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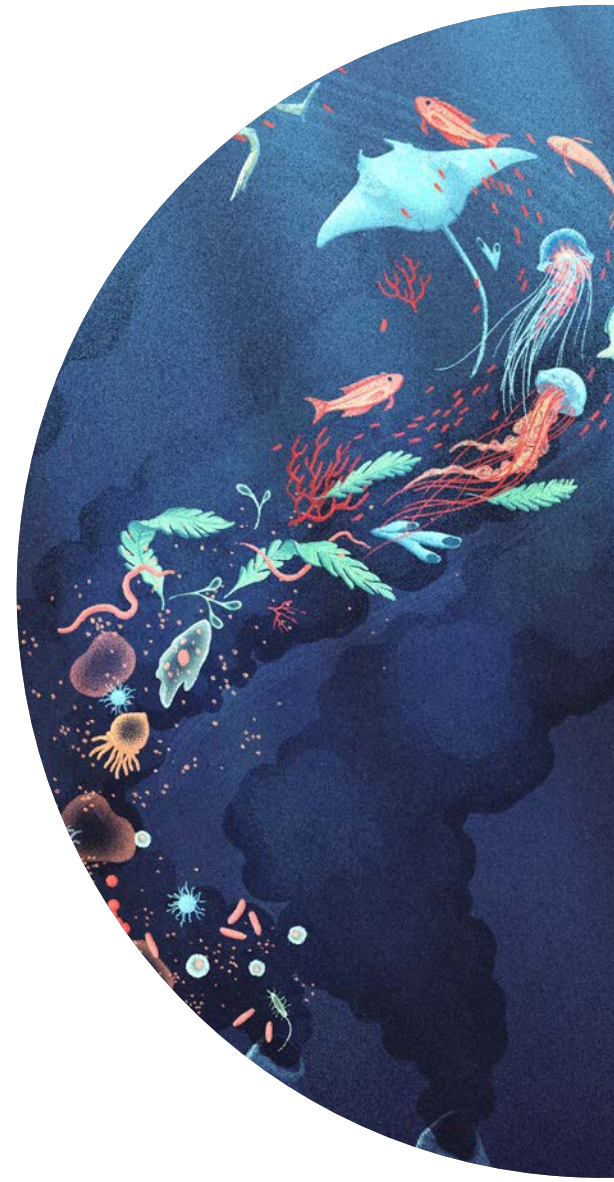

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Original Minds

BY KEVIN BERGER

IT WAS A PLEASURE bringing together Philip Ball and Nick Lane for this issue's cover story. A pleasure because Ball and Lane are two of my favorite science writers. Both translate the daunting languages of biology and physics and more into lucent articles and books that make us feel we are fluent speakers in complex science ourselves. In "The Big Thinker," Ball plumbs the depths of Lane's research into how life first arose on Earth. Learning how inorganic minerals catalyzed into organic cells is not for the faint of mind. Fear not. Ball frames Lane's bold science in a warm and engaging profile.

Ball has crossed paths with Lane, a professor of evolutionary biochemistry at University College London, several times over the years. A couple of years ago at a science conference, Ball ran into Lane, who told him he was writing a book about the Krebs cycle, the bane of students, a dry foundation of biochemistry. "The Krebs cycle is basically extremely dull even to the people who work on it," Lane said. "And yet somehow it's making me excited. I remember reading Primo Levi, who said a good writer should be able to make any subject interesting. And maybe I took that as a challenge."

Ball has taken the same challenge. In "Behind the Scenes," which appears every Sunday in our email newsletter, Ball told *Nautilus* associate editor Brian Gallagher, "I studied as a chemist at Oxford University and went on to do a Ph.D. in physics at the University of Bristol. I joined *Nature* in 1988 when it was a very different era in science communication and a very different journal. Today, *Nature* is a big publishing empire. In those days, it was just a single journal run out of a relatively small office with a very small staff. That meant as editors we had to cover a lot of ground, and so it was a very steep learning curve. It could be that if my colleague was away for one week who handled astronomy, then I would be handling the astronomy papers or the Earth sciences papers."

As an editor, Ball explained, he grew increasingly restless to write. "I gradually went part time, and that part time got smaller and smaller, and the writing got bigger and bigger," he said. "Around the turn of the millennium, I decided to go completely freelance and just focus on writing, and that's what I've been doing ever since. Now I feel fortunate to make a living by being able to follow my own curiosity and interest, and to spend two or three years really digging into a particular subject that interests me and writing a book about it."

Ball's books constitute a cabinet of wonders. Open them to explore art and the invention of color, a secret history of China, a biography of water, our music instinct, the patterns of nature, the world of Renaissance magic and science, and the nature of curiosity. His most recent book, *The Book of Minds*, gently explains that humans are not the kings of the jungle, that the road to understanding our own minds, and selves, begins with appreciating the unique minds of other beings, from animals to artificial intelligences to aliens.

With this issue, as always, we're proud and delighted to have Ball bring his original mind to yours.

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Preludes

FROM LEFT, ALAIN ASPECT, JOHN F. CLAUSER, AND ANTON ZEILINGER. COURTESY OF NOBELPRIZE.ORG

PHYSICS

They Probed Quantum Entanglement While Everyone Shrugged

AMONG THE QUIRKS that my wife chooses to find amusing, I have a habit of waking up extra early every year on the first Tuesday of October. That's the time when the Royal Swedish Academy of Sciences announces new recipients of the Nobel Prize in Physics. I have been repeating this ritual every year for about a dozen years, waiting—hoping—to hear a particular announcement. This year it finally arrived.

The winners of the Nobel Prize in Physics for 2022, Alain Aspect, John Clauser, and Anton Zeilinger, have been pioneers in the study of quantum entanglement, one of the most beguiling features of quantum theory. Albert Einstein and colleagues helped to identify the notion back in the 1930s, only to reject the idea as too outlandish to be true. Thirty years later, physicist John Bell introduced an ingenious way to design an experimental test that might confirm or rule out such strange-sounding behavior.

Quantum theory predicts that if two or more particles are prepared in a particular way, their behavior should remain correlated, even after they have moved very far apart. Perform a measurement of some property of particle A and—*wham!*—particle B should display specific behavior, even if they are light-years apart. Stranger still, the particles' properties should align even when physicists measure *different* properties of each particle, selecting the measurements to perform on each member of the pair at random.

The experiments that Bell had in mind were clever, and they also seemed feasible. No need to build a huge particle accelerator or launch a massive new satellite. And yet years went by before other physicists even cited Bell's article, let alone rolled up their sleeves to give it a go.

One of the first to reach out to Bell was a young John Clauser. Clauser had stumbled upon Bell's article while browsing journals in the library as a graduate student. Excited by what he read, he rushed to his Ph.D. supervisor to suggest they conduct the type of experiment that Bell had proposed. To Clauser's frustration, his advisor responded with (no doubt well-intentioned) advice: Stick with more mainstream topics for the dissertation, don't chase such "philosophical" topics as entanglement.

Yet Bell's idea stuck, and a few years later, as Clauser was preparing for his postdoctoral position at the Lawrence Berkeley National Laboratory, he wrote to Bell

to ask if other physicists had conducted any such tests in the interim. As Bell later recalled, Clauser's letter was the first time any experimental physicist had evinced interest in Bell's work. Bell quickly responded: If Clauser did manage to measure behavior different than the quantum predictions—and hence more in line with Einstein's expectations—that would "shake the world!"

They published their results in a flagship journal in 1972, and then … nothing.

With Bell's encouragement, along with critical input from a few like-minded colleagues, Clauser and Stuart Freedman (a graduate student at the time) set out to conduct the first Bell test. After scrounging for spare parts around the laboratory, they managed to collect data on thousands of pairs of particles, finding exactly the correlated behavior predicted by quantum theory. They published their results in a flagship journal in 1972, and then … nothing. The following year, citations to Bell's work, previously just a trickle, dropped by more than half. Some academic leaders doubted whether investigations of entanglement counted as "real physics."

An ocean away, just outside Paris, Alain Aspect had also become captivated by entanglement. Like Clauser, he aspired to conduct a Bell test in a laboratory. His main ambition was to perform an experiment that could home in on the instantaneousness of entanglement. He made a pilgrimage to CERN in Geneva, where Bell worked, to ask Bell himself whether such an experiment would be worthwhile. Bell's first question: "Do you have a permanent position?" The topic still moldered on the margins.

Like Clauser, Aspect pressed on. In a virtuoso experiment with colleagues in 1982, Aspect used super-fast switches that could change each particle's path en route to the measuring devices. The switches changed back and forth 100 million times per second. The detector toward which a given particle would be directed was determined while that particle was in flight. Moreover, the two measuring stations were far enough apart that information from one side of Aspect's experiment couldn't possibly be communicated to the other side before measurements on both particles had been completed. Aspect and his colleagues sent nearly a trillion pairs of particles through the apparatus and they, too, found the spooky correlations precisely as quantum theory predicted.

At first Aspect's beautiful experiment, like Clauser's a decade earlier, was met with a collective shrug. For the next several years he focused on other areas of physics, frustrated by many colleagues' indifference to topics like entanglement.

The third recipient of this year's prize, Anton Zeilinger, showed equal tenacity, ingenuity, and persistence. With several colleagues he extended Bell's work to the case of three or more entangled particles. In the 1990s, he and his group first succeeded in teleporting an entangled state, transferring the special correlated behavior to a third particle. Soon after that, his group measured the telltale correlations among particles even after they had flown 100 miles apart.

Zeilinger, too, pressed on even when many colleagues considered entanglement to be a sideshow. In fact, for decades he worked tirelessly to shore up Bell tests, conducting several trailblazing experiments to address various "loopholes"—far-fetched but still logically consistent scenarios by which an Einstein-like scenario might account for all of those correlated measurements on pairs of particles.

My friends Andy Friedman, Jason Gallicchio, Alan Guth, and I had the great luck to partner with Zeilinger and his group on some of his most recent experiments. In our "Cosmic Bell" tests, we turned the universe itself into a pair of random-number generators, determining which measurements to perform on Earthbound particles based on split-second measurements of light from distant galaxies. Our goal was to ensure that the patterns in the Earthbound particles' behavior could not be traced to information, obtained in advance, about which particular measurements would be performed on each particle.

Prior to experiments like ours, there had remained open the possibility that the correlated measurement outcomes might have been due to a prior correlation between the production of entangled particles and the choices of measurements to perform on each. That would be as if a student had received a copy of a pop

quiz the night before it was handed out in class: She would know in advance which specific questions would be posed, and in which order.

So Zeilinger and our team took advantage of the huge distances to faraway galaxies to separate the production of entangled particles on Earth from the events that would decide which measurements would be performed on them. In the end—thanks to Anton's prowess as a negotiator as well as a physicist—we were able to secure valuable telescope time at the beautiful mountaintop observatory on the island of La Palma, in the Canary Islands. By using light from high-redshift quasars, we managed to constrain any such pop-quiz-in-advance mechanism to need to have occurred no more recently than 8 billion years ago—eons before there was a planet Earth, let alone an Albert Einstein to ponder entanglement.

Remarkably, the achievements by Clauser, Aspect, and Zeilinger now stretch well beyond esoteric questions about how the world works. Around the world today, research expenditures in the field of quantum information science exceed $1 billion per year, spanning academic laboratories, government facilities, and industrial efforts. Next-generation technologies like quantum encryption and quantum computing are now being built by turning entanglement into a resource and not just a curiosity.

Max Planck, who helped to create quantum theory more than a century ago, famously quipped that new scientific ideas do not triumph by convincing the skeptics. Rather, Planck argued, the critics eventually die and a new generation grows up for whom the once-strange notions seem familiar. Thankfully Alain Aspect, John Clauser, and Anton Zeilinger did not have to wait quite that long. Nonetheless, their special recognition marks the tail end of a half-century journey. Driven by curiosity and skill—mixed with a bit of stubbornness—they dug in, did their best, and never lost sight of the long view.

—David Kaiser

PSYCHOLOGY

Should Social Psychologists Experiment with Psychedelics?

One question for Sonja Lyubomirsky, a psychologist at the University of California, Riverside studying the sources and benefits of happiness, and the author of The How of Happiness: A New Approach to Getting the Life You Want.

Should social psychologists experiment with psychedelics?

Yes. That's the premise of my recent paper, "Toward a New Science of Psychedelic Social Psychology: The Effects of MDMA (Ecstasy) on Social Connection." I should add that some researchers put MDMA in a psychedelic category, but it's usually called an empathogen or an entactogen. On MDMA, people report feeling understood, loved, and cared for—valued. So, it serves as a window into those processes.

For example, we know what brain pathways, and some of the psychological processes, that MDMA affects. There's more eye contact. People disclose more about themselves. That reveals some of the key ingredients that are important for connection. The key to relationships, according to partner-responsiveness theory, is feeling understood, valued, and loved by your partner, or by the person that you have a relationship with. On MDMA, people who are lonely or socially anxious, or have experienced trauma, can feel like they really connect with other people, or with a particular person, and that carries over to their regular life. I'm not suggesting that people be on this drug all the time, obviously, but it's a way to bolster this connection that will endure, maybe even have permanent impact.

PHOTO COURTESY OF SONJA LYUBOMIRSKY

Have I used it myself? I've been told that, in answering this, you are screwed either way. If you say, "No, I don't use it," whatever the drug you study, then people respond, "Well, you don't know what you're talking about." And if you say you do use it—"Oh, you're biased." I don't think it's a magic drug. There's a little

Psychedelics can be an important tool in studying connection.

bit of magic to it, I guess. The reason I'm studying it is not because I've used it, though I have. It's because it's incredibly relevant to what I study. I've never seen anything else that can boost connection as much. If that can happen on MDMA, maybe we can bring that into the non-drug world, and borrow the insights.

I'm not an evangelist for these substances. I'm not saying, "Everyone should go do it." You don't know what you're getting on the street. In our studies, we get research-grade MDMA from, I think, Purdue University. So I'm saying, "Do research on it." We are planning a study right now using a citizen-scientist approach. We're going to ask people to get together with a friend and have a deep conversation. We're going to have a placebo, which may be either a lower dose of the drug, or it could be another drug. We use a paradigm called Fast Friends, popularized actually by *The New York Times* in an article called "The 36 Questions That Lead to Love." They increase in how deep and personal they are. You might start with asking, "If there's a famous person you'd want to have dinner with, who would it be?" Later on, you're asking, "When was the last time you cried in front of another person, and why?"

Psychedelics can be an important tool in social psychologists' toolbox in studying connection. As well as other things, of course—the self, creativity, prejudice. I wrote the paper because it didn't feel at all like MDMA and other drugs were on social psychologists' radar. I wanted to put it on their radar. We'll see what happens.

—Brian Gallagher

NEUROSCIENCE

How We Remember Last Weekend

ONE OF THE MOST DIFFICULT questions for the science of memory deals with the most obvious fact about memories: We can, well, recollect them. The problem is that no one knows exactly how we call to mind, and with such ease, that party last weekend, with all the samba dancing and clinking of ice in glasses, the scent of circulating *hors d'oeuvres*, the jolt up the spine from catching a lover's eye across a crowded room. All these emotional and sensory elements, we know, are registered in distinct areas of the brain—but how is it that we can reminisce and conjure them all up at once, recalling the mental event as a single experience?

A group of scientists based at the University of California, San Diego, have found a promising mechanism that may explain not just how recollection works, but also, more broadly, conscious experience itself.

In a recent paper published in the *Proceedings of the National Academy of Sciences*, lead author and neurophysiologist Charles Dickey identified patterns of ripples—brief high frequency oscillations in neural activity—that synchronize across the human brain during spontaneous waking and memory recall. These ripples fan out across distant areas of the cerebral cortex (the wrinkly surface of the brain) that are responsible for the sensory elements involved in any mental event, and extend to the hippocampus, a seahorse-shaped structure key to memory. Many studies had previously investigated ripples in the rat hippocampus and their relationship to memory, but Dickey only recently identified ripples in the human cortex.

There are several competing theories about networks of neuronal activity that may facilitate communication between different areas of the brain to give rise to conscious experience. But this may be the first observed mechanism that could potentially solve the so-called "soft problem" of consciousness—the quest to identify the physical processes in the brain that

GOODSTUDIO / SHUTTERSTOCK

underpin mental events. The soft problem is in contrast to the so-called "hard problem" of consciousness, the question of how something physical like the brain can possibly generate the rich, clearly mental quality of lived experience.

The difficulty behind the soft problem of consciousness is that there isn't a readily identifiable locus of consciousness, though many possibilities have been proposed over the centuries. Rene Descartes, the 17th-century philosopher, thought the seat of consciousness was the pineal gland, a small gland in the center of the brain, but we now realize it's probably responsible for producing and regulating melatonin for our sleep cycles instead. Two hundred years later a German physiologist named Johannes Müller suggested the medulla oblongata, the stem-like structure at the bottom of the brainstem, was responsible for consciousness. (We now know it's chiefly responsible for involuntary functions like heartbeat, breathing, vomiting, and sneezing.)

Later, the English physiologist William B. Carpenter nominated the thalamus, a boot-shaped structure in the middle of the brain, as the hub of consciousness, and then celebrated biologist Francis Crick considered the claustrum, a neural structure that appears like a crown of thorns around the cortex. It turns out that both the claustrum and the thalamus may indeed play important roles in certain features of consciousness, but their candidacies as coordinating centers for consciousness remains largely conjectural.

The largest hurdle for the search for consciousness in the brain was somewhat inadvertently discovered by 20th-century neurosurgeon Wilder Penfield, who was treating patients with severe epilepsy by lesioning the malfunctioning areas of the brain that were instigating seizures. During his surgical procedures, Penfield noticed that certain movements or perceptions could be manufactured by stimulating different areas of the cortex; stimulation via an electrode on your forehead could produce the smell of a bandage, while one on the back of your head might make you see the Buddha and wiggle your pinky. This presented a problem of brain geography that is sometimes called "the binding problem": How do distant areas—the ones involved in, say, the smell of bandages and the ones involved in the throbbing pain of the wound under the bandage—communicate with one another to produce a seamless experience? Enter brain ripples.

Brain ripples are so named because these high-frequency oscillations of neural activity appear as ripples on stereogram readouts of the cortex called electroencephalograms.

"The cortex is where we have all our sensory areas, so experiences are primarily a cortical phenomenon," Dickey said. "The idea is that an experience happens, and this affects the firing of synapses between specific sets of sensory neurons, strengthening their connections." He added, "Ripples may modulate this synaptic activity to consolidate the memory within the cortex."

Ripples emanate and multiply across the cortex spatially, but in the way that music fills a room. Ripples form fleeting but repeated patterns. They come and go like memories and experiences themselves.

While these specific kinds of human cortical brain ripples are newly discovered, the purely theoretical underpinnings of them have been around since the late 1970s. One popular theory of consciousness is known as "binding-through-synchrony," which postulates that a synchronization of neural activity is what organizes different sensory cues from different regions of the cortex into coherent experience. The theory has been around for decades, but evidence for it was limited. Brain ripples are the first observable and testable mechanism that could corroborate the binding-through-synchrony hypothesis.

What could this mean for consciousness and the study of the mind? The mechanism of brain ripples seems to suggest that consciousness may not have a

Ripples unify our experience by the moment, playing a memory like a song.

center, or a fixed unifying organ controlling it. Instead, they suggest a decentralized consciousness, where frequencies accompany and hold our thoughts like ghostly electrical consorts, appearing and disappearing as quickly as they do. Instead of a single ghost in the machine, we may host an infinite number of ghosts, in the form of an incredible procession of ripples, unifying the entirety of our experience by the moment, playing a memory like a song, taking its notes from the distributed and diverse functions of our sensory apparatuses.

In the end, perhaps the search for consciousness was impeded for so long because we were searching for the wrong kind of thing, something physical or structural rather than phenomenal—a pineal gland instead of an electric signature, a neuro-chemical ghost that pulses across the cortex.

The real test for whether brain ripples underpin conscious experience might include cortical stimulation experiments in humans to test if certain kinds of experiences can be induced by ripples (or, conversely, if conscious experiences can be interrupted by disrupting cortical ripples). If further research concludes that ripples do in fact coordinate the communication of all the different parts of the brain responsible for an experience of, say, a beach in August (with its hot sand everywhere, the blazing sun and cooling ocean, and drying off while waves whoosh nearby), then Dickey's study could be an immense step forward for solving the soft problem of consciousness.

—Marco Altamirano

TECHNOLOGY

The Chess Cheat in the 21st Century

WOLFGANG VON KEMPELEN, the 18th-century inventor and author, once claimed to have created a chess-playing robot, called the Mechanical Turk. How was this possible, almost two centuries before computers were invented? Easy. By fraud.

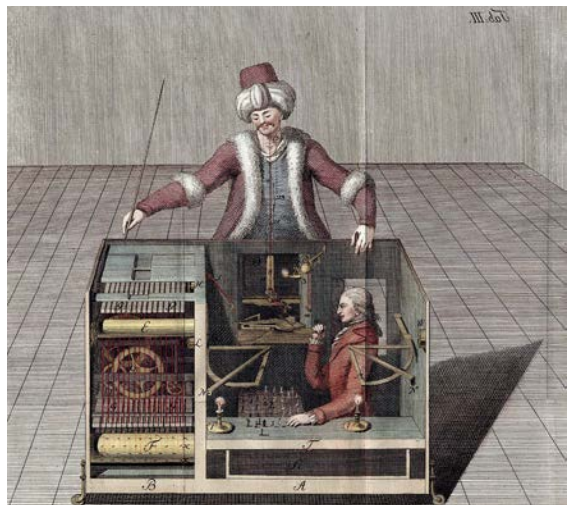
The Turk was just a box containing a hidden chess master. Back then, the idea of an automaton that could play good chess was impossible. Even in 1997, when the IBM computer Deep Blue defeated the then-reigning chess champion Garry Kasparov, he suspected that one of the moves Deep Blue made during the game had actually come from a human.

How times have changed.

Since Deep Blue, the best chess playing entities have been computer programs, not humans. It's trivially easy to cheat online, on platforms like Chess.com, where many people and some of the world's best play. You simply have a chess program running off to the side and put your opponent's moves in as your own, then move as the computer would against your opponent. You're guaranteed to win. Unless, of course, they are cheating, too.

In September, Magnus Carlsen, the reigning five-time world chess champion, withdrew from an over-the-board match with Hans Niemann, a 19-year-old grandmaster, at the prestigious Sinquefield Cup in St. Louis. Carlsen accused Niemann of cheating. Niemann denied it, and admitted to cheating online just twice in his life—when he was 12 and 16 years old. An investigation by Chess.com, released on Oct. 4, states Niemann likely cheated in more than 100 online games.

In the Sinquefield Cup match, there was no hard evidence that Niemann had cheated against Carlsen. No device, speaker, computer, or wires have been discovered. How would it be possible? I'm reminded of the scene from *Goldfinger*, where someone cheats at cards with the aid of an accomplice with binoculars



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and an audio connection. You can fit a chess computer into a small, silicone-covered box the size of a small salt shaker. It buzzes to indicate where to move which piece, allowing one to have the chess computer on their person.

If Niemann cheated, he could have also recruited some conspirator to put Carlsen's moves into a chess AI, and then communicate the recommended move via some device, hidden somewhere on Niemann's person. Historically, others have cheated by having a vibrating device signal morse code from an accomplice watching the game or giving subtle hand signals from the crowd. This recent turmoil has caused some beefed-up security at chess tournaments, including allowing people to spectate only from another room with a 30-minute delay in the video, to thwart real-time assistance.

Many people seem sure that Niemann cheated somehow. Why? Carlsen's suspicions carry weight. Niemann was playing unrealistically well, Carlsen said in a public statement. "Throughout our game in the Sinquefield Cup I had the impression that he wasn't tense or even fully concentrating on the game in critical positions, while outplaying me as black in a way I think only a handful of players can do."

If Niemann cheated, it may not have been on every move. For excellent chess players, the next best move is often relatively obvious. The player would only need to consult a chess AI at certain key points—as few as one or two—to beat their competitor. This is known as "selective cheating." A savvy cheater might even make some low-cost moves they know are sub-optimal, just to throw cheater detectors off the scent.

Chess.com found that Hans Niemann's results in many online games were unlikely.

In its report, Chess.com compared Niemann's moves to that of Stockfish, the best chess AI out now. It's so good it would probably beat Carlsen, or any other human player, every time. It can look over 40 moves ahead, far more than any human being. This means that chess AIs can make moves that humans never would—moves that look, to skilled chess players, like bad ideas in the short term but pay off further ahead in the game than human grandmasters can mentally simulate. Human chessmasters tend not to make such moves, and if they do, we might suspect them of cheating.

Chess.com found that Niemann's results in many online games were extraordinarily unlikely, given his skill. They also looked at how long Niemann took to make the more difficult moves—if the moves are made too fast, it adds evidence to the idea that he was using an AI. This is similar to how "doping" is detected in sports: Contenders on drugs perform at inhuman levels of speed and strength.

In September, chess enthusiast Yosha Iglesias conducted an analysis of Niemann's games using a program that estimates how close to optimal each move was. What Iglesias found supported Carlsen's suspicions: Niemann's moves were close to optimal. Most chess masters play at around 70 to 75 percent of optimality, and Niemann played at close to 100 percent over the course of several games. Clever Hans might be taking cues from outside his own mind.

Where once we had machines cheating at chess by using humans, now we have humans cheating by using machines.

An anti-Mechanical Turk.

—Jim Davies

Branching Out

ON EITHER SIDE of a highway in Tibet, gullies formed by rainwater erosion span out like a tree. "Branching Out" by Li Ping, from China, is the grand prize winner in The Nature Conservancy's 2022 photo contest.

The contest invites professional and amateur photographers from around the world to submit their best nature photos in a variety of categories. This year, the competition attracted more than 100,000 entries from 196 different countries and territories. The other winners can be seen at https://bit.ly/TNCphotos.

Credit: Li Ping / Courtesy TNC Photo Contest 2022

The Big Thinker

Nick Lane is asking—and answering—the vital questions about life

BY PHILIP BALL

THERE IS A BLACK HOLE at the heart of biology," Nick Lane writes at the start of his 2015 book *The Vital Question*. "Bluntly put, we do not know why life is the way it is." It takes some chutzpah to lay down the gauntlet to the life sciences so starkly—to suggest they are engaged more in documenting life than in explaining it.

Lane, a professor of evolutionary biochemistry at University College London, doesn't seem the kind of person you might expect to make such a provocative challenge. He's disarmingly modest, explaining his own answer for why life is the way it is with enthusiasm and conviction but also with frequent disclaimers and frank recognition that he could be wrong. "I've come to realize that being wrong is actually really good fun," he says.

But then his self-assurance kicks back in. Sure, he could be wrong on the details, but on the big picture, "I can't possibly be, because at bottom all I am saying is that energy is important to life, and that the peculiar method by which it works surely tells us something important about how life operates."

Lane and I are sitting in the Wellcome Collection in London, the flagship public space of the Wellcome Trust medical charity set up in 1936 from the legacy of Victorian pharmaceutical entrepreneur and collector Henry Wellcome. We are surrounded by Wellcome's collection of bone saws, religious relics, and medical-themed paintings—an apt setting for talking about how life began, how it proceeds, and ends.

Lane displays the curious and perhaps even contradictory mindset that seems to characterize many creatively provocative scientists: open to being wrong, but convinced he is fundamentally right. He is eclectic in his sources of inspiration but focused on his personal vision. His independent turn of mind is reflected in his unconventional career path, which—along with the breadth of his vision—puts one in mind of the late James Lovelock, who also thought deeply about the relationship between life and the planetary environment it inhabits and transforms. And like Lovelock, Lane has the gift of being a clear communicator, which has allowed him to bring to wider attention a new perspective on living organisms that might otherwise have languished in the corners of specialist journals.

By asking questions about life that few others seem to be asking—and then offering ingenious answers—Lane has earned wide recognition, praise, and admiration. His 2010 book *Life Ascending* won the Royal Society Book Prize for science books, and in 2016 he was given the Royal Society's prestigious Michael Faraday Medal and Prize for communication of science to the public. Bill Gates has said *The Vital Question* "blew me away"—and has funded Lane's work to the tune of $1.2 million.

