

NAUTILUS

MY REAL PROBLEM

Confessions of a theoretical physicist

OUT OF MIND

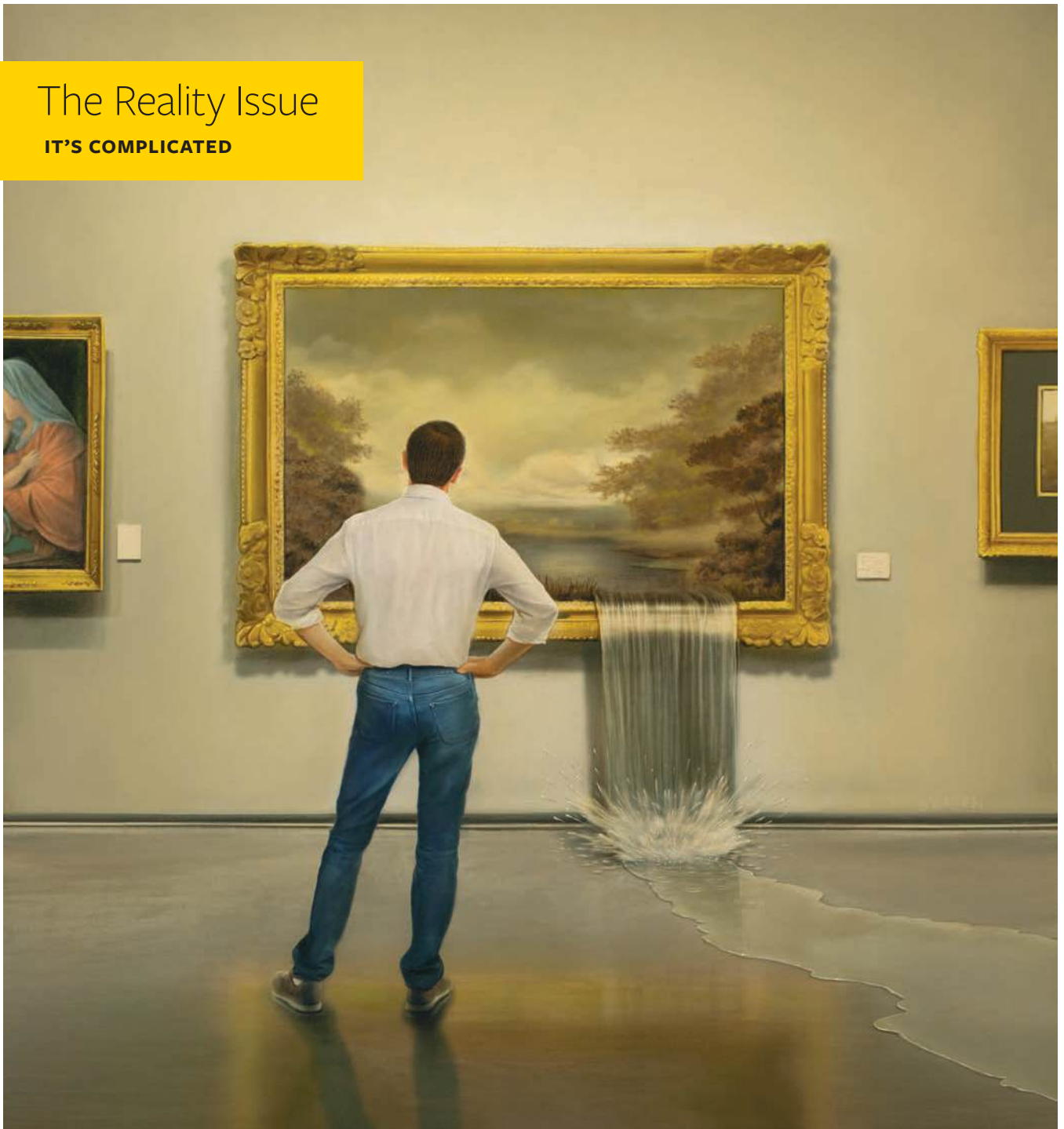
Do psychedelics open another reality?

THE REALITY CODE

All life is computation

The Reality Issue

IT'S COMPLICATED





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IMAGE: Marie Curie, the only person to win the Nobel Prize in two different scientific fields

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NAUTILUS

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NAUTILUS *Next*

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Let's Get Real

BY KEVIN BERGER

THIS PAST SPRING on my way to the Santa Fe Institute, home to polymath thinkers and thinking, tucked into the foothills of the Sangre de Cristo mountains, I thought of writer Don DeLillo. I was bound for a conference called “Investigating Reality” that would feature talks by renowned physicists, mathematicians, philosophers, computer scientists, and artists. A scene from DeLillo’s novel *White Noise* came to mind because it captures for me what reality has felt like for so long.

The characters Jack and Murray take a drive in the country to a tourist attraction. Both are popular culture professors. As they near the attraction, they see road signs for it: THE MOST PHOTOGRAPHED BARN IN AMERICA. They stand in a grove of trees and watch the tourists click their cameras at the barn. Nearby a booth sells postcards of the barn. After a prolonged silence, Murray says, “No one sees the barn. Once you’ve seen the signs about the barn, it becomes impossible to see the barn.” He pauses. “They are taking pictures of taking pictures.”

The barn has been replaced by the representation of it. “We see only what the others see,” Murray says. “We’ve agreed to be part of a collective perception.”

DeLillo published *White Noise* in 1985, years before the omnipresence of cellphone cameras and Instagram. Today his prophecy is complete. The Grand Canyon, *Mona Lisa*, the Eiffel Tower, have been vanquished from the public mind as real objects. Only the selfie taken at them is real.

It’s incredible how the mediated world has uprooted us from feeling meaningfully connected to the physical world and one other. Our consciousness seems afloat in a world of empty images and symbols. How do we get back to seeing the barn again?

A mission of the Santa Fe Institute has been to reveal the infinite dimensionality of reality, and even more, its

How do we get back to seeing the barn again?

interconnections. Its conference on reality, the inspiration for this issue of *Nautilus*, was a roundtable of ideas that penetrated the surfaces of reality to reveal essences and connections beneath.

Reality means many things. We live with social, political, and economic realities. The reality of families and health. The focus in this issue is on the science and scientists whose aim is to illuminate the threads that make up the very fabric of physical reality—but not to the exclusion of the realities around us. Their interplay is always on view. “At every scale, life is an ecology,” writes Blaise Agüera y Arcas in his essay in this issue, “In the Beginning, There Was Computation.”

Piercing the surface of “collective perception,” as DeLillo would have it, to the heart of reality, unite the articles here. You will read the confessions of a reality-hunting physicist, meet a composer who brings his music alive in the darkest realities, and follow a hermit on his search for God in the Italian Alps. You will meet psychedelic drug users convinced their trips tap a universal reality not explained by neuroscience and read how the physics experiments that have led to the discovery of black holes are like magical realism. Insights into interconnections abound, like this gem from math journalist Ananyo Bhattacharya: “the experience of mathematical beauty excites the same parts of the brain as beautiful music, art, or poetry.”

The goal of writing and science is to peel back illusion and reveal the world anew. This issue of *Nautilus* brings you reality as you’ve never seen it before.



BOLDLY EXPLORE

OUR UNKNOWN OCEAN

R/V Falkor (too)

2026

2027

2031

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2025

2028

2029

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2032

2033



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A man with a beard and sunglasses, wearing a bright yellow jacket and white shorts, is climbing a rocky mountain. He is leaning forward, gripping a rock with his right hand, and has a wide, joyful shout on his face. The background shows a clear sky and distant mountain peaks.

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Pictured: Josh Armstrong, Associate Professor of Philosophy at University of California at Los Angeles (UCLA)

HARPER'S

MAGAZINE

Findings

A mother is 4.6 percent more likely to give birth in the same month she was born.  Half of all beef consumed in the United States is eaten by 12 percent of adults.  The playing speed of a metal guitarist directly correlates with his intrasexual competitiveness but not his mating success.  Scientists advised against consuming hypersexual zombie cicadas infected with psychoactive fungus.  A metal scar on the surface of the white dwarf WD0816310 indicated that it has cannibalized other bodies in its orbit.  Dwarf rock-wallabies were found to have unusually large teeth. "If I were a vegetable," said a skull-shape researcher, "I would not mess with a pygmy rock-wallaby." 

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THE PORTHOLE

Short sharp looks at science

PSYCHOLOGY

How to Tell False Memories From Real Ones

OUR ABILITY to imagine is an awesome power. But since it uses the same brain machinery as other thoughts and perceptions, and because we can remember what we imagine, we face a serious problem: How can we make sure we can tell the difference between memories of things that happened from memories of things we simply imagined?

Distinguishing memories of things that really happened from those that did not is a mental process known as reality monitoring. When we look at something in the environment, powerful signals from the eyes make their way up through the visual cortex, leading to recognition in higher-order parts of the brain. During imagination, the information comes from the other direction: Higher-order areas of the visual cortex are activated first. Because imagination is often deliberate, we also see more recruitment of the frontal cortex, important for cognitive control. These distinctions are key when it comes to determining the source of memories, a task in which the anterior medial prefrontal cortex—thought to be critical to attention, and to working, spatial, and long-term memory—seems to play an



important role. When this part of the mind is doing its job, we are pretty good at distinguishing memories of what we saw from what we imagined.

But it doesn't always work. There are now decades of research on false memory that examine how people sometimes mistake remembered imaginings for remembered real experiences—first demonstrated in the 1990s by the work of Elizabeth Loftus, and a phenomenon that has plagued everything from eyewitness testimony to talk therapy. But can people somehow recategorize these false memories, which they can be very convinced really happened, to the correct source, as imagined rather than real?

A recent study by University College Dublin psychologist Ciara Greene and colleagues replicated



We rely on our memory to understand the reality we live in.

