSTOCK

WASN'T FAZED ONE BIT as the tequila hit the table for the third time in an hour.

You see, while I wore the name tag Matt Kaplan, Science Correspondent at *The Economist*, I had once been a part of this tribe. Long ago they welcomed me as one of their own. I had wandered with them in the desert, shared their meals, and labored alongside them under the beating sun to pluck bones from the earth. Yes, I had been a paleontologist. The tequila was there from day one.

“She’ll ruin us,” hissed one of the scientists as his hand clenched a shot glass.



I had spent years staring at fossils at the University of California. My lab at Berkeley used tequila to make poor man’s margaritas with Minute Maid Lemonade in the field. They may not sound like much, but after spending a day in the scorching heat, sifting through sediment for the teeth of rodents that died a million years ago, kicking back with one of these drinks under the stars was a great way to relax. Unfortunately, as the shots were poured this time—in a noisy bar near the 72nd annual meeting of the Society of Vertebrate Paleontology—nobody at my table was even remotely relaxed. I quietly removed my press pass and name tag to avoid reminding my present company that I was not, in fact, part of their tribe any longer.

“She’ll ruin us,” hissed one of them as his hand clenched a shot glass.

Language too vile to publish here, referring to female genitalia, slipped off the tongue of another.

“It is contrary to everything that we know,” stated another with a cold and calm precision that I found decidedly disturbing amid all the anger. While this fury made me feel as if I had traveled back in time to the days when evolutionary theory was being shouted down by

the Church, this was 2012. Moreover, this wasn’t anger from the religious right toward a liberal scientist. No, this was a blue-on-blue event. Science was attacking itself.

The conference was in Raleigh, North Carolina. The general presentations, where paleontologists talk about their findings, get asked questions by the audience, and then sometimes argue, were over for the day. London, five hours ahead, was asleep for the night. I took the opportunity to step out of the hotel into a cool and clear autumn evening for a light meal. Feeling refreshed from the break, I decided to visit the conference floor one last time before sequestering myself in my room and writing nonstop until midnight.

I came upon the poster session of the conference, where newbie scientists, mostly Ph.D. students, present findings that tend to be relatively minor. Journalists usually skip them. Not me.

Poster sessions are a bit like old-fashioned marketplaces where traders stand around trying to sell their wares—only, instead of traders pushing fruit, you have scientists pushing ideas. As I wandered past poster after poster with explanations of what the researcher did, why they did it, and what they found, the quiet of the hall was

shattered by a sudden burst of shouting. I hurried over to find out what the commotion was about and, as I turned a corner, I saw a woman surrounded by a group of men.

The woman had blond hair and was in her 20s. The men were decades older and clearly very angry. I would later learn that she was a Ph.D. student named Alison Moyer. Behind her was an older woman with steel gray hair, whom I immediately recognized as Mary Schweitzer, a scientist who had created a lot of important controversy by suggesting that soft organic materials that ought to rot away quickly after death (like blood cells) can sometimes survive the test of time and endure within fossilized bone for us to find millions of years later. Standing quietly along the periphery of the growing crowd I also spotted Jack Horner, a legendary maverick in the paleontological community who, among other things, revealed evidence that dinosaurs were social, engaged in maternal care, and grew quickly like mammals.

Nasty language was increasingly emerging from the hostile crowd, and my curiosity about this poster was growing by the minute. I snuck around to the side to have a look and realized that, of course, this was another fight about color.

Working out what color dinosaurs were when they ruled the planet over 66 million years ago might not sound particularly important, but it has increasingly taken center stage at conferences during the past decade. The reason is because the colors found on an animal tell us a great deal about how that animal lives its life. Think about it. Poison arrow frogs have brilliant hues to communicate, “eat me at your peril.” Stick insects are a drab brown to help them trick predators into believing they are inedible twigs. Yet those are the simple examples. Birds take things to an entirely different level.

Female blue-footed boobies always seek out males with the brightest and bluest feet. Why? Because booby immune systems rely upon the same chemical compounds found in their food to fight off diseases as they do to color their feet blue. A booby fighting an infection has to send these chemical compounds to its immune system rather than using them to brighten foot color. The females, being a rather discerning lot, use foot color to determine whether a given male is healthy enough to be worthy of breeding with.

Bluebirds, flamingos, pheasants, peacocks, toucans, and hundreds of other avian species use similar strategies. This matters because, while many dinosaurs like stegosaurus, triceratops, and diplodocus went extinct long ago, birds are the living relatives of velociraptor and Tyrannosaurus rex. Many paleontologists have argued that, since we know so much about how birds use color today, we should be able to use any color information that we can gather about dinosaurs to work out how they behaved, too.



COLOR MATTERS The debate over animal colors is important, as it tells scientists a great deal about how that animal lives its life. Male blue-footed boobies, for example, with the brightest and bluest feet, are in prime health, signaling their appeal to females.

This violent reaction was not the way science was supposed to be functioning.

Color in fur, feathers, and skin comes from tiny structures called melanosomes that are contained within the cells of these structures. Like red blood cells, these were thought to rot away shortly after animals die but, building on Schweitzer's findings, scientists began to question whether this might not be true. In 2008, a group of researchers announced that they had found melanosomes in fossil feathers belonging to what can best be described as very late dinosaurs or very early birds. Those researchers noted that these melanosomes were arranged in interesting patterns and suggested that these patterns might indicate the color that the feather once had. This encouraged other labs to look closely at this and, suddenly, melanosomes were absolutely everywhere. Paper after paper was being published on the subject. Many of these articles came with artistic renderings of T.rex and its kin painted in vibrant hues reminiscent of bluebirds and peacocks that the most prominent journals were gobbling up and publishing on their covers.