Through scientific and popular publications as well as lab experiments, Lane has been steadily developing an unconventional narrative about how life works and how it began and evolved. At its core, it is a tale not of genetic inheritance of information but of how life harnesses energy from its environment and uses it to build complex molecular systems. "The difference between being alive or dead," he writes in his new book *Transformer: The Deep Chemistry of Life and Death* in an aphoristic summary of his central concept, "lies in energy flow."

PHILIPP AMMON

Transformer presents an explanation for the origin of the Krebs cycle, the central biochemical process of metabolism in all organisms that live by respiration, whereby large molecules are broken down into small ones and energy is generated in the process. Both prokaryotic organisms like bacteria and eukaryotes like us use the Krebs cycle, which was identified in 1937 by the British biochemist Hans Krebs (it is sometimes called the citric acid cycle). It generates cellular energy while producing the precursors of amino acids and other vital cell ingredients via a cyclic series of enzyme-catalyzed reactions.

The Krebs cycle is often seen as an important but extremely dry piece of textbook biochemistry. When I chatted to Lane a year ago at a science reception and he told me that this was the topic of his next book, he wore a wry grin that implied he was on a fool's errand. "The Krebs cycle is basically extremely dull even to the people who work on it," he tells me now. "And yet somehow it's making me excited. I remember reading [the Italian chemist and writer] Primo Levi, who said a good writer should be able to make any subject interesting. And maybe I took that as a challenge."

It's no surprise that as gifted an expositor as Lane meets that challenge in style. The story in *Transformer* is not just lively and engaging but filled with stimulating ideas about life's origins and evolution, about what regulates health and disease, and about the fundamental nature of life itself. "It's about metabolic biochemistry, but also it's about the origin of life, it's about the origin of animals, it's about cancer, it's about consciousness," Lane says. "These are really big ideas."

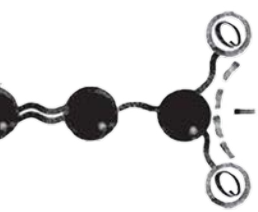
IN HIS POSITION as leader of the largest group in UCL's biology and biochemistry departments, Lane conducts experiments that seem closer to the inventive and speculative chemical cookery of the 1950s than to the cutting-edge wizardry of much of today's molecular and chemical biology. The ingredients could hardly be simpler: carbon dioxide (CO_2), hydrogen, iron minerals, salts. Out of them are coming, not exactly signs of life itself, but clues to how it began.

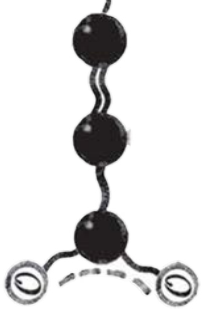
Lane got here along an unusual path. Having studied biochemistry at Imperial College London, he completed a Ph.D. at the Royal Free Hospital in London in the 1990s, which subsequently became part of UCL. "I got a good enough degree, but only just, and I had a big debt," he says. "I got a job in a lab to pay off the debt, and it came with the opportunity to do a Ph.D." The lab was run by a professor of surgery, Colin Green. Lane remembers Green as "an extraordinary man who set up the first medical school in Palestine and was director of the London City Ballet at the time."

Lane worked on organ transplantation, trying to understand why transplants can lead to the condition called ischemia, where tissues are damaged by low levels of blood oxygen. A transplant can lead to a burst of free radicals in the body—reactive, oxidizing chemical agents with unpaired electrons. Lane tried introducing antioxidants to reduce the damage. "But nothing ever worked, and you think the dose is wrong or the timing is wrong or something," he says. "In some ways, it was great fun and I realized that I love research. In other ways, it was frustrating." Yet in retrospect, the essence of Lane's grand vision of life was already contained in those failing experiments.

Seeking a postdoctoral position in free-radical chemistry without knowing anyone in the field was never likely to be successful, but Lane found an alternative. "I had just been a runner-up in a newspaper writing competition, so I looked for writing jobs," he explains. "Some of them were dreadful—writing up clinical trials reports for pharmaceutical companies, unbelievably dull." He eventually landed a position working on medical animations. "It was basically soft marketing for pharmaceutical companies," Lane says. "I did that for a couple of years, and I learned a lot about writing. First, tell a straight story. Second, use plain international English. And I found I could master a subject I knew little about; I could grasp the essence quickly. It turned out to be a useful skill."

The job was only fun for so long. "My way out was that I'd try to write a book," Lane says, as if it were the obvious option. In the 1990s, free-radical chemistry caused by oxygen-based respiration was thought to be central to many disease mechanisms. Why that is so was the organizing question for his first book, *Oxygen: The Molecule That Made the World*, published in 2002. "But I had no idea where the oxygen came from," he says. "I didn't know anything about the evolutionary history of life on Earth." As he explored that question, "I kind of fell in love with science all over again."



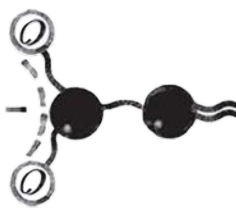


It takes chutzpah to lay down the gauntlet to the life sciences so starkly.

But he was left with a puzzling question. "Oxygen in evolutionary terms seems to have been a wonderful thing. The more oxygen in the atmosphere, the more profuse life has been. And yet here's the medical profession saying too much oxygen is going to poison you with free radicals." It all came down, he figured, to aerobic metabolism in the mitochondria: the compartments in cells where energy is generated in the form of the molecule ATP, via the Krebs cycle. That became the topic of his next book, *Power, Sex, Suicide*, published in 2005.

Mitochondria are widely believed now to be the remnants of an entirely distinct single-celled organism that merged with another cell long ago in evolutionary history, perhaps around 1.5 billion years ago, in a process called endosymbiosis. This would explain, for example, why our mitochondria today contain a small number of their own genes, separate from the rest of the genome in the cell nucleus. (It's the possession of this nucleus that defines the distinction between cells like ours, called eukaryotic, and those of single-celled organisms such as bacteria and archaea, which are prokaryotes.)

There remains an argument, some of it heated, about what this momentous merger consisted of. Some researchers believe it happened between an already extant eukaryotic cell and a prokaryote. Others argue that both cells were prokaryotic. Lane favors the latter, saying those who advocate for the "eukaryote-first" picture do so for "basically emotional reasons." He says the idea that mitochondria appeared when a bacterial endosymbiont merged with an archaeal host cell is consistent with all we know about the evolution of eukaryotes.



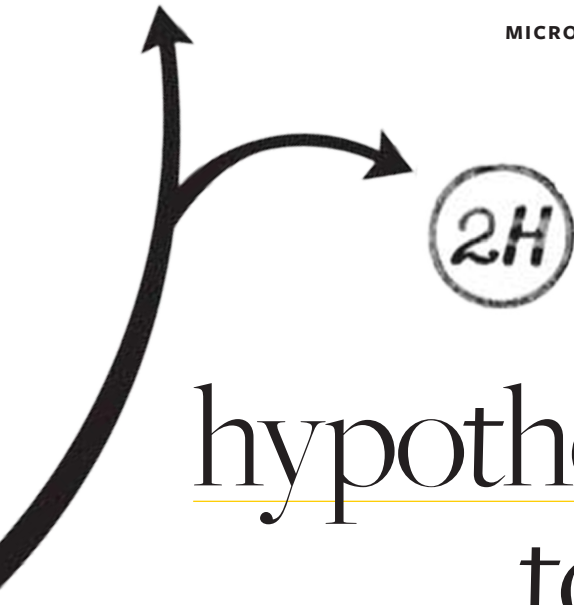
At any rate, cells that acquired their own internal powerhouse were suddenly able to do entirely new things—like group together to make multicellular organisms. Lane sharpened his ideas in conversations with the microbiologist Bill Martin of the University of Düsseldorf in Germany. Martin had an unconventional view of what happened in the endosymbiosis that led to eukaryotes with mitochondria, in which a central role was played not by oxygen but by hydrogen. In this "hydrogen hypothesis," the host cell was an archaeon that metabolized by using hydrogen, and the bacterium that became the mitochondria produced hydrogen (as well as carbon dioxide) via anaerobic respiration—so it supplied the fuel that the host needed.

"Around 2002, when *Oxygen* came out, I went to a discussion meeting at the Royal Society and Bill was there and gave a pretty amazing talk on the origin of life," Lane says. There Martin laid out the hydrogen hypothesis and explained why in his view early life was much more about metabolism and energy flow than about genes and proteins. "It was all very radical, it still is radical, but back then it seemed crazy," Lane says. Martin, he adds, "was one of the biggest influences on my thinking."

Stimulated by such ideas, Lane found that the book he was developing, *Power, Sex, Suicide*, started to take a new direction. "It went from being a book about mitochondria to being a book about the origin of complexity," he says. "It really boiled down to the fact that it wasn't about oxygen after all—it was about mitochondria and the energetics of genomes. I still think it's basically the right way of seeing the question."

Later, Lane and Martin teamed up, and in 2010 they made the case that what changed with the acquisition of mitochondria was the "energy per gene." By their calculations, eukaryotes have up to 200,000 times more energy per gene than prokaryotes. With those resources, eukaryotes could do things unavailable to prokaryotes, such as become multicellular and develop complex forms and collective behavior. Thanks to that energy boost, large animals—and eventually us—became possible, as did behaviors, such as sexual reproduction, that are inaccessible to bacteria and archaea.

DEEP HISTORY Nick Lane at the Wellcome Collection in London, a museum that ventures through the corridors of health and human history. The museum was an apt setting for the evolutionary biochemist to describe his compelling research into how life began.



Lane's bold hypothesis is life *had* to be this way.

WITH THESE IDEAS about the energetics of life's origins arising in the mid-2000s, Lane realized he was at a turning point. He was doing fine with science writing. He was embarked on writing *Life Ascending*, which looked at "the ten great inventions of evolution" (including the endosymbiosis that he believes led to eukaryotes). But he had, almost by accident, found a hypothesis about a key stage in evolutionary history, with a welter of wide-ranging implications.

The question of how life began is often posed in terms of how to make its molecular ingredients, such as amino acids and nucleotides, the building blocks of proteins and the nucleic acids RNA and DNA, from simple inorganic compounds that might have been present on the early Earth—carbon monoxide, water, and cyanide. If you succeed in making, say, nucleotides in such prebiotic reactions, the next challenge is to link them up into chains and polymers—for example, to progress toward the "RNA World" hypothesized in the 1980s, where RNA molecules served the dual role of acting as catalysts and carriers of inheritable "genetic" information before proteins and DNA took over those respective roles.

That's all very well, says Lane, but to make such molecules and to do anything with them, you need a source of energy. In early work on prebiotic chemistry, like that of Harold Urey and Stanley Miller, the energy source driving the chemical reactions was often assumed to be light or ultraviolet radiation from the sun, or lightning discharges in the atmosphere. But pretty much all the energy in living cells today, whether of bacteria or plants or animals, is ultimately "chemiosmotic": The cell's ubiquitous molecule, ATP, produces energy by harnessing the driving force created by differences in concentration of ions—especially hydrogen ions, which are merely lone protons—across biological membranes. Like dam water driving a hydroelectric turbine, this "proton-motive force" powers the enzyme ATP synthase, a protein that sits embedded in the membrane and churns out ATP molecules as its head rotates in a membrane-bound sleeve. ATP synthase is found in almost all bacteria, archaea, and eukaryotes, says Lane. "It is as universal as the genetic code itself," Lane writes in *The Vital Question*, and "should be as symbolic of life as the double helix of DNA." In other words, life is really all about the flow of electrical charge (electrons and protons) as a driving force for making biomolecules and powering metabolic pathways.

"I was actively trying to think, how can I test some of these ideas?" he recalls. "How can I get back into academia?" Then he got a lucky break.

PAGES 24-25: PHILIPP AMMON

In 2008, Lane met the author and scientist Don Braben, an advocate of "blue-skies research" that is curiosity-led rather than aimed at specific questions or applications. Braben was working at UCL, where he now holds an honorary position in the Office of the Vice-Provost for Research. "Don's view is that some of the great breakthroughs in the 20th century would never have happened with the current funding model," Lane says. Braben persuaded the provost at UCL to back research proposals with basically no peer review. "He wanted very short proposals on ideas that were potentially transformative," Lane says. "It became clear that this was by far my best opportunity to get back into academia."

After much back-and-forth, Lane's application elicited a funded position called the Provost's Venture Research Fellowship from 2009 until 2012. "It was strange for me to go back into the lab," he says. "It was incredibly cack-handed and amateurish, and I didn't have any equipment—I had to beg and borrow other people's. I was doing amazingly stupid things, but some of it worked."

Lane's proposal was titled *Chemiosmosis and the foundations of complex life*. "It only took one or two meetings for me to be convinced that Nick is an exceptional scientist who might one day win a Nobel Prize," says Braben. "He did not try to persuade me that his research would lead to this or that wonderful outcome but would concentrate entirely on the science involved."

"Nick's performance at our meetings convinced me that here was a scientist who would do something important and radically change the way we think," Braben adds. "But with funding success rates running at about 20 percent, the chances of his winning support from normal sources would be negligible."

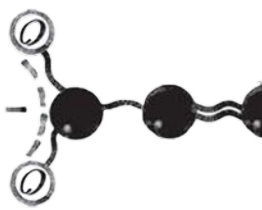
Lane praises UCL as "an environment where people do give a damn about ideas and about other people's work. It's a really bottom-up, collaborative place, where you can easily infect people with your own enthusiasm."

IN *THE VITAL QUESTION*, Lane offered a detailed and concrete scenario for how life might have got started on Earth. It builds on the idea proposed in the 1970s that it all began not in some prebiotic soup such as ponds or shallow oceans rich in organic molecules and warmed by sunlight, but deep down in the oceans at structures called hydrothermal vents, where volcanic activity sends mineral-rich hot fluids spewing from mineralized chimney-like structures on the seabed.

In the late 1980s, British chemist Mike Russell began to develop a detailed scenario for how the necessary chemistry could have arisen. Iron sulfide minerals might act as the source of the energy and electrons needed to drive the fixation of carbon, he said. Some vents are rich in such minerals, which can drive "redox chemistry" (for example, adding and subtracting oxygen and hydrogen atoms from carbon compounds) as the iron ions cycle between two states with differing electrical charge. Even today, clusters of iron and sulfur atoms are commonly found in some enzymes, including those that catalyze the reactions of respiration—a remnant, Russell suspected, of the early role played by iron sulfide minerals.

This picture, called the chemoautotrophic origin of life, drew on work in the 1980s by the German chemist Günter Wächtershäuser, who argued that the Krebs cycle, running in reverse, could have been the first biochemical metabolic pathway, powered by iron-sulfur chemistry. In 1997, Russell and his colleague Allan Hall showed how the gradients in pH at alkaline vents could couple to iron sulfide redox chemistry to drive the emergence of the first living entities, which used a proton-motive force to power their metabolism.

To harness such a "chemiosmotic" concentration gradient, you need a membrane that partitions space into regions of different concentration, so that this difference is not just washed away by diffusion of the molecules or ions. At hydrothermal vents, Russell argued, such membranes can be *inorganic*—made from mineral compounds such as iron sulfides or hydroxides. Perhaps once such structures were producing pseudo-metabolic chemical processes that generated molecules like organic fatty acids, they could create their own organic membranes, the precursors to the phospholipid membranes of today's cells. A system like this could act to transfer electrons from hydrogen molecules to carbon dioxide molecules (both are abundant in hydrothermal vents): the first step in generating more complex organic molecules such as formaldehyde, carboxylic acids, and ultimately the components of the Krebs cycle of metabolism.



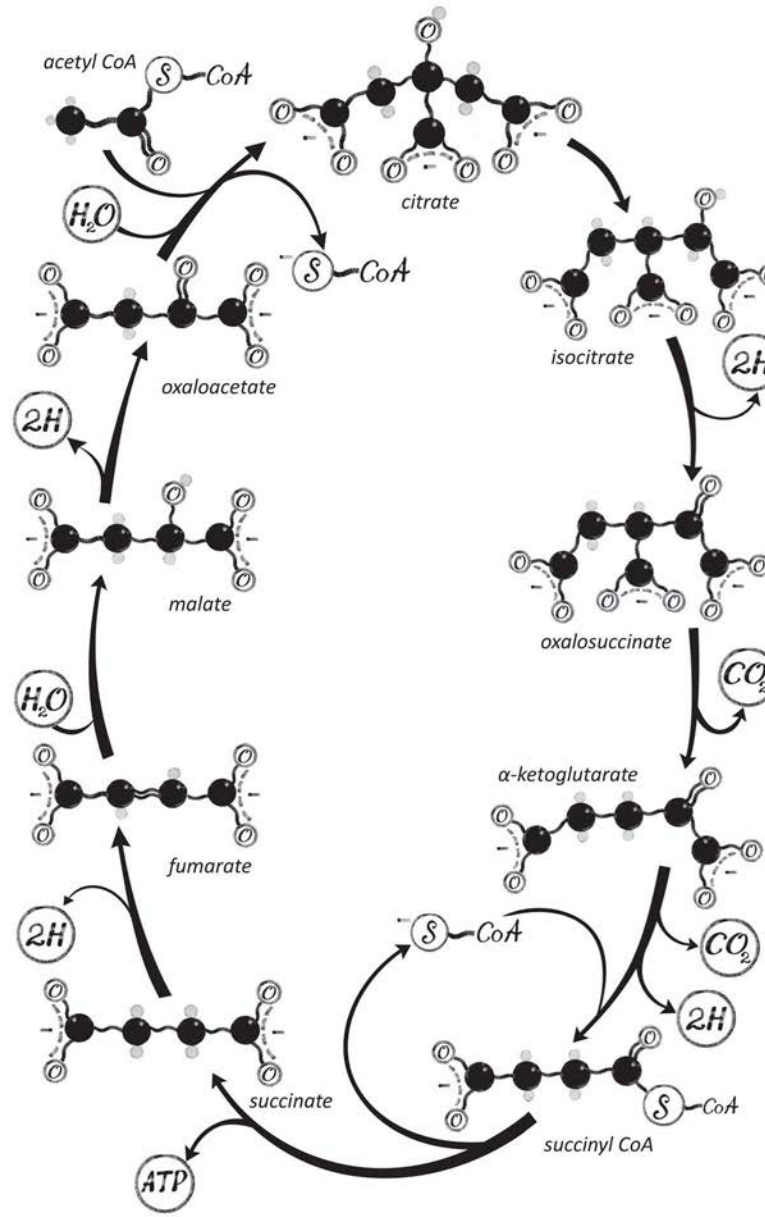
In other words, rather than finding separate routes for making the biomolecular components of the first proto-cellular organisms and then having to hope they somehow all come together in an organized entity, redox chemistry at hydrothermal vents could have given rise to compartmentalized chemical reactors with a ready-made energy source, spinning out the complex organic ingredients needed for life to begin.

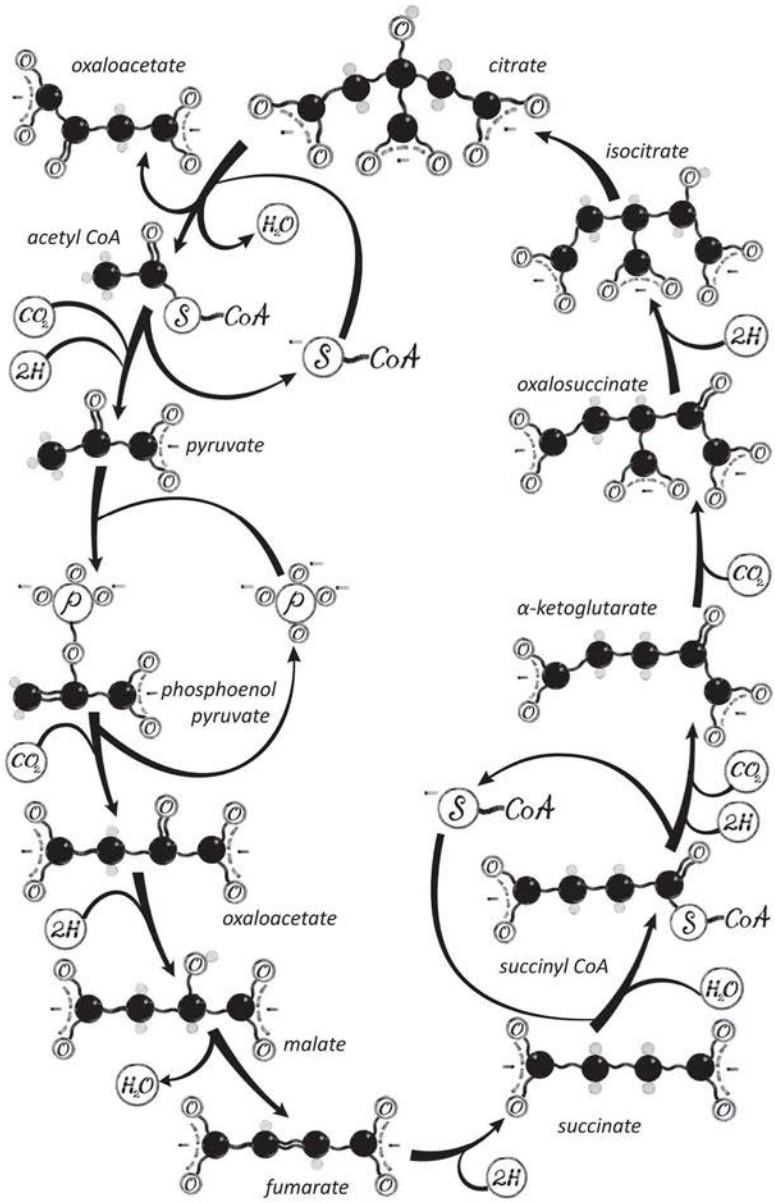
Russell's scenario in which proton gradients and the proton-motive force operate in cell-like cavities at alkaline hydrothermal vents "really excited me," says Lane. "Mike Russell was and is inspirational in linking geochemistry and structure with the beginnings of biochemistry."

"An environment like hydrothermal events provides everything we think we need" to kickstart life, Lane says: the raw ingredients such as a carbon source (CO_2), a source of energy (pH gradients), agents that can catalyze redox chemistry (such as iron sulfides), and compartmentalization by membranes.

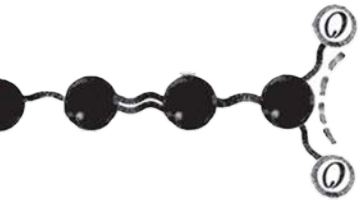
Indeed, in the mid 2000s Martin and Russell elaborated the theory of an origin of life at alkaline hydrothermal vents and how the inorganic chemistry happening there could have given rise to the beginnings of the Krebs cycle that fixes carbon from CO_2 into a form usable by early organisms. They developed a scenario in which these proto-organisms might have developed first into simple bacteria-like cells with an organic membrane, and then, about 2 billion years ago, merged to form eukaryotes with mitochondria.

Work by Martin and Russell is a foundation of Lane's theory of the origin of life. Broadly speaking, Russell says, "Nick seems to have followed me in most of his ideas, although with a more biochemical grounding compared to mine, which was developed from geological exploration and





VISUAL AID Nick Lane's inclusion of illustrations like the Krebs cycle (left) in his books signals his mission to communicate without proselytizing or saying to readers, "Trust me, I'm a scientist." "I'm not patronizing them," Lane says. "I'm giving them the opportunity to see why it's this way."



"It's so simple. It solves so many problems. It's quite thrilling."

geochemical knowledge and experience." Martin is less sanguine. He says he has not been given enough credit for initiating some of the ideas described in Lane's books (even though he is duly cited many times). Russell says he harbors no ill feelings about the way Lane has extended and popularized his ideas. "I, for one, am very happy about the way he proselytizes this work," he says.

AS LANE EXPLAINS HIS VISION in the gloom of the Wellcome exhibition room, while the occasional visitor wanders past, peering into the glass cases, I can see how convinced he is that this story, despite its chemical complexity, provides a coherent picture of the way life gained a foothold on the planet. Putting chemiosmotic energy and metabolic reactions at the heart of it all, he says, fits nicely with what genetic studies suggest the first organisms might have looked like. And his hypothesis "makes a terrifying prediction," he says. "All of this biochemistry is just going to spontaneously happen. But what a beautiful prediction!" Now he's trying to test it in the lab.

Transformer fleshes out this story by explaining how it could have led to the Krebs cycle itself. As Lane writes, this complex, cyclical series of reactions generates ATP "by stripping out hydrogen atoms from the carbon skeletons of food [molecules] and feeding them to the ravenous beast that is oxygen": the process of cellular respiration. On paper it looks like a rather arbitrary sequence of conversions of molecules related to citric acid—a headache for biochemistry students to learn and understand. But Lane now believes that a consideration of what is needed to drive metabolism involving CO_2, oxygen, and hydrogen makes almost all this chemistry *inevitable*.

Five or six years ago, Lane says, he'd have conceded only that something vaguely resembling this sequence was bound to arise. "It kind of beggars belief that that level of reaction networks will happen spontaneously. But it looks more and more like they do." Lane is referring to not just the cycle itself but the reactions that spin off from it, which form amino acids and the specific nucleotide bases found in DNA and RNA. "If you've got this molecule here in this context, you ask,

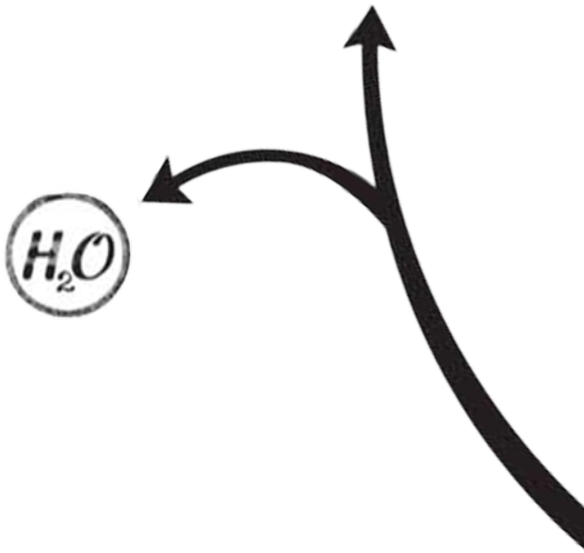
what's going to happen next? And you can see what it will be. You are going to form this one, and so on. You start drawing these things, and you think—Jesus, here's the Krebs cycle! You almost can't end up with anything else."

If Lane is right, it suggests that identical biochemistry will arise on any other planet with an environment something like that of the prebiotic Earth. In other words, the principles of chemical thermodynamics and kinetics dictate a kind of pre-Darwinian convergent evolution that creates something at least close to a Krebs cycle. "All it's asking for is a wet rocky planet or moon with CO_2 in the atmosphere," Lane says. "That's not a big ask, right? There are probably billions of exoplanets in the Milky Way that fit that set of criteria." And you need chemical disequilibrium like that found at hydrothermal vents. "What really matters is converting this environmental disequilibrium into living matter: CO_2 and hydrogen into cycling intermediates, and amino acids and nucleotides." The bold hypothesis is that life *had* to be this way—and not just terrestrial life, but any life in Earth-like environments. "It's so simple," Lane says. "It solves so many problems. It's quite thrilling."

Where evolution might take it after the first primitive protocells have appeared is another matter. So far Lane has elaborated his picture to account for the production of the first nucleotides and their polymers, and recently he and his group have argued that the energetics of CO_2 fixation might explain why the genetic code, which relates the nucleotide sequence of DNA to the amino-acid sequence of proteins, takes the form it does. "I've just got up to the origins of information and evolvability," Lane says, "but I'm a long way from molecular machines like ribosomes," the multi-molecule assemblies that make proteins from the information in RNA. "So there's an interesting next question: What's the simplest possible molecular machine that you can imagine?"