Loftus' early work by intentionally giving study participants a false memory (of getting lost at the mall as a young child). Some 52 percent of participants believed the fabricated incident had actually happened to them. I talked to Greene about what might be happening in this process: "There's a lot of evidence suggesting that true memories tend to have more sensory detail like smells and sounds—and tend to have more emotion," she said. The more vividly you imagine the memory, the more like real life it seems.

Greene and her colleagues wanted to see if simply explaining to people that their memory was false would cause them to change their minds. Two to four weeks after researchers gave participants the false memory—attempting to trick their reality monitoring network—participants were fully debriefed and told that the incident they'd been led to believe was true, was in fact made up. In a survey three days after that, only 8 percent of people said they still believed that the false memory had actually happened.

If we judge the reality of the memory based on its vividness, then why might this debriefing work? Debriefing on its own doesn't make memories less vivid. This is because reality monitoring can chuck "memories" into the false category through two primary ways. The first is the assessment of the richness of the memory. If a memory seems too just-the-facts, without those other enriching impressions, it seems more likely not to have truly happened to us. The second involves inference. That is, we reason, at some level, that a memory must have been originally imagined, for some reason or other. If we have a vivid memory of flying through the air with arms outstretched, we can conclude that we must have dreamed or imagined it because we know people cannot fly.

It appears that, even though participants' memories of the false incident were as vivid as before and the incident was entirely plausible, hearing that the memory was false was enough for most of them to stop believing

that it had actually happened. Telling someone something is a message to the executive control part of the mind, where reality monitoring also lives.

The psychological literature abounds with findings of human irrationality and distortions of perception. What makes work like Greene's so important is that it shows how using our rational faculties can sometimes overcome our default conclusions—and how we might shape our beliefs to be more accurate.

Participants of course didn't have the lost-in-the-mall incident wiped clean from their memory. But most did refile it as something they'd generated internally, rather than having a source in a real experience.

We rely on our memory to understand the reality we live in. But our ability to simulate the world in our heads—doing copious mental cartwheels of remembering and imagining, and remembering what we imagined—introduces a problem the mind has to solve, which it does imperfectly. It's nice to know that simple logic and hearing the truth can offer a quick fix, at least in this kind of experimental setup. Though we all know distinguishing reality outside the lab can be a little more complicated.

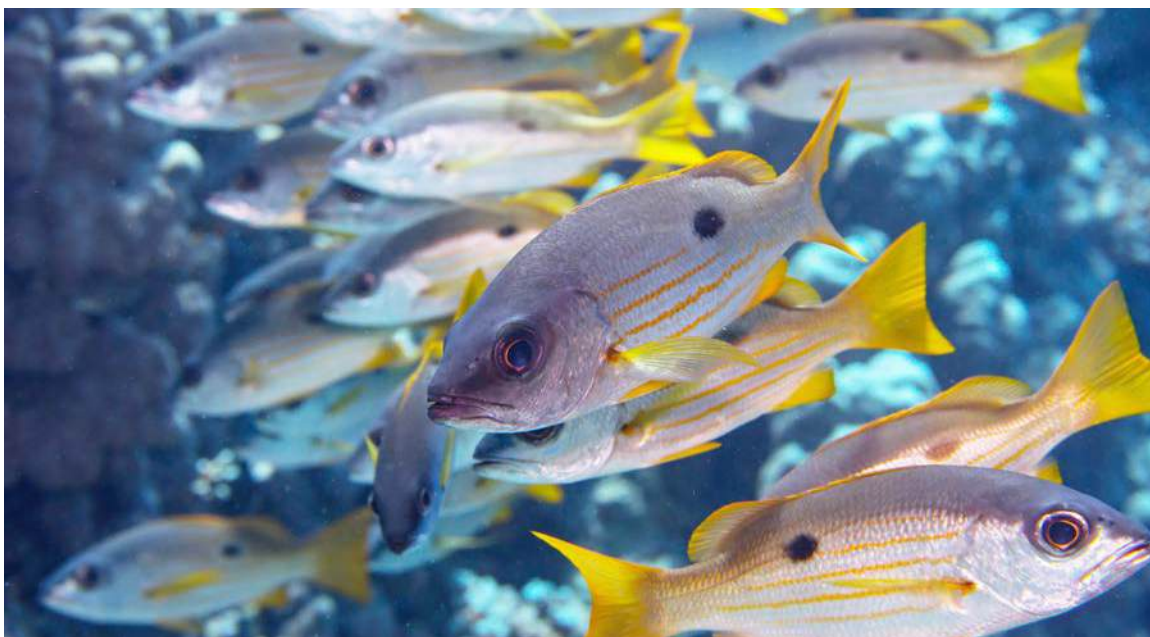
—Jim Davies

ZOOLOGY

The Wisdom of Fish Schools

MANY ANIMALS LIVE in communities where individuals rely on each other for safety: herds of buffalo, murders of crows, schools of fish. Multiple pairs of eyes and other sensory organs are better at detecting a threat, and a reliable social alarm system can make the difference between life and death.

One longstanding assumption among behavioral ecologists has been that individuals in a network make decisions based on the average responses of their neighbors. So, for instance, a reef fish would flee to safety if enough of its neighbors showed signs of distress associated with an approaching predator.



But fleeing a foraging ground carries a cost, especially if the alarm turns out to be false. A fish might have a hard time finding its way back to a particularly desirable feeding spot, or forfeit the spot to a competitor. And while skipping dinner may not seem like a huge price to pay for possibly avoiding the jaws of a predator, for smaller bodied animals, including many species of birds and reef fish, failure to consume enough calories during the day can be life-threatening. Bolting also carries extra energy costs.

“If you always follow your friends, you’ll keep running from non-existent threats, wasting energy and missing out on food,” says Ashkaan Fahimipour, a community ecologist from Florida Atlantic University.

When Fahimipour watched videos of reef fish going about life in their natural habitat, he realized they were actually quite selective about which social signals to heed. In some cases, anti-predator behaviors, such as darting, trigger a community-wide response, while in others, the shoal quickly chalks it up to a false alarm and ignores the signal.

“There’s a memory component in the circuit that acts sort of like a timer, waiting a bit to see if the [alarm] clears or if it gets stronger,” Fahimipour says. “This

timer inhibits the alarm from going off immediately. In a way, this lets the system tune its own sensitivity.”

Fahimipour is the author of a recent study that shows fish rely on a sophisticated decision-making circuit, where responses are adjusted according to the overall state of the network. The results of the analysis open the door for further insights into how information travels across animal social networks.

“Initially, we were a bit taken aback by how good these fish are at ignoring misinformation and quickly correcting when false alarms happen,” Fahimipour says. “But after building a computational model and diving into the neuroscience of decision-making, it was more of an ‘of course’ moment.” False alarms carry enough of a cost that it makes sense there is an adaptive mechanism that helps the fish filter out misinformation, he says. “Without that balance, their behavior would be a mess.”

Simon DeDeo, a cognitive scientist who studies complex systems at Carnegie Mellon University, believes the results support the idea that “*Homo sapiens* is not the only political animal.” Together with Elizabeth Hobson from the University of Tennessee, DeDeo has previously used studies of monk parakeets and pig-tail macaques to demonstrate the point that, much like



humans, animals rely on the other members of their social group to make decisions. “The idea is that every action exists within a social context,” DeDeo says. “If you have a computer, and it gets a signal from the internet, there’s a protocol and that signal is interpreted the same way every time. But with these animals, the meaning of a signal is contingent upon other things that have happened previously.”

In DeDeo’s reading, Fahimipour’s reef fish follow the same score: They partly outsource decision-making to their network, which fluctuates between various states of sensitivity. “These animals understand that more information is not necessarily better,” DeDeo says. “There’s a sort of wisdom of the crowd.”

Fahimipour is particularly interested in how animals might respond to alarm overload—and how that might compare to human behavior. “One way animals seem to handle the issue of distinguishing between

Homo sapiens is not the only political animal.

true and false alarms is by tuning down sensitivity to [their] neighbors and their actions when there’s too much information coming in,” he says.

Humans are a lot like the fish, he says. Bombarded with too much information? “It might be a good idea to take a step back and assess the situation for yourself.”

—Elena Kazamia

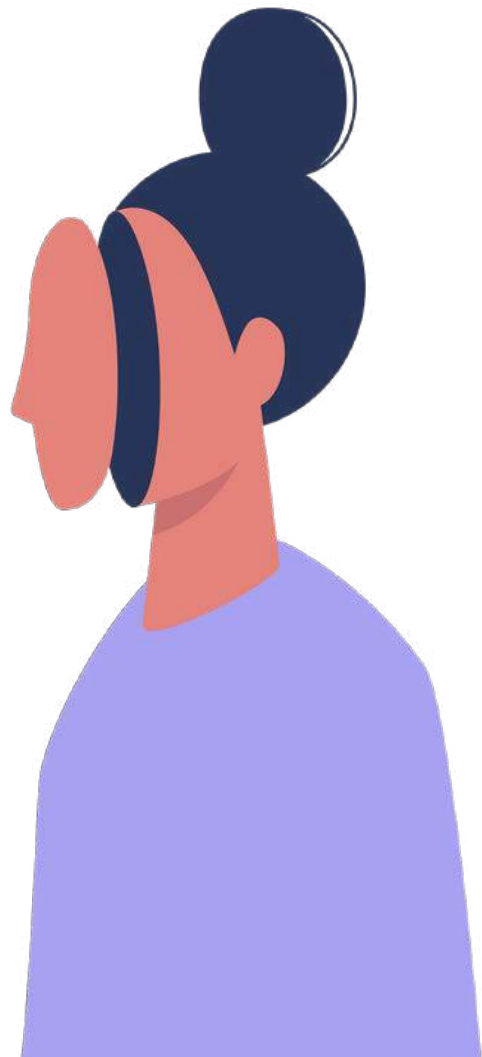
NEUROSCIENCE

When Reality Feels Unreal

FOR SOME PEOPLE, it arrives with a car crash. Others an assault or a medical diagnosis. Still others with a drug dose or a period of sustained stress. Suddenly a veil unfurls, and the world around them seems unreal. The same furniture is in the living room. The same trees are outside turning shades of gold in the sun. But it’s all not quite ... *right*. Even one’s hand doesn’t seem like their own.