Dozens of these scientists were gaining considerable prestige from all of this work. Indeed, their reputations hinged on it. So, any suggestion that what people were seeing were not melanosomes was going to be met with considerable resistance. Unfortunately for Schweitzer's student Moyer—standing before me at the conference—this is exactly what she had found.

Moyer questioned whether the melanosomes being discovered might actually be something else. Advised by Schweitzer, who was well trained by Horner, Moyer was tasked with proving that what people were seeing

were not in fact melanosomes. To explore this, she collected chicken feathers and buried them in fine sediment. This allowed the feathers to decompose in the way that many animals would before becoming fossils. She then collected the remains and studied them under her microscope. She made two important discoveries.

The first was that the microbes and the melanosomes overlapped each other both in size and in shape. She found this alarming, because paleontological papers have routinely argued for the presence of melanosomes based only upon the sizes and shapes of the fossilized objects in question. The second was that the melanosomes in her feathers were always embedded in the keratin of which the feather is made. The microbes, by contrast, grew across the surface. Most of the supposed melanosomes associated with fossil feathers have been distributed in dense mats over the surface of the feathers, rather than being embedded within them.

In short, Moyer was presenting evidence that powerful scientists in her field, who had achieved considerable prestige by publishing papers about color in extinct animals, were wrong. This was why Moyer was at the center of an angry mob. This was why everyone around me in the bar was seething. This was not why the paleontologists were drinking heavily—they do that anyway. Perhaps more importantly, this violent reaction was not the way science was supposed to be functioning.

Sure, Moyer might have been wrong. Indeed, one of her critics had recently considered in a paper that what was being seen were bacteria. This notion was

then discounted because of the clear patterns that the grains seemed to form. Several other researchers who were in the midst of the mob had also investigated the chemical properties of the melanosomes. None had found any indication that they were bacterial. Yet, to focus on whether Moyer was right or wrong misses an important point.

Scientists are supposed to ask questions about the world around them, test these questions with experiments to try to prove themselves wrong, and then present their results to their peers. When new findings contrast with older findings, scientists are supposed to write papers exploring why the findings create the contrast and run more experiments to study the matter. This structure of question, test, challenge, and present is known as the scientific method. It has been around for hundreds of years and is meant to make science function smoothly.

Unfortunately, it failed Moyer. Paleontologists at the time were just using shape and size to identify melanosomes in fossils. Her work revealed that this was a flawed approach because bacteria get preserved, too, and they have the same shape and size as melanosomes. Yes, we now know that melanosomes can be preserved in fossils, but lots of bacteria were incorrectly being counted as melanosomes when she presented her findings in 2012. Moyer should have been celebrated for revealing such a serious problem.

But she wasn't. At the 2012 conference, I was stunned to see all of the men losing their minds at Moyer's work, but I should not have been. Because this has all happened before.

Copernicus feared how the outside world would respond to his discovery that the Earth went around the sun, and hid his notes away in a desk drawer, just like Schweitzer tried to do. He kept them unpublished until he was so seriously ill that he was certain he would be dead before the Inquisition could come for him. Contrary to popular legend, Darwin did not really fear that the public would lynch him for his theory of evolution, so much as worry that the rest of the academic

Scientists are supposed to ask questions, test these questions with experiments to prove themselves wrong.

community would think less of him for coming up with such a wild idea. Even so, his concerns over being thought, as he put it in his own notes, "a complete fool" by other researchers played an important part in leading him to check and double-check his arguments for nearly two decades. It was not until he learned that his colleague Alfred Russell Wallace had come to the same evolutionary conclusions that he made the tough decision to publish. Others

carefully managed their relations with the outside world. Galileo had to consider the church with every step that he made. Joseph Lister and Louis Pasteur had to constantly handle emotional reactions from both the government and the wider scientific community. They didn't hide their findings, but political games were essential to their survival. Pasteur even turned to fraud.

Science is going to be critical for tackling the big challenges that our society faces. Solving the energy crisis, defeating cancer, countering climate change, feeding 8 billion people ... the list is long. We need it operating at its best to confront these problems and, while science might look like a well-oiled machine spitting out findings to those glancing at it from the outside, it looks more like a clunky old engine prone to breakdown to those of us on the inside. It fills me with doubt. Can science defeat our big challenges? Yes. What remains unclear is whether it can do so in time. ☺

MATT KAPLAN has been a science correspondent at *The Economist* for two decades, with a particular fondness for overlooked species and how they quietly improve human life. His latest book is *I Told You So! Scientists Who Were Ridiculed, Exiled and Imprisoned for Being Right*. He is also the author of *Science of the Magical* and *Science of Monsters*, exploring how ancient cultures explained the natural world through myth. A Knight Fellow in 2014, he studied immunology at MIT and folklore at Harvard.

Adapted from *I Told You So! Scientists Who Were Ridiculed, Exiled, and Imprisoned for Being Right* by Matt Kaplan. Copyright © 2026 by the author and reprinted by permission of St. Martin's Publishing Group.