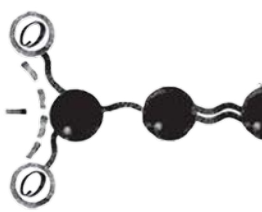
But is there any proof that this is really how life began—and *had* to begin? "It makes a bunch of predictions that may or may not be true," Lane admits. "It's very easy to delude yourself into thinking that because it's a beautiful idea, it's got to be true. Maybe it's not—maybe these associations are just not strong enough or there is some other explanation for it."

These things are where happiness in science lies.



The proposal needs to be tested in the lab—and that's what Lane is now doing. He and his team are using microfluidic systems to see if, starting with CO_2, hydrogen, and simple inorganic ingredients such as silicates and iron salts, they can generate some of the Krebs cycle compounds. They're getting somewhere, slowly. "We're getting at least acetate, and possibly pyruvate," he says—two of the key molecules in the cycle. They have also shown that "protocells"—closed compartments made from organic membranes composed of simply fatty acids—will form spontaneously under the conditions that exist at alkaline hydrothermal vents.

"I seem to have assembled around me a bunch of people who are very free thinkers," he says. "I encourage them to disprove everything that I say, and they seem to try and do it with relish. It throws lots of googlies at you on an almost daily basis: Either this is wrong or what can we do next, how can we get out of this corner?"



What keeps most scientists going is the excitement of the unknown.

For all the grand ideas about some of the most profound questions contemplated by science, Lane hasn't lost sight of his early days working on disease. That's all part of the picture too. "The issue with cancer is it's about growth," he says. "It's about how a cancer cell can optimize metabolic flux so that it can make copies of itself." Cancer is also about the Krebs cycle. "The cancer people have been thinking along these lines for a little while, and it links up with aging as well. It's hooking up three different fields in a way which they *should* hook up."

An interest in this chemistry of carbon fixation has also come from another unexpected direction. "Part of the reason it's become more interesting to people is because of the issues with CO_2 capture and climate change," Lane says. "People are now taking the idea that you can reduce CO_2 and convert it into something useful like hydrocarbons much more seriously than they were a few years ago."

Lane is willing to take his ideas about the centrality of energy and electron flow in some speculative directions. *Transformer* ends with a discussion of its role in the evolution of thought and consciousness. "The electrical potential humming away on cell membranes is movement too, dancing charge, electrons and protons, the elementary particles of life," Lane writes. "Moving charge generates electromagnetic fields that permeate our being. And clearly, the flux of metabolism generates electromagnetic fields on cells. Could feelings somehow be related to this dance of charge, the ephemeral states of cells?"

"I think the likelihood of that being completely true is probably quite small," Lane admits. "But the possibility that it might be true is intriguing."

This seems to be the next direction in which Lane's fertile mind is taking him. "If you'd asked me a couple of years ago which question I'd like to see answered in my lifetime, I'd almost certainly say something to do

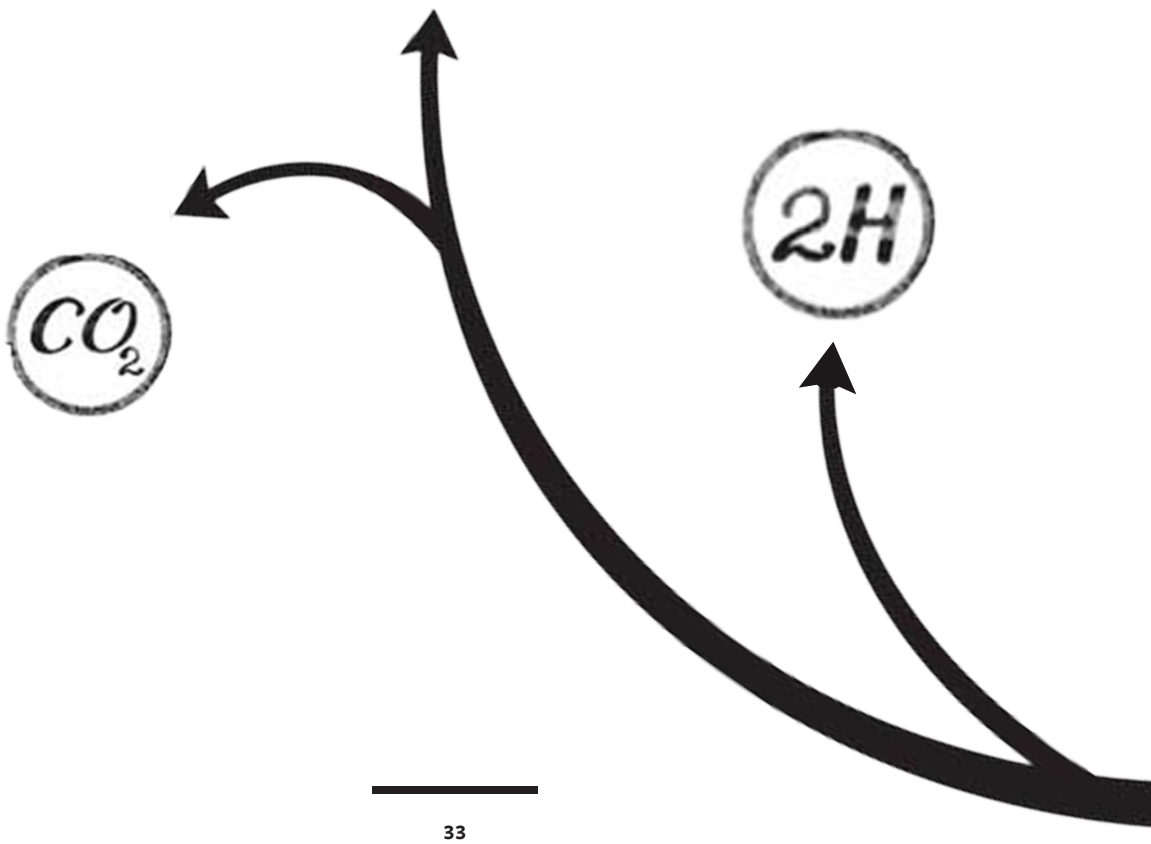
with the origin of life," he says. "But in a strange way, I feel as if conceptually I can almost understand it now. There's an awful lot of work in the lab to do, but I think I can join the dots. So now I'd say it's consciousness, because I think that's more out there."

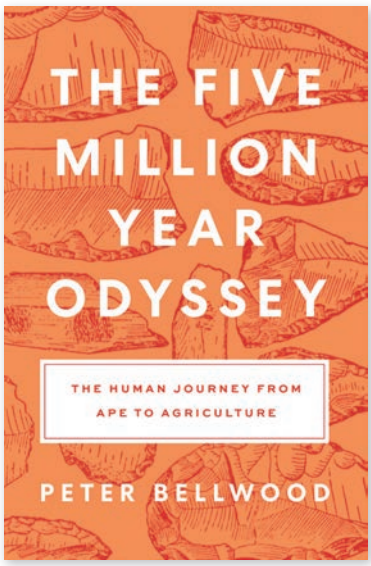
Despite being head of a large research group, formulating and testing complex hypotheses, Lane retains his passion—indeed, almost a sense of urgent obligation—for communicating science to the widest possible audience. "Asking the big questions and trying to excite other people with them—these things are where happiness in science lies," Lane says. "Somehow we've got to get across to people that science is a human activity, that it's about finding out what we don't know about the world."

In a time when popular science can end up over-simplifying ideas for general consumption, Lane's books might seem uncompromising. *Transformer* is filled with illustrations of the Krebs-cycle intermediates and their reactions: yes, *molecules*, a pretty reliable deterrent for those with bad memories of school chemistry classes. "It's going to require patience," he admits. "It's going to require some commitment on the part of the reader. But I'm not patronizing them. I'm giving them the opportunity to see why it's this way."

This urge to communicate without proselytizing or saying simply "Trust me, I'm a scientist," is at the core of Lane's mission. "What keeps most scientists going most of the time is the excitement of the unknown," he says. "Yet somehow that's not transmitted through to the public very well. If we can do that, I think there will be much more excitement about and sympathy for science in society, and then better decisions about what we do about climate emergencies or pandemics. It's not just a case of getting science across to people, it's a case of getting people to participate, to be part of it, to feel that science is for them."

PHILIP BALL is a science writer and author based in London. His most recent book is *The Book of Minds*.





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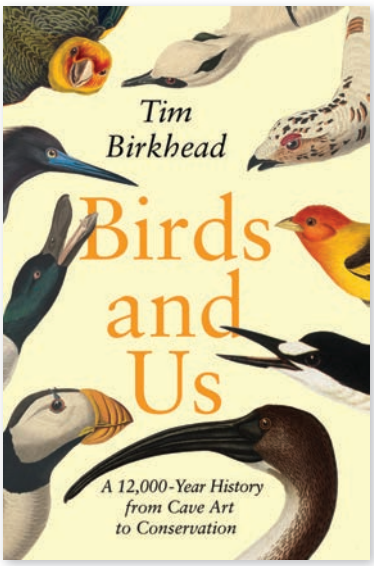

"[Tim Birkhead] delivers a masterclass.... This is a must-read for nature lovers."

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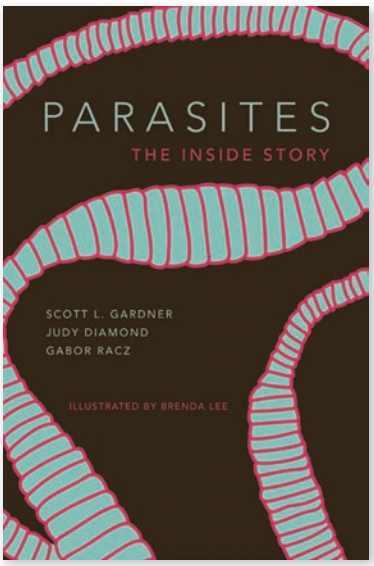

"*Parasites* contains excellent illustrations, sound scholarship, and fine writing."

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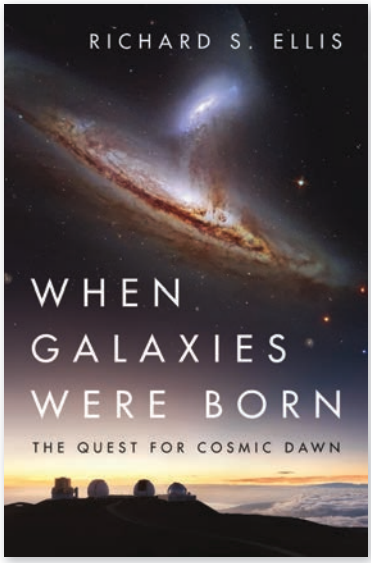

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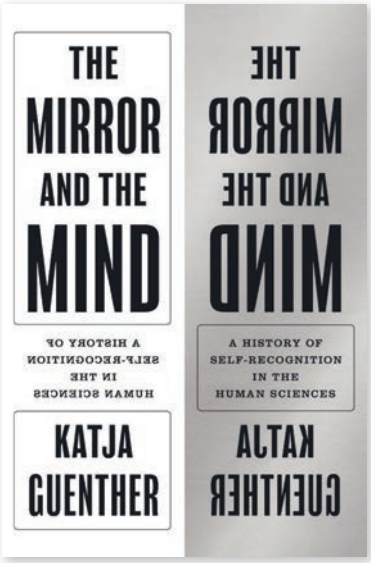

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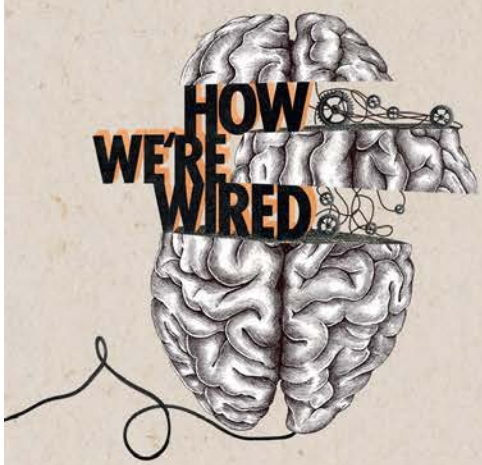

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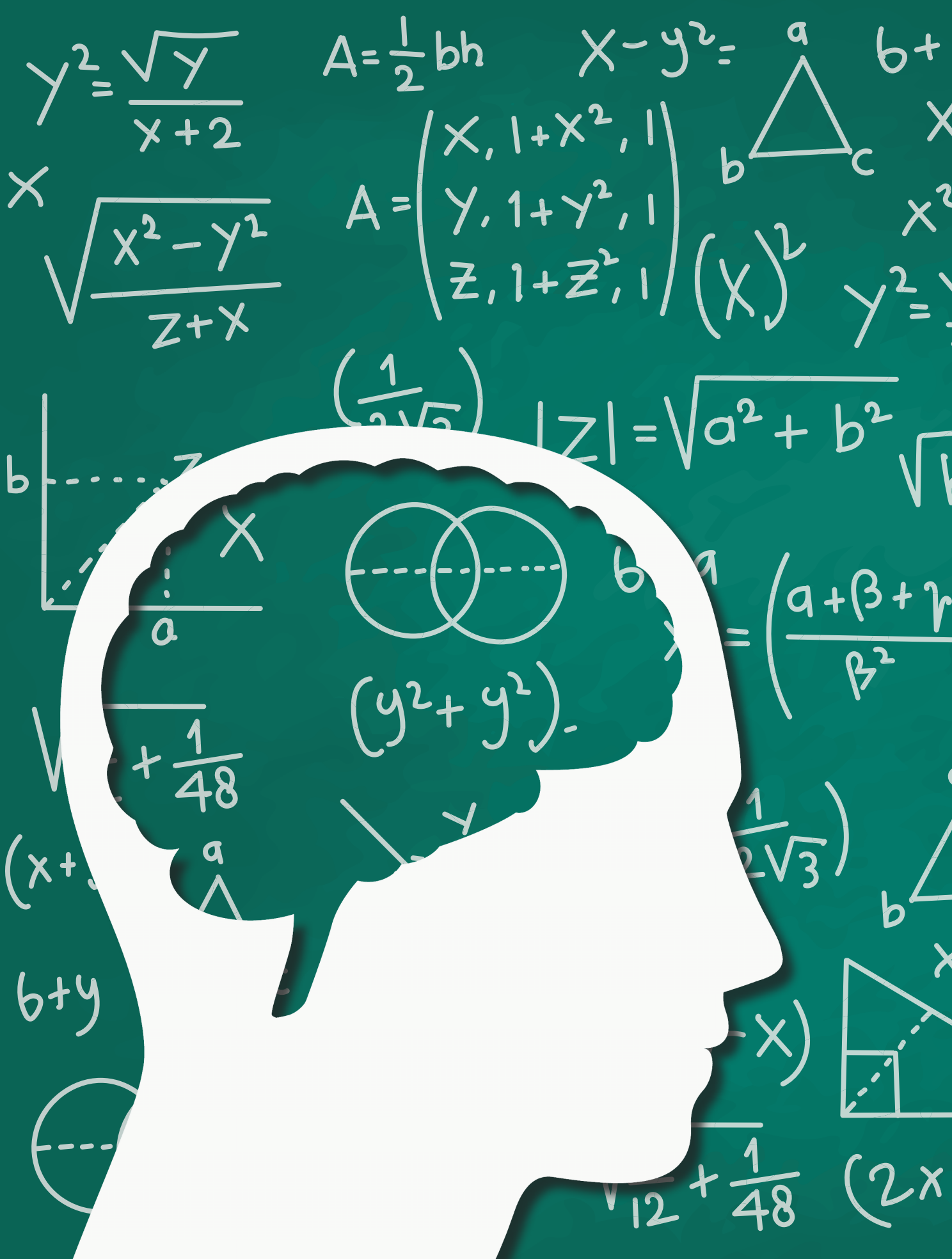
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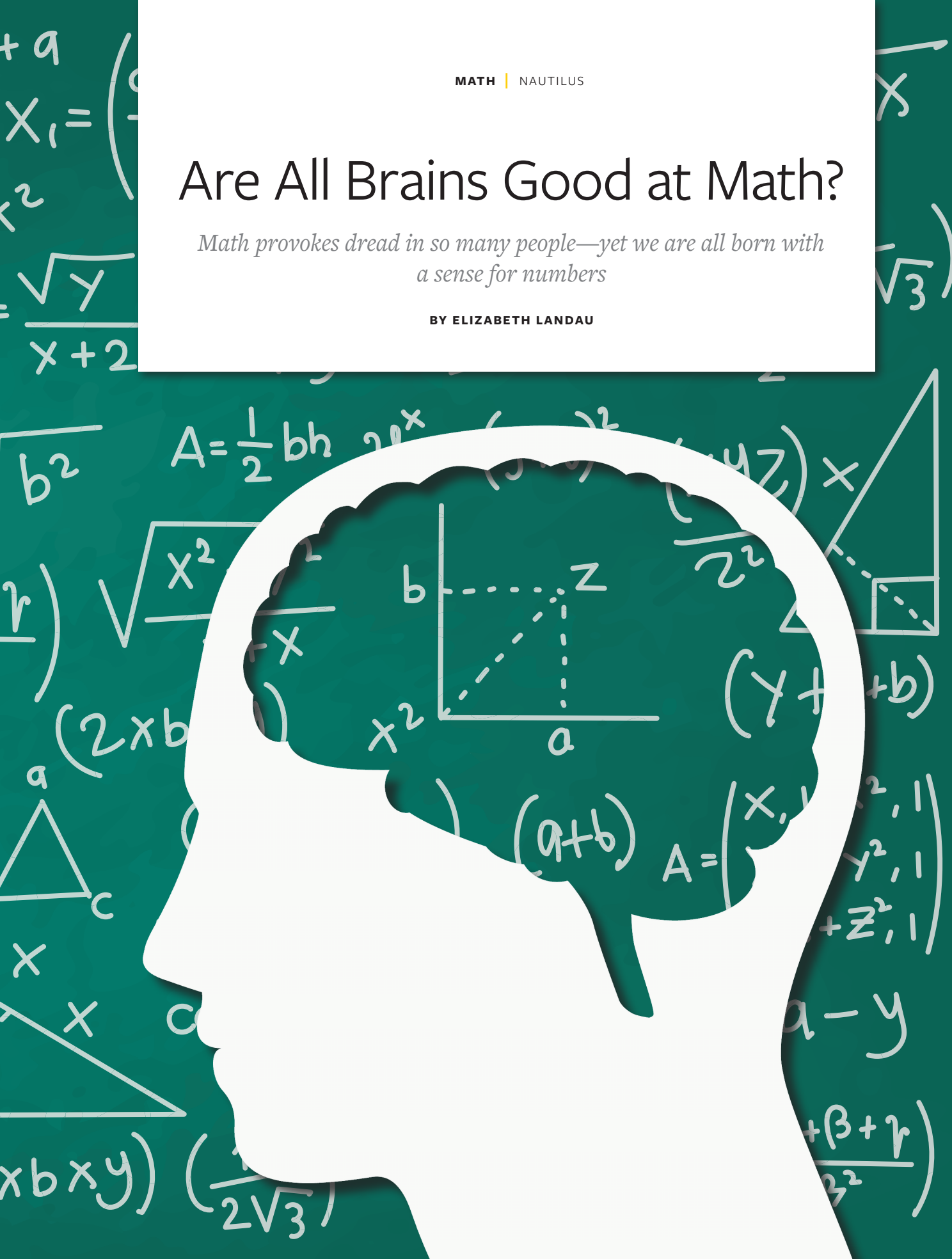
Are All Brains Good at Math?

Math provokes dread in so many people—yet we are all born with a sense for numbers

BY ELIZABETH LANDAU



KEN ONO GETS EXCITED when he talks about a particular formula for pi, the famous and enigmatic ratio of a circle's circumference to its diameter. He shows me a clip from a *National Geographic* show where Neil deGrasse Tyson asked him how he would convey the beauty of math to the average person on the street.

In reply, Ono showed Tyson, and later me, a so-called continued fraction for pi, which is a little bit like a mathematical fun house hallway of mirrors. Instead of a single number in the numerator and one in the denominator, the denominator of the fraction also contains a fraction, and the denominator of that fraction has a fraction in it, too, and so on and so forth, ad infinitum. Written out, the formula looks like a staircase that narrows as you descend its rungs in pursuit of the elusive pi. The calculation—credited independently to British mathematician Leonard Jay Rogers and self-taught Indian mathematician Srinivasa Ramanujan—doesn't involve anything more complicated than adding, dividing, and squaring numbers. "How could you not say that's amazing?" Ono, chair of the mathematics department at the University of Virginia, asks me over Zoom.

As a fellow pi enthusiast—I am well known among friends for hosting Pi Day pie parties—I had to agree with him that it's a dazzling formula. But not everyone sees beauty in fractions, or in math generally. In fact, here in the United States, math often inspires more dread than awe. In the 1950s, some educators began to observe a phenomenon they called mathemaphobia in students,[1] though this was just one of a long list of academic phobias they saw in students. Today, nearly 1 in 5 U.S. adults suffers from high levels of math anxiety, according to some estimates,[2] and a 2016 study found that 11 percent of university students experienced "high enough levels of mathematics anxiety to be in need of counseling."[3]

Math anxiety seems generally correlated with worse math performance worldwide, according to one 2020 study from Stanford and the University of Chicago.[4] While many questions remain about the underlying reasons, high school math scores in the U.S. tend to rank significantly lower than those in many other countries. In 2018, for example, American students ranked 30th in the world in their math scores on the PISA exam, an international assessment given every three years.

Some scholars argue that American culture's saturation with negative stereotypes around math in combination with current approaches to teaching the subject are perpetuating anxiety, making some kids think they are bad at math, and preventing them from excelling. Research shows that humans are born with an inherent sense of numbers, known as numerosity.[5] The concept of numerosity is one of the only high-level cognitive functions that is mapped to a specific region of the brain. In other words, we are primed to do basic math, but culture gets in the way. Recent neuroscientific, behavioral, and cognitive research could help us redesign math education so that it supports rather than undermines learning—and even inspires a love for the mysterious elegance of math along the way.

PAGES 36-37: ILLUSTRATOR096 / PETER HERMES FURIAN / SHUTTERSTOCK

THE SUBJECT OF "MATH" is far-reaching and wide-ranging—it covers everything from counting to prime numbers to algebraic topology. But at the most rudimentary level, science suggests that we are all born with a sense of quantity.[6] Human infants are able to understand this concept as early as 6 months old, long before they have had substantial exposure to human culture or language. And this preverbal sense for numbers is thought to be a building block for later math ability in both childhood and adulthood.[7] In one study, researchers found that 3-year-old children who had higher intuitive number sense as infants scored significantly better on math achievement tests, even when the researchers controlled for general intelligence. And a 2013 study by Joonkoo Park and psychologist Elizabeth Brannon, both then at Duke University, found that students could improve their math proficiency through training that engaged their ability to estimate quantities.[8]

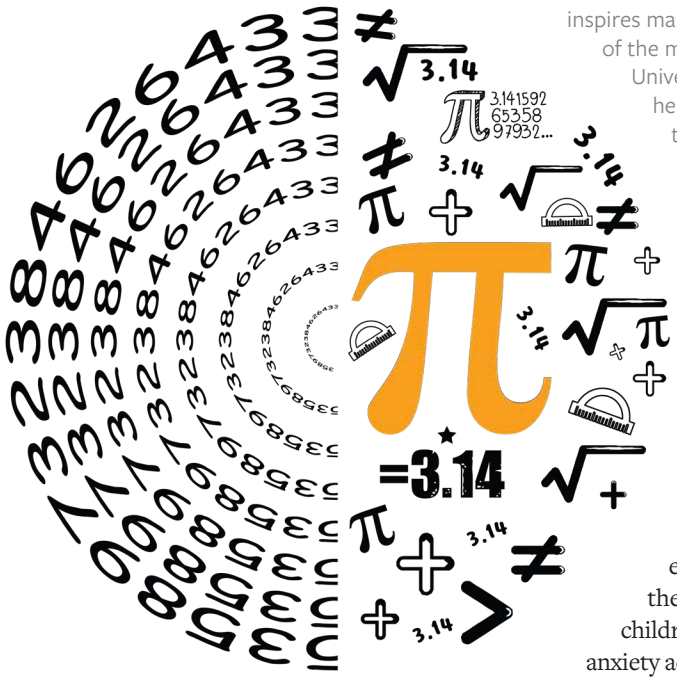
This ability to estimate and understand quantity may have evolved as a basic survival skill. It could have helped our ancestors and members of other species quickly assess whether they were outnumbered by predators, for example, or to forage in places with more available food relative to others. Andreas Nieder of the University of Tübingen in Germany, who has studied numerical perception in a diversity of species, believes that a cognitive system for perceiving numbers evolved independently, and in parallel, in species such as monkeys, birds, and insects, that lie far from one another in the evolutionary tree. Pigeons can be trained to peck a certain number of times on a board.[9] Dolphins seem to be able to understand the numerical concept of "less"[10] and honeybees, according to one study, can grasp the concept of "zero."[11]

There seems to be consensus among scientists, however, that only humans mentally represent numbers precisely and with symbols, and that we need some kind of education to do so. This is potentially because many higher math skills, including arithmetic, depend on the use of language—a symbols-based system—where quantity-based judgments are preverbal.[5] Indeed, arithmetic is difficult to do if one does not have the language for it. One 2004 study, for example, looked at speakers of an Amazonian language called Mundurukú, which does not have words for numbers larger than 5, and found that speakers did not do well "in exact arithmetic with numbers larger than 4 or 5."[12] A 2013 study in *Trends in Neuroscience and Education* compared the relative mathematical abilities of schooled and unschooled Western adults, and found significant differences in their abilities to approximate large numbers.[13]

We could redesign math education so that it supports rather than undermines learning.

If we have the innate ability to understand math and acknowledge its importance in making sense of the world, why are so many—in Western culture, mainly—averse to it? Scholars who study math and math education have a hard time answering this question.

Perhaps it is related to the way we in the U.S. tend to conceptualize math ability. People in the West often say, "I'm bad at math," as though it were a personality trait or even a badge of honor. Compared to other school subjects, "I think people have more of a fixed mindset about it," as though they have "a knob turned to a certain setting," says Jordan Ellenberg, professor of mathematics at the University of Wisconsin-Madison and author of *Shape: The Hidden Geometry of Information, Biology, Strategy, Democracy, and Everything Else*. "That's a pretty bad misconception," he added.



FOR THE LOVE OF PI The elusive number inspires many math lovers. Ken Ono, chair of the mathematics department at the University of Virginia, when asked how he would convey the beauty of math to the average person, mentions a formula for pi that is at once simple and complex.

AL MAMUN DESIGNER / SHUTTERSTOCK

Of course, some kids do have clinical learning disabilities that are not caused by anxiety, cultural myths, or poor teaching. Developmental dyscalculia, a clinical term for someone who has a math-related learning disability, affects about 3 to 7 percent of the population. This is the lesser-known analog of dyslexia, a learning disability related to reading, and the two conditions often occur together.

But believing you are bad at math can become a self-fulfilling prophecy. Evidence suggests that cultural assumptions that women are less skilled at math than men may account for much of the gender gap in math performance. Racial stereotypes can also undermine performance. Ebony McGee, professor of diversity and STEM education at Vanderbilt University, has spent more than a decade looking at issues of systemic racism in STEM fields. In her book *Black, Brown and Bruised: How Racialized STEM Education Stifles Innovation*, she notes that Black, Indigenous, and Latinx students regularly report experiences of "isolation, feeling or being positioned as an impostor," as well as other racialized biases that distract them from their studies and sap their energy.

Math anxiety may be transmitted from teachers and parents to kids, too. "Evidence from the United States suggests that children who interact with high-math-anxiety adults show impaired math performance relative to their peers," the authors of a 2017 study wrote.[4] Taking the approach that kids should be rewarded for struggling and spending time learning math concepts, not just for giving correct answers, Jo Boaler and colleagues at Stanford University are developing an online resource for parents called Struggly. "The neuroscience very clearly shows everybody's on a growth journey," Boaler said. "There's no kind of cut off where somebody becomes gifted."