Most people will experience this sensation at some point in life, a passing haze of disconnection for a few moments, hours, or days. For some, however—an estimated 1 to 2 percent of the population—it persists for months, years, even decades, becoming a chronic “depersonalization-derealization disorder.” Some psychiatrists think that figure is low, and that the condition is widely underdiagnosed, frequently hiding within the layers of depression or anxiety.

Rachael Murphy first began exploring the disorder a few years ago. She’s the author of a neuroscience review of this existential purgatory and has spent years meeting with patients who have the disorder, as a resident in the department of psychiatry at Lehigh Valley Health Network in Pennsylvania.



NADIA SNOPEK / SHUTTERSTOCK



“I know this is my hand, but it doesn’t really feel like it belongs to me.”

We wanted to know what is happening in the brain when reality ceases to feel real, what that experience is like, and what that might tell us about the nature of our constructed reality. So we called Murphy and ended up talking about all of this, as well as nihilism, photons, and the importance of an emotional connection to your couch.

What is this disorder like to those experiencing it?

It’s almost a nihilistic sensation to feel like you’re not in your body anymore, to feel like you’re not connected to reality anymore. We see the philosophers like Nietzsche describe it, but it becomes an experience in itself, even at the physical level. I’ve worked with probably thousands of patients, and they tell me, “I feel like there’s no more meaning.”

What attracted you to this slippery and, some might say, neglected corner of psychiatry?

I was interested in the brain, but also in the humanities, philosophy, religion, and in knowing the deeper metaphysical aspects of what’s going on in the mind. In 2020, I switched disciplines from neurology to psychiatry. I wanted to show how many people I saw struggling with this phenomenon, especially during the pandemic. There were a lot of stressful conversations happening in the world, and people were paying more attention to trauma and how it manifests in the body. Because being a human being means having a body. I wanted to explain that in a way that would prove to other people that, “Hey, this isn’t just a subjective-mind experience.”

You mentioned trauma, which seems like it’s often a trigger for this sort of persistent disconnection with reality?

Yes, this can largely be explained through how the brain is reacting to stress, to trauma. Having a near-death experience or an assault or having witnessed those

things can completely unravel somebody’s trust in how they previously perceived the world. Because if reality is something that can no longer be trusted, you’re going to have hypervigilance.

Your brain will dampen down its emotional response—because that experience opened up a floodgate of negative emotions—which can help in survival mode. The problem comes when that mode is no longer serving you.

When we perceive threats, our brain usually hyperactivates the amygdala circuits in the limbic system. But one of the features of this condition is an increased activation of the prefrontal cortex—to try to dampen that overwhelm from the limbic system—that becomes chronic.

So why, in this mode, do things become unfamiliar and alien? If you think about the amygdala, it’s attaching emotional salience to memories, and it’s in the limbic system, which also involves the memory circuits, the hippocampus. When it’s working well, it’s retaining the emotional quality of your memories, and that’s giving everything a personal significance. So when you’re dampening down your limbic system, things are going to feel strange.

How does this “strange” lens on reality feel, in daily life?

When you’re dissociated, the integration of emotional information and the factual information is severed. When you’re in survival mode, you don’t have room for the emotional information. But that’s the information that’s tied to everything you feel and your sense of self.

So even looking at the most simple things becomes distressing. Because all you have is just the factual information. I’ve heard someone say: “This is my couch. I know it is my couch. But it doesn’t *feel* like my couch.” Others say, “I know this is my relative, or my spouse, but how come I’m not feeling a connection?” Or even, “I know this is my hand, but it doesn’t really feel like it belongs to me.”



What happens when that becomes chronic? Now the problem is the anxiety and fear about the disconnection causes people to stay in that fearful, survival state. Then it becomes a fixed cycle, and it's hard for people to get out of it, it becomes this feedback loop. Some have even described it as like an existential OCD.

The paradoxical thing about depersonalization and derealization is that it feels like it's the opposite of insanity. There are no perceptual disturbances. One psychiatrist who was describing this in earlier years said, you feel like you're *too* sane to function.

That ties back to philosophers who describe something similar, like Nietzsche, right? Some people have even described the experience as a dark enlightenment. Because it seems like this is what reality *is*. But the brain is severing that connection with the emotional experience that is actually part of reality, too.

We often think of reality as being just the facts, the perceptions we're taking in—like I'm looking out my window and seeing sunlight coming through the leaves of the aspen trees in my yard. I can observe those details. That, I would have thought, would be a description of my reality right now. So it sounds like, from what you're saying, emotion really is a foundational element of our construction, our feeling of reality?

I would say, yes. It's that relational connection to things. What happens when those emotional connections are taken away? What's left? Who are you? Because everything is relational.

I guess that's something we take for granted, the emotional layer that creates our experience of reality. Like the aspens. Even if I wasn't consciously thinking about it, part of my implicit experience of looking at the light coming through the leaves was also feeling connected to when I planted them, the emotional valence of my life at that time—and its place on a continuum with life now. Is that more of a full definition of reality, than describing just the details of the leaves and the sunshine?

Yes, definitely. Another example is looking up at the moon. In human history, there is so much poetry, music, art, and cultural significance around the moon, right? There's the sense of awe, that mystery. So because of the human emotional attachment to the moon, there's a greater reality to it than a rock floating up there. Or like when you said the sun was filtering through the leaves. When you have that disconnection, the sun is just photons, the moon is just a rock.

I think what I've learned through all of this is that our sense of reality is always attached to something. Who are we? We're fitting into things.

Does all of this make you think that our ability to make sense of reality plays a larger role in our ability to make meaning out of life?

I think reality and meaning go together. When we think they're separate things, that's when we run into issues.

—Katherine Harmon Courage

TECHNOLOGY

The Galaxies in Your Eyes

THE EYES ARE THE WINDOW to the soul, as the old adage goes—but they also, apparently, can help us spot a fake.

According to new research, analyzing reflections in a person's eyes with tools used by astronomers to survey the cosmos can accurately determine whether a photo is AI-generated about 70 percent of the time.

Kevin Pimblet, director of the Centre of Excellence for Data Science, Artificial Intelligence, and Modelling at the University of Hull, United Kingdom, who oversaw the new work, says he became interested in applying new methods to the problem of deepfakes when he started creating AI-generated images himself. He began to notice that the eyes in the pictures didn't obey the laws of physics—there were subtle differences between



the reflections in the left and right eyes. It made him want to look deeper.

Deepfake photos can be used to spread misinformation—and pose a threat to privacy and security. It's a particularly salient problem in a year of elections around the world, including the United States, United Kingdom, and India. Some researchers call AI-generated content the biggest new threat to elections in 2024.

For the study, Pimbblet and his student, Adejumo Owolabi, created a series of fake images themselves and collected real ones from an online dataset of 70,000 faces called the Flickr-Faces-HQ Dataset. Then they analyzed these images using two tools often employed in astronomy research: the Gini Index and the CAS system. Their findings, which served as the basis for Owolabi's master's thesis, were presented at the U.K. Royal Astronomical Society's National Astronomy Meeting earlier this year.

The Gini index, created in 1912 by an Italian statistician, is a way to measure the inequality in a set of data. Astronomers use it to assess the distribution of light in photographs of galaxies. An analysis of the photograph's pixels can tell them if the light is evenly distributed or concentrated in places, which would suggest chunks of stars. CAS—which stands for concentration,

asymmetry, and smoothness—can similarly be used to measure the distribution of light in a galaxy or other object.

With the two tools, Pimbblet and Owolabi analyzed the reflections in the eyes of people in their photographs. They found that Gini worked better than CAS at finding fakes. If the reflections were the same size and shape in both eyes, the photo was probably real—and if not, it was probably a fake.

"It's not foolproof," says Pimbblet of the new method. "It's merely another way in which you can add to a string of arguments to say it might be fake."

Pimbblet admits that publishing the results will likely encourage deepfake creators to simply adjust their algorithms to create more accurate eyes in the photos. "It's very much an arms race," he says, "where the people who are generating the fakes get better at it, and the people who are trying to tell the difference get better at their game as well."

Pimbblet plans to use CAS and the Gini index to analyze larger datasets. He says that similar methods could be used to determine fakes from variations in skin tone.

Tommaso Treu, an astrophysicist at the University of California, Los Angeles, says it's exciting to see



The eyes in the pictures didn't obey the laws of physics.

astrophysics tools applied outside of the discipline. The new research is “a very interesting idea,” he says. “Astrophysicists have invested a lot of brainpower in analyzing images so their tools should have very broad applications.”

History is full of examples in which the tools of one discipline enabled breakthroughs in a different discipline, such as neural networks that can be applied to everything from character recognition to astronomy. He also points out that the Gini index—which measures inequality—was originally designed for use in economics, and only later applied to astronomy.

“We’re transferring technology across from one area of endeavor to another,” says Pimblet, “and that’s really where the forefront of a lot of research lies.”

—Katharine Gammon

SOCIOLOGY

Placebo Science Is Rooted in Witch Hunts

IN 1599, A YOUNG WOMAN in the Loire Valley of France began to suffer violent behavioral outbursts, rolling around on the floor in convulsions, eyes rolled back in her head, tongue lashing out, a tortured voice erupting from her stomach. Named Marthe Brossier, she accused her neighbor of using witchcraft to cause a demon to possess her, and she quickly became famous. Her family took her on tour from town to town, and priests were called in almost daily to conduct exorcisms, with large audiences drawn to the spectacle.

At the time, a violent conflict was afoot between Catholics and Protestants in France. Brossier came from a Catholic community and her demon claimed, among other things, that all Protestants belonged to Satan. Fearing political consequences, King Henry IV sent a medical commission to study the girl in private.