The Confabulations of Oliver Sacks

A neurologist reckons with recent revelations about the celebrated doctor and author

BY PRIA ANAND

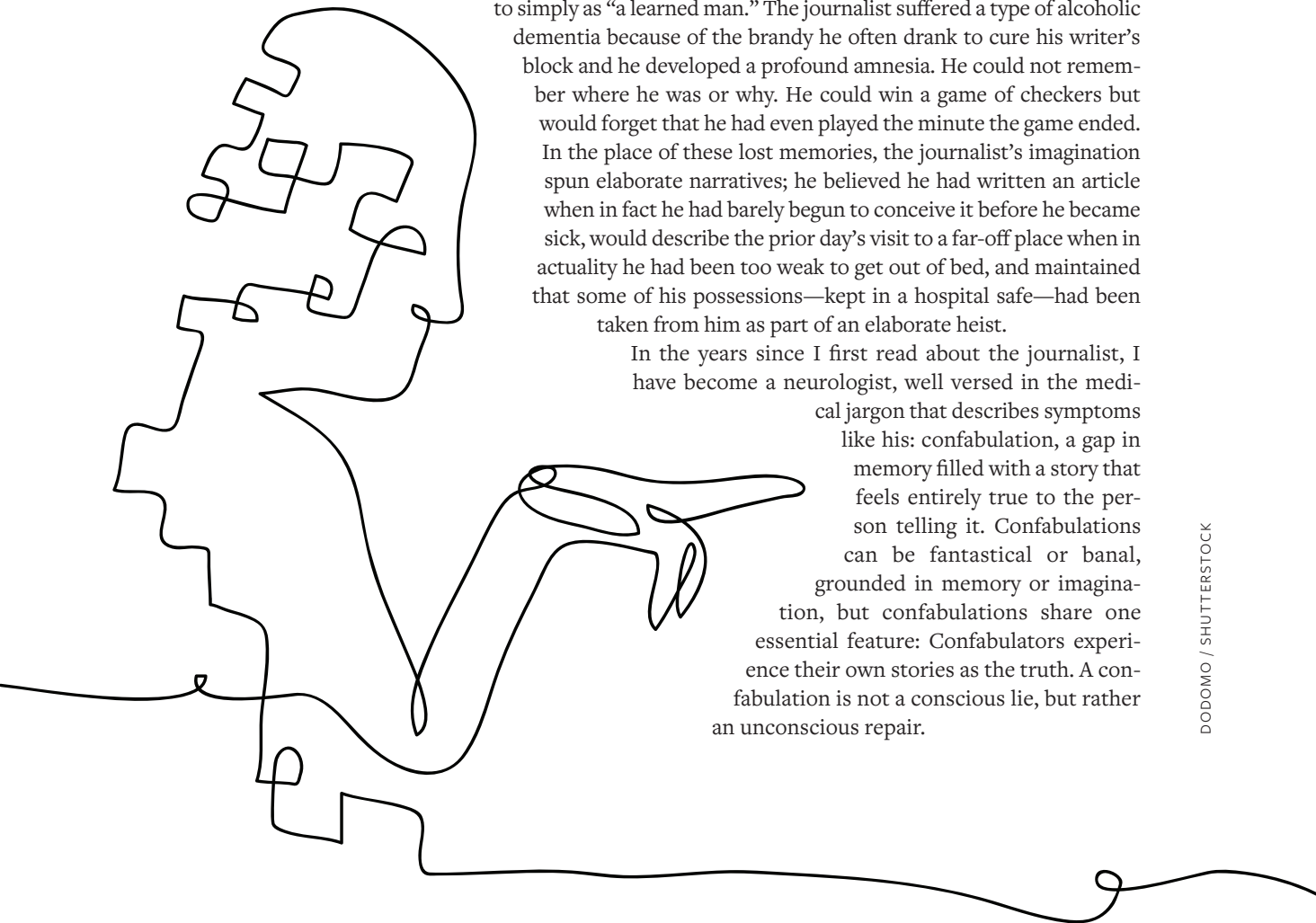
LOVED LITERATURE BEFORE I loved medicine, and as a medical student, I often found that my textbooks left me cold, their medical jargon somehow missing the point of profound diseases able to rewrite a person's life and identity. I was born, I decided, a century too late: I found the stories I craved, not in contemporary textbooks, but in outdated case reports, 18th- and 19-century descriptions of how the diseases I was studying might shape the life of a single patient.

These reports were alive with vivid details: how someone's vision loss affected their golf game or their smoking habit, their work or their love life. They were all tragedies: Each ended with an autopsy, a patient's brain dissected to discover where, exactly, the problem lay, to inch closer to an understanding of the geography of the soul. To write these case studies, neurologists awaited the deaths and brains of living patients, robbing their subjects of the ability to choose what would become of their own bodies—the ability to write the endings of their own stories—after they had already been sapped of agency by their illnesses.

Sacks' journals suggest he injected his own experiences into the stories of his patients.

Among these case reports was one from a forbidding state hospital in the north of Moscow: the story of a 19th-century Russian journalist referred to simply as “a learned man.” The journalist suffered a type of alcoholic dementia because of the brandy he often drank to cure his writer’s block and he developed a profound amnesia. He could not remember where he was or why. He could win a game of checkers but would forget that he had even played the minute the game ended. In the place of these lost memories, the journalist’s imagination spun elaborate narratives; he believed he had written an article when in fact he had barely begun to conceive it before he became sick, would describe the prior day’s visit to a far-off place when in actuality he had been too weak to get out of bed, and maintained that some of his possessions—kept in a hospital safe—had been taken from him as part of an elaborate heist.

In the years since I first read about the journalist, I have become a neurologist, well versed in the medical jargon that describes symptoms like his: confabulation, a gap in memory filled with a story that feels entirely true to the person telling it. Confabulations can be fantastical or banal, grounded in memory or imagination, but confabulations share one essential feature: Confabulators experience their own stories as the truth. A confabulation is not a conscious lie, but rather an unconscious repair.