Even calling a child "gifted" or "smart"—or telling them that they have a "math brain," as Boaler puts it—can have unintended consequences by setting an expectation that can later be hard to meet. I relate to this. I loved learning advanced math in "gifted" summer programs in high school, but later struggled in multivariable calculus during my first college semester and became convinced the gift had expired. No one suggested that my frustrating long nights of study just to come off with a B were supposed to be part of a journey. Instead, like so many others, I just didn't take any more math courses.

People in the West often say, "I'm bad at math," as though it were a personality trait.

ONE KEY QUESTION for math educators has long been how to teach broad concepts and foster deep understanding while balancing the parts of the classroom that kids often dread most: memorization and repetition.

Just over a decade ago, most U.S. states adopted the Common Core State Standards in Mathematics, which set out ambitious targets for student learning from kindergarten through 12th grade. The standards apply not just to the content of math instruction, but to the ways it is taught. One of the aims was to transition teaching methods away from drills and memorization toward a greater emphasis on understanding mathematical concepts and how they relate to one another. Research on whether the new standards have led to improvements in math achievement is "sparse and full of caveats," write the authors of a 2021 paper in *AERA Open* journal. They found in their study of Chicago schools that when teachers have been specifically trained to implement the standards, kids who had been under-performing had significantly better grades, pass rates, and test scores.[14]

Boaler and colleagues advocate for reforming California's Mathematics Framework, a set of teaching standards that sits alongside the Common Core, to group math concepts together into "big ideas" that have relevance to the lived world. For example, third graders could learn concepts like fractions and polygons—which are typically taught separately—together in the context of floor tile shapes. By combining them, "teachers can focus on fewer things, but richer with more connections," she said. And Boaler is down on timed memorization drills, which she says contribute to math anxiety. The facts of math—the results of 7 times 8 and the like—are still important, Boaler says, but lessons that emphasize their meaning and situational relevance best help students learn them.

A seemingly opposing perspective comes from Barbara Oakley, author of *A Mind For Numbers: How to Excel at Math and Science*, who argues that, ultimately, learning math is more like learning a language or learning music than it is like some other forms of learning. In a personal essay for *Nautilus* about how she turned on to math and became a mathematician late in life, she wrote that repetition and memorization are essential, and that a focus on understanding concepts over rote practice can undermine math learning. While this might seem like a debate, it doesn't have to be—no curriculum is going to be purely concept driven or purely memorization-driven. Everyone needs to understand the concepts, but also practice using them. In fact, students who rely on memorization alone to learn math—the U.S. has ranked high in this category in the past—consistently perform worse than those who focus on understanding the relationship between concepts on the PISA math assessment.[15]

A method that seems to combine both concepts and practice is called "chunking." It involves turning the material you need to learn into "chunks," which are "pieces of information that are bound together through meaning," Oakley writes in her book. The idea is that by breaking down big problems, concepts, or processes, you can focus on tackling the individual components in digestible pieces.

In interviews, Oakley often uses the example of backing up a car. If you have never driven before, you need to think about the entire sequence of actions to make this happen: Look in the mirrors, check blind spots, put the car

in reverse, turn the steering wheel, etc. But once you back up your car often enough, it becomes second nature—you don't even think about the individual steps. The same can be said for any math principle you're trying to learn, Oakley writes. She outlines a three-step process for chunking: focusing attention on the chunk, understanding the underlying idea behind that piece of information, and looking at its context. As you memorize and thoroughly practice each chunk, you can meld them into bigger chunks that are connected conceptually.

There are correlations between math and music in terms of common brain areas.

Boaler also argues for more multisensory approaches to learning, pointing to research published by cognitive neuroscientist Vinod Menon in 2015.[16] Menon and his colleagues at Stanford found that when a child works on a math problem, five different brain areas are active, and two of them are related to visual pathways. If math lessons involved more visualizations and other multisensory components, they would tap into these math-learning networks, she argues.

"When they build or model with maths or move with maths, all of these help develop these different parts of the brain," she said. A 2016 paper that Boaler's group published in the *Journal of Applied and Computational Mathematics* makes the point that even higher mathematics is highly visual.[17]

In Ireland, Flávia Santos' group has been exploring how the interconnectedness of math and music might be used to help kids with dyscalculia. Neuroscience research supports the idea that there are correlations between math and music in terms of common brain areas activated during relevant activities.

Both math and music are inherently systems with symbols, Santos points out. It's impossible to prove that proficiency in one causes excellence in the other, but fractions, ratios, and pattern-recognition are important to both. So, Santos figured, musical training may have benefits for math learning, too.[18] Studies show that it enhances spatial-temporal reasoning, which supports learning mathematical concepts. So far, the results are promising, although only small groups have been observed. For example, in a 2020 study in the journal *Frontiers in Psychology*, her group reports that a training involving singing, percussion, and corporal movement had positive associations with scores on math comprehension tests in a small sample of kids in Brazil.[19]

Ultimately, individual kids have specific needs, and parents can work with teachers on figuring out tailored approaches. But, generally parents can create a positive attitude toward math by refraining from sharing their own math anxieties and encouraging creative problem solving. "Never share with your child, 'I was bad at math,' 'I hate math,' any of those statements we know can negatively affect students," Boaler says. "But also just try and engage in math, to help them see it as an interesting puzzle."

Ono's father Takashi, a professor of mathematics at Johns Hopkins University, urged him to pursue math from a young age. "For the longest time, math meant calculations, or memorization," Ono says. But he developed a true passion for it in 10th grade when a "magical letter" arrived from India to the family's Lutherville, Maryland, home. Typed on rice paper, the letter came from the widow of mathematician Srinivasa Ramanujan, who had died at age 32. She thanked Ono's father for helping to fund the creation of a bust of Ramanujan in his memory. Takashi, teary-eyed, told his son about the obstacles Ramanujan overcame—racial prejudice, poverty, dropping out of college twice—to become one of the most influential mathematicians of the 20th century.

Ono saw parallels between Ramanujan's story and his own father's journey to mathematics. And Ramanujan, who came up with that continued fraction formula for pi that Ono showed me, stuck with him. Ono went on to pursue an academic career and has become famous in the math world for solving mysteries and questions that arose from Ramanujan's work.

"For me, Ramanujan symbolizes true creativity, flights of imagination that you might think would be like poetry coming out of the mind of a great poet," Ono told me. "You don't know where it comes from. And then you have to ponder them deeply and appreciate the words or the formulas that are on a page. That, I like."

ELIZABETH LANDAU is a freelance science writer based in Washington, D.C. Her work has also appeared in *The New York Times*, *Washington Post*, *Undark*, and others. Follow her on Twitter at @lizlandau and read more of her writing at lizlandau.com.

REFERENCES

1. Furness, E.L. Are we victims of linguaphobia? *The Modern Language Journal* **42**, 20-22 (1958).

2. Ashcraft, M.H. & Moore, A.M. Mathematics anxiety and the affective drop in performance. *Journal of Pscyhoeducational Assessment* **27**, 197-205 (2009).

3. Richardson, F.C. & Suinn, R.M. The mathematics anxiety rating scale: Psychometric data. *Journal of Counseling Psychology* **19**, 5510554 (1972).

4. Foley, A.E., *et al.* The math anxiety-performance link: A global phenomenon. *Current Directions in Psychological Science* **26**, 52-58 (2017).

5. Reas, E. Our brains have a map for numbers. *Scientific American* (2014).

6. Xu, F., Spelke, E.S., & Goddard, S. Number sense in human infants. *Developmental Science* **8**, 88-101 (2005).

7. Starr, A., Libertus, M.E., & Brannon, E.M. Number sense in infancy predicts mathematical abilities in childhood. *Proceedings of the National Academy of Sciences* **110**, 18116-18120 (2013).

8. Park, J. & Brannon, E.M. Training the approximate number system improves math proficiency. *Psychological Science* **24**, 2013-2019 (2013).

9. Morell, V. No joke: Pigeons ace a simple math test. Science.org (2011).

10. Jaakkola, K., Fellner, W., Erb, L., Rodriguez, M., & Guarino, E. Understanding of the concept of numerically "less" by bottlenose dolphins (*Tursiops truncatus*). *Journal of Comparative Psychology* **119**, 296-303 (2005).

11. Howard, S.R., Avargués-Weber, A., Garcia, J.E., Greentree, A.D., & Dyer, A.G. Numerical ordering of zero in honey bees. *Science* **360**, 1124-1126 (2018).

12. Pica, P., Lemur, C., Izard, V., & Dehaene, S. Exact and approximate arithmetic in an Amazonian indigene group. *Science* **306**, 499-503 (2004).

13. Nys, J., *et al.* Does math education modify the approximate number system? A comparison of schooled and unschooled adults. *Trends in Neuroscience and Education* **2**, 13-22 (2013).

14. Allensworth, E., Cashdollar, S., & Gwynne, J. Improvements in math instruction and student achievement through professional learning around the common core state standards in Chicago. *AERA Open* (2021). Retrieved from DOI:10.1177/2332858420986872

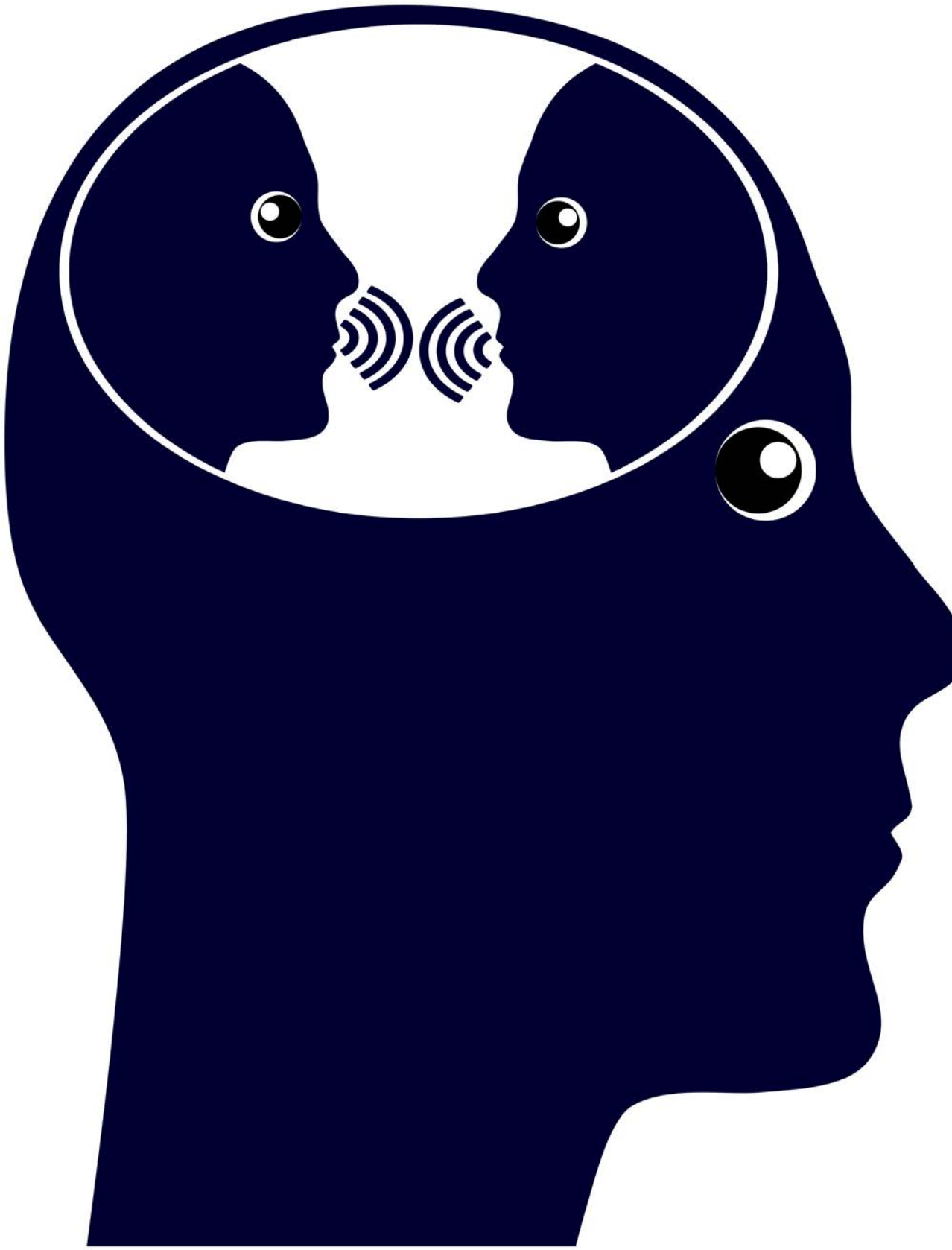
15. Boaler, J. & Zoido, P. Math education in the US doesn't add up. *Scientific American Mind* (2016).

16. Menon, V. Salience network. In Toga, A.W. (Ed.) *Brain Mapping: An Encyclopedic Reference, Volume 2* Academic Press, Cambridge, MA (2015).

17. Boaler, J., Chen, L., Williams, C., & Cordero, M. Seeing as understanding: The importance of visual mathematics for our brain and learning. *Journal of Applied & Computational Mathematics* **5** (2016).

18. Ribeiro, S. & Santos, F.H. Enhancement of numeric cognition in children with low achievement in mathematic after a non-instrumental musical training. *Research in Developmental Disabilities* **62**, 26-39 (2017).

19. Ribeiro, S. & Santos, F.H. Persistent effects of musical training on mathematical skills of children with developmental disabilities. *Frontiers in Psychology* **10** (2020).



I Didn't Know My Mind Was So Strange Until I Started Listening to It

I took part in an experiment to decipher my inner thoughts

BY PHIL JAEKL

ONE FINE SPRING AFTERNOON this year, as I was out running errands in the small Norwegian town where I live, a loud beep startled me into awareness. What had just been on my mind? After a moment's pause, I realized something strange. I'd been thinking two things at the same time—rehearsing the combination of a new bike lock and contemplating whether I should wear the clunky white beeper that had just sounded out into a bank.

How, I wondered, could I have been saying two things simultaneously in my mind? Was I deceiving myself? Was this, mentally, normal? I silenced the beeper on my belt and pulled out my phone to make a voice memo of the bizarre experience before I walked into the bank; aesthetics be damned.

I was in the midst of an experiment that involved keeping a log of my inner thoughts for Russ Hurlburt, a senior psychologist at the University of Las Vegas. For decades, Hurlburt has been motivated by one question: How, exactly, do we experience our own mental life?

SANGOIRI / SHUTTERSTOCK

It's a simple enough question. And, one might argue, an existentially important one. But it's a surprisingly vexing query to try to answer. Once we turn our gaze inward, the subjective squishiness of our mental experience seems to defy objective scrutiny.

For centuries, philosophers and psychologists have presumed our mental life is composed primarily of a single-stream inner monologue. I know that's what I had assumed, and my training in cognitive neuroscience had never led me to suppose otherwise.

Hurlburt, however, finds this armchair conclusion "dramatically wrong."[1] Sure, it's relatively common to experience "brain chatter," those voices in our head that keep us up at night or haunt us with things we should have said. But Hurlburt's research suggests that inner speech is not nearly as consistent, frequent, or even as universal as many of us might assume.[2] He takes a much broader perspective on our inner lives, one that goes way beyond the contents of *what* we say to ourselves to include experiences that are hard to put words to at all.

Emerging from engineering school in the 1970s, Hurlburt decided to forgo a career in his field and instead take up psychology to pursue his growing obsession with how we experience the mind. The best way to try to capture the intangible aspects of inner life, Hurlburt reasoned, was to sample people's thoughts at random times throughout the day—"in the wild" as he calls it. To that end he created oversized beepers that prompt wearers to make a note of what they were experiencing at the moment right before a beep. Soon after, they share their experiences—with him or with trained members of his team—in more detail through careful interviews.

I had written about Hurlburt and his long-running experiment before, and I was intrigued. So I decided to try the experience out myself. When my beeper arrived, I put appearances aside, donned the unwieldy contraption—complete with its dangling, wired-earpiece—and embarked on my own journey into my inner experience.

Over the course of a few months, I made notes on 54 random moments, and I spoke with Hurlburt about each one in detail during nine separate interviews, all lasting at least an hour.

Hurlburt calls his full approach Descriptive Experience Sampling.[3] The process purports to reveal, in detail, the contents, forms, and nuances of our "pristine" inner experience. It requires considerable skill because there's no ready vocabulary for the contents of inner life. Obtaining accurate descriptions requires being very delicate and careful not to unintentionally lead or persuade participants into a particular belief or assumption. Inner experiences can be dreamlike and elusive. They can include inner speaking, inner hearing, sensory stimulations, feelings, or even just a wordless sense of knowing or thinking something.[4] Inside our heads, it seems, almost anything is possible.

My career in cognitive neuroscience didn't prepare me for this.

According to decades of Hurlburt's data from hundreds of participants, much of what we presumed about mental life appears incomplete—or just plain wrong.

Take fully formed inner speech, for example, which I had assumed made up much of my own inner life. As Hurlburt explained to me, "People come in thinking to themselves that they are talking to themselves all of the time." On beeps where they reported inner speech he says, "I would ask them what exactly they are saying to themselves—a pretty reasonable, straightforward question. When they [consistently] can't answer that question, they come to the conclusion, 'Well, I wasn't really talking to myself. I don't really talk to myself.'" The DES data indicate that on average, inner speaking takes up only about a quarter of mental life.[1]

When I first started wearing the beeper, I was surprised that I often found it difficult to have any idea what my experiences were, even though they had just occurred. The beeper would go off at relatively mundane moments when there were no significant distractions: walking my dog, sitting at my desk, or eating lunch. Despite having the utmost enthusiasm for immediately describing the content of my inner life, only a moment ago, I found myself drawing complete blanks. Was my mind empty?

There's no agreement on what "thinking" actually is.

Perhaps it was. After slight embarrassment in revealing such inner vacancy, Hurlburt explained that although most participants are able to describe their experiences more easily, "There is no reason why there has to be inner experience at all." At any wakeful moment, our brains are processing many things in parallel while skillfully keeping most of them out of our attentional focus—things like our body position, the temperature, the noise of an air conditioner. There is no reason why any one must be present in our experience.

As I got more practice with the beeper, I became more adept at identifying and describing my inner life. I began to see that my mind was often pursuing multiple avenues simultaneously.

One day a beep went off as I was eating lunch at home. In what seemed like an insignificant, ordinary moment, I realized I was having many different, disconnected inner experiences. I was contemplating what to make for dinner (yes, I like food) and was innerly beginning to say "I think I want ..." hoping that an idea for a dish would suddenly spring into mind. At the same time, I was watching the bright leaves of a currant bush just outside a nearby window as they shook vigorously in the wind against the clear blue sky. What's difficult to describe is that I also felt an awareness of the location of the bush relative to a cardboard box that had blown from my patio into a neighbor's yard. I couldn't see the box, but it drew my attention because I was planning to sneak into their yard to nab it before they noticed it. It's difficult to describe the feeling, but the box felt somehow embodied with the leafy bush, and me. It was like a sense of the relevant, connective geometry.

As I reflected on this moment and the one by the bank where I caught myself with multiple simultaneous streams of inner speech, I realized they felt so strange because they challenge the common assumptions that mental life exists as a singular thread of experience[5] and that multiple thought streams typically arise only during altered states of consciousness. The bank incident was even weirder because it comprised two experiences within inner speech. Unlike, say, an audio-visual experience of hearing and seeing someone speaking, for which our brains integrate multisensory information,[6] the notion of innerly speaking multiple phrases at once is basically unheard of in established science.

After I revealed these odd experiences with slight uneasiness, Hurlburt quelled my apprehension by one-upping me. Without hesitation he averred that these simultaneous occurrences are not infrequent and, in fact, often have an uncanny spatial element to them. He explained that some, perfectly normal people attribute varied locations to inner voices. "People can have two different inner speeches going on at the same time; one 'in the back of their mind' and one in the 'front' of their mind, about two different topics at the same time and somehow keep those things straight," he explained to me. "And inner voices don't have to be in your head. They can be in your chest or outside of your body."

Submitting to this research, I also learned that I frequently experienced a kind of opposite feat of inner

HEARING VOICES Constantly monitoring and making notes about his mental life, writes Phil Jaekl, was like listening to a narration of his thoughts: "I felt like the words were somehow coming to mind, rather than my actively constructing phrases."

speech—the "feeling" or apprehension of having just executed non-vocalized speech, but without words. The first instance occurred while I was sitting on my back deck, watching the shadow of a huge cloud front swiftly covering a nearby mountainside. As I watched a portion of the shadow sweep completely across a snow-covered region it moved onto a large, dark, rocky area, where I could no longer see it. At the moment just prior to the beep I felt a notion of "can't see it anymore" but without actually saying those words in my head. Was it possible to conceptualize specific thoughts without having called upon language at all?

By this point my mind was starting to be more open about the strange world of inner life. Hurlburt maintains that there are many ways to experience even something as seemingly straightforward as inner speech. "It's possible to have a sense of having spoken, a sense of speaking, but without any words: So I feel myself to be speaking and I actually know what I'm speaking. I'm speaking 'I can't see it anymore,' even though I don't experience the words," he explained.

What Hurlburt found unique about my experiences was that I often had difficulty distinguishing my own inner speaking from inner hearing. Although I had true inner hearing experiences such as a song "in my head," which felt similar to actually listening to the song, these other instances were somehow different. I felt like I was hearing a voice that was clearly mine yet it was somehow more passively apprehended. It wasn't like true voice hearing, though, where the heard voice can attribute its own, separate identity and agency.[7] As odd as it sounds, the experiences were remotely comparable to listening to a narration of my thoughts. That is, I felt like the words were somehow coming to mind, rather than my actively constructing phrases, as when explaining something difficult and choosing my words carefully. Like now.

When you think a lot about thinking, it gets complicated. Even the term is more ambiguous than one might think (contemplative pun intended). Hurlburt explained that dictionaries define it as a cognitive thing whereas many philosophers and psychologists equate it with inner speaking. After listening in on the inner experiences of so many people over the years, Hurlburt finds each of these assumptions at once partially correct and partially misguided. "Thinking" is a tricky term, it turns out, and, just like "consciousness," its definition depends on who you ask.

VECTORMINE / SHUTTERSTOCK

I found myself drawing complete blanks. Was my mind empty?

Hurlburt explained further that people often assume that others experience inner life similarly to themselves. But DES reveals that's not the case. How people experience inner life can be as unique as they are. Someone who innerly speaks only seldomly but visualizes often might believe thinking is a visual thing. And so on with other forms of inner experience. So there's no agreement on what "thinking" actually is, according to Hurlburt.

As the days logging and describing my thoughts went on, I had lingering questions about the deeply subjective aspects of this approach. So I called Alain Morin, a psychologist at Mount Royal University in Calgary, who also researches inner life. He and many other psychologists have long relied on questionnaires to understand phenomena like inner speech. Recent analysis has found these types of retrospective assessments to be relatively reliable for capturing patterns of self-talk, although not immune to the influence of bias and presupposition.[8] They also leave out a vast swath of the inner experience that is difficult to put words to, such as the emotional tone of one's inner voice or other vague sensations, like my moment gazing at the currant bush. Which is where, Morin contends, DES has much greater power of depth. "It's probably the best method we have, short of wearing a brain recording device," Morin told me. "But that's science fiction, obviously, for now."

Yet without such advanced technology, Hurlburt's humble beeper prompted me to learn things about my own mind that even 45 years of existence and a career in cognitive neuroscience had kept hidden from my perception. Multiple speech streams, wordless speech, a strange geometric sense … I would never have known about these capabilities of the mind because my common assumptions about what consciousness is and how we experience it precluded these possibilities. It was at once dispiriting and wondrous to realize just how unaware we are of what our minds are doing almost all of the time. I now can start to imagine the vast oceans of potential experiences within our inner worlds—and the utter uniqueness of those to individual minds. And I owe it all to the awkward white beeper, which I am supposed to ship back to Las Vegas next week, but which I'm tempted to keep.

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REFERENCES

1. Hurlburt, R.T., Heavy, C.L., & Kelsey, J.M. Toward a phenomenology of inner speaking. *Consciousness and Cognition* **22**, 1477-1494 (2013).

2. Krumm, A.E. & Hurlburt, R.T. A complete, unabridged, "preregistered" descriptive experience sampling investigation: The case of Lena. *Phenomenology and the Cognitive Sciences* (2021).

3. Hurlburt, R.T. & Heavy, C.L. *Exploring Inner Experience* John Benjamins Publishing Company, Amsterdam, Netherlands (2006).

4. Hurlburt, R.T. & Akher, S.A. Unsymbolized thinking. *Consciousness and Cognition* **17**, 1364-1374 (2008).

5. Fernyhough, C., Alderson-Day, B., Hurlburt, R.T., & Kühn, S. Investigation multiple streams of consciousness: Using descriptive experience sampling to explore internally and externally directed streams of thought. *Frontiers in Human Neuroscience* (2018).

6. Jaekl, P., Pesquita, A., Alsius, S., Munhall, K., & Soto-Franco, S. The contribution of dynamic visual cues to audiovisual speech perception. *Neuropsychologia* **75**, 402-410 (2015).

7. Larøi, F., *et al.* The characteristic features of auditory verbal hallucinations in clinical and nonclinical groups: State-of-the-art overview and future directions. *Schizophrenia Bulletin* **38**, 724-733 (2012).

8. Racy, F., Morin, A., & Hagerty, J. Concurrent validity and reliability of representative inner speech questionnaires. *Psychological Reports* **0**, 1-8 (2022).

The Wizards of Mind Control

How parasites manipulate the behavior of their hosts

BY LAITH AL-SHAWAF

WHAT IF SOME OUTSIDE FORCE could control your mind and make you act against your own interests? It's a terrifying prospect—one that captures our imagination and recurs frequently in our fiction. It's the goal of one of the three Unforgivable Curses in *Harry Potter*. It's the purpose of Newspeak, the fictional language in George Orwell's *1984*. It enthralls in classics such as *Brave New World* and *The Manchurian Candidate*. In the 1950s, the CIA was so concerned that the communists had developed mind-control techniques that they launched their own secret program called MK-ULTRA, whose purpose was to use hallucinogenic drugs and biological manipulation to achieve mind control in ways that could be used against the United States' enemies. It didn't work—but mind control is real, and it can be observed in nature. Parasites do it all the time.

Parasites are organisms that live in or on other creatures, feeding on their hosts and taking their resources. They infect animals and pull their behavioral strings, manipulating them like marionettes. Such parasites are "essentially neuroengineers," as one recent paper puts it, "capable of controlling the central nervous systems of the hosts they infect."[1] Their tactics are astonishing.

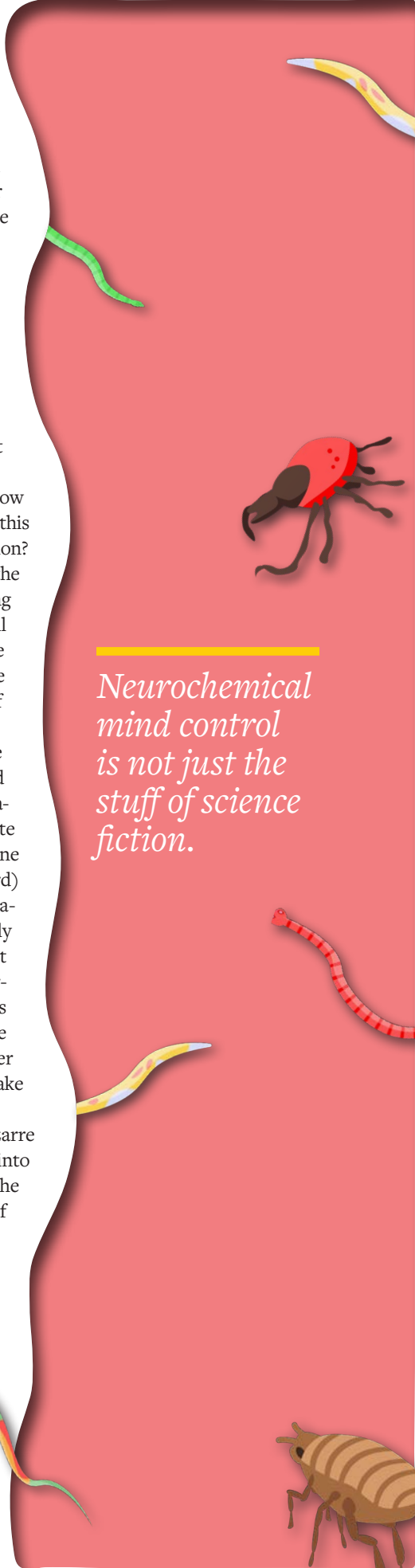
Consider the fluke parasite *Dicrocoelium dendriticum*. It masterminds a cycle that starts in the liver of a hoofed animal—a cow or sheep. First, it lays eggs that end up in the animal's digestive system. When the eggs are pooped out, a snail feeds on them. The parasite's eggs hatch inside the snail's intestines. Once the larvae are able, they drill through the snail's gut into its digestive tract, where they become juveniles. The parasites exit when the snail excretes a ball of slime.