Royal physician Michel Marescot decided that the way to divine the truth would be to bring both real and sham religious objects—unconsecrated water or wafers held in a bottle or box normally reserved for holy ones—and compare Brossier’s reactions to them. Over a period of 40 days, he and his cadre ran their tests and found no discernible difference in the way the girl responded to the different objects: When a sham relic was held against her skin, she would scream as though

it were made of fire. So Marescot and the other physicians concluded that Brossier was not possessed. Other special investigations organized by Catholic clergy, considered politically motivated, found the opposite, however, and reports from the different teams made their way around Europe.

From our 21st-century perspective, of course, it comes as no surprise that poor Marthe Brossier was not possessed. Still, Marescot’s trickery constitutes one of the first ever placebo-controlled trials—centuries before we had a name for them, says neuroscientist Karin Jensen, of the Karolinska Institutet in Sweden.

Scholars have long held that the placebo control, as such, was invented during the Enlightenment, or even in more modern times, after the Protestant Reformation, says Jensen. But she and a medieval scholar named Racha Kirakosian of Freiburg University were convinced there must be precursors. “During medieval days, there were people with pretty advanced scientific thinking,” says Jensen, so Kirakosian suggested they look among the scholastics, a medieval school of philosophy that relied on an Aristotelian form of analysis. These were early skeptics like French theologian Jean Gerson, Italian Dominican friar and priest Thomas Aquinas, and Italian bishop Saint Bonaventure. Back then, there was no real separation between theology



and science. “Theology was the language of science, so to speak,” says Jensen.

Jensen and Kirakosian eventually found what they were looking for in medieval texts about witch hunts. Together with Harvard University scholar of placebo research Ted Kaptchuk, they published their findings earlier this year in the *Journal of the Royal Society of Medicine*.

In the paper, they show that the royal physician Marescot was borrowing from the writings of Gerson, a medieval public intellectual and Chancellor of the University of Paris. In the late 14th century, divine revelations were in vogue. Women were often the ones to claim that God was speaking through them, and their pronouncements often contained bold ideas that had powerful social and political influence. The women were talked about extensively during meetings at the Vatican, says Jensen, and Gerson became obsessed with finding ways to tell when a revelation was real and when it was a trick. Like other scholastic theologians and philosophers, Gerson wrote a lot about divine and sham relics—how the objects’ transformation happened and how difficult it was to tell the difference. But he was the first to call for a rigorous look at divine revelations in his writings, and these writings ultimately found a wide audience.

Early medieval pre-scientific ideas were mainly spread in manuscripts that were handwritten in

monasteries, but when the printing press was invented, among the very first books printed were Gerson’s texts explaining how to discern true from false. Gerson’s books sat, together with manuals that discussed how to tell a witch from a regular woman, on the desks of every judge and inquisitor in Europe. Their influence was enormous. “That’s when the exorcisms started to happen,” says Jensen. “The women who were allegedly possessed were, in the end, assessed by physicians. And that’s the first time when we moved from this religious realm to the medical realm.”

Gerson’s ideas about placebo controls were later used to identify charlatans like German physician Franz Anton Mesmer, for instance—who falsely claimed that something called animal magnetism could heal tissues and disorders—and to debunk miracle cures. Today, placebo controls are used in almost every rigorous form of clinical trial, to identify medicines that have a measurable biological effect from ones that work primarily through suggestion, and to discern the role of the psyche in healing. They remain one of the most clever ways we have in science to tell when a medicine’s real power resides mostly in the mind.

—Kristen French



NEUROSCIENCE

Reality Is in There

This brain map pictures a network essential to consciousness

BY KRISTEN FRENCH

THE COOL BLUE OF DAWN, the slosh of coffee in your cup, the ring of a familiar phrase which calls up an expression your mother often made. Such impressions make up our minute-to-minute awareness, the content of our consciousness. But consciousness is more than just awareness, it requires arousal, or wakefulness, something governed by primitive instincts and brain networks.

The images seen here were created by scientists from the United States and France, who recently mapped for the first time a network in the brain they call the default ascending arousal network, or dAAN. Much like the brain's default mode network governs resting awareness, during daydreaming or mind-wandering, the dAAN is thought to support the resting or default state of arousal.

The dAAN is found in subcortical regions of the brain, starting in the brainstem, and ascending through structures that govern things like hormone release, the relay of sensory signals from the body to the cortex, and attention and reward processing.

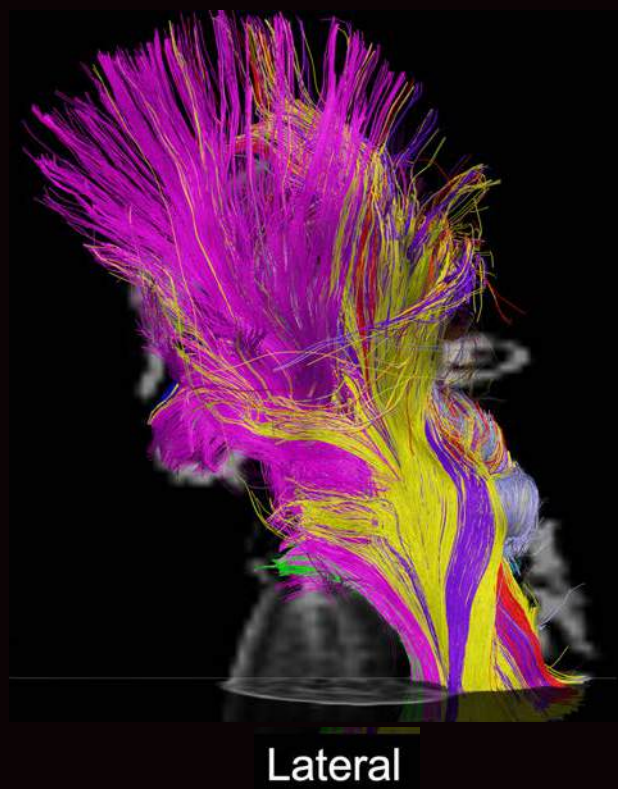
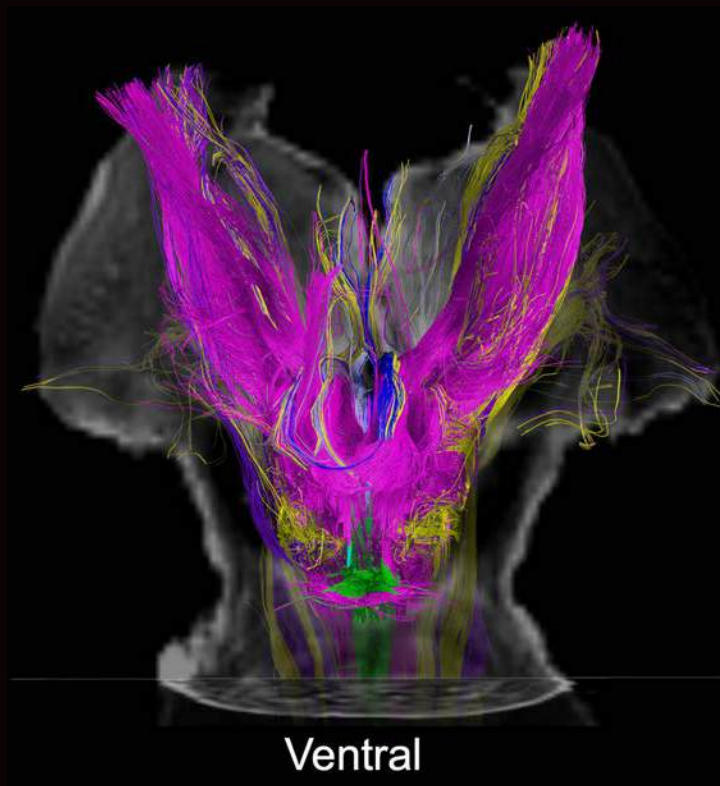
By contrast the default mode network is thought to primarily whiz through the cortex, which evolved later—a wrinkled layer of tissue that covers the cerebral hemispheres like crinkly tissue wrapped around a melon. In mapping the dAAN, the researchers found that it is also connected to various cortical networks.

The images show the dAAN from front and side views. The colored strands reveal the different structures that are connected in the network, identified in the legend below.

Legend

-  Ventral tegmental area: midbrain structure that plays a role in reward and addiction
-  Median raphe: contributes to memory formation
-  Dorsal raphe: involved in organizing reward related behaviors
-  Locus coeruleus: a spot on the brain stem responsible for responses to stress and panic
-  Pedunculotegmental nucleus: involved in sleeping and waking
-  Laterodorsal tegmental nucleus: involved in sleep, attention and reward-related behaviors
-  Periaqueductal gray: responsible for the modulation of pain and learning and action of defensive and avoidance behaviors

Edlow, B.L., *et al.* Multimodal MRI reveals brainstem connections that sustain wakefulness in human consciousness. *Science Translational Medicine* (2024).





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Investigating Reality

BY KEVIN BERGER

NEXT YEAR SIGNALS the 100th anniversary of when reality came undone. That's when physicist Werner Heisenberg, working together with fellow physicist Niels Bohr in Copenhagen, produced a theory about atomic behavior called "quantum mechanics." "Working together" is the civil term. Much of Bohr's and Heisenberg's time together over the next few years, including with other physicists, among them Albert Einstein and Erwin Schrödinger, was spent arguing.

The sharp point of dispute was Heisenberg's "uncertainty principle," which stated the attempt to measure atomic behavior, such as the position and speed of an electron, would inevitably disturb the behavior trying to be measured. Nature at its most elemental couldn't be known for certain. The consequences of Heisenberg's principle were literally earth-shattering. In "When Reality Came Undone," in the pages that follow, our special issue on reality, writer Philip Ball spells out the implications.