Neurologist Oliver Sacks, who died in 2015, was perhaps the most prolific chronicler of symptoms like confabulation, filling the pages of his books with detailed descriptions of his own patients' wounds and blindnesses. I first read Sacks as a college student studying cognitive science and again as a neurology resident steeped in the strangeness and wonder of wounded brains. In his foreword to *Awakenings*, the stories of patients who had survived the "sleeping sickness" epidemic of the 1920s, alive but lethargic and permanently immobilized, Sacks wrote that the book was possible in large part because of the Bronx hospital where he practiced, which he called "a chronic hospital, an asylum," where his patients resided for decades.

Sacks bore witness to "situations virtually unknown, almost unimaginable, to the general public and, indeed, to many of my colleagues." Years after I first read *Awakenings*, I wrote my own book, *The Mind Electric*, informed in part by my own experiences at a city safety-net hospital in Boston, where I now practice neurology. I admired Sacks because he found inspiration in places others had not thought to look, because he centered stories from the margins that had previously gone untold. I wanted to do the same.

Among the chapters of Sacks' 1985 *The Man Who Mistook His Wife for a Hat*, a collection of medical tales, is a case study titled "A Matter of Identity." It's the story of William Thompson, an ex-grocer struggling with a form of dementia born of longstanding alcoholism. Thompson, Sacks wrote, could not remember that he lived in a hospital. When Sacks visited him in a white doctor's coat, Thompson imagined that he was a customer at his deli, then a kosher butcher, then an old gambling buddy, and then a Mobil station mechanic. Thompson, Sacks wrote, suffered a sort of "narrative frenzy ... He must seek meaning, make meaning, in a desperate way, continually inventing, throwing bridges of meaning over abysses of meaninglessness, the chaos that yawns continually beneath him."

In a *New Yorker* article published in December, 2025, journalist Rachel Aviv dissects Sacks' own desperate quest for meaning, reporting on unpublished journals suggesting that Sacks invented patient narratives, sometimes injecting parts of his own experiences into the stories of his patients. In *Awakenings*, Sacks wrote that his patient, Leonard, likened his frozen body to a caged panther in a Rainer Maria Rilke poem. In fact, Sacks' letters and notes suggest, it was Sacks, not Leonard, who identified with the poem, writing to a friend that the experience of writing his first book, *Migraine*, made him feel like "Rilke's image of the caged panther, stupefied, dying, behind bars." In a chapter of *The Man Who Mistook His Wife for a Hat*, Sacks wrote about a woman he called Rebecca, who blossomed despite her cognitive limitations after the death of her grandmother. In the book, Sacks reported that she joined a theater group and emerged from her grief as "a complete person." Sacks' journals, filled with transcriptions of his conversations with Rebecca, suggest that the reality was messier: Rebecca never joined a theater group but rather succumbed to her grief, telling Sacks that she wished she'd never been born.



STORIES KEEP US ALIVE “I loved *The Arabian Nights* as a child because it felt fantastical,” writes author and neurologist Priya Anand. “From Scheherazade, I learned that stories keep us alive.”

What emerges from Aviv’s deeply reported work is not conscious deception, but the gravitational pull of confabulation, a tidy narrative mistaken for truth. Aviv quotes a letter Sacks wrote to his brother, Marcus, enclosed with a copy of *The Man Who Mistook His Wife for a Hat*. In the letter, Sacks calls the book a collection of “fairy tales,” explaining “these odd Narratives—half-report, half-imagined, half-science, half-fable, but with a fidelity of their own—are what I do, basically, to keep MY demons of boredom and loneliness and despair away.” In fact, Sacks writes, Marcus would likely call them “confabulations.”

As a doctor, I, too, traffic in stories, hunger for coherence rather than chaos.

Science has a long tradition of using neurological wounds like confabulation as windows, opportunities to catch a glimpse of the complex ways our brains work when they are whole. We understand something about the biological basis of communication from studying people bereft of language, about the underpinnings of human perception from studying people who have experienced blindness, and about the neural pathways that generate movement from studying people suffering paralysis. Even the most esoteric-seeming neurological injuries speak to universal features of our brains.

For patients like Thompson and the 19th-century Russian journalist with amnesia, confabulation bridges a discontinuity, stepping in when memory fails. For Sacks, deeply closeted until his 80s, Aviv suggests confabulation served a different, more poignant purpose: His stories offered a place to put those parts of his own identity that he had been forced to sublimate. In his journals, Sacks wrote that he gave the patients in his books “some of *my own powers*, and some of *my phantasies too*.” He gave his patients his own inner monologues, his own desires, projections of his own insecurities. “I write out symbolic versions of myself,” he wrote.

I have always loved Sacks best when he wrote, not about his patients’ symptoms, but his own. His early experiments with psychotropics are catalogued in *Hallucinations*, the symptoms of his own visual auras in *Migraine*, and his alienation from his own body in *A Leg to Stand On*, the story of how he tore his quadriceps while mountain-climbing in Norway and found himself unable to move the leg, even after a surgery to repair muscle. Sacks describes the leg as “foreign,” a part of himself that he cannot relate to.