Ants then swallow the slime balls loaded with flukes. The parasite now needs its ant host to be eaten by a hoofed animal to restart the cycle—but this is a problem because hoofed animals eat grass, not ants. The parasite's solution? Make the ant climb to the tip of a blade of grass and immobilize it there—in the exact location where it has the highest likelihood of being eaten by a grazing cow or sheep. But being in full view of the midday sun might scorch and kill the ant before it has a chance to get eaten. To solve this problem, the parasite makes the ant retreat down the blade of grass when it gets too hot. When the weather cools, *D. dendriticum* drives the ant back to the top after the risk of death by scorching has passed.

Not all parasites are microbial. Take brood parasites—birds that leave their eggs in other birds' nests so that these abandoned eggs can be raised by unwitting foster parents. Some brood parasites use mafia-like manipulation strategies: If the host parents reject the foreign egg, the brood parasite will come back and punish the hosts by destroying their entire nest. In one study, researchers experimentally manipulated whether parasite (cowbird) eggs were rejected from host (warbler) nests, and found that cowbird parasites came back and destroyed 56 percent of rejector nests compared to only 6 percent of acceptor nests.[2] The point of this parasite strategy is that it incentivizes compliance in the host parents: If the host tolerates one foreign egg, it will be allowed to raise several of its own offspring. If it rejects the foreign egg, it will lose all of its own offspring. The host is therefore pressured into tolerating parasite eggs. Researchers don't yet know whether regular, non-brood parasites ever use similar "mafia-like" strategies to make their hosts fall in line.

The parasitic flatworm *Euhaplorchis californiensis* takes a more bizarre approach. Its mission: Infect a fish, hijack the fish's mind, and coerce it into getting eaten by a bird, where the flatworm can complete its life cycle. The flatworm manipulates the fish into spending more time at the surface of the water—the perfect location for a fish who wants to become bird dinner.[3] The parasite also has a second trick up its sleeve: It makes the fish repeatedly roll to the side and display its belly, which gives off a conspicuous silvery glint that catches the attention of predatory birds overhead.

Neurochemical mind control is not just the stuff of science fiction.



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ZOMBIE ANT
The fungus growing out of this dead ant's head had taken over the insect's mind, directing it to settle down on a plant positioned over an ant trail, so that its spores might infect more victims.

DAVID HUGHES

How does *E. californiensis* do it? It sets up shop in the fish's brain and alters its neurochemistry.[4] Although the exact mechanisms remain to be discovered, evidence shows that the parasite modulates the fish's levels of dopamine and serotonin—related to arousal and locomotion—inhibiting its natural response to stress. In essence, the parasite encourages the fish to remain mobile and conspicuous, which makes it more likely to get eaten by its predators. Neurochemical mind control is not just the stuff of science fiction. It's a successful strategy that some parasites have turned into a finely tuned art.

Like *E. californiensis*, the flatworm *Leucochloridium* also manipulates its host into getting devoured by predators. This wily flatworm infects snails with artistic flair. To make its host look more like a tasty caterpillar—extra juicy and attractive to birds—the parasite turns the snail's eye stalks into a throbbing, pulsating dance of color.

PARASITES HAVE MORE THAN ONE method of getting their way. Sometimes they manipulate their host into seeking the environment that they need to breed or to release their eggs. When a hairworm parasite infects a cricket, it spurs the cricket to do something shocking: commit suicide by jumping into water. This kills the cricket but benefits the worm: The parasite can now emerge from its cricket host and begin the next stage of its life cycle, which involves finding a mate and releasing its parasite eggs into the water. If you think this sounds too bizarre to be real, trust me, I'm sympathetic. But the evidence shows that this strategy—driving one's host to a watery suicide—is so effective that it has evolved more than once among different lineages of parasites.

Parasitic fungi have a similar trick. Their manipulation doesn't involve water, but it is equally dramatic. The fungus forces its infected ant host to climb to an elevated branch on a tree so that the ant can die where conditions are better for the parasite. From the parasite's perspective, an elevated branch is the perfect vantage point from which to rain down fungal spores onto new hosts.

To appreciate how sophisticated this tactic is, it helps to know that ants are masters at stopping the spread of infectious disease. They quarantine diseased members of their group, and when a nestmate dies, they quickly remove the cadaver from the nest. By forcing infected ants to leave the nest and die elsewhere, the fungus manages to circumvent the ants' quarantining practices. Because the infected ant dies outside home base, it becomes impossible for its nestmates to safely dispose of its corpse. Amazingly, this tactic—manipulating hosts into deserting their colony so they can die in a location that better suits the parasites' needs—is so successful that it has evolved at least four times independently among living organisms.

"There is something both unnerving and entrancing in the spectacle of an animal moving against its instinct to the drumbeat of a parasite inside its body," write neuroethologist Frederic Libersat and his co-author David Hughes in a 2019 paper in *Current Biology*.[1] "For biologists, the fact that such machinations have evolved repeatedly in the natural world offers us great opportunities to understand the why and how of manipulation and include such impressive adaptations into our framework for understanding evolution by natural selection." Natural selection: the most marvelous of algorithms.

Another way for parasites to get from host to host is to infect an organism and use it as a vehicle or vector to help the parasite spread. The malaria-causing parasite *Plasmodium* has mastered this tactic. When it settles in mosquitoes, it interferes with their ability to drink properly. The point of this is that if the mosquito remains thirsty, it will need to draw blood from a greater number of hosts, which enables the parasite to get into more hosts.[5]

As for us, the parasite impairs our blood's ability to clot, which helps it pass from our bloodstream into mosquitoes. Some studies suggest that the malaria parasite may even make infected people *smell more attractive* to mosquitoes. If true, it wouldn't be the only species to do something like this: The parasite that causes Leishmaniasis, a tropical disease that can cause skin sores, alters the odor of its hosts, and the virus that causes Dengue fever manipulates genes in the mosquito's antenna that affect its olfactory receptors, improving the mosquito's sense of smell.[6] Parasites may be small and invisible to the naked eye, but they are powerful manipulators.

Another parasitic route is a favorite among wasps: Spend some time maturing inside your host, emerge when you're ready, lay your eggs nearby, then manipulate the host into taking care of you and your offspring.[7] Parasitoid wasps use this classic strategy, or a variant of it, with their spider and caterpillar hosts. In some cases, the wasp makes its host act like a bodyguard. A 2008 study finds that after the wasp larvae leave the host

Parasites outperform our most cutting-edge neuroscience when it comes to behavioral manipulation.

THE SLY DR. WASP The jewel wasp *Ampulex compressa* can perform neurosurgery on a cockroach to make it docile, which allows the wasp to walk the roach back to its den, to use as food for its hatchlings.

SCADIDI / SHUTTERSTOCK

to pupate, "the host stops feeding, remains close to the pupae, knocks off predators with violent head-swings, and dies before reaching adulthood."[8]

In other cases, the wasp turns its host into a zombie construction worker. The hijacked spider or caterpillar works hard to weave a web or a cocoon that protects the wasp and its offspring rather than the host—only to be killed as soon as it's done weaving! In a 2000 study published in *Nature*, behavioral ecologist William Eberhard shows "the mechanism employed by the larva to manipulate the spider's behavior is fast-acting, apparently chemical, and has long-term effects."[9]

An important caveat: When infected hosts engage in weird behavior, it isn't always due to parasitic manipulation. Consider a host that gets infected and then moves to a new microhabitat. This *could* be manipulation: The parasite might need the new habitat to enter its next life stage, as with the hairworm that emerges from the cricket in water. However, infected hosts often seek hotter microhabitats in order to kill the parasites infecting them.[10] To kill foreign invaders, warm-blooded animals will often run a fever, whereas cold-blooded animals use external heat sources to raise their body temperature—by seeking a hot rock in the sun, for example. Both strategies successfully kill parasites.[11]

The upshot is that when infected hosts behave strangely, we can't automatically infer parasitic manipulation. Weird post-infection behavior could be one of three things: parasitic manipulation, a simple byproduct of illness, or an adaptive host response to infection, as in the fever example above.[7] Because all three possibilities are real, biologists try to be as careful as possible when disentangling the alternative interpretations.

It's pretty clear, though, that the jewel wasp *Ampulex compressa* is achieving mind control with the little act of neurosurgery it perpetrates on its cockroach victim. The wasp locates a specific region of its cockroach host's brain and injects it with a neurochemical cocktail that seems crafted for a specific purpose. The wasp's precise injection doesn't paralyze the roach,

but it does *rob it of its will to escape*—a distinction crucial to the parasite's success.[12] If the roach were paralyzed, it would be too big for the wasp to drag. Because the roach is not paralyzed, the tiny wasp is able to drag it, and the victim moves along helpfully like a trained animal on a leash. In this way, the wasp takes the zombie roach to its den, lays an egg on its victim, and buries it alive. Throughout this entire macabre process, the roach shows no interest in escaping. By using neurosurgery to rob the roach of its will to escape—but refraining from physically paralyzing it—the wasp has crafted the exact solution it needs.

The solution is so precise it's shocking. But maybe it shouldn't surprise us that parasites outperform our most cutting-edge neuroscience when it comes to behavioral manipulation. After all, evolution has given them a millions-of-years-long head start.

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REFERENCES

1. Hughes, D.P. & Libersat, F. Parasite manipulation of host behavior. *Current Biology* **29**, R45-R47 (2019).

2. Hoover, J.P. & Robinson, S.K. Retaliatory mafia behavior by a parasitic cowbird favors host acceptance of parasitic eggs. *Proceedings of the National Academy of Sciences* **104**, 4479-4483 (2007).

3. Lafferty, K.D. & Morris, K.A. Altered behavior of parasitized killifish increases susceptibility to predation by bird final hosts. *Ecology* **77**, 1390-1397 (1996).

4. Shaw, J.C., *et al.* Parasitic manipulation of brain monoamines in California killifish (*Fundulus parvipinnis*) by the trematode *Euhaplorchis californiensis*. *Proceedings of the Royal Society B* **276**, 1137-1146 (2009).

5. Lefèvre, T., *et al.* Chapter 3 Invasion of the Body Snatchers: The diversity and evolution of manipulative strategies in host-parasite interactions. *Advances in Parasitology* **68**, 45-83 (2009).

6. Staniek, M.E. & Hamilton, J.G.C. Odour of domestic dogs infected with *Leishmania infantum* is attractive to female but not male sand flies: Evidence for parasite manipulation. *PLoS Pathogens* **17**, e1009354 (2021).

7. Poulin, R. Chapter 5 – Parasite manipulation of host behavior: An update and frequently asked questions. *Advances in the Study of Behavior* **41**, 151-186 (2010).

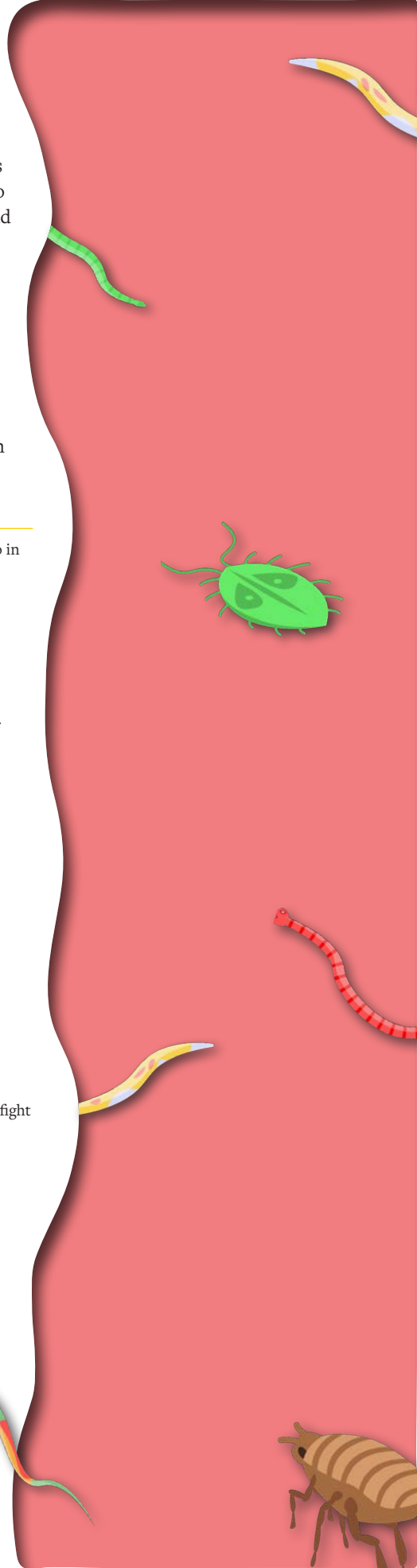
8. Grosman, A.H., *et al.* Parasitoid increases survival of its pupae by inducing hosts to fight predators. *PLoS One* **3**, e2276 (2008).

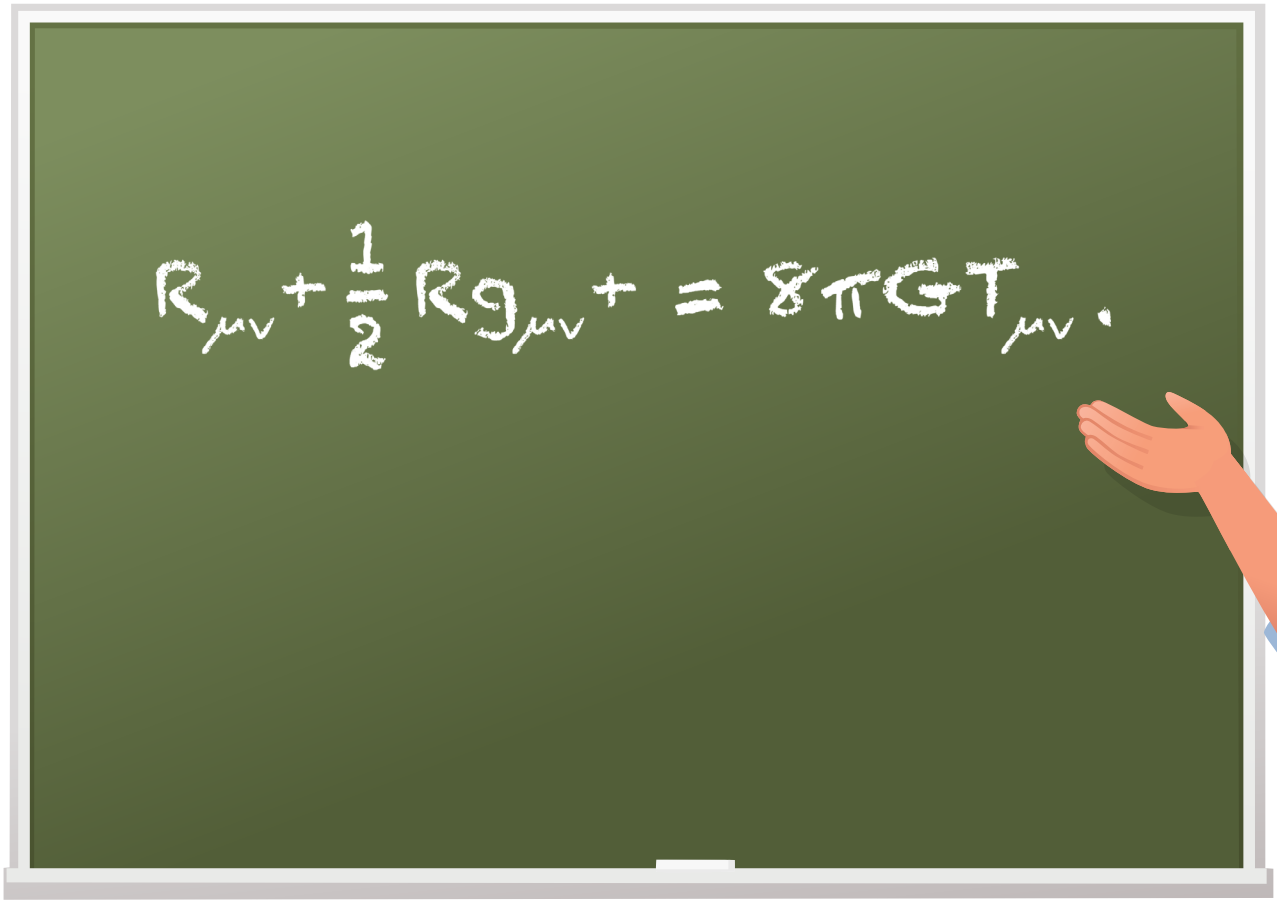
9. Eberhard, W.G. Spider manipulation by a wasp larva. *Nature* **406**, 255-256 (2000).

10. Moore, J. The behavior of parasitized animals. *BioScience* **45**, 89-96 (1995).

11. Neese, R.M. & Williams, G.C. *Why We Get Sick: The New Science of Darwinian Medicine* Vintage Books, New York, NY (1996).

12. Al-Shawaf, L. The why is not the same as the how: Levels of analysis and scientific progress in psychology. *Areo* (2020).





Are We Getting the Real Stuff in Popular Science?

When it comes to physics, says Sean Carroll, you need the math

BY KEVIN BERGER

TYNYUK / SHUTTERSTOCK

SEAN CARROLL IS ONE of the best writing scientists in the business. He's the paragon of a writer who understands his subject completely and can explain it with clarity and ingratiating authority. The physicist transforms concepts in his field into prose that makes lay readers like me think we can understand the emergence of spacetime and quantum mechanics and explain them to friends at dinner parties. Which I have done, thanks in part to two of Carroll's books, *The Big Picture* and *Something Deeply Hidden*.

Carroll has a felicitous phrase for his approach to describing "the world at its deepest level," and that's "poetic naturalism." He adopted the phrase from poet Muriel Rukeyser, who wrote, "The universe is made of stories, not of atoms." Throughout his career, for years as a research professor at Caltech, and now a professor of natural philosophy at Johns Hopkins University, Carroll, 55, has told stories about the ways of the natural world—poetic in how they ring true.

Which is why Carroll's latest book, The Biggest Ideas in the Universe: Space, Time, and Motion—the first in a trio of books that verse readers in the laws of the universe—is a jolt. It exposes an anxiety lurking beneath the surface of popular science, which is we're never getting the full picture. And why not? Because we're missing math. In The Biggest Ideas in the Universe, Carroll sets out to rectify our wayward knowledge. You can read all the words you like about Einstein's theory of general relativity, how mass and energy cause spacetime to curve, Carroll writes, "but until you understand this equation you won't really understand Einstein's theory":

$$R_{\mu\nu} + \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} .$$

Carroll fleshes out the relatively short book with patient and cogent explanations of the equation's symbols and the concepts behind them. Comprehension is challenging, for sure, for readers like me without a math background. But Carroll, as he explains with poise in our recent interview, is undaunted. He's certain good readers will emerge, if not the next Fields Medal winners, new converts to calculus. What jolted me most about the new book, though, was its implication, seemingly in contrast to Carroll's poetic naturalism, that readers will never grasp the world at its deepest level from prose alone. Carroll was revealing a crack in the popular science mission, and I was excited to ask him about it.

Let's start with the first sentence of *The Biggest Ideas in the Universe*: "My dream is to live in a world where most people have informed and passionate views about modern physics." That's a very admirable dream, Sean.
Well, I'm someone who is a professional physicist, but I also have broader intellectual interests. I'm a little jealous of people in other fields whose work can be discussed knowledgeably by people outside their own disciplines, whether it's economics, biology, or history. But there's a barrier in physics and math. The way we speak about what we do to nonexperts is limited in a way the other fields aren't. My strategy is to bite the bullet and teach people the equations.

You write, "You can read books, go to lectures, watch videos, listen to podcasts. The good news is that we do have a vibrant ecosystem of such resources, and it's possible to learn quite a bit, albeit in a somewhat haphazard way. But at the end, you know you're not getting the real stuff." What is the real stuff?
The real stuff is precise, it's rigorous, it's clear, it's unambiguous. What that means in practice is it takes the form of equations. It also means it's not allegorical or analogical. It just says what it says.

The real stuff is precise, it's rigorous, it's clear, it's unambiguous. It takes the form of equations.

My previous book, *Something Deeply Hidden*, was about quantum mechanics and the many worlds interpretation of quantum mechanics. Whenever you measure a little quantum system, different outcomes become real in different worlds. There are various objections to this view, and various arguments for it. Some of the objections are perfectly good objections. I get it. I don't think they're definitive, but I understand why you're making that objection.

With other objections, I was like, "No, you don't get it." One objection was, "Where does the energy come from? Where does the energy come from when you make all these universes?" This is not a question that anyone who understands the equations would ask. If you don't understand the equations, and you're just talking about images, and intuitions, and metaphors, that question doesn't go away.

There are other examples like Noether's Theorem, the idea that if there's a symmetry of nature, there's a conserved quantity. How do you get those kinds of answers? There are a set of things which are crystal clear when you know the math, and utterly obscure when you don't. I feel guilty if I'm forced to say, "Shut up and listen to the equations." I never want to do that. I want to provide an explanation.

I understand concepts from physics pretty well when I read good science writers like you. But what am I missing if I don't get the math?

You're missing various implications and connotations of the words. I've written books without equations. I'm all in favor of it. But whenever you use an analogy, there's a problem because unwanted implications go along with the analogy. Someone says the expanding universe is like a balloon with galaxies being little dots drawn on the surface of the balloon. You might ask, "What is it expanding into?" The answer is it's not expanding into anything. You might respond, "But the balloon must be expanding into something." No, the balloon is just an analogy. "OK, the dots expand. Does that mean galaxies expand?" No, the galaxies don't expand. So that's what I mean: The analogy doesn't give you the real stuff about the expansion of the universe.

Are analogies for math always going to fail?

If we try to make perfect analogies, yes. There's no reason why something like the expansion of the universe or the collapse of the wave function should have an analogy with anything in our everyday experience. It's a different realm. It's a realm that we didn't know about thousands of years ago when language was invented.

There are times when I talk about the geometry of space, and I say, "Look, here is the formula. It works in any number of dimensions. It doesn't matter whether space is three-dimensional, four-dimensional, five-dimensional. If you get the equation, the concept is clear." If you don't get the equation, how do you visualize 10-dimensional spacetime? The answer is you don't. You need the equation that tells you how spacetime behaves.

I admit that without a background in math, I struggled with the equations in *The Biggest Ideas in the Universe*, despite your fluid explanations of the symbols and what they mean. I did, though, gain a good sense of how universal principles are established in physics. The universe has foundational behaviors, regardless of the situation—the math says so.

I'm glad to hear you say that. And there are many examples. For instance, when the universe expands, light redshifts. Distant galaxies are redshifted. There was an early theory that was a competitor to that idea, the "tired light theory," that idea that light just gets tired. No, it doesn't. How do you know? Here's the equation that says what light does. Light can propagate by itself, according to its equation. That's its natural thing to do.

GOOD SPORT Sean Carroll says his goal to deepen people's knowledge of the natural world by explaining key math equations is analogous to things he's done in his personal life, notably learning more about poker and basketball. "When you're watching people play basketball or poker, you ask, 'Why did they just do that?' Usually there's a good reason. And knowing that reason provides new insights."

In science, we propose hypotheses, and we build theories in an attempt to fit the data. The data comes in and we try to make a model from it. And when we succeed like Einstein did, the equations are much smarter than us. The equations that work can be extrapolated way beyond what we expected.

Einstein himself didn't know about the Big Bang, but his equation did. And that's just endlessly amazing. That's why physics—even though I try to be ecumenical—is the most amazing science: These little ideas we come up with in our offices correctly describe things happening billions of years ago and billions of light-years away. And that's only possible because of the equations.

So do we need to understand the language of math before we can touch the foundational truths about the universe?

Yes, I think that's true. But I would emphasize that it's a continuum, not a yes or no. When someone says A squared plus B squared equals C squared, Pythagoras' theorem, most people don't struggle with that. They get it. If you see a right triangle, and A, B, and C are drawn on the lines, and C is the hypotenuse, and you know what squared is, and you know what plus is, you're not really going to struggle with that. To go from there to Einstein's equation is a matter of degree, not of kind. And different people will be comfortable going different distances, but to pretend it's an insuperable barrier is a mistake.

I appreciate what you're saying about getting the "real stuff." Knowledge deepens our appreciation. I was once traveling with a wolf biologist in Montana and I always remember something she said to me in the forest, "If you don't understand ecology, nature is just scenery." Are you saying something similar about physics? You can look up at the night sky and be awed. But it's just scenery unless you know what you're seeing. Would you agree?

I would completely agree. I've had similar experiences, but with geologists, not wolf biologists. If you go through the mountains with a geologist, it's an entirely different experience. If you have a meal with a great chef, it's an entirely different experience. There's a depth of understanding if you go to a concert with a composer or a musicologist.

The only reason we're doing it is because humans are curious creatures and want to understand.

I have been to concerts with composers and musicologists and it's an incredible experience to have them describe what we've heard. Though I've also been to concerts with people who don't want the explanation, just the experience.

Right. It's not for everybody. And no one person, no matter how ambitious they are, can be an expert in everything. So hopefully everybody has some pleasures that they just enjoy at a superficial level. I'm like that about classical music. I have no deep understanding of it, but I like it. I have a mildly deeper understanding of jazz, but I couldn't tell you what mode someone was improvising in during their solo. And that's fine.

But with the things that I am an expert on, there's no question that the character of the pleasure is different. That's why I keep hammering on about the equations. In part, my hammering on about the equations is so people don't feel cheated when they get *The Biggest Ideas in the Universe*. I'm not hiding the fact that there's a lot of equations in there. But I try very hard to explain the principles behind them. I'm not just saying, here's what a derivative is. I'm saying, here's how physics works in the Laplacian Paradigm, where you have the positions and velocities of everything, and you can predict the future. Why should you be able to predict the future from the positions and velocities of everything? That's something that can be understood.

I'm not insisting that everyone become an expert in physics. What I'm trying to do is open a door for people who don't want to become professional physicists but want to understand things better. I don't think there should be this hard and fast wall between physicists and non-physicists.

Not all scientists agree, right? Even though I'm in the popular science business, I respect scientists who want to remain in their labs, do their work, and not feel they have to explain it to the lay public. Have you encountered scientists like that?

Sure.

What do you say to them?

I have a very consistent line. I don't think every scientist has a duty to explain themselves to the wider world. I do think every scientific field has a duty to explain itself to the wider world. I don't have an issue with people who don't want to do it themselves, but with people who don't value it when their colleagues do it. They should be extraordinarily grateful if they don't want to talk to the public, but somebody else does. That's taking a huge burden off them.

In fields like mine, where we're thinking about dark matter and the birth of the universe, there's no practical, technological, or economic application. The only

reason we're doing it is because human beings are curious creatures and want to understand. If we do the research and understand something, and don't tell anybody, what's the point? Why should we be supported by society? So I think the endeavor to explain what we're doing to the public is extraordinarily valuable.

Did you have a Road-to-Damascus moment in your career when you realized you wanted to explain physics to people?

Not really. I always wanted to explain it to people. I am a physicist, technically, but also a philosopher. My job now is more about thinking and understanding and sharing and learning than it is about the subject matter of physics. The joy I've always had in physics was not only understanding new things but talking about them and explaining them to other people. And appreciating the good explanations I could get from other people. Do you know the famous dedication page of the general relativity textbook, *Gravitation*, by Misner, Thorne, and Wheeler?