"Heisenberg challenged the idea that causes in nature lead to predictable effects. That seemed to undermine the very foundation of science, and it made the world seem like a lawless, somewhat arbitrary place. Reality, previously a world in which well-defined particles interacted through precise laws, so that in principle the future could be predicted from a complete knowledge of the present, seems to dissolve into a haze of possibilities, within which there was no longer any objective viewpoint for an observer to stand."

A century later the foundations of reality are still trembling. Scientists are still debating the ramifications of the Copenhagen circle's insights, offering alternative theories, attempting to make reality whole again—just as Santa Fe Institute president David Krakauer and professor David Wolpert do in this issue's The Last Word. Existential uncertainty, too, has woven into our social and personal realities.

This issue, then, is a stage for investigations into reality that cross the fields of science and culture, from physics to philosophy, geology to music. It's an issue of narratives, stories, the uniquely human way to reckon with and explore what the Copenhagen circle of scientists wrought 100 years ago. ☺

ILLUSTRATION BY TIM O'BRIEN

Confessions of a Theoretical Physicist

*My life among the elementary particles has made me question
whether reality exists at all*

BY VIJAY BALASUBRAMANIAN


$$ds^2 = -\left(1 - \frac{2GM}{r}\right) dt^2 + \left(1 - \frac{2GM}{r}\right)^{-1} dr^2 + r^2 (d\theta^2 + \sin^2 \theta d\phi^2)$$



REMEMBER THE DAY when, at the age of 7, I realized that I wanted to figure out how reality worked. My mother and father had just taken us shopping at a market in Calcutta. On the way back home, we passed through a dimly lit arcade where a sidewalk bookseller was displaying his collection of slim volumes. I spotted an enigmatic cover with a man looking through a microscope; the words “Famous Scientists” were emblazoned on it, and when I asked my parents to get it for me, they agreed. As I read the chapters, I learned about discoveries by Antonie van Leeuwenhoek of the world of microscopic life, by Marie Curie about radioactivity, by Albert Einstein about relativity, and I thought, “My God, I could do this, too!” By the time I was 8, I was convinced that everything could be explained, and that I, personally, was going to do it.

Decades have passed, and I am now a theoretical physicist. My job is to work out how all of reality works, and I take that mission seriously, working on subjects ranging from the quantum theory of gravity to theoretical neuroscience. But I must confess to an increasing sense of uncertainty, even bafflement. I am no longer sure that working out what is “real” is possible, or that the reality that my 7-year-old self conceived of even exists, rather than being simply unknown. Perhaps reality is genuinely unknowable: Things exist and there is a truth about them, but we have no way of finding it out. Or perhaps the things we call “real” are called into being by their descriptions but do not independently exist.

I am steeped in the cultural traditions of physics, a field that is my calling and trade, and in the philosophies of India with which I was raised. As a physicist, I remain committed to a system of thought which posits that: (1) things we observe are definitely real, (2) the details may be unknown, (3) bounded resources may slow progress, but (4) physical inquiry can lead us to the real truth, as long as we have time and proceed with patience. On the other hand, I am also acutely aware of philosophical traditions to the effect that: (1) there may be a reality, but (2) measurements from the world are inherently misleading and partial, so that (3) the real may be formally indescribable, and that (4) we may not have a systematic way to reach the fundamentally real and true.

Things exist and there is a truth about them, but we have no way of finding it out.

The idea that the real may be unknowable is very old. Consider the creation hymn in the *Rig Veda*, composed around 1500 to 1000 B.C., called the “Nasadiya Sukta.” This verse addresses fundamental questions of cosmology and the origin of the universe. In a beautiful translation by Juan Mascaró, it asks:

Who knows the truth? Who can tell whence and how arose this universe? The gods are later than its beginning: Who therefore knows whence comes this creation? Only he who sees in the highest heaven: He only knows whence came this universe and whether it was made or un-created. He only knows, or perhaps he knows not.

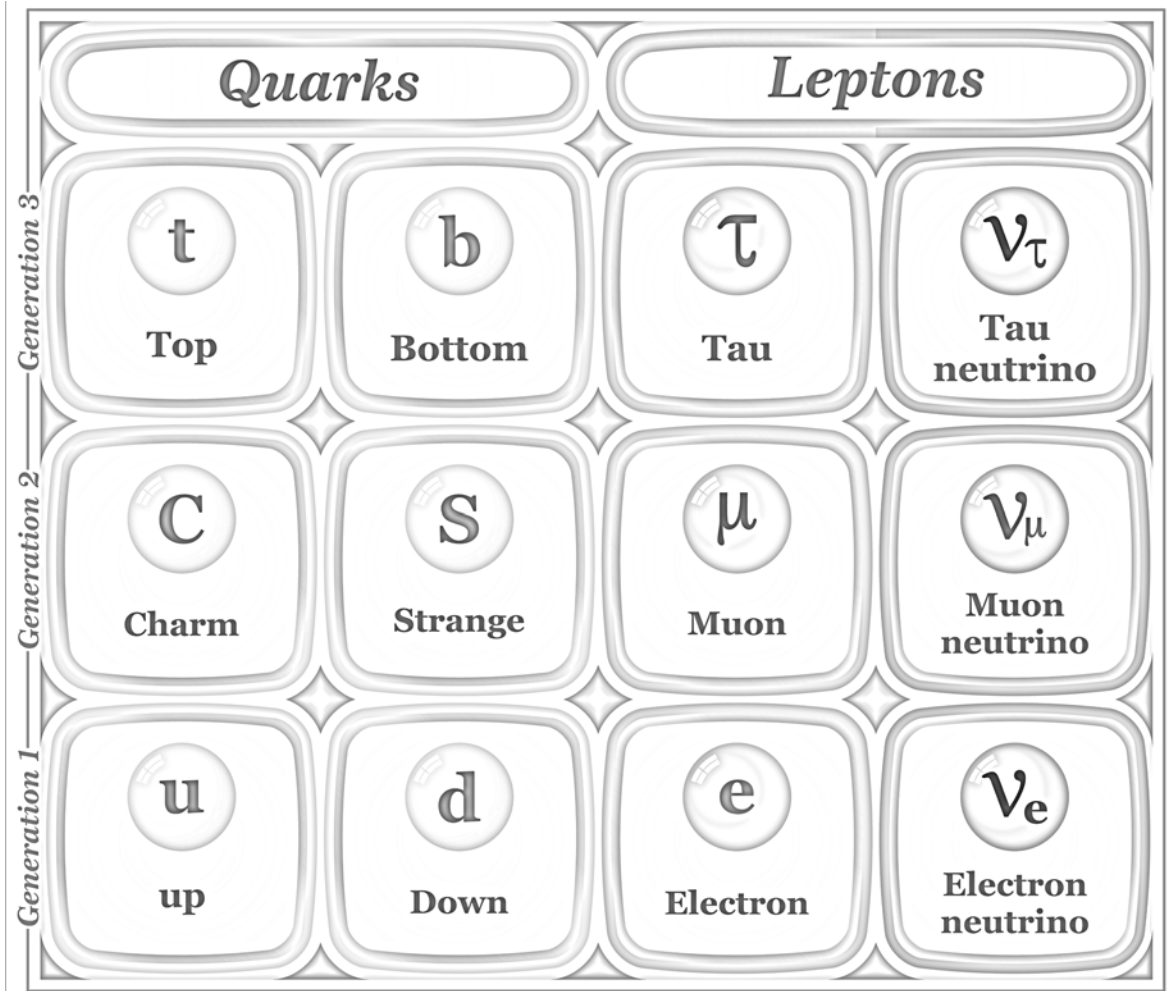
The poet who wrote this verse points out the fundamental problem of epistemology: We don’t know some things and may not even have any way of determining what we don’t know. Some questions may be intrinsically unanswerable. Or the answers may be contradictory. The “Isha Upanishad,” a Sanskrit text from the first millennium B.C., attempts to describe a reality that escapes common sense: “It moves and it moves not, it is far and it is near, it is inside and it is outside.”

A second problem is that perception fundamentally limits our ability to apprehend reality. A prosaic example is the perception of color. Eagles, turtles, bees, and shrimp sense more and different colors than we humans do; in effect, they see different worlds. Different perceptual realities can create different cognitive or conceptual realities.

Jorge Luis Borges pushed this idea to the limit in his story “Funes the Memorious,” about a man who acquires a sort of infinite perceptual capacity. Borges writes: “A circle drawn on a blackboard, a right triangle ... are forms that we can fully grasp; ... [Funes] could do the same with the stormy mane of a pony ... with the changing fire and its innumerable ashes.” Funes’ superpower sounds wondrous, but there is a catch. Borges writes that Funes was “almost incapable of ideas of a general, Platonic sort. Not only was it difficult for him to comprehend that the generic symbol *dog* embraces so many unlike individuals of diverse size and form; it bothered him that the dog ... (seen from the side) should have the same name as the dog ... (seen from the front).” The precision of Funes’ perception of reality prevents him from thinking in the coarse-grained categories that we associate with thought and cognition—categories which, necessarily rough, texture our imagined reality.

The arbitrariness of categories was the subject of another Borges story, “The Analytical Language of John Wilkins,” in which Wilkins imagined dividing animals into those belonging to the Emperor, those that are crazy-acting, those painted with the finest brush made of camel hair, those which have just broken a vase, those that from a long way off look like flies, and other oddly specific groupings.

The philosopher Michel Foucault, in his book *The Order of Things*, drew inspiration from Borges’ stories to reflect on the nature of categorization. He suggested that the categories and concepts that we define control our bounded cognition and, in their intrinsic arbitrariness, structure the realities that reside in our minds.



SKETCHY Students and the public are often told the world consists of real particles called quarks and leptons. Yet these are only concepts that approximate a certain sketch of the structure of the world.

Foucault's analysis resonates with me because it reminds me of categories in physics. For example, we routinely tell our students and the public that the world consists of particles called quarks and leptons, along with subatomic force fields. Yet these are concepts that reify a certain approximate sketch of the structure of the world. Physicists once thought that these categories were fundamental and real, but we now understand them as necessarily inexact because they ignore the finer details that our instruments have just not been able to measure.