Four years before Sacks died, he wrote about his own body in *The Mind's Eye*, meditating on the childhood eye cancer that would eventually kill him alongside the stories of other artists and scientists who found themselves unable, in some essential way, to see. In a deeply personal chapter titled "Face-Blind," Sacks revealed his own blindness: prosopagnosia, the inability to recognize even the most intimately familiar faces. Sacks remembered failing to recognize his own therapist five minutes after leaving an appointment and birthday parties at which he asked friends to wear name tags. Sometimes, he wrote, he apologized to his own reflection in the mirror, unable to recognize even himself. Still, he was oblivious to his prosopagnosia until late in his life, when he visited his brother in Australia for the first time in decades and recognized his own deficiency in his brother's face-blindness.

For all Sacks knew about the ways that brains are able to hide their wounds, he had failed to acknowledge his own.

The genius of Sacks was that he insisted on centering people rather than illnesses, stories rather than jargon. His patients find ways to repair their reality rather than succumbing to their illnesses. As an epigraph to *The Man Who Mistook His Wife for a Hat*, Sacks chose to focus not on science, but rather fables: "To talk of diseases is a sort of Arabian Nights entertainment." The quote is attributed to William Osler, the 19th-century internist who founded the hospital where I would train a century later.

I loved *The Arabian Nights* as a child because it felt fantastical. I read of caliphs and sorcerers, of jinn born of fire and of seas peopled with merfolk. *The Arabian Nights* is a strange, protean text, a shapeshifting, Russian-doll narrative of stories nested within stories to which tales have been added, subtracted, mutated over centuries and continents. The fables themselves are framed by the story of Scheherazade, the latest bride of a monstrous king who weds a new woman each night only to have her beheaded the following dawn. The night of their wedding, the resourceful and brilliant Scheherazade begs to be allowed to say goodbye to her beloved younger sister, Dunyazad, for whom she begins to weave a marvelous bedtime story while the king lies awake and listens. When dawn breaks, the tale remains unfinished, and the king, anxious for a resolution, spares Scheherazade's life for one more night. The next night, and the next night, and the next, Scheherazade spins a web of endless stories that enthrall the king, always ending on a cliff-hanger so that he will keep her alive. From Scheherazade, I learned that stories keep us alive. But stories can also mislead.

When I was a medical student, reading the old case reports, I wondered whether writers were particularly prone to confabulation, primed to search for a coherent plot. Since becoming a physician, I have wondered even more whether *doctors* are particularly prone to confabulation. Medical students are taught to imagine a binary: doctor and patient, science and faith, objective truth and subjective report, us and them. Our morning rounds are an exercise in telling and retelling patients' stories in a way that explains their illnesses, cloaked in the sense of objectivity offered by a white coat.

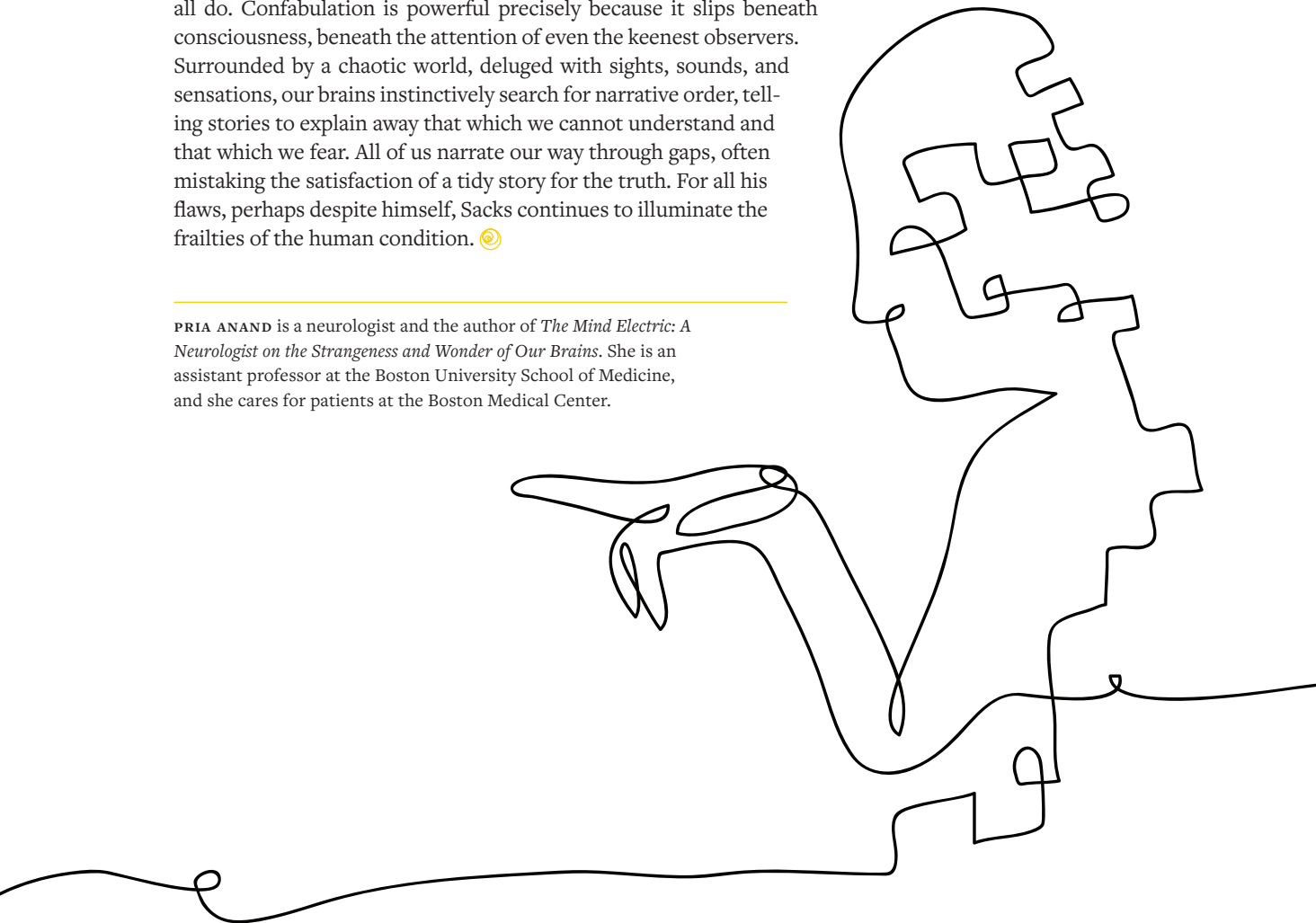
But the stories told on these rounds are just as prone to false truths as the reports of an amnesia patient, subconsciously shaped by our priors, our communities, our own narratives. On rounds, a woman's pain might be recast as anxiety, for instance, while a vitamin deficiency born of alcohol use might be regarded as a deserved punishment.