No, I don't.

I just unpacked it here in my new office. It's 1,000 pages. It's known as the phone book. Here's the dedication. "We dedicate this book to our fellow citizens who, for love of truth, take from their own wants, by taxes and gifts, and now and then send forth one of themselves as dedicated servant, to forward the search into the mysteries and marvelous simplicities of this strange and beautiful universe, our home."

So that's the idea. We are supported by society. We're not putting food on the table or anything like that. But a healthy society has enough resources to have some musicians and some artists and some scientists. Some scientists have direct economic, tangible benefits. Some don't. Some of us are closer to musicians and artists. And so we have to give back as a field. It's an absolutely central part of the endeavor.

You're a great public defender of science against pseudoscientists, intelligent designers, religious figures—the whole parade. In my more cynical moments, I wonder, Why bother?

It's true that there are plenty of people whose minds are made up. The closest correlation is, how old are they? You're not going to reach some people of a certain age. But you do reach the young people. They are not hardened yet. I don't see myself as a proselytizer or as a debater. I just want to help people understand and let them make up their own minds. And the good news is once you do that, they often are led in good directions.

The joy I've always had in physics was talking about new things and explaining them to other people.

Are science and religion "non-overlapping magisteria," as Stephen Jay Gould believed?

I am not in any way a believer in the non-overlapping magisteria. I think these magisteria overlap seriously. There are ways of thinking about the world and what it's made of, how it works, what its purpose is, that belong to both science and religion and spirituality. They overlap in certain places. And don't overlap in others. Religion is a more comprehensive set of ideas, dealing with morality and community and behavior, about which science doesn't say anything. But religion also says something about the nature of reality. And science also has something to say about that.

What are specific places where science and religion overlap?

Why does the universe exist? Why is there something rather than nothing? A scientific answer or even a modern philosophical answer, might be, "There need not be any answer to that question." But that's not what the religious arguments are going to tell you. They're going to say, "No, we need an explanation for this." There is a principle of sufficient reason, following Leibniz and so forth. It's just very different.

I tell my colleagues this because it's strange for modern physicists and philosophers to remain silent about religion, especially the physicists and philosophers who

work in fundamental metaphysics, ontology, quantum mechanics, or spacetime. In those fields, as I said, we're not building a better smartphone. We're not curing cancer. What is the overlap we have with people's everyday lives? Well, it's the fundamental nature of reality. And the fact that the world works perfectly fine as a system obeying laws, without any support from anything supernatural. It's much easier to understand natural selection or the origin of the universe at the Big Bang when you understand the science. And that might affect your views on the need for God.

Who was the first good popular science writer in physics?

We are in the special situation that one of the early pioneers was named Galileo. I mean, great popular physics writing was the invention of physics, and Galileo was really good at it. Even Einstein was pretty good at explaining things. And then people like Richard Feynman, George Gamow, and in a different way, Carl Sagan, came along. So we've always had that tradition. We didn't have to invent it, but we do need to be reminded that it's important and it needs to be rediscovered and appreciated.

Where does popular science go wrong?

Like popular anything, or media anything, it can sensationalize. It wants everything to be the latest and the greatest. The world has changed now with the internet. But it used to be that if you wanted to write something that would help explain some concept, you would need a news hook to explain it. Why would anyone care about science unless something had just happened? And I'm like, well, relativity is still true, even if nothing happened recently.

There's an ecosystem where researchers want to get attention. They want to get grant money. They have media relations departments at their universities. They want to over-claim what they do. And the journalist naturally must place some degree of credence in what the experts say. But you have to check against people who are not the ones doing the study, and you have to take their warnings seriously.

I'm a big believer in science writing and science journalism. As I said, I don't think every scientist should be devoting their efforts to popularization. I think that some should, but almost every scientist has some interesting work that they're doing.

So there's plenty to be done by good journalists to think about what's interesting that is going on, and not just what is the work being done by the most charismatic scientist out there. And they have to make it explicable, understandable, and tell some of the human story. I'm a big believer in the human story. That's something that should be emphasized.

But you have to balance it. It defeats the purpose if it's just the human story. There's something extra in science journalism that's not there in celebrity journalism. The other thing that is special about science journalism is the scientist can explain something and it's the job of the journalist or the writer to translate it. That translation, as we were saying, often involves either analogies or extrapolation. And it's possible to go wrong. So, to me, science journalism, more than political journalism or celebrity journalism, needs to be a back and forth.

I remember my very first experience with my own work being written about was when I was a graduate student. I was working on a project of whether you can build a time machine in a simplified three-dimensional spacetime. The journalists talked to us and got it right. At some point in the article, they mentioned a closed universe. And the editor, trying to clear things up, added a line saying, "A closed universe is one that will expand and then collapse." But that's not true in a three-dimensional spacetime. It's true in a four-dimensional spacetime. They didn't check with the scientist before putting it in.

Journalists are professionals at writing and explaining. Scientists are professionals at doing science. So it needs to be teamwork between them in a way that is different from economics or political science reporting.

Although we can't always take you at your word. As you say, we have to check what you tell us against other scientists and perhaps contrary evidence, and use our own judgment about how best to inform readers. That's why you get paid the big bucks.

KEVIN BERGER is the editor of *Nautilus*.

The Real Magic of Rituals

We might call them superstitions or spells, but they genuinely drum anxiety away

BY DIMITRIS XYGALATAS

SIPA USA VIA AP

TENNIS STAR **RAFAEL NADAL** performs an elaborate repertoire of rituals before and during every match. When he arrives at the stadium, he enters the court holding a racket in his hand, taking great care never to step on the lines and always crossing each line right-foot first. He places his bag on the bench and turns his tournament ID face up. His chair must be perfectly perpendicular to the sideline. He checks his socks to make sure they are perfectly even on his calves. During the coin toss he faces the net and starts jumping until the coin falls, then runs to the baseline, where he drags his foot across the entire line in a single sweeping motion before hitting each shoe with his racket.

When the game begins, Nadal starts performing repetitive hand gestures that resemble those of Catholics crossing themselves. With his right hand he touches the back and front of his shorts, then his left shoulder, then the right, then his nose, left ear, nose again, right ear and finally his right thigh. At each changeover he picks up two towels. He waits for the other player to cross the line, and then he crosses right-foot first to take his seat. He carefully folds one towel and puts it behind him without using it. Then he folds the second towel and places it on his lap. He takes one sip from a bottle of water, then another sip from a second bottle. Very carefully, he returns the two bottles to the exact same position, the labels facing the same way.

Nadal insists he is not superstitious. In his autobiography, he writes, "Some call it superstition, but it's not. If it were superstition, why would I keep doing the same thing over and over whether I win or lose? It's a way of placing myself in a match, ordering my surroundings to match the order I seek in my head." Who could deny that Nadal's rituals don't help him manage his anxiety and find order on the court? He is one of the greatest tennis players of all time.

OVER THE DECADES, anthropological studies, including my own, have shown that ritual practices come naturally to us, regardless of our cultures, and further, we expect them to have an effect. But is ritual really an effective stress-management strategy? Or is it simply an illusion, a waste of time or, worse, a dangerous distraction from our real problems?

Field observations suggest that ritual may indeed help people cope with anxiety. In a study conducted in Israel, researchers interviewed local women during the Lebanon War of 2006. They found that among those women who lived in war zones and experienced the stress of war, reciting psalms was associated with lower overall stress levels.[1] No similar association was found for women living outside the war zones. While participants in this study were the judges of their own anxiety, similar effects were found at the physiological level.

In my lab at the University of Connecticut, my colleagues and I observed a group of students during the midterm exams, one of the most stressful periods of the year. In addition to surveys, we collected hair and saliva samples, which we used to measure levels of cortisol, a hormone associated with stress. Salivary cortisol changes over the course of a few minutes, so it can be used to measure stress around a specific activity. But traces of the hormone also accumulate in our hair, and they can be used to track long-term anxiety. We found that students who participated in more rituals had lower anxiety across all these measures.

But these are correlational findings. They help us point to an association but cannot establish a causal relationship. For that, we need to turn to experimental studies. Fortunately, several experiments have been conducted on this topic in recent years.

In one of these studies, Matthew Anastasi and Andrew Newberg randomly assigned Catholic college students to either reciting the Rosary (a set of repetitive prayers) or watching a religious film, and measured anxiety levels before and after those tasks. They found that those who recited the Rosary experienced a greater decrease in anxiety.[2]

Alison Brooks and her colleagues found similar results when they asked participants to enact an artificial ritual that resembled a magical spell. As it turned out, performing this ritual helped people engaged in various stressful tasks such as taking a math test or participating in public karaoke to cope with anxiety.[3] In another study, Michael Norton and Francesca Gino asked participants to think about a loss they had experienced—someone who had passed away, a broken relationship or even a monetary loss. They found that, when they asked some of them to perform a ritual, they were better able to cope with the anxiety caused by the loss.[4]

Moving from the lab into the real world, my colleagues and I designed a field experiment on the Indian Ocean island of Mauritius.[5] To see whether some of the traditional local rituals helped people reduce anxiety, we measured a property of the autonomic nervous system known as heart-rate variability. A healthy heart does not beat evenly like a metronome. When we have a heart rate of 60 beats per minute, this does not mean that our heart ticks exactly once every second. Rather, it means that all the slightly different periods between each two successive beats average out as one second. This variance in the timing between beats is known as heart-rate variability. When it is high, the nervous system is more balanced, and the body is better able to respond to changing circumstances. But when we are stressed, this balance is disrupted and the heart beats in a more rigid way—it has low variability. As a result, the body maintains a state of high alert, which is experienced as anxiety.

Our study took place in a small fishing village called La Gaulette. As is often the case with such villages, most public life took place near the coast. All restaurants, shops, and other commercial activities were arranged alongside the coastal road, and so were all public services, including a police station and two places

"It's a way of ordering my surroundings to the order I seek in my head."

of worship: a Catholic church near the south entrance, and a Marathi Hindu temple on the north side. Sitting at the cafe each morning, we could see many of the local Hindu women, dressed in colorful saris, walk to the temple to perform religious prayers. Those prayers involved making offerings to the statues of various Hindu deities and executing circular movements with an incense burner or incense stick. These were just the kind of repetitive action patterns that we were interested in and, importantly, ones that were culturally scripted rather than dictated by the experiment.

We recruited 75 of these women and split them into two groups. We asked those in the first group to meet our team at the temple. The second group arrived at a makeshift lab we had set up in a non-religious building of similar size and arrangement to the temple. This would be our control group. Participants wore a small monitor that recorded their heart beats before being invited to engage in a task that was designed to be stressful: We asked them to write an essay describing the kinds of precautions they would take when faced with an impending flood or cyclone. Such natural disasters regularly plague the island, often with catastrophic consequences, and are a constant source of anxiety for the locals. To create additional stress, we also told them that their essay would be evaluated by a group of public safety experts. After the stressor task, those who were in the temple were asked to go to the prayer room and perform their rituals in the same way as they always did. They

FORTUNE TELLER Our brains are prediction machines. They look for patterns and statistical regularities everywhere. But when they can't make sense of something, we experience anxiety. That's where ritual comes in. Its repetitive actions help us cope.

EKOSUWANDONO / SHUTTERSTOCK

Whether the sense of control is illusory is of little importance.

entered the room in privacy, lit the incense, and made their offerings to the deities. Those in the control group went through the exact same procedure but performed no rituals. Instead, they were told to sit and relax.

As we predicted, the ritual had beneficial results. Reflecting on natural disasters caused a rise in anxiety for both groups. But those who performed the ritual were faster to recover from that anxiety. Their heart-rate variability increased by 30 percent, suggesting that they were better able to cope with the stress. This was also consistent with how they felt: Subjective ratings of anxiety were twice as high for those who had not performed the ritual. These are no trivial differences: Clinical studies have documented effects of similar magnitude between healthy individuals and people suffering from major depression.[6] Ritual, it turns out, can be as effective in reducing stress as some of our best anxiety medications.

HOW CAN WE EXPLAIN these findings? Rituals are highly structured. They require rigidity (they must always be performed the "correct" way), repetition (the same actions performed again and again), and redundancy (they can go on for a long time). In other words, they are predictable. This predictability imposes order on the chaos of everyday life, which provides us with a sense of control over uncontrollable situations.

Studies show that, when people experience uncertainty and lack of control, they are more likely to see patterns or regularities where there are none. These patterns can range from visual illusions (such as seeing faces in the clouds) to seeing causality in random events and forming conspiracy theories.[7] Under these circumstances people are also more likely to turn to ritualized behaviors. This is known as the compensatory control model: We compensate for lack of control in one domain by seeking it in another.[8] Whether this sense of control is illusory is of little importance. What matters is that ritual can be an efficient coping mechanism, and this is why those domains of life that involve high stakes and uncertain outcomes are rife with rituals.

In the experiments conducted by Brooks and her colleagues, engaging in rituals helped participants to perform better in mathematics contests and sing more accurately in karaoke competitions. And in Israel the women who recited more psalms felt less need to take other precautions, which might have impeded them from going about their normal life. In contrast, those who did not perform as many rituals seemed overcome by anxiety. This led them to avoid public places, buses, restaurants, and large crowds after rocket attacks. This sounds very sensible until you learn that, even at the height of the conflict, the chances of getting killed in a terrorist attack in Israel were lower than those of dying in a car accident. Living in fear could do more harm than good, and rituals helped those women deal with their fears and live a normal life in the face of the conflict.

Similar effects extend to a variety of other domains. A group of German psychologists found that people who used lucky charms and rituals such as keeping their fingers crossed performed better in an assortment of skill games and puzzles.[9] Other studies have found that ritualization may help athletes perform better. Basketball and golf players are more successful after performing pre-shot rituals.[10] Stopping them from performing these rituals

Our predictive brain does not like unpredictability.

can be detrimental to their performance, leading them to miss more shots.[11] The reason for these remarkable effects appears to be that these rituals allow the athletes to ease their own anxiety, regaining a sense of control.

In recent years, philosophers, psychologists, and neuroscientists have revised their models of the human mind. The classical view was that our cognitive apparatus functions as a data-processing device: It receives input from the environment and reacts by producing the appropriate responses. But evidence has been mounting that our brain is much more sophisticated than that. It is a *predictive* device. Rather than passively absorbing information about the state of the world, it actively works to make inferences (predictions) about what types of stimuli it is most likely to encounter at any given situation. Those predictions are based on information derived from our prior experience and socialization, our surroundings, as well as hardwired knowledge.

Take the blind spot in our vision. The optic nerve, a bundle of nerve fibers that carry information from the eye to the brain, passes through the retina itself. Consequently, the spot where the optic nerve enters the eyeball has no photoreceptor cells to detect light. This is why it is called a blind spot: Whatever part of our visual field falls on to that spot becomes invisible to us. If you had never noticed that you have a blind spot, that is because your brain makes up the missing part of the image by using information from the surrounding environment to fill in the gap.

Our brain makes similar types of inferences in all sorts of other domains. Imagine that you live on the outskirts of San Francisco, and as you wake up you feel your bed shake. Fearing it might be an earthquake, your immediate response might be to try to get out of the building as quickly as possible. But now imagine that you live in New York, which does not experience many earthquakes, and that an elevated train line runs alongside your building. Perhaps

the first time that you wake up to the vibration you rush to the door, only to embarrass yourself as you run down the hallway in your underwear. But once you know what to expect when you feel the shake, it will no longer cause you to panic. As your brain has now updated its prior knowledge, it can predict with greater confidence that the shaking will not cause the roof to fall on your head. The situation is no longer stressful. In fact, over the years, the familiar sensation of the train going by at regular intervals may even start to feel comforting.

Because our brain never stops making these kinds of predictions, we tend to look for patterns and statistical regularities everywhere around us. This is extremely important, because any computational device (and the human brain is no exception) becomes dramatically more efficient when it can build on prior knowledge. This way, we do not have to learn everything from scratch. But one consequence of this cognitive architecture is that when our predictive potential is limited—that is, when there is high uncertainty—we experience anxiety. Our predictive brain does not like unpredictability.

This is where ritual comes in. The repetitive action patterns found in ritual function as cognitive gadgets that help us cope with stress. By embedding these gadgets into our cultures, all human societies—and their individuals—can capitalize on their potential.

Just ask Rafael Nadal.

DIMITRIS XYGALATAS is an anthropologist and cognitive scientist who studies some of the things that make us human. Most of his research has focused on rituals and their ability to soothe, excite, unite, and divide us. To study these effects, he combines ethnographic field work with scientific experiments. He is based at the University of Connecticut, where he directs the Experimental Anthropology Lab.

REFERENCES

1. Sosis, R. & Handwerker, P. Psalms and coping with uncertainty. *American Anthropologist* **113**, 40–55 (2011).

2. Anastasi, M.W. & Newberg, A.B. A preliminary study of the acute effects of religious ritual on anxiety. *Journal of Alternative and Complementary Medicine* **14**, 163–165 (2008).

3. Brooks, A.W., *et al.* Don't stop believing: Rituals improve performance by decreasing anxiety. *Organizational Behavior and Human Decision Processes* **137**, 71–85 (2016).

4. Norton, M.I. & Gino, F. Rituals alleviate grieving for loved ones, lovers, and lotteries. *Journal of Experimental Psychology* **143**, 266–272 (2014).

5. Lang, M., Krátký, J., & Xygalatas, D. The role of ritual behaviour in anxiety reduction: An investigation of Marathi religious practices in Mauritius. *Philosophical Transactions of the Royal Society B* **375**, 20190431 (2020).

6. Udupa, K., *et al.* Alteration of cardiac autonomic functions in patients with major depression: A study using heart rate variability measures. *Journal of Affective Disorders* **100**, 137–141 (2007).

7. Whitson, J.A. & Galinsky, A.D. Lacking control increases illusory pattern perception. *Science* **322**, 115–117 (2008).

8. Hockey, G.R.J. Compensatory control in the regulation of human performance under stress and high workload: A cognitive–energetical framework. *Biological Psychology* **45**, 73–93 (1997).

9. Damisch, L., Stoberock, B., & Mussweiler, T. Keep your fingers crossed! How superstition improves performance. *Psychological Science* **21**, 1014–1020 (2010).

10. Gayton, W.F., Cielinski, K.L., Francis-Keniston, W.J., & Hearns, J.F. Effects of preshot routine on free-throw shooting. *Perceptual and Motor Skills* **68**, 317–318 (1989).

11. Foster, D.J., Weigand, D.A., and Baines, D. The effect of removing superstitious behavior and introducing a pre-performance routine on basketball free-throw performance. *Journal of Applied Sport Psychology* **18**, 167–171 (2006).

The Wisdom of Gay Albatrosses

Same-sex couples are everywhere in the animal kingdom. Only humans make a big deal about it.

BY JUSTIN GREGG

OUTSIDE OF HUMANS, the best (worst?) example of repugnant same-species violence is found in chimpanzees. When compared to other nonhuman great apes, chimpanzees are notoriously bloodthirsty. I mean that literally. Rival chimpanzee groups defending their territories will engage in open battle where they will occasionally beat one another to death. But they also conduct clandestine raids into enemy territory, targeting rival males to kill. In the book *Demonic Males: Apes and the Origins of Human Violence*, primatologist Richard W. Wrangham and science writer Dale Peterson note that these raids are "marked by a gratuitous cruelty—tearing off pieces of skin, for example, twisting limbs until they break, and drinking a victim's blood—reminiscent of acts that among humans are regarded as unspeakable crimes during peacetime and atrocities during war."[1]

The primatologist Sarah Blaffer Hrdy describes the violent nature of chimpanzees in the opening pages of her 2011 book, *Mothers and Others: The Evolutionary Origins of Mutual Understanding*.[2] Humans, she notes, can spend hours crowded together in an airplane without resorting to violence, even when faced with rude passengers and crying babies. "What if I were traveling with a planeload of chimpanzees?" she asks. "Any one of us would be lucky to disembark with all 10 fingers and toes still attached, with the baby still breathing and unmaimed. Bloody earlobes and other appendages would litter the aisles." In other words, chimpanzees are terribly violent and often outright murderous, and they inflict this upon one another.

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But even this behavior pales in comparison to the kind of violence that humans exhibit, and our moral reasoning justifies it. Chimpanzees have never been observed killing every individual (males and females, juveniles and newborns) within a rival group; the unspoken behavioral rule or norm that chimpanzees live by when they battle is to only remove a select few individuals (usually the adult males) so as to make the rival group less of a threat. Perhaps, if they had the humanlike cognitive abilities that allowed them to formalize their norms into morals, these raids would be far more expansive and destructive. But they don't. In contrast, when humans go to battle, they justify the killing of entire cities filled with noncombatants (including children) if it serves the greater (morally defensible) goal of winning the war in order to bring about peace.

This is how we ended up with the infamous quote, "It became necessary to destroy the town to save it," spoken by a United States Army major when justifying the bombing of Bến Tre during the Vietnam War despite there being children in the town.[3] Like so many human moral decisions, the Army's decision to kill civilians emerged from our unique capacity for moral reasoning (i.e., the ability to formalize, analyze, revise, and propagate normative behavior on a large scale), a skill that chimpanzees lack, and the reason that even our most violent animal cousins are still less violent than us. While it's entirely true that the human capacity for cooperation is why, as Hrdy argues in *Mothers and Others*, "face-to-face killings are a much harder sell for humans than for chimpanzees," and why, despite 1.6 billion airline passengers every year, "no dismemberments have been reported yet," it is also this human capacity for cooperation that gives humans (but not chimpanzees) the ability to bomb the children of Bến Tre.[2]

While same-sex attraction is not unique to humans, homophobia is.

But to drive my point home that humans often wind up with unnecessarily violent behavioral norms due to our complex ability for moral reasoning, I don't want to talk about war. I want to talk about homosexuality. In the introduction to the book *The Biology of Homosexuality*, the biologist Jacques Balthazart writes that "homosexuality in humans is to a very large extent, if not exclusively, determined by biological factors acting prenatally or soon after birth." Balthazart arrives at this conclusion through the study of same-sex sexual behavior in animals, where there is a mountain of evidence showing that not only is homosexuality not unique to humans, but it's rather the norm for most animal species. This is old news for scientists studying animal behavior and biology, which is why Balthazart writes, "Scientists reading this book will think, 'We have heard all this before.'... But somehow that information has either not made its way into the world outside the laboratory or has not been presented in a sufficiently definitive matter to affect the general population's view on the matter."

He's right. I'm surprised at the number of people I talk to about animal behavior that are shocked at how common homosexual behavior is in the animal kingdom. I often point gay animal skeptics to *Biological Exuberance* by Bruce Bagemihl—a 1999 book detailing more than 300 different animal species that engage in a diverse array of behaviors that fall under the umbrella of homosexuality. Everything from same-sex sex, affection, pair bonds, and parenting. It might seem odd that homosexuality should be so widespread given that evolution is based on the need for animals to produce offspring. This is often a topic broached by anti-gay groups hoping to (misguidedly) show that same-sex behavior is not "natural." But the literature on animal homosexuality shows that same-sex sexual behavior in a given species does not negatively impact a species' reproductive rates, so it's a non-issue.

Take the example of the Laysan albatross. This species of giant bird forms lifelong pair bonds—where two individuals stay together for life, mating and raising offspring together over the course of many decades. Some of these lifelong pair bonds are between same-sex couples. In one study of Laysan albatrosses living on Oahu, one-third of the lifelong pairs were female same-sex couples.[4] In many of these cases, however, one or both females would mate with a male at some point, resulting in fertilized eggs that the female pairs

PAGES 72-73: PORCO_ROSSO / SHUTTERSTOCK

UNLIKE OTHER ANIMALS
In many modern human cultures, homosexuality is not just socially unacceptable or controversial, but illegal and punishable by death.

raised together. Many of the cases of homosexuality in the animal kingdom work like this, where same-sex behaviors are just part of an individual's typical behavioral repertoire, and reproduction still occurs to ensure species survival. Bonobos are perhaps the best example: Individuals engage in sex between same- and opposite-sex partners on a regular basis, resulting in lots of gayness, but also lots of babies.

Exclusive attraction to members of the same sex is rarer, but not unheard of. In domestic sheep, it's estimated that 10 percent of rams (the males) are only interested in mating with other rams.[5] Researchers studying this phenomenon found that these gay rams had differences in their brains—a thicker cluster of neurons in part of their hypothalamus—when compared to straight sheep. The reason for the differences being the relative amount of estrogen levels that the developing ram was exposed to before birth. In other words, as Balthazart argues in his book, these rams were born gay. All this to say that there's nothing particularly unusual or controversial about (inborn) gayness in the animal kingdom.

Despite the frequency with which it crops up, same-sex attraction does not threaten the survival of the hundreds of species for which homosexuality has been observed. Which is why no animal species seems to have evolved any social norms around punishing individuals for engaging in same-sex acts. In other words, while same-sex attraction is not unique to humans, homophobia is.

VLADIMIR MULDER / SHUTTERSTOCK

Why then, are humans uniquely homophobic?

Of course, there are many past and present cultures where homosexuality is normalized, accepted, and even embraced. Throughout most of Japanese history, for example, same-sex relationships have not been stigmatized, and stories of male-male love and sex have long been associated with the samurai warrior class.[6] But in many modern cultures—and especially Western European, Middle Eastern, and African cultures with Judeo-Christian roots—homosexuality is not just socially unacceptable or controversial, but illegal and punishable by death. Iran's Islamic Penal Code—enacted after the Islamic revolution of 1979—declares gay sex between men a capital offense, penalized by execution. A Pew Research Center poll from 2013 found that many Middle Eastern countries have negative views of homosexuality, with 97 percent of people in Jordan, 95 percent in Egypt, and 80 percent in Lebanon believing that homosexuality "should be rejected."[7]

Even in current Western countries ostensibly tolerant of LGBTQ people, anti-gay sentiment abounds, rooted in Judeo-Christian values. Conversion therapy—an attempt to change people's unwanted and "unnatural" sexual orientation through various forms of "therapy"—is often aimed at minors, and is legal in most parts of the United States. It is often administered by Christian faith-based therapists, even though, according to a 2009 report by the American Psychological Association Task Force, "results of scientifically valid research indicate that it is unlikely that individuals will be able to reduce same-sex attractions or increase other-sex sexual attractions through [conversion therapy]."[8]

It's not the case that this moral rejection of homosexuality always has religious origins. The Nazis famously did not approve of homosexuality (especially male homosexuality) for the simple reason that it deviated from the norm, and anything abnormal was simply not fit for inclusion in the Third Reich. Subsequently, more than 100,000 gay men were arrested, and tens of thousands were executed in concentration camps.

The reality is that, in recent history, millions of humans around the globe have suffered violence or death because of anti-gay sentiment. LGBTQ people are four times more likely than the general population to be the victims of violent crime, and that's just in the U.S., where homosexual behavior is no longer criminalized, and where corporations like

Animals have a superior—less violent—system for dealing with differences than humans.

McDonald's proudly fly rainbow flags during Pride Month.[9] One can only speculate what the rates of violence must be in countries like Russia (which does not compile data on homophobic attacks), where a 2018 survey found that 63 percent of Russians believed that gays were conspiring to "destroy the spiritual values generated by Russians, through the propaganda of nontraditional sexual relations,"[10] and 1 in 5 Russians believed that gays should be "eliminated."[11] And all this despite the fact that homosexuality is just as common in humans as it is in other species. Around 7 percent of people in the U.S. self-identify as lesbian, gay, or bisexual, while more than 8 percent of people in the report had engaged in same-sex sexual behavior, and 11 percent acknowledged at least some attraction to the opposite sex.[12] These numbers are right on par with sheep, but significantly lower than the same-sex activity found in bonobos.

The conclusion here is that humans, through our complex capacity for moral thinking, have taken something that does not constitute a normative problem for any other species and turned it into an issue which we use to justify marginalization, criminalization, execution, and even genocide. This is, I argue, a case of animals having a far superior—that is, less violent and destructive—normative system for dealing with difference than almost all human cultures. Homosexuality is quite clearly not just normal in the animal world, but entirely non-destructive. Maybe even beneficial for maintaining animal societies.