If our categories determine the reality we perceive, can having an idea call a reality into being? This question is a version of the "simulation hypothesis," whereby all of reality as we know it is simply a simulation in some computational engine, or perhaps a version of the idealism of Plato, where things that we can conceive in the world echo imperfectly an ideal that is the true reality.

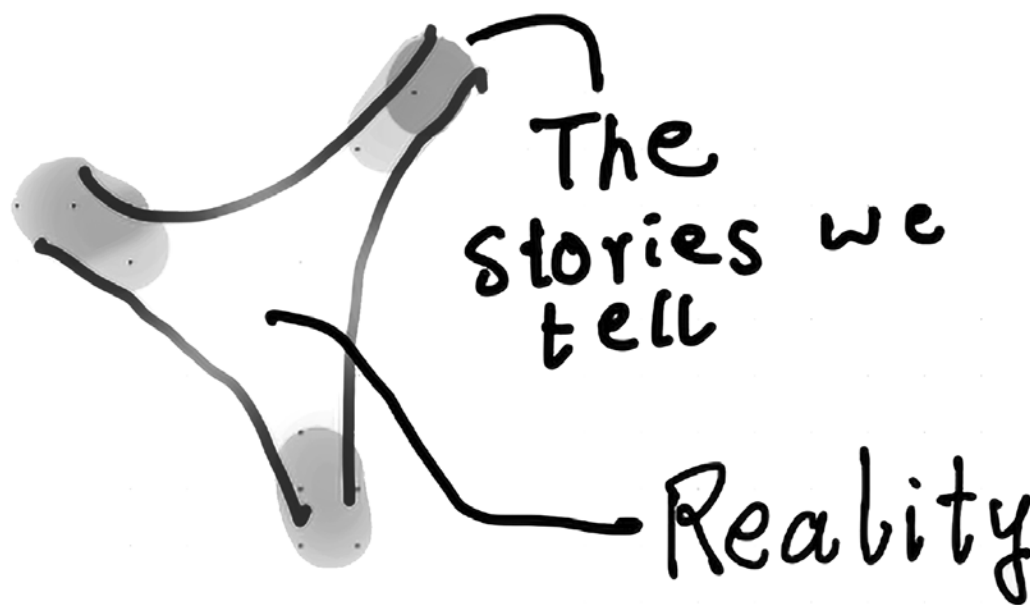
Consider, for example, Mymosh the Self-begotten, the tragic hero of a story by Polish writer, Stanislaw Lem, in his volume *The Cyberiad*. Mymosh, a sentient machine self-organized by accident from a cosmic garbage heap,

conjugates up entire worlds and peoples just by imagining them. Are those people real, or are they all in his head? In fact, is there a difference? After all, Mymosh's imagination is a physical process—electrical impulses in his brain. So perhaps the people he imagines are real in some sense.

Some of these philosophical conundrums have concrete avatars in theoretical physics. Consider the notion of “duality” between physical theories. In this context, a “theory” means a mathematical description of a hypothetical universe, which we develop as a stepping-stone to understanding the actual universe in which we live. Two theories are said to be “dual,” or equivalent, if every observable in one matches some observable in the other. In other words, the two theories are different representations of the same physical system. Often in these dualities the elementary variables, or particles, of one theory become the collective variables, or lumps of particles, of the other, and vice versa. Dual theories scramble some of the most basic categories in physics, such as the difference between “bosonic” particles (any number of which can be in the same place at the

same time) and “fermionic” particles (no two of which can be in the same place at the same time). These two kinds of particles have entirely different physical properties, so you would think that they could not be equivalent. But through dualities, it turns out that lumps of bosons can act like fermions, and vice versa. So, what's the reality here?

Even more dramatic are dualities involving the force of gravity. On one side, we have theories of matter and all the forces except gravity; on the other, we have theories of matter and forces including gravity. These theories look very different. They are couched in terms of different forms of matter, different types of forces, and even different numbers of spacetime dimensions. Yet they describe precisely the same fundamental physics. So, what is “real” here? If one theory says the force of gravity operates and the other says it doesn't, what do we conclude about the reality of gravity? Perhaps we can use my sketch to visualize the situation—we are able to tell stories about the corners of this diagram of possible worlds, where simplifications and approximations suffice, but the



If our categories determine the reality we perceive, can having an idea call a reality into being?

categories and concepts that we have been capable of, at least to date, fail to describe the interior where reality is actually located.

Quantum mechanics makes things even more confusing. Quantum-mechanical states of a system can be combined, or superposed, in seemingly contradictory ways. So, the spin of an electron can be in a superposition of pointing up and down—an idea that might seem akin to suggesting that, say, a cat can be in a superposition of alive and dead. Does that mean these objects are in both states or neither state? Some theories suggest that measuring a cat (to continue with this metaphor) could cause it to collapse into a state of aliveness or deadness; others, evoking something like the many-worlds theory, suggest that the combined superposition continues through time. This is a *casse-tête*, a head breaker.

Where does this leave me? Perhaps we can reconcile all these ideas by following Ludwig Wittgenstein, who proposed in his *Tractatus Logico-Philosophicus*, possibly referencing previous ideas of Søren Kierkegaard, that the theories and concepts we build are like ladders or nets we use to reach the truth, but we must throw them away upon getting there. I myself am trying to find my way by working in multiple fields, both physics and neuroscience, studying both the world and the mind that perceives it, because I believe that the quest

to understand the reality of the universe must contend with the truncations imposed by the perceptual and cognitive limitations of the mind.

Should we bother seeking truths about the world in light of the doubts I have set out? I am hardly the first to ask. Socrates, according to Plato, remarked to Meno: “I would contend ... that we will be better [people], braver and less idle, if we believe that one must search for the things one does not know, rather than if we believe that it is not possible to find out what we do not know and that we must not look for it.”

I am with Socrates on this one—his attitude is wise and pragmatic. If there is a reality and a truth about it, we will be better off and more likely to find it by searching, rather than assuming that it is not there. And even if the search, and the ladders we use to climb obstacles, do not lead us to the truth, we will enjoy the journey. ☺

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In the Beginning, There Was Computation

Life is code, and code is life, in nature as it is in technology

BY BLAISE AGÜERA Y ARCAS

ABIOTENESIS

How did life on Earth first arise? Despite his clear articulation of the principle of evolution, Charles Darwin didn't have a clue. In 1863, he wrote to his close friend Joseph Dalton Hooker that "it is mere rubbish, thinking, at present, of origin of life; one might as well think of origin of matter."

Today, we have more of a clue, although the details are lost to deep time. Biologists and chemists working in the field of abiogenesis—the study of the moment when, 3 or 4 billion years ago, chemistry became life—have developed multiple plausible origin stories. In one, proto-organisms in an ancient "RNA world" were made of RNA molecules, which both replicated and folded into 3-D structures that could act like primitive enzymes.¹ In a competing "metabolism first" account, chemical reaction networks sputtered to life in the porous rock chimneys of "black smokers" on the ocean floor, powered by geothermal energy; RNA and DNA came later.²

Either way, even bacteria—the simplest life forms surviving today—are a product of many subsequent evolutionary steps. The most important of these steps may have been large and sudden, not the everyday, incremental mutation and selection theorized by Darwin. These "major evolutionary transitions" involve simpler, less complex replicating entities becoming interdependent to form a larger, more complex, more capable replicator.³

As maverick biologist Lynn Margulis discovered in the 1960s, eukaryotic cells are the result of such a symbiotic event, when the ancient bacteria that became our mitochondria were engulfed by another single-celled life

form, related to today's archaea. At moments like these, the tree of life doesn't just branch; it also entangles with itself, its branches merging to produce radically new forms. Margulis was an early champion of the idea that these events are what drive evolution's leaps forward.

It's likely that bacteria are themselves the product of such symbiotic events—for instance, between RNA and proteins.⁴ Even the feebly replicating chemical reaction networks in those black smokers can be understood as such an alliance, a set of reactions which, by virtue of catalyzing each other, formed a more robust, self-sustaining whole.

So in a sense, Darwin may have been right to say that "it is mere rubbish" to think about the origin of life, for life may have had no single origin, but rather, have woven itself together from many separate strands, the oldest of which look like ordinary chemistry. Intelligent design isn't required for that weaving to take place; only the incontrovertible logic that sometimes, an alliance creates something enduring, and that whatever is enduring ... endures.

Often, enduring means both occupying and creating entirely new niches. Hence eukaryotes did not replace bacteria; indeed, they ultimately created many new niches for them. Likewise, the symbiotic emergence of multicellular life—another major evolutionary transition—did not supplant single-celled life. Our planet is a palimpsest, with much of its past still visible in the present. Even the black smokers are still bubbling away. The self-catalyzing chemistry of proto-life may still be brewing down there, slowly, on the ocean floor.

We are made out of functions, and those functions are made out of functions, all the way down.

II

COMPUTATION

While most biochemists have focused on understanding the particular history and workings of life on Earth, a more general understanding of life as a phenomenon has come from an unexpected quarter: computer science.

The theoretical foundations of this connection date back to two of the field's founding figures, Alan Turing and John von Neumann.

After earning a degree in mathematics at Cambridge University in 1935, Turing focused on one of the fundamental outstanding problems of the day: the *Entscheidungsproblem* (German for “decision problem”), which asked whether there exists an algorithm for determining the validity of an arbitrary mathematical statement. The answer turned out to be “no,” but the way Turing went about proving it ended up being far more important than the result itself.⁵

Turing's proof required that he define a general procedure for computation. He did so by inventing an imaginary gadget we now call the “Turing Machine.” The Turing Machine consists of a read/write head, which can move left or right along an infinite tape, reading and writing symbols on the tape according to a set of rules specified by a built-in table.