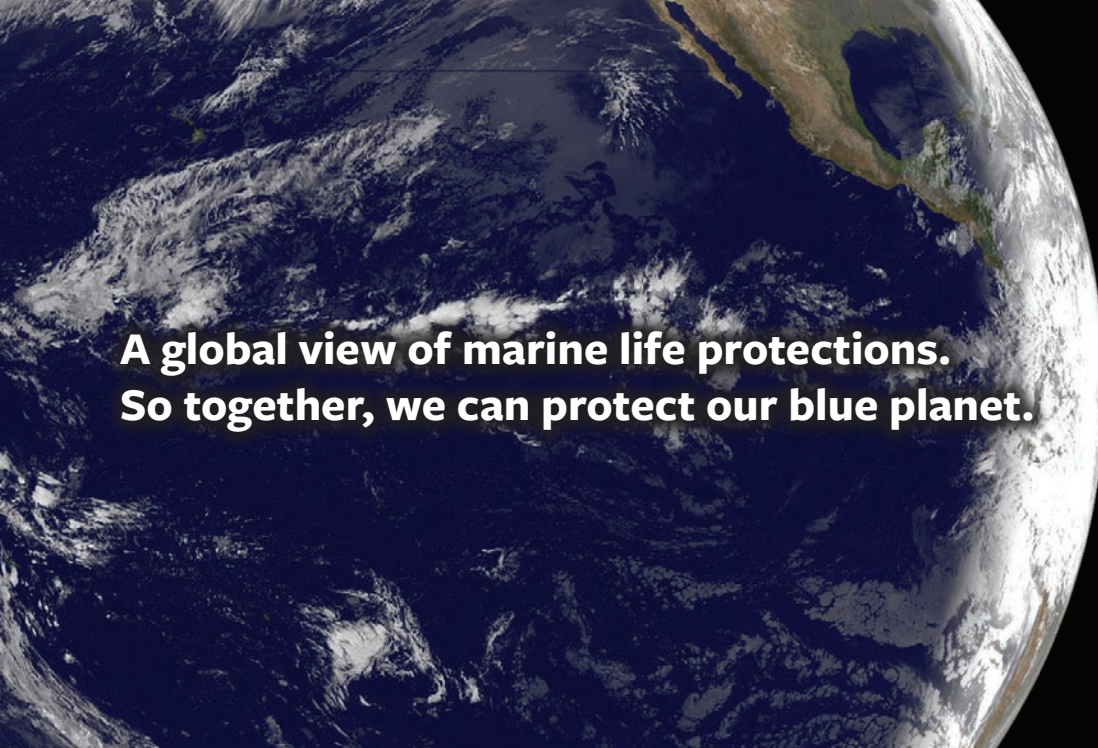
As a doctor, I, too, traffic in stories, hunger for coherence rather than the chaos and uncertainty that medicine and bodies often offer. In medicine, we arbitrate which stories are important and which don't matter, which are true and which are false, as if we were omniscient rather than subjective beings, as if our training somehow excises the humanity, the personal, from our practice. In my own writing as in my medical practice, I remind myself to always leave room for uncertainty, for that which I cannot possibly know about someone else's body, about their story.

I loved Sacks for his unflinching desire to bear witness to the complexity of illness, and it pained me to read that he sometimes put his own story ahead of his patients' realities. Hospitals are places of both ruin and miracles, heartache and wonder, the narratives they contain as spellbinding as they are messy. Sacks knew this better than any writer. And so, for all that feels profoundly, universally human about his vulnerabilities, I struggle to understand his impulse to confabulate on the page when the unvarnished truth would have been more compelling.

But Aviv's article also left me with an unsettling revelation that transcends Sacks' writing: not simply that Sacks revised reality, but that we all do. Confabulation is powerful precisely because it slips beneath consciousness, beneath the attention of even the keenest observers. Surrounded by a chaotic world, deluged with sights, sounds, and sensations, our brains instinctively search for narrative order, telling stories to explain away that which we cannot understand and that which we fear. All of us narrate our way through gaps, often mistaking the satisfaction of a tidy story for the truth. For all his flaws, perhaps despite himself, Sacks continues to illuminate the frailties of the human condition. 🌀

PRIA ANAND is a neurologist and the author of *The Mind Electric: A Neurologist on the Strangeness and Wonder of Our Brains*. She is an assistant professor at the Boston University School of Medicine, and she cares for patients at the Boston Medical Center.