Why, then, are humans uniquely homophobic? It's a mystery that can only be solved if you understand how we can reason ourselves into a corner via our capacity for moral thinking. A handful of cultures and religions have convinced themselves that homosexuality is a moral problem, and millions of our fellow humans suffer because of it. Not only does anti-gay sentiment have no real counterpart in the behavior of any other species, but it actively creates barriers to our species' success. It not only sows societal discord but leads to the suffering of a large swath of the human population. What biological benefit has been given to our species through our bizarre moral posturing around the non-problem "problem" of homosexuality? Precisely none. It is a sad testament to the cruelty of human moral reasoning.

The history of our species is the story of the moral justification of violent acts resulting in the pain, suffering, and deaths for billions of our fellow humans who fall into the category of "other." That could be the Indigenous peoples, the LGBTQ community, Jews, Blacks, the disabled, women, etc. In contrast, most animal norms exist to maintain a social equilibrium that minimizes the need for pain, suffering, and death. If we operate from the base principle that pain, suffering, and death is generally a bad thing, then it seems as if animals have the right idea (and the higher moral ground) most of the time. But does this mean that human morality is "bad" in the evolutionary sense? Could it be the case that our capacity for moral reasoning—our philosophy, religions, and legal structures—is

precisely the thing that gave our species the edge these past few millennia? The thing that has helped us organize our societies and spread across the globe in our great civilizations?

I don't think it was our moral capacity per se that was responsible for our success, but the other components of the human mind that gave us the ability to coordinate our efforts, like language and theory of mind. And it was our unique capacity for causal reasoning that did the heavy lifting when it came to divining the nature of the physical universe and the biological world, giving us the technological know-how that put our species on the map. Human morality, in contrast, wasn't necessary for any of this. As I've been arguing, I think we would've been better off without the ability to turn our ancient primate norms into absurd and destructive moral rules that gave us things like anti-LGBTQ legislation. But you can't unlink these things. You cannot have that laundry list of positive cognitive skills without the negative consequences.

Human moral reasoning was unavoidable. But that doesn't necessarily make it good, in an evolutionary sense. Human moral reasoning might be a bug and not a feature—an evolutionary spandrel that cropped up as our unique cognitive skills blossomed, but not itself a trait that natural selection selected for. Humans might currently be succeeding as a species not because of, but despite, our moral aptitude. We have taken this universal normative system that governs and constrains social behavior for most animals to weird extremes. Animals, with their less sophisticated normative systems, are the ones living the good life.

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REFERENCES

1. Wrangham, R.W. & Peterson, D. *Demonic Males: Apes and the Origins of Human Violence* Houghton Mifflin Harcourt, New York, NY (1996).

2. Hrdy, S.B. *Mothers and Others* Harvard University Press, Cambridge, MA (2011).

3. Associated Press. Major describes moves. *Associated Press* (Feb. 8, 1968).

4. Young, L.C., Zaun, B.J., & VanderWerf, E.A. Successful same-sex pairing in Laysan albatross. *Biology Letters* **4**, 323–325 (2008).

5. Resko, J.A., Perkins, A., Roselli, C., & Fitzgerald, J.A. Endocrine correlates of partner preference behavior in rams. *Biology of Reproduction* **55**, 120–126 (1996).

6. Leupp, G.P. *Male Colors* University of California Press, Oakland, CA (1995).

7. A.L. How homosexuality became a crime in the Middle East. *The Economist* (2018).

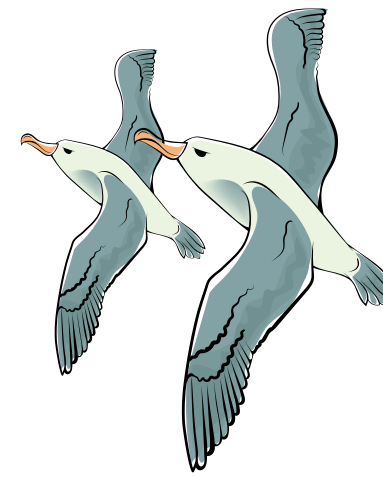
8. Glassgold, J.M., *et al.* Report of the American Psychological Association Task Force on appropriate therapeutic responses to sexual orientation. apa.org (2009).

9. Flores, A.R., Langton, L., Meyer, I.H., & Romero, A.P. Victimization rates and traits of sexual and gender minorities in the United States: Results from the National Crime Victimization Survey, 2017. *Science Advances* **6**, eaba6910 (2020).

10. Translated from wciom.ru/analytical-reviews/analiticheskii-obzor/teoriya-zagovora-protiv-rossii-

11. Kuhr, E. 1 in 5 Russians want gays and lesbians "eliminated," survey finds. nbcnews.com (2020).

12. Gates, G.J. How many people are lesbian, gay, bisexual and transgender? The Williams Institute (2011).



TETIANA DICKENS / SHUTTERSTOCK

The Sorcerer's Apprentice

An anthropologist schooled in spiritual healing offers wisdom for troubled times

BY ANNA BADKHEN

ONCE UPON A TIME, in a thatched spirit hut in the Nigerien village of Tillaberi, the Songhay master sorcerer Adamu Jenitongo told the American anthropologist Paul Stoller that the bush was angry. "People who speak with two mouths and feel with two hearts anger the spirits of the bush," Adamu Jenitongo said. "When the bush is angry there is not enough rain. When the bush is angry there is too much rain. When the bush is angry locusts eat our crops. When the bush is angry sickness kills our people."

Today, Stoller is a professor of anthropology at West Chester University, a permanent fellow at the Center for Advanced Studies in the Humanities and Social Sciences at the University of Erlangen-Nuremberg, and the author of 15 books. His awards include fellowships from the Guggenheim Foundation and the National Endowment for the Humanities, and the Anders Retzius Gold Medal in Anthropology, given once every three years by the King of Sweden. He is also what the Songhay call a *Sohanci benya*, a healer who did not inherit his powers but was taught—often a captive or an enslaved person, or, in Stoller's case, a cultural anthropologist from the United States studying the medicinal properties of plants used in Songhay ethnomedicine. Stoller ended up apprenticing with Adamu Jenitongo for 17 years. He explained his teacher's comment to me this way: "His whole thing was that when things are out of kilter, when things are out of balance, when there's a lack of harmony in social relations, then we suffer as human beings."

Who would deny the lack of harmony in social relations today? It felt like high time to ask Stoller, whose 16th book, *Wisdom from the Edge of the Village: Writing Ethnography in Troubled Times*, comes out next spring, about what he has learned during his long career, the phenomenon of "spirit possession," and what wisdom we can take from the villages and people he has studied.

You've spent years in Niger and other parts of West Africa, and later in the West African communities in New York. What was the focus of your work in those places?

My early work in Niger focused on how local political actors used competing discourses of Islam and pre-Islamic spirit possession in the arena of village politics. I discovered that in Western Niger many local political actors—avowedly pious Muslims—tapped into pre-Islamic ancestral practices like spirit possession in their play for influence and power. In later work in Niger, I studied the healing properties of medicinal plants, many of which proved to be effective in the treatment of skin disorders, minor infections, gastrointestinal issues, and hepatitis. My teachers provided the names and treatment regimens of these plants and I later linked them to their scientific classifications. The research[1] underscored the deep pharmacological knowledge that Songhay healers possessed, knowledge passed down from generation to generation.

In New York City, I focused on economic practices of Nigerien street traders who from the early 1980s to the present have sold a variety of items (African art, perfumes, pomades, baskets, and beaded jewelry). With few resources, they were able to use traditional economic practices, shaped through Islamic principles of trading, to build successful multi-ethnic and multinational networks that provided the wherewithal to build thriving businesses. In short, their past economic and cultural experience created for them an impressive degree of social resilience—a model of social adaptation in troubled times.

> I've been observing and thinking about spirit possession for more than 30 years.

PAGES 80-81: GOODSTUDIO / SHUTTERSTOCK

THE STUDENT A young Paul Stoller outside the spirit hut of his teacher, Adamu Jenitongo, in Tillaberi, Niger.

IDRISSA GODJI

What kind of insights have you learned that can help us, or teach us something about what we can do better at this time of global calamity?

Our sorry state of being stems from the notion that we, as masters of the universe, can extract what we want from nature, which, in turn, leads to the "rich" mastering the "poor." We need fundamental transformation. Adamu Jenitongo said that we need to listen to one another. We need to engage in deep listening. We need to be more modest about our capabilities, and we have to be much more respectful of the environment. If we don't make these changes, our future will be exponentially worse. Listening is not just hearing what other people say. It's tuning in to the other person. Such listening is a multi-sensorial experience. It does take a little bit of practice. In the end, these simple interpersonal practices can immeasurably enrich your life-in-the-world. In my experience, the results are transformative.

The experience of wonder leads us to change. It expands our imagination.

What was Adamu Jenitongo's solution to the disbalance in the bush?

His immediate solution was to restore the balance. He would make offerings. He'd perform rituals. That was his solution.

Did it work?

To some extent, but, you know, people continue to do things that anger the bush, anger nature. What can one do in these troubled times? As an anthropologist it is my obligation to write, engage in interviews, and try to bring Adamu Jenitongo's humane wisdom to the attention of as many people as possible. For example, a central Songhay offering is called the *genji how*. You start by speaking to the seven heavens and to the seven hells, speaking to the north, to the south, the east, and the west. When you recite this incantation, it focuses your awareness. It attunes your awareness to the environment.

And as an ethnographer/anthropologist, what have you learned yourself?

I have learned that it takes a long time to understand—even partially—the mysteries of social relations and the whys and wherefores of systems of cultural belief. Having sat and listened to my mentor, Adamu Jenitongo, for 17 years, I've learned to be more modest in my pursuit of knowledge, which means that one never stops refining one's knowledge of the human condition. Everyone commits errors of interpretation. By confronting those errors, one gradually refines his or her comprehension of the world. I've been observing and thinking about spirit possession for more than 30 years but am still discovering new dimensions of a powerfully compelling ritual.

Describe "spirit possession" for us.
Spirit possession occurs when an external force colonizes the body of a person. In some cases, the possession results in a permanent change in the person's behavior and/or identity, as when a person defies social and cultural norms—talking with invisible presences or behaving inappropriately, or sleeping in the cemetery or using foul language in public. The more common form of spirit possession is spirit mediumship, as when a spirit takes the body of a medium during a spirit possession ceremony, which features spirit music, the old words of spirit praise-poetry, symbolic costumes, and spirit objects. Once possessed, the medium speaks to the community on matters of social life, respect for the ancestors, sickness and health and life and death. In short, spirit mediumship underscores the existential issues that give shape to the human condition.

How does anthropology, as a science, reconcile with events like spirit possession?
As scientists, anthropologists have tried to explain spirit possession as a cult of affliction, the result of calcium deficiencies, an expression of cultural resistance, as an example of psychodynamic process or as a performance of cultural theater. These various approaches—sociological, biological, psychological, and performative—provide partial explanations, but fall short of explaining the total phenomenon. There is an aspect of spirit possession—it's wonder—that escapes explanation.

Why does spirit possession escape explanation? What can't you explain about it?
Spirit possession is greater than the sum of its parts. I attempted to extend explanatory theories to what I have witnessed over the years, and they tend to be insufficient. Asking an anthropologist to "explain" spirit possession is like asking Mozart to "explain" his music.

Do you believe this spirit is supernatural?
I don't know if spirit possession is supernatural, but I do know that it is an intrinsic part of the social lives of many peoples for whom the natural and supernatural are part of an experiential continuum. Most anthropologists have witnessed events that defy explanation. How can a medium, who I know is monolingual in

The Great Transition

What Western science can learn from traditional Songhay understanding of death

In many parts of West Africa, death is seen as a transitory state. For the Songhay people, a person consists of three aspects: flesh (*ga*), spirit (*bia*, the immaterial self as in an image on the surface of water, or the shadow cast on sand, or the image reflected on a mirror), and life force (*hundi*), which forms in the heart at birth. At death, flesh disintegrates, but the immaterial self and life force ascend to one of seven heavens. It is believed that on the occasion of a birth, those energies come down to Earth, which means that in many West African societies, people will greet a new baby as the temporary re-incarnation of a recently deceased relative, who demands attention and respect for a period of time. Sometimes, the newborn will be named after the recently deceased relative. Sometimes, the family will postpone a naming ceremony until they think that the recently deceased relative has received her or his due and is ready to depart his or her temporary incarnate host, to reside forevermore with the ancestors.

Continued on next page

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Death is pervasive in places like Niger. When you go to a Songhay funeral, the greeting is "*Fonda tilas*"— "the path of necessity,"—to which one responds "*Tilas wala*," "Necessity, indeed." In Niger, one in eight children die before the age of 5, and infant mortality rates are often even higher in rural areas. Poor sanitation, hunger, infections, and scourges like malaria or epidemics like cholera and meningitis routinely take from the Songhay world the young and the old, the fit and the frail, which is why traditionally, Songhay people see death as a common and necessary phenomenon. In the shadow of painful loss, the Songhay historically understand the finitude of a human being and the limits of existence. In so doing, they reestablish the social bonds that enable them to live well in challenging social, economic, and ecological circumstances. For them, death is not to be feared, for it creates and reinforces linkages between the living and the dead, between social beings and the ancestors.

If a Songhay person lives a long life, he or she hopes for a dignified death. When word spread that my teacher Adamu Jenitongo was dying, people traveled to Tillaberi to pay their respects. They sat by his bedside and told stories of here and there, of past and present. In this way, my teacher experienced a dignified death. At his funeral, we traveled to a crossroads in the bush, stripped naked, and washed away the filth of death with a special ablution. So purified, we then received the objects of his sorcerous practice—rings, medicinal powders, bracelets, and staffs. In this way, Adamu Jenitongo, like all Songhay sorcerers, defied physical death, because his spirit, his force, is embodied in the objects he bestowed to his family and to his apprentices.

My New York City trader friend Al Hajj Yaya endured two years of chemotherapy for colorectal cancer. His doctors told him to continue with the painful treatments that would keep him alive. He elected to return to Niger, which meant that he chose to die with dignity. The cancer took its toll. Soon after his arrival in Niger, he could no longer walk. World spread that a great trader was on his deathbed. People from miles away in Niger came to visit him. They told stories of trading adventures in New York City, Abidjan, Cote d'Ivoire, Paris. They laughed, and through laughter and talk conveyed their respect for a man who had lived fully and well. His was a dignified death.

As scientists and human beings, we have much to learn from traditional attitudes toward death of people like the Songhay. Their example can teach us about how the dignity and inevitability of death (*fonda tilas*) can compel us to steer clear of distraction, the pervasive presence of which wastes our precious time on Earth, and recognize what is important in life: our social relations and the contributions we make, however small, to the well-being of the world.

As a scientist, I can say that my experience in the Songhay world has compelled me to take a clear-eyed, long view of life and death. The sinuous path I have taken in science has led me not to some grandiose conclusion about the nature of human beings, but to accept the ultimate impermanence of things. Like many before me, I am forever between things. I am between Africa and America, between Songhay and English, between self and other, between health and illness. I am between sky and earth. Below me, I have left traces of my knowledge for the next generation. Above me, the ancestors patiently await my arrival.

—Paul Stoller

Songhay, speak French and other African languages? One can try to find explanations for these kinds of phenomena, of which there are many—or one can, as I have tried to do in my writing, describe a hot topic with a cool hand and invite readers to debate the ontological contours of the inexplicable.

If Western societies don't have a vocabulary to explain such things, as you've said, is there a vocabulary to explain them?

There's a wonderful quote by Nietzsche in *The Birth of Tragedy*. He writes about how there's a certain set of experiences that defy explanation, where logic bites its own tail. And when you reach that point beyond explanation, then, he says, the remedy is art. The best way to try to describe events that defy explanation—and many of the events that I've witnessed defy explanation—is through narrative. And that's the way, of course, that many Indigenous groups convey their wisdom from generation to generation.

One of my favorite anthropology books is the late Keith H. Basso's, *Wisdom Sits in Places*. It's a beautiful text that describes how Western Apache people consider space and place. For them, every place has a story attached to it, and that story gives that place its philosophical significance. Embedded in the story is the wisdom that that place embodies. The story is a kind of a covenant you make with the place. That place, the memory of which is preserved in stories, represents a whole set of historical events and experiences that are meaningful to that particular culture. The same is true for Songhay people: There are certain spots in the Niger River basin that are sacred spaces. But labeling them sacred spaces is reductive; it robs them of their full significance. I make this point in much of my writing, and certainly in my new book. In many respects we have lost our ability to take the time to tell stories. In our times, we tend to reduce complexity to a series of formulae. We think we can understand something that's partially true. But there's an awful lot of non-Western phenomena that cannot be reduced to a formula. These are phenomena that do not lend themselves to theoretical extraction.

I also think people have lost their capacity—and this is part of the ideology of explication—for experiencing the wonder of not being able to understand something, of not being able to explain things that are mysterious. For me, the experience of wonder leads us to change. It enables us to expand our imagination. It leads us to a space of creativity where we can devise things that can make life sweeter for us now and in the future. For me, the experience of the inexplicable wonders of Adamu Jenitongo's world fired my imagination, expanded my consciousness, and prompted me to try different forms (memoir and fiction) of anthropological expression. One thing is certain: The wonders embodied in the ethnographic record make anthropologists the custodians of important insights about the human condition, insights that could help us confront the life-threatening issues that define our troubled times.

Are you saying that what people in the West call science simply may not yet have "discovered" what people in the West called magic?

The great ethnographer Jean Rouch says: "There are things not yet known to us." There is much in the world that defies explanation. Perhaps the way to approach these phenomena is to live through the experience and slowly come to a partial understanding, knowing full well it could take a lifetime to comprehend something as extraordinary as spirit possession. As Adamu Jenitongo liked to tell me, "To understand us fully, you'll have to grow old with us."

In 2001 you were diagnosed with lymphoma, and you sought Western-style medical treatment: chemotherapy, immunotherapy. But you also have written a book, *Stranger in the Village of the Sick*, about how what we'd call magic helped you maybe bring yourself to remission, or survive that shock and grief of the diagnosis. How did you combine science and magic in your healing process?

I had learned from my teacher a great deal about healing the body which, for him, emerges from seeking harmony-in-the-world. When I began chemotherapy and faced my mortality, I didn't know exactly what to do. My doctor described what was going to happen to me—the horrible side-effects of chemotherapy drugs. Then,

Anthropologists are the custodians of insights about the human condition.

I suddenly felt this inexplicable tingling in my stomach. At that time, I hadn't really thought about my teacher, who had died in 1988. What's more, it had been a long time since I'd been to Niger. In a flash I knew that my approach to cancer had to extend beyond the scientific. I realized that I needed to perform some rituals to bring harmony between my body and the external world.

And so, I told my doctor: That healing can't take place if there is no harmony between the inside, my body, and the outside, the external world. At that moment, I recited the incantation I mentioned earlier, the *genji how*. I then spat in the direction of his office's four corners—north, south, east, and west. During each of my treatment sessions, which last up to four hours, I recited incantations not just for me, but for all the others undergoing chemotherapy or immunotherapy. In so doing, I felt that my teacher, although he was long dead, had my back. That knowledge gave me the considerable will to move forward, despite the uncertainty of my circumstances. In addition to the chemotherapy drugs and good doctor, I felt like I had a lot going for me. This other dimension of treatment enabled me to confront my situation with strength and a measure of grace.

And what was your good doctor's reaction to your use of your other dimension?

He thought it was cool. If he hadn't agreed, I would have changed doctors. He was interested in what he called complementary medicine, and he was okay with me spitting in his examination room.

So, here you are, a white man born in Washington, D.C., performing rituals that you learned in the bush. How do you justify it, ethically? How do you approach the conversation around the extractive nature of anthropology?

It is a complex issue. I was not a seeker of a sorcerer's knowledge, nor was I a seeker of an apprenticeship. A series of events pointed my teachers out to me,

and they thought it was important for me to learn about their practices and their very particular way of being-in-the-world. My teacher saw something in me. He thought he could trust me to convey his knowledge to the next generation. He also gave me objects and materials for personal use as well as to help other people. I use what he taught me on a limited basis. Ultimately, I see myself as a storyteller who is committed to a faithful representation of this kind of knowledge. If I've done my job well, then people, including, of course, Songhay people, will appreciate what I do. The ultimate test of the material I have presented in my work is whether it is correct or not correct, whether or not it preserves the knowledge.

When Adamu Jenitongo died, his eldest son told me: "You know, Baba shared his knowledge with you. The reason he did was because we weren't ready to learn it. He wanted you to pass it on. You must come," he told me at Adamu Jenitongo's mortuary ceremony, "and spend some time with us to teach us what he wasn't able to." They had much to learn about the healing properties of plants, about the power of incantations, and about the profoundly important relation of the village to the bush.

And did you?

Yes, that was my obligation. In all kinds of healing practices, at least in West Africa, the idea is that knowledge is precious, and you learn it over a long period of time. In time, you become the custodian of that knowledge. Your greatest obligation, however, is to pass that knowledge onto the next generation. If the knowledge is correct, it will continue to be used. Everything that I've written about my teacher and my own experiences as his apprentice, has been an attempt to convey the wonder of the world he exposed me to. My hope is that my work will in some way ensure that this knowledge will not disappear. My hope is that Adamu Jenitongo's wise practices will persevere and that they will be recognized, appreciated, and extended to the issues that we face today in the world.

ANNA BADKHEN's seventh book, *Bright Unbearable Reality*, comes out in October 2022. She is a Guggenheim Fellow and a contributing editor at *Nautilus*.

FOOTNOTE

1. The results of Stoller's research on plants were published in *In Sorcery's Shadow* (Stoller and Olkes, University of Chicago Press, 1987); *Yaya's Story* (Stoller, University of Chicago Press, 2014); and *The Power of the Between* (Stoller, University of Chicago Press, 2008). For further exploration of Stoller's work in Niger and New York City see *Fusion of the Worlds: An Ethnography of Possession in Niger* (University of Chicago Press, 1989); *Money Has No Smell: The Africanization of New York City*, (University of Chicago Press, 2002); and *Wisdom from the Edge of the Village: Writing Ethnography in Troubled Times*, forthcoming from Cornell University Press in Spring 2023.

The Afterlife Is in Our Heads

The real meaning of near-death experiences

BY KRISTEN FRENCH

ONE SUNDAY EVENING in September, nearly 30 years ago, Xavier Melo, then 23, was driving home from his job as a private math tutor in Barcelona, Spain. It was one of his two weekend jobs, and his car was stacked with study notes and practice tests for an upcoming business school entrance exam. Melo retraced the familiar route home at a leisurely pace, to savor a gentle breeze and the satisfaction of a weekend's work complete. As he pulled into an intersection, a Volkswagen Golf violently crashed into his car, destroying it. Melo himself suffered head trauma, lost consciousness, and fell into a coma. He woke up in his hospital bed, screaming, again and again, "I have been with God!"

LIDIIA / SHUTTERSTOCK

Melo's memory of the immediate aftermath of the crash is vivid and mysterious; it follows the familiar arc of the near-death experience. He recalls that he flew out of his body and hovered above it, that he observed a nurse in the ambulance who held his hand and called out, "We're losing him, we're losing him," as he watched his papers swirl and scatter in the street. Then he began to rise, the ambulance receding from him in the distance, until he came to a tunnel, where scenes of his life as a child began to play out. He felt an overwhelming sense of belonging, of kinship with the trees, the wind, and the water, and saw an indescribable light that drew him in, a light he began to believe was a being. "It was like the magnetism of love, something that attracts the deepest part of you," he told me. "I have never been more alive, I have never felt more lucid in my life." Regaining awareness and sense of his physical body, Melo said, was traumatic.

As Melo relived his story for me over Zoom, from his home in Barcelona, he repeatedly became so overwhelmed with emotion that he had to stop to regain his composure. The experience, he said, transformed him, but not until 25 years after his accident. In 2017, after years in the insurance industry, and upon graduating from a business school program in management, he formed a foundation, Icloby, to promote socially responsible business practices. This fall, the foundation will also embark on a study of near-death experiences in cardiac arrest patients, including children, among Spanish speaking people across Spain, Cuba, Mexico, Colombia, and Argentina. The research project aims to replicate an earlier study of 344 cardiac arrest survivors published in the British medical journal *The Lancet* in 2001[1] and led by Pim Van Lommel, a cardiologist, author, and researcher in near-death studies from the Netherlands. "For us, it's important to demonstrate that death is only for the material body," said Luján Comas, vice-president of the Icloby foundation, who joined us on the Zoom call.

The idea that near-death experiences, also known as NDEs, offer proof of an afterlife for the soul has been remarkably persistent, despite an accumulation of scientific evidence to the contrary. Such claims have existed in the historical record since at least Plato's time; the earliest known account of near-death experiences appeared in the fifth century B.C. But they weren't widely popularized until the 1970s, when American physician and philosopher Raymond Moody published his best-seller *Life After Life*, based on his collection of 150 coma survivor's reports.[2]

Many studies and books that bear witness to life after life have sprung up since Moody's book, none more notorious than *Proof of Heaven: A Neurosurgeon's Journey into the Afterlife*, a *New York Times* bestseller in 2012, by neurosurgeon Eben Alexander. Increasingly, these supernatural claims have taken on a scientific veneer. Van Lommel, the cardiologist from the Netherlands, has made it clear in his many popular writings, public talks, and interviews that he believes NDEs serve as proof that consciousness exists independently of the brain, that it is "non-local." And Sam Parnia, who researches resuscitation science and NDEs at New York University Grossman School of Medicine and was the lead researcher on a 2022 paper that proposes a framework for future study of NDEs,[3] recently told me, "The [big] question that we're trying to explore is, 'What happens to consciousness when you die, does it die or continue?' And the evidence so far is that it doesn't die when you and I cross over into death."

But neuroscientists who study consciousness and have weighed the decades of research into NDEs told me these claims that consciousness survives death are not supported by the research. Though they are highly personal and often transformative for those who experience them, NDEs are nonetheless explained by physiological processes, they said, which have been pieced together over the past 50 years. In the decades since Moody published *Life After Life*, advances in critical care medicine and resuscitation science have made it easier to revive patients whose hearts have stopped, which has made it easier to systematically identify and study people who have had an NDE. Some estimates now suggest that between 4 to 15 percent of the global population and 10 to 23 percent of cardiac arrest patients have had an NDE.[2] We now have a better grasp of how they happen, what purpose they may serve and why they are so transformative for those who experience them. At the most basic level, neuroscientists say, when a person's brain changes in profound ways—as happens when that person goes into cardiac arrest, for example—their perceptions and emotions change in profound ways, too.

"I have never felt more lucid in my life."

"Having an out-of-body experience is not proof that the soul or the mind can leave the body and go floating about," said Anil Seth, a professor of cognitive and computational neuroscience at the University of Sussex who studies consciousness and is the author of a recent book on the subject, *Being You*. Those who tout near-death experiences as something more than biological, Seth added, "are confusing the content of the experience with a claim about the nature of the universe. There's a much more interesting explanation, which is that the location that we feel ourselves to be is something that is generated by the brain and can be changed when the brain is in a particular state."

IN 2019, A GROUP of critical care specialists, anesthesiologists, and psychiatrists, as well as a neurologist from New York Medical College and a neurophysiologist specializing in sleep and epilepsy from Kings College in London, got together in New York to discuss the future of NDE studies. Sam Parnia, the resuscitation researcher from New York University Grossman School of Medicine, was among them. The result of that meeting was the 2022 paper in the *Annals of the New York Academy of Sciences*.[3] Among other things, the authors proposed a new name for the NDE: "recalled experiences of death," or REDs, to limit the field to the study of just those experiences that occur when someone is in critical condition, or a near-death state, such as cardiac arrest, when the brain no longer receives blood and oxygen.

Parnia told me the new name was meant to reflect the authors' belief that near-death experiences actually happen after someone is dead. "What we're saying is science is showing you that death is not the end that we thought," Parnia said. "It's almost like a new, uncharted, unexplored territory."