First, Turing showed that any calculation or computation that can be done by hand could also be done by such a machine, given an appropriate table of rules, enough

time, and enough tape. He then showed that there exist certain tables of rules that define *universal* machines, such that the tape itself can specify not only any input data, but also the desired table, encoded as a sequence of symbols. This is a general-purpose computer: a single machine that can be programmed to compute *anything*.

In the early 1940s, von Neumann, a Hungarian-American polymath who had already made major contributions to physics and mathematics, turned his attention to computing. He became a key figure in the design of the ENIAC and EDVAC—among the world's first real-life Universal Turing Machines, now known as “computers.”

Over the years, a great deal of thought and creativity has gone into figuring out how simple a Universal Turing Machine can get. Only a few instructions are needed. Esoteric language nerds have even figured out how to compute with just a single instruction (a so-called OISC or “one instruction set computer”).

There are irreducible requirements, though: The instruction, or instructions, must change the environment in some way that subsequent instructions are able to “see,” and there must be conditional branching, meaning that depending on the state of the environment, either one thing *or* another will happen. In most programming languages, this is expressed using “if/then” statements. When there's only a single instruction, it must serve both purposes, as with the SUBLEQ language, whose only instruction is “subtract and branch if the result is less than or equal to zero.”

III

FUNCTIONALISM

Both Turing and von Neumann were keenly aware of the parallels between computers and brains, developing many ideas that would become foundational to neuroscience and AI. Von Neumann's report on the EDVAC explicitly described the machine's logic gates as electronic neurons.⁶ Whether or not that analogy held (it did not; neurons are more complex than logic gates), the key insight here was that both brains and computers are defined not by their mechanisms, but by what they *do*—their function, both in the colloquial and in the mathematical sense.

A thought experiment can illustrate the distinction. While we still have much to learn about the brain, biophysicists have thoroughly characterized the electrical behavior of individual neurons. Hence, we can write computer code that accurately models how they respond to electrical and chemical inputs. If we were somehow able to replace one of the neurons in your brain with a computer running such a model, plugging its inputs and outputs as appropriate into neighboring neurons, would the rest of your brain—or “you”—be able to tell the difference?

If the model is faithful, the answer is “no.” That answer remains the same if one were to replace a million neurons ... or all of them. What matters, whether at the scale of an individual neuron or a whole brain, is *function*. We are made out of functions, and those functions are made out of functions, all the way down.

In 1950s popular culture, computers were often thought to be “like” brains for superficial reasons, like the fact that they both rely on electricity. For Turing, such details were irrelevant, and attaching importance to them was mere superstition. A computer could just as well be made out of cogs and gears, like the steampunk “Analytical Engine” Charles Babbage and Ada Lovelace dreamed of (but sadly, never built) in the 19th century. The deeper point was that a sufficiently powerful general-purpose computer, suitably programmed, can compute whatever the brain computes.

AI was the search for that program, and the point of Turing's Imitation Game, a thought experiment known nowadays as the Turing Test, was that when such a program can behave functionally like an intelligent human being, we should conclude that the computer (or the running program) is likewise intelligent.

In its usual form, the Turing Test simplifies things by restricting interaction to a chat window, but when one zooms out to consider a whole living body, not just a brain in a vat, this simplification no longer seems adequate. Evolutionarily speaking, the most basic function of an organism is not to send and receive text messages, but to reproduce. That is, its output is not just information, but a real-life copy of something like *itself*. How, von Neumann wondered, could a machine (in the broadest possible sense) reproduce? How, in other words, is life possible?



COMPLEXITY RISING These images are from a video excitedly taken by the author of digital life emerging in one of the first runs of bff, a programming language, on his laptop. Imperfect replicators arose almost immediately, with a sharp transition to whole-tape replication after approximately 6 million interactions, followed by several further symbiotic “complexifications.” As these transitions took place, the number of computations (“ops”) per interaction rose from a few to thousands.

IV

REPRODUCTION

Von Neumann imagined a machine made out of standardized parts, like LEGO bricks, paddling around on a reservoir where those parts could be found bobbing on the water.⁷ The machine’s job is to gather all the needed parts and construct another machine like itself. Of course, that’s exactly what a bacterium has to do in order to reproduce; in fact it’s what every cell must do in order to divide, and what every mother must do in order to give birth.

On the face of it, making something as complex as you yourself are has a whiff of paradox, like lifting yourself up by your own bootstraps. However, von Neumann showed that it is not only possible, but straightforward, using a generalization of the Universal Turing Machine.

He envisioned a “machine A” that would read a tape containing sequential assembly instructions based on a limited catalog of parts, and carry them out, step by step. Then, there would be a “machine B” whose function is to copy the tape—assuming the tape itself is also made out of available parts. If instructions for building machines A and B are *themselves* encoded on the tape, then *voilà*—you have a replicator.

Instructions for building any additional non-reproductive machinery can also be encoded on the tape, so it’s even possible for a replicator to build something *more* complex than itself. A seed, or a fertilized egg, illustrate the point.

Remarkably, von Neumann described these requirements for a self-replicating machine before the discovery of DNA’s structure and function. Nonetheless, he got it exactly right. For life on Earth, DNA are the tape; DNA polymerase, which copies DNA, is “machine B”; and ribosomes, which build proteins by following the sequentially encoded instructions on DNA, are “machine A.” Ribosomes and DNA polymerase are made out of proteins whose sequences are, in turn, encoded in our DNA and manufactured by ribosomes. That is how life lifts itself up by its own bootstraps.

V

EQUIVALENCE

Although this is seldom fully appreciated, von Neumann's insight established a profound link between life and computation. Machines A and B are Turing machines. They must execute instructions that affect their environment, and those instructions must run in a loop, starting at the beginning and finishing at the end. That requires branching, such as “*if* the next instruction is the codon CGA, *then* add an arginine to the protein under construction,” and “*if* the next instruction is UAG, *then* STOP.” It's not a metaphor to call DNA a “program”—that is literally the case.

There are meaningful differences between biological computing and the kind of digital computing done by the ENIAC, or your smartphone. DNA is subtle and multilayered, including phenomena like epigenetics and gene proximity effects. Cellular DNA is nowhere near the whole story, either. Our bodies contain (and continually swap) countless bacteria and viruses, each running their own code. Biological computing is massively parallel; your cells have somewhere in the neighborhood of 300 *quintillion* ribosomes. All this biological computing is also noisy; every chemical reaction and self-assembly step is stochastic.

It's computing, nonetheless. There are, in fact, many classic algorithms in computer science that *require* randomness, which is why Turing insisted that the Ferranti Mark I, an early computer he helped to design in 1951, include a random number instruction. Randomness is thus a small but important extension to the original Turing Machine, though any computer can simulate it by computing deterministic but random-looking or “pseudorandom” numbers.

Parallelism, too, is increasingly fundamental to computer science. Modern AI, for instance, depends on both massive parallelism *and* randomness—as in the “stochastic gradient descent” algorithm, used for training most of today's neural nets, and the “temperature” setting used in virtually all chatbots to introduce a degree of randomness into their output.

Randomness, massive parallelism, and subtle feedback effects all conspire to make it very, very hard to reason about, “program,” or “debug” biological computation by hand. (We'll need AI help.) Still, we should keep in mind that Turing's fundamental contribution was not the invention of any specific machine for computing, but a general theory of computation. Computing is computing, and all computers are, at bottom, equivalent.

Any function that can be computed by a biological system can be computed by a Turing Machine with a random number generator, and vice versa. Anything that can be done in parallel can also be done in series, though it might take a very long time. Indeed, much of the inefficiency in today's artificial neural net-based AI lies in the fact that we're still programming serial processors to loop sequentially over operations that brains do in parallel.

VI

ARTIFICIAL LIFE

Von Neumann's insight shows that life depends on computation. Thus, in a universe whose physical laws did *not* allow for computation, it would be

impossible for life to arise. Luckily, the physics of our universe *do* allow for computation, as proven by the fact that we can build computers—and that we're here at all.

Now we're in a position to ask: In a universe capable of computation, how often will life arise? Clearly, it happened here. Was it a miracle, an inevitability, or somewhere in between? A few collaborators and I set out to explore this question in late 2023.

Our first experiments used an esoteric programming language called (apologies) Brainfuck.⁸ While not as minimal as SUBLEQ, Brainfuck is both very simple and very similar to the original Turing Machine. Like a Turing Machine, it involves a read/write head that can step left or right along a tape.

In our version, which we call “bff,” there's a “soup” containing thousands of tapes, each of which includes both code and data. The tapes are of fixed length—64 bytes—and start off filled with random bytes. Then, they interact at random, over and over. In an interaction, two randomly selected tapes are stuck end to end, creating a 128-byte-long string, and this combined tape is run, potentially modifying itself. The 64-byte-long halves are then pulled back apart and dropped back into the soup. Once in a while, a byte value is randomized, as cosmic rays do to DNA.

Since bff has only seven instructions, represented by the characters “< > + - , []”, and there are 256 possible byte values, following random initialization only 2.7 percent of the bytes in a given tape will contain valid instructions; any non-instructions are skipped over. Thus, at first, not much comes of interactions between tapes. Once in a while, a valid instruction will modify a byte, and this modification will persist in the soup. On average, though, only a couple of computational operations take place per interaction, and usually, they have no effect. In other words, while

computation is *possible* in this toy universe, very little of it actually takes place. When a byte is altered, it's likely due to random mutation, and even when it's caused by the execution of a valid instruction, the alteration is arbitrary and purposeless.

But after a few million interactions, something magical happens: The tapes begin to reproduce. As they spawn copies of themselves and each other, randomness gives way to complex order. The amount of computation taking place in each interaction skyrockets, since—remember—reproduction requires computation. Two of Brainfuck's seven instructions, “[” and “],” are dedicated to conditional branching, and define loops in the code; reproduction requires at least one such loop (“copy bytes until done”), causing the number of instructions executed in an interaction to climb into the hundreds, at minimum.