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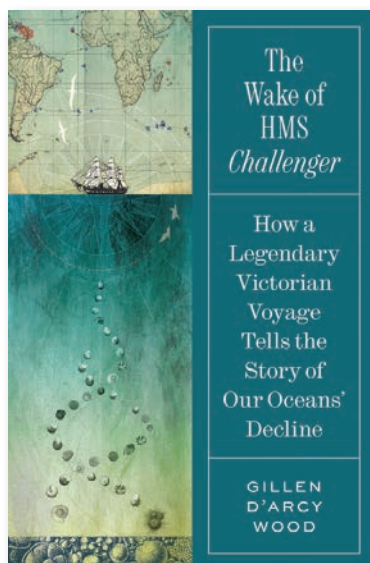
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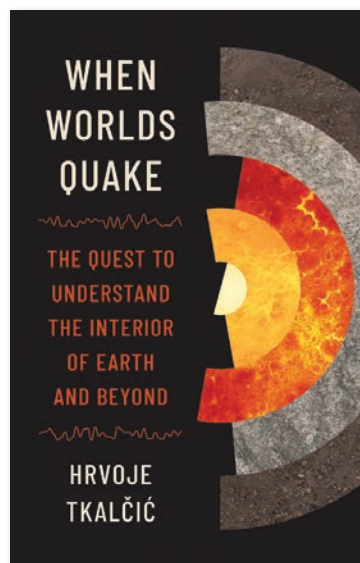




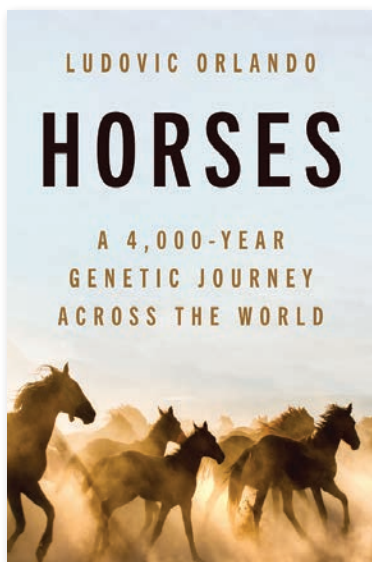
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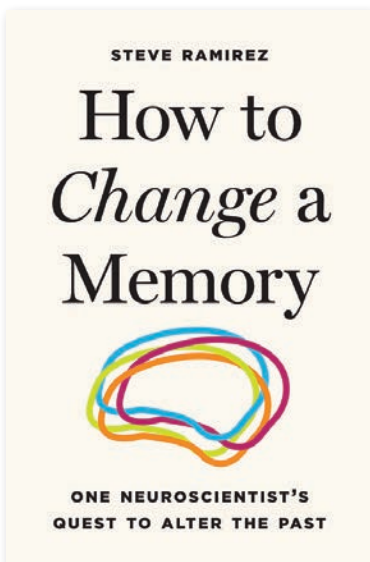
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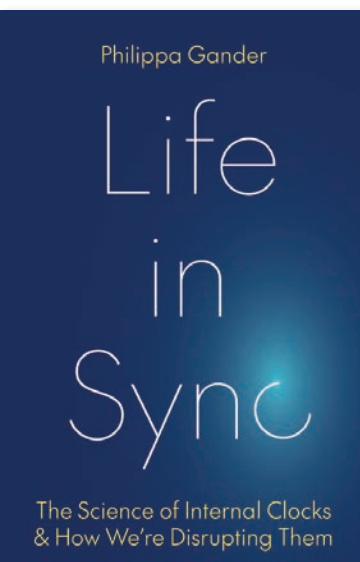
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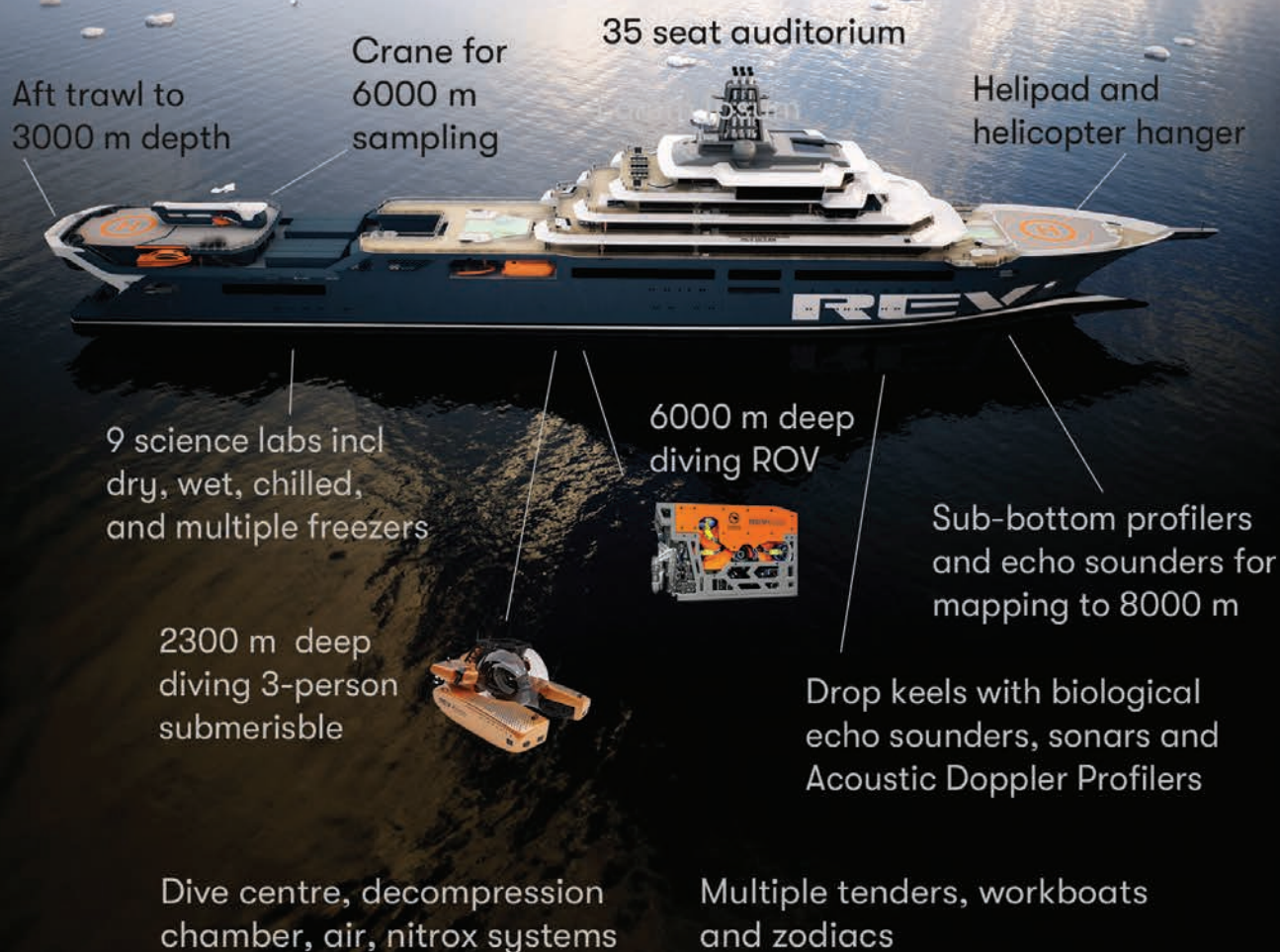