The group also identified 51 core features, or themes, of REDs. These include "separating from the body," "realization of having died," "a higher purpose: I wish I had known," and "loss of fear of death." These experiences, the paper states, are characterized by "a paradoxical lucidity and a heightened sense of consciousness, awareness, and well-structured thought processes, typically without external or visible signs of consciousness." In a supplement to the paper, the authors allow the possibility that consciousness "is a separate entity that, while undiscovered by science today, is not produced by conventional brain cell activities."

NDEs have been reported under many circumstances, a list of which appeared in Van Lommel's 2001 paper: cardiac arrest in myocardial infarction, shock in postpartum loss of blood or in perioperative complications, septic or anaphylactic shock, electrocution, coma from traumatic brain damage, intracerebral hemorrhage or cerebral infarction, attempted suicide, near-drowning or asphyxia, and apnea. According to Van Lommel, they are also reported by patients with serious but not immediately life-threatening diseases, and in those with major depression. Experiences that bear many similarities to NDEs can even happen in the terminal phases of illness or after situations in which death seemed inevitable, such as mountaineering accidents.

But NDEs can also occur in circumstances that do not bear any direct relation to imminent death or even fear of death, such as meditation or intense grief, according to numerous studies, said Renaud Evrard, a clinical psychologist and assistant professor at the University of Lorraine in France, who works with patients grappling with exceptional and paranormal experiences, including NDEs. In a response paper published a few months later in the same journal, the *Annals of the New York Academy of Sciences*, Evrard accused Parnia and his co-authors of ignoring the actual data on NDEs.[4] "They focus too much on the interpretation of testimonies and not enough on the evidence," said Evrard. Bruce Greyson, professor of psychiatry and neurobehavioral sciences at the University of Virginia and the creator of the Greyson scale used to identify and rate NDEs, agreed, even though he is listed as an author on the 2022 paper. The evidence suggests NDEs experienced by patients whose hearts have stopped are no different from those experienced by people who simply fear death—for example, if someone is falling off of a mountain, Greyson said.

Prior belief in god or an afterlife does not, perhaps surprisingly, seem to influence one's propensity to have an NDE, according to the research, but there is a strong association between the "depth" of the NDE a person experiences—as measured by the Greyson NDE Scale[5]—and the likelihood that they will experience a religious or spiritual transformation afterward, including reduced fear of death, greater empathy, and decreased interest in material possessions.[6]

NDEs are generally understood to begin with a feeling of detachment from the physical body—known as an out-of-body experience, or OBE—followed by deep feelings of peacefulness, entering a gateway or tunnel, seeing a bright light[7] and finally feeling a "return" to the body. It is the OBE that is perhaps the most defining element of the NDE: Some 80 percent of people who report experiencing an NDE have one, according to the research of Steven Laureys, a clinical professor of neurology who leads the Coma Science Group at the University of Liège in Belgium. His lab searches for behavioral and neural correlates of consciousness in patients with severe brain damage and studies nonordinary states of consciousness.

But a wealth of neuroscience research describes how OBE-like experiences—a loss of the sense of self and disturbed body perception or ownership—can be triggered by brain damage, epilepsy, and migraine,[8] as well as by stimulation of the part of the brain where the right temporal and parietal lobes meet. This region is known as the right temporal-parietal junction (TPJ), and it is understood to play an important role in multisensory integration, our sense of embodiment, feelings of agency and self-other distinction.[9] Stimulation of this junction can disrupt the brain's ability to coherently process the positioning of the body and the sense of body ownership, which can lead to the sensation of seeing oneself from above.

OBEs often also involve awareness of specific details of the scene that feature the body in a comatose state–doctors discussing one's chances of survival, for example, or attempting CPR. In the past, accounts from people who have recovered from being unconscious or in a minimally conscious state, and have recalled sensory details of their environments, might have seemed miraculous. But recent studies of people who are in coma, or under anesthesia, and seem unresponsive, have shown these individuals can perceive things in their environment and respond physically to commands.[10] For example, while higher-level semantic processes can be impaired in people with low levels of sedation or minimally impaired consciousness, a person's ability to process speech more generally has been found to be resilient even during deep sedation.[11]

Cardiac arrest may be similar. How much activity is present in the brain under these conditions is not clear. Positron emission tomography scans suggest that there is about a 60 percent reduction in global activity compared to baseline following cardiac arrest, said Laureys, but it's not zero.[11] But if a brain has flatlined, showing no activity on an EEG monitor, it would most likely be incapable of forming a memory or having any other conscious experience, said Seth, who has been studying the neuroscience of consciousness for decades. He and many others believe that most NDEs are "false" or imagined memories—that the brain constructs a memory after the fact to fill in for an inexplicable series of mental events.

"You don't want to undermine the person's lived experience," Seth said. "If they experience flying through a tunnel of light, into a beautiful white open

FREE FALLIN' You don't want to undermine someone convinced they had a glimpse of the other side, says neuroscientist Anil Seth. "If they experience flying through a tunnel of light, into a beautiful white open space, then that's what they experience." But that experience depends on brain activity. "No brain activity, no mental process."

FRAN_KIE / SHUTTERSTOCK

space, then that's what they experience. But memories, things that minds do, like remember things and talk about them, depend on brain activity. No brain activity, no mental process. If somebody with no brain activity were able to experience something and remember it later, then pretty much everything we know about the brain, about science, about physics, is wrong."

WHILE NO SINGLE OVERARCHING EXPLANATION for the NDE has yet been established, neuroscientists have discovered a series of neurophysiological mechanisms that could, together, account for many aspects of the phenomenon. One hypothesis is that NDEs are produced by the release in the brain of a natural hallucinogen with neuroprotective properties. London researcher Karl Jansen, a member of the Royal College of Psychiatrists, is a leading expert on the hallucinogen ketamine, which is used to treat depression and, during surgery, as an analgesic to induce loss of consciousness and reduce pain. Jansen proposed in the 1990s that a ketamine-like substance may play a role in the emergence of NDEs among patients with life-threatening injuries or disorders of the brain or spinal cord given the parallels between NDEs and ketamine trips, and the potentially protective properties of ketamine-like substances.[12]

The "dissociative anesthetic ketamine can reproduce all aspects of the near-death experience," Jansen wrote. That includes a sense of ineffability, timelessness, that what is experienced is "real," that one is actually dead, a perception of separation from the body, vivid hallucination, rapid movement through a tunnel, and emerging "into the light."

No brain activity, no mental process.

Although many psychedelic experiences bear some similarities to NDEs, recreational ketamine trips top the list. In a massive 2019 study comparing psychedelic experiences to NDEs, Laureys' group used natural language processing tools to assess the semantic similarity between 15,000 accounts linked to the use of 165 different psychoactive substances and 625 NDE narratives. They found that accounts of ketamine trips most closely resembled those of NDEs.[13]

Ketamine is also an N-methyl D-aspartate (NMDA) receptor antagonist, and so could counter neurotoxic processes that are set into motion by NMDA receptors when blood flow and oxygen to the brain are cut off, "with a short lived, dissociative hallucinogenic state occurring as a side effect." At least one naturally occurring substance that could play this role, called an endopsychosin, has been identified. In fact, critical conditions like hypoxia—oxygen deficiency—or temporal lobe epilepsy, have been shown to trigger NDEs or NDE-like experiences. And many studies and clinical trials have established that ketamine has neuroprotective and neuroregenerative effects in humans, even after stroke, brain injury, and epileptic seizures.[14]

There is likewise some experimental evidence that near-death experiences that occur at the time of a trauma might help to ward off post-traumatic stress disorder. Bruce Greyson, of the Greyson NDE Scale, led a study published in 2001 that showed that people who have NDEs report more intrusive memories of their close brushes with death but make fewer efforts to avoid reminders of the event, which is considered the more pathological dimension of PTSD.[15]

"One feature that distinguishes NDEs from other forms of [traumatic] dissociation is the strong positive affect," which might help defend against full-blown PTSD, Greyson wrote in the 2001 paper. "If so, we might speculate about the possible survival value of having NDEs when close to death." (Of course, some NDEs have been documented to feature negative and even nightmarish features, though some question whether these are "true" NDEs.)

Independently, serotonin, a neurotransmitter involved in mood, cognition, reward, learning, and memory, might play a role in certain features of the NDE. In a small placebo-controlled experiment with 13 individuals, Laureys' group assessed the experiences induced by injection with a drug called DMT that stimulates serotonin production, which triggered feelings such as entering an unearthly environment, heightened senses, feelings of peace and harmony or unity with the universe. All participants scored above the cut-off score of seven on the most widely used reference scale for NDEs, the Greyson scale.[16] Hypoxia itself has also been considered as a possible contributor. Hypoxia is sometimes experienced by fighter pilots during acceleration maneuvers, which have been documented to provoke tunnel visions, bright lights, OBEs, pleasant sensations, and visions of beloved ones.

To attempt to confirm this in a controlled study, one group induced temporary loss of consciousness via loss of blood pressure in 42 volunteer participants and found that 16 percent reported OBEs, 35 percent reported feelings of peace and pleasantness, 17 percent had a vision of a light, 47 percent felt they entered

Ketamine can reproduce all aspects of the near-death experience.

another world, 20 percent encountered preternatural beings, and 8 percent experienced a tunnel. Likewise, abnormally elevated levels of carbon dioxide in the blood, known as hypercarbia, can induce recollections of past memories, life reviews, visions of a light, OBEs, or mystical experiences, according to research conducted in 1950 and again in 2010.[17] Yet another study showed higher prevalence of NDEs in people with REM sleep intrusions.

Other work suggests that some kind of last-gasp survival mechanism may be at work when near-death experiences occur, in which the brain marshals all of its remaining resources to try to keep itself alive. Recent EEG studies in humans and rodents seem to show highly coherent electrical activity in the brain just before death. This was first found in a small human case series in 2009 by researchers who identified transient electrical spikes in half of their sample of critically ill patients immediately before cardiac arrest. They speculated that critical hypoxia—loss of blood flow to the brain—unleashes a cascade of pathological neuronal activity. These findings were replicated on a larger sample of 35 patients in 2017.

Similar episodes of so-called paradoxical lucidity have been identified in patients with Alzheimer's disease just before they die, despite irreversible degeneration in the cerebral cortex and the hippocampus and corresponding memory loss. Researchers who have studied brains in the throes of electrical surges just before death have posited that they represent "a last gasp attempt by the brain to survive a lethal loss of blood flow," which could serve as an "evolutionary survival event."[18] Why some people experience these surges and others don't, and how they are set into motion, is unknown.

Scientists haven't assembled all the pieces to explain why brains in desperate throes generate feelings of peace and joy, ineffability, and the sense of being in the presence of something transcendent. "It's always difficult for science to answer the big why questions," Laureys said. Comas, of the Icloby Foundation, told me that by educating the public about near-death experiences, she and Melo hoped to "to eradicate the fear of death." After all, she said, "The fear of death is the mother and father of all fears." Who could argue with that? Scientific evidence says near-death experiences are directly linked to the workings of our brains. But evolution is a sly master. Perhaps our biology in its final hour is easing us gently into that good night.

KRISTEN FRENCH is a contributing editor at *Nautilus*.

REFERENCES

1. van Lommel, P., van Wees, R., Meyers, V., & Elfferich, I. Near-death experiences in survivors of cardiac arrest. A prospective study in the Netherlands. *The Lancet* **358**, 2039-2045 (2001).

2. Martial, C., Cassol, H., Laureys, S., & Gosseries, O. Near-death experience as a probe to explore (disconnected) consciousness. *Trends in Cognitive Sciences* **24**, 173-183 (2020).

3. Parnia, S., *et al.* Guidelines and standards for the study of death and recalled experiences of death—a multidisiplinary consensus statement and proposed future directions. *Annals of the New York Academy of Sciences* **1511**, 5-21 (2022).

4. Evrard, R., Pratte, E.A., & Rabeyron, T. Sawing the branch of near-death experience research: A critical analysis of Parnia *et al*'s paper." *Annals of the New York Academy of Sciences* **1515**, 5-9 (2022).

5. Greyson, B. The near-death experience scale. *The Journal of Nervous and Mental Disease* **171**, 369-375 (1983).

6. Greyson, B. Near-death experiences and spirituality. *Zygon* **41**, 393-414 (2006).

7. Martial, C., Cassol, H., Laureys, S., & Gosseries, O. Near-death experience as a probe to explore (disconnected) consciousness. *Trends in Cognitive Sciences* **24**, 173-183 (2020).

8. Blanke, O. & Arzy, S. The out-of-body experience: disturbed self-processing at the temporo-parietal junction. *Neuroscientist* **11**, 16-24 (2005).

9. Blanke, O. & Mohr, C. Out-of-body experience, heautoscopy, and autoscopic hallucination of neurological origin: Implications for neurocognitive mechanisms of corporeal awareness and self-consciousness. *Brain Research Reviews* **50**, 184-99 (2005); Blanke, O., Faivre, N., & Dieguez, S. Leaving body and life behind: Out-of-body and near-death experience. In Laureys, S, Gosseries, O., & Tononi, G. (Eds.) *The Neurology of Consciousness (Second Edition)* Academic Press, Cambridge, MA (2016).

10. Laureys, S., Perrin, F., Schnakers, C., Boly, M., & Majerus, S. Residual cognitive function in comatose, vegetative and minimally conscious states. *Current Opinion in Neurology* **18,** 726-33 (2005).

11. Owen, A.M., *et al.* Detecting awareness in the vegetative state. *Science* **8**, 5792 (2006).

12. Jansen, K. Near death experience and the NMDA receptor. *The BMJ* **298**, 1708 (1989).

13. Jansen, K.L.R. The ketamine model of the near-death experience: A central role for the N-Methyl-D-aspartate receptor. *Journal of Near-Death Studies* **16**, 5–26 (1997).

14. Fujikawa, D.G. Neuroprotective effect of ketamine administered after status epilepticus onset. *Epilepsia* **36**, 186-195 (1995).

15. Greyson, B. Posttraumatic stress symptoms following near-death experiences. *American Journal of Orthopsychiatry* **71**, 368-373 (2001).

16. Timmermann, C., *et al.* DMT models the near-death experience. *Frontiers in Psychology* **9** (2018).

17. Klemenc-Ketis, Z., Kersnik, J., & Grmec, S. The effect of carbon dioxide on near-death experiences in out-of-hospital cardiac arrest survivors: a prospective observational study. *Critical Care* **14**, R56 (2010).

18. Chawla, L.S., *et al.* Characterization of end of life electroencephalographic surges in critically ill patients. *Death Studies* **41**, 385-392 (2017).


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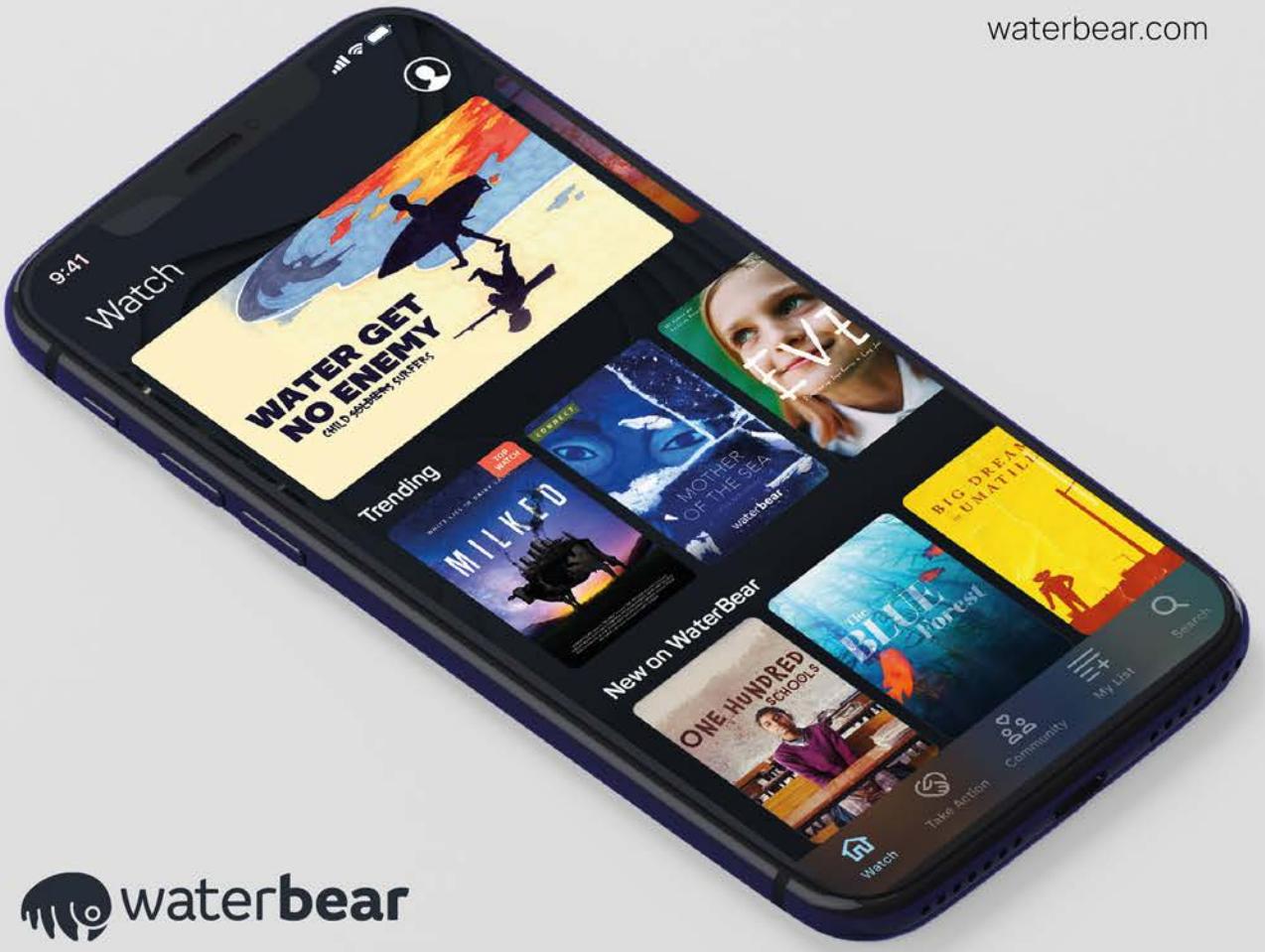

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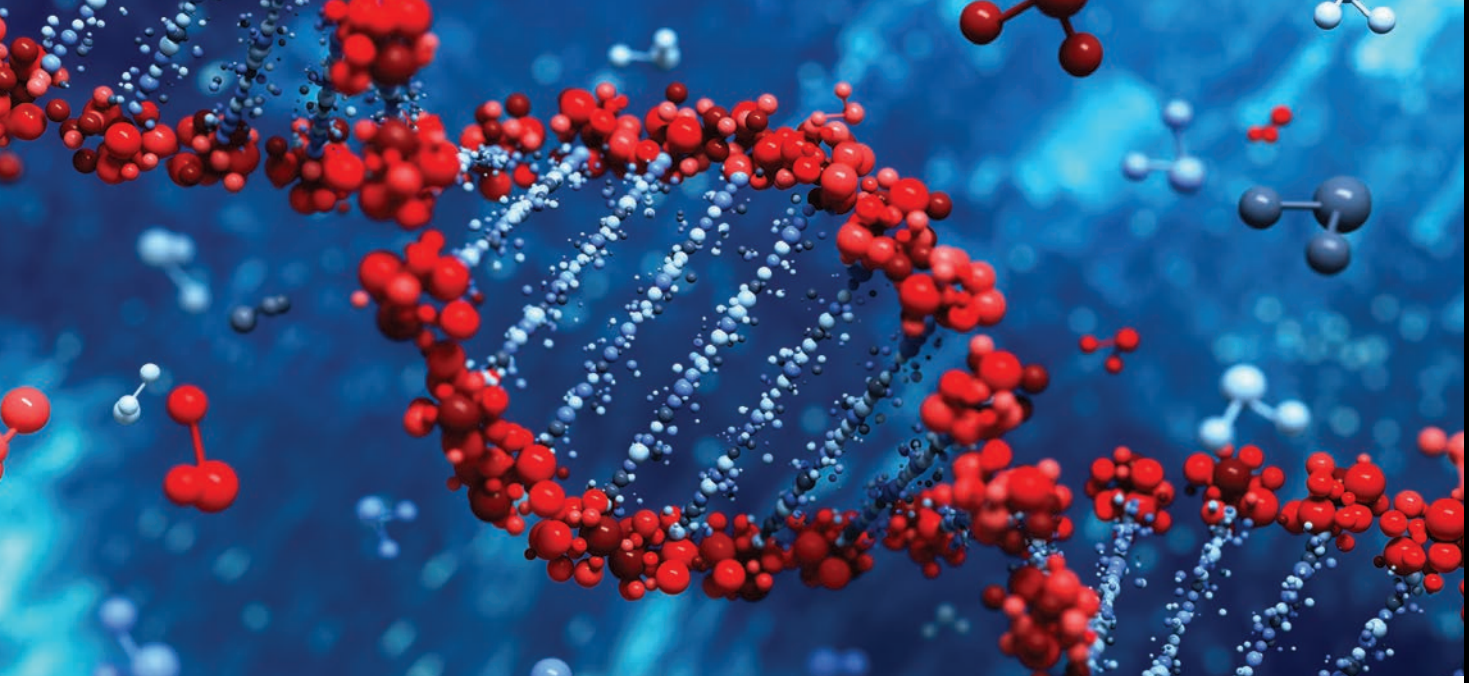

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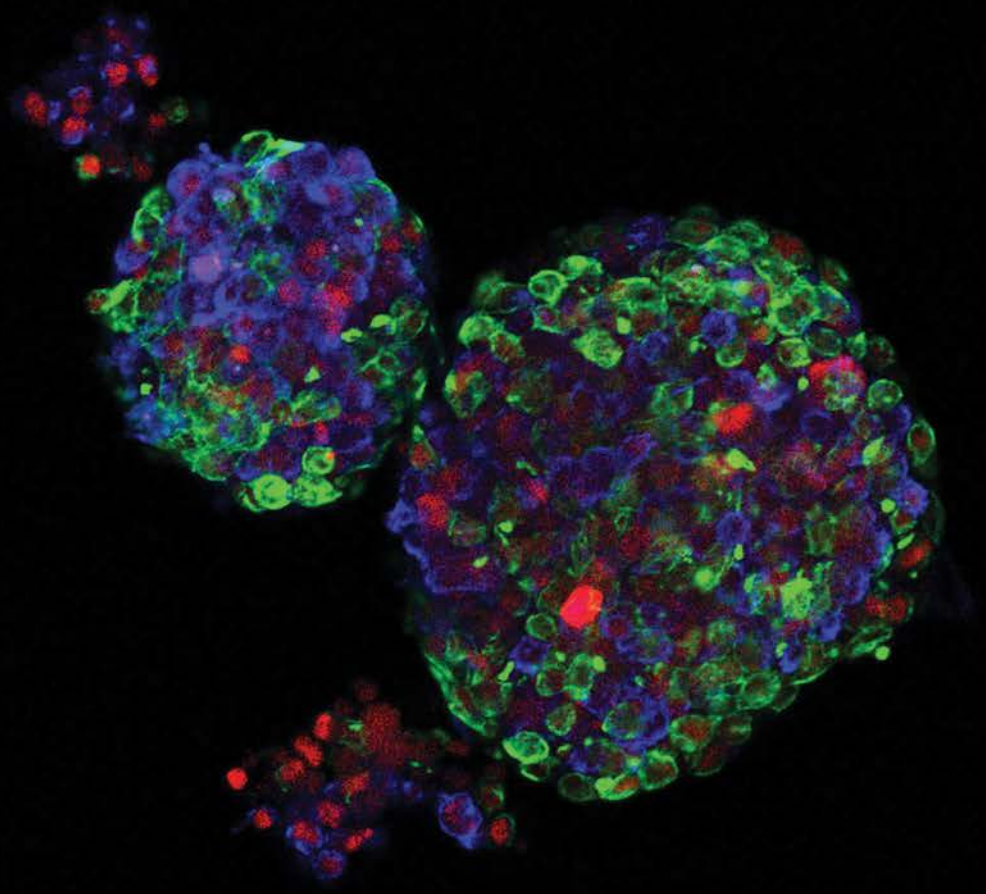

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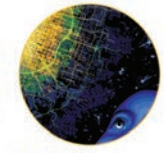

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Siddhartha Mukherjee

The Pulitzer Prize-winning author, cancer biologist, and physician on the wonders of the cell

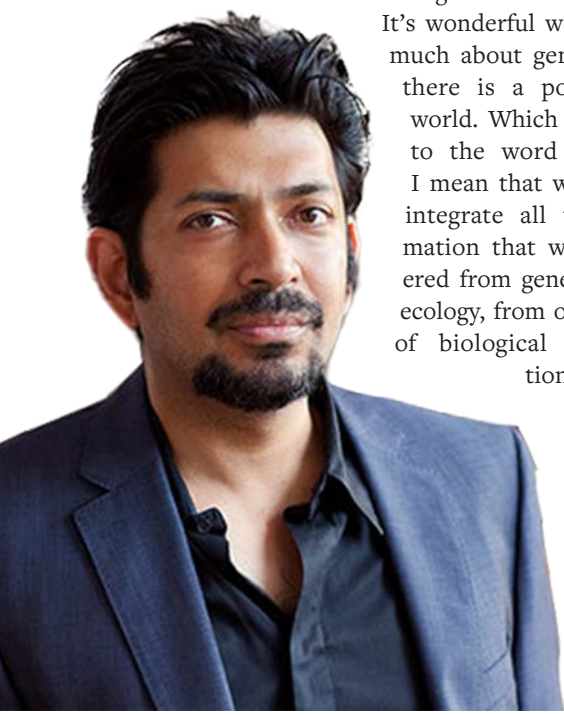
INTERVIEW BY MICHAEL DENHAM

WHAT A GENE NEEDS

The gene and DNA have been iconographic elements of ourselves for a century. But a gene is lifeless without a cell. It's a molecule. It's the cell that allows the integration of information, that emerges from the genome and integrates that information to create function. And function is the basis of physiology. The cell is many machines. The first thing is that it's an information-decoding machine. The second is that it's an information-integrating machine. And then it's a dividing machine. It integrates information, divides, and perpetuates that so that you can form a multicellular organism. What we really are is agglomerations of cells, which interpret DNA, integrate signals, and create everything that's functional about ourselves, our metabolics and our capacities.

BEYOND THE GENOME

Cancer isn't just mutated genes. There is a cell biology, and there's a human beyond that cell. And there are mysteries of cancer that you cannot solve by decoding the cancer genome. It's wonderful we know so much about genetics. But there is a post-genetic world. Which brings me to the word "holism." I mean that we need to integrate all the information that we've gathered from genetics, from ecology, from other kinds of biological investigation. It's only when we integrate that information that we can understand how the human body is built in normalcy, and how the human body goes wrong in the context of illness.



DEBORAH FEINGOLD

SCIENCE STARTS SIMPLE

For me, it's very much about beginning with very low-brow things, just looking at cells, looking at how they interact. The first experiments that I design when I design a new experiment are usually extraordinarily simple. Let's put this and this together and see what happens. And then we go into much more complex things like data analysis, genomics, and proteomics. But it's not as if I'm coming home and thinking, Oh gosh, let's apply proteomics to this cell. We're studying bone a lot. What does it look like? What does an arthritic bone look like under the microscope? That's where I begin all my experiments. The first thing I do is try to see, what is it about these things? What is special? What's different? And, how can I manipulate it if I can? And what will be the result?

WRITING TO THINK

I don't really make a distinction between "big L" literature and writing about science. If you read Leonardo's books, or if you read Lewis Thomas or others, you'll quickly realize that distinction is an arbitrary distinction. They were writing as much literature as the next person. Writing is writing. Writing is a mechanism for us to understand and express ideas. I write to think. How do you construct a story? What does a story mean? Where do pieces of a story fit in? How do you not give away the punchline before a certain point? How do you build a sense of wonder, a sense of suspense, a sense of achievement or failure? Those ideas cross all boundaries of disciplines.

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