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The Books That Blew These Scientists' Minds

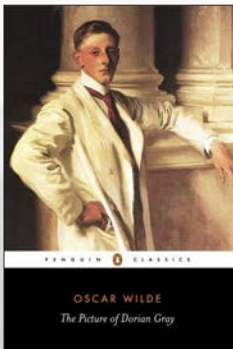
3 leading researchers on the book that opened a new world for them

INTERVIEWS BY NAMIR KHALIQ

HEATHER BERLIN, NEUROSCIENTIST

A neuroscientist and clinical psychologist at Mount Sinai's Icahn School of Medicine. When not hosting the *Science of Perception Box* podcast, she researches and writes about the neural basis of phenomena such as time perception, creativity, and psychiatric disorders.

***The Picture of Dorian Gray* by Oscar Wilde**



"I first encountered *Dorian Gray* while studying abroad in London, reading it on trains as I wandered through the U.K. Wilde's story landed for me as a gothic thought experiment: What if the truth of our choices were perfectly recorded, just not where anyone could see it? As a scientist, I'm trained to trust evidence—even when it's

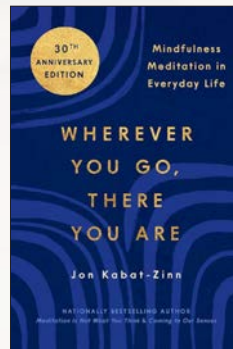
inconvenient—and Dorian made me ask what kinds of evidence we ignore when we're trying to look polished, confident, or 'right.' Years later, when I arrived as a graduate student at Magdalen College, Oxford, where Wilde had also been a student, the book felt less like a Victorian scandal and more like a modern warning. In an era of curated identities and quantified achievement, Wilde's fable still does what the best science does: It forces you to look at the data you'd sometimes rather not see."

ROBERT WALDINGER, PSYCHIATRIST

Directs the Harvard Study of Adult Development, the longest longitudinal study of its kind, an effort that first began at Harvard in the early 1940s.

***Wherever You Go, There You Are* by Jon Kabat-Zinn**

"I read this book when I was in my early 30s, and it completely turned my head around with its very simple explanations of Buddhist philosophy. The truth of impermanence, the myth of a separate and isolated

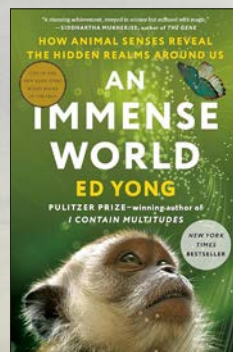


and fixed self, and the interconnection of everyone and everything helped me make sense of the world and my life in a completely new way. I eventually found my way to practicing Zen, received rigorous Zen training over 20 years, and am now a Zen teacher, Roshi. The book literally changed my life."

SHERI WELLS-JENSEN, LINGUIST / ASTROBIOLOGIST

A professor at Bowling Green State University, studies phonetics, braille, and language creation and acquisition as they relate to possible extraterrestrial languages. As a blind person, Wells-Jensen writes on the mismatches and limitations of human communication.

***An Immense World: How Animal Senses Reveal the Hidden Realms Around Us* by Ed Yong**



"It's not just that this book contains something utterly fascinating on almost every page, it's that Yong is clearly unapologetically gobsmacked by the beauty of the natural world without sacrificing the keen scientific approach. The writing is fleet and witty, the research is deep and he really

does manage to dip our reluctant toes into other perceptual realms. The goal is not to try hard to understand other beings by adding or subtracting sense impressions from our own experience of the world, but to radically respect the complexity and completeness of the way other beings live. Please, can we have Yong on the team that meets the first aliens." 🐾



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