The code is no longer random, but obviously *purposive*, in the sense that its function can be analyzed and reverse-engineered. An unlucky mutation can break it, rendering it unable to reproduce. Over time, the code evolves clever strategies to increase its robustness to such damage. This emergence of function and purpose is just like what we see in organic life at every scale; it's why, for instance, we're able to talk about the function of the circulatory system, a kidney, or a mitochondrion, and how they can “fail”—even though nobody designed these systems.

We reproduced our basic result with a variety of other programming languages and environments. In one especially beautiful visualization, my colleague Alex Mordvintsev created a two-dimensional bff-like environment where each of a 200×200 array of “pixels” contains a tape, and interactions occur only between neighboring tapes on the grid. The tapes are interpreted as instructions for the iconic Zilog Z80 microprocessor, launched in 1976 and used in many 8-bit computers over the years (including the Sinclair ZX Spectrum, Osborne 1, and TRS-80). Here, too, complex replicators soon emerge out of the random interactions, evolving and spreading across the grid in successive waves.

It's not a metaphor to call DNA a "program"—that is literally the case.

VII

THERMODYNAMICS

We don't yet have an elegant mathematical proof of the sort Turing would have wanted, but our simulations suggest that, in general, life arises spontaneously whenever conditions permit. Those conditions seem quite minimal: a physical environment capable of supporting computation, a noise source, and enough time.

Replicators arise because an entity that reproduces is more dynamically stable than one that doesn't. In other words, if we start with one tape that *can* reproduce and one that *can't*, then at some later time, we're likely to find many copies of the one that can reproduce, but we're unlikely to find the other at all, because it will either have been degraded by noise or overwritten.

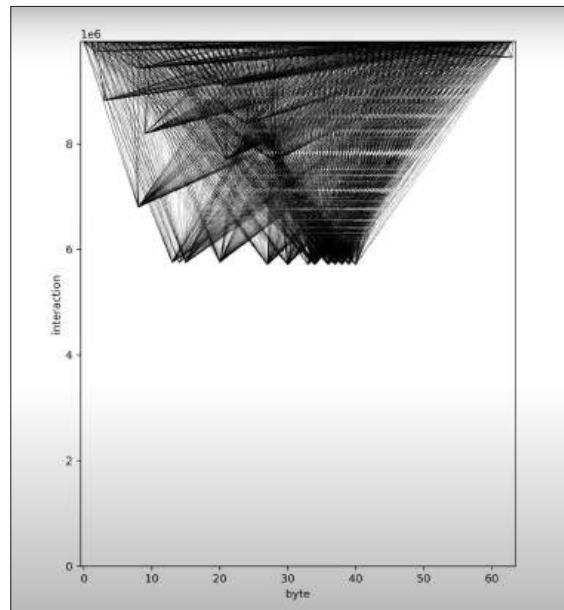
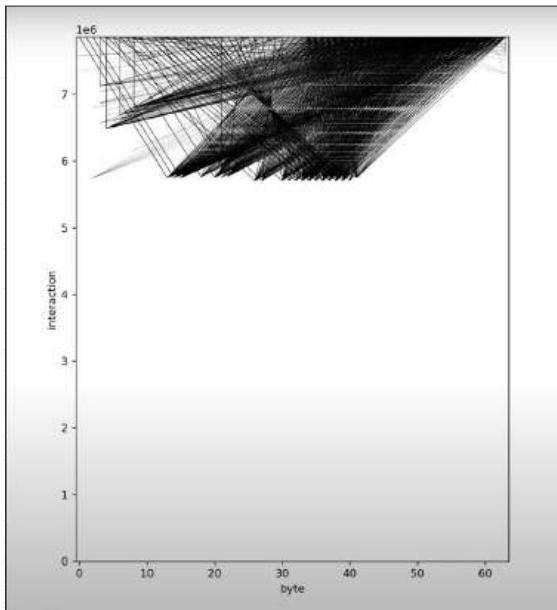
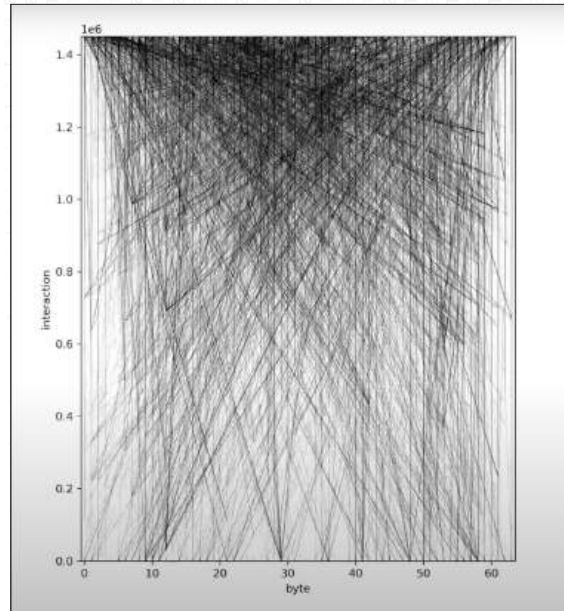
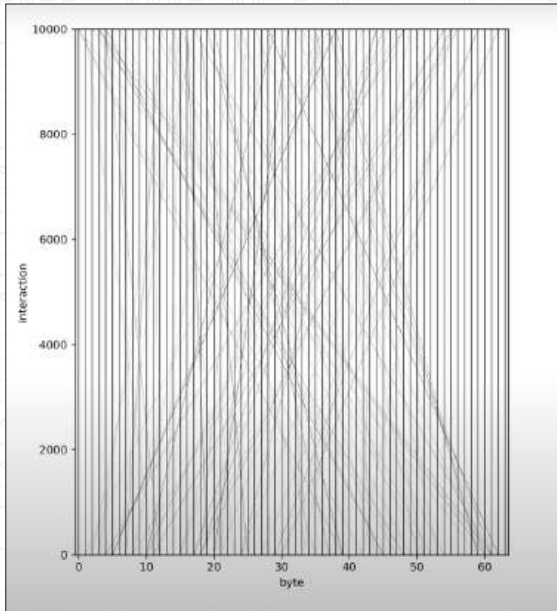
This implies an important generalization of thermodynamics, the branch of physics concerned with the statistical behavior of matter subject to random thermal fluctuations—that is, of all matter, since, above absolute zero, *everything* is subject to such randomness. The famous second law of thermodynamics tells us that, in a closed system, entropy will increase over time; that's why, if you leave a shiny new push mower outside, its blades will gradually dull and

oxidize, its paint will start to peel off, and in a few years, all that will be left is a high-entropy pile of rust.

To a physicist, life is weird, because it seems to run counter to the second law. Living things endure, grow, and can even become more complex over time, rather than degrading. There is no strict violation of thermodynamics here, for life can't exist in a closed system—it requires an input of free energy—but the seemingly spontaneous emergence and complexification of living systems has seemed beyond the purview of physics.

It now seems clear, though, that by unifying thermodynamics with the theory of computation, we ought to be able to understand life as the predictable outcome of a statistical process, rather than regarding it uneasily as technically permitted, yet mysterious. Our artificial life experiments suggest that, when computation is possible, it will be a "dynamical attractor," because replicating entities are more dynamically stable than non-replicating ones, and, as von Neumann showed, computation is required for replication.

In our universe, that requires an energy source. This is because, in general, computation involves irreversible steps, and these consume free energy. Hence, the chips in our computers draw power and generate heat when they run. Life must draw power and generate heat for the same reason: because it is inherently computational.



EVOLUTION THROUGH SYMBIOSIS These images are from an animation created by the author in the programming language bff. Vertical lines in the beginning showed bytes tracing their lineages to the original (random) values; diagonal lines showed bytes increasingly copying themselves from one location to another. Around 2 million interactions, imperfect replicators begin competing, chaotically overwriting each other to create short-lived chimeras; then, at about 5.6 million interactions, a symbiotic whole-tape replicator suddenly emerged out of the chaos like a cat's cradle, subsequently undergoing further evolutionary changes, yet conserving elements of its original architecture indefinitely.

VIII

COMPLEXIFICATION

When we pick a tape out of the bff soup after a few million interactions, when replicators have taken over, we often see a level of complexity in the program on that tape that seems unnecessarily—even implausibly—high. A working replicator *could* consist of just a handful of instructions in a single loop, requiring a couple of hundred operations to run. Instead, we often see instructions filling up a majority of the 64 bytes, multiple and complex nested loops, and thousands of operations per interaction.

Where did all this complexity come from? It certainly doesn't look like the result of simple Darwinian selection operating on the random text generated by a proverbial million monkeys typing on a million typewriters. In fact, such complexity emerges even with *zero* random mutation—that is, using only the initial randomness in the soup, which works out to a novella's worth of gibberish. Hardly a million monkeys—and far too little to contain more than a few consecutive characters of working code.

The answer recalls Margulis' insight: the central role of symbiosis, rather than mere random mutation and selection, in evolution. When we look carefully at the quiescent period before tapes begin replicating, we notice a gradual, steady rise in the amount of computation taking place. This is due to the rapid emergence of *imperfect* replicators—very short bits of code that, in one way or another, have some nonzero probability of generating more code. Even if the code produced isn't like the original, it's still code, and *only* code can produce more code; non-code can't produce anything!

Thus, there's a selection process at work from the very beginning, wherein code begets code. This inherently creative, self-catalyzing process is far more important than random mutation in generating novelty. When bits of proliferating code combine to form a replicator, it's a symbiotic event: By working together, these bits of code generate more code than they could separately, and the code *they* generate will in turn produce *more* code that does the same, eventually resulting in an exponential takeoff.

Moreover, after the takeoff of a fully functional tape replicator, we see further symbiotic events. Additional replicators can arise *within* a replicating tape, sometimes producing multiple copies of themselves with each interaction. In the presence of mutation, these extra replicators can even enter into symbiotic relationships with their "host," conferring resistance to mutational damage.

Computers and cellphones are certainly purposive, or we wouldn't talk about them as being buggy.

IX

ECOLOGY

Fundamentally, life is code, and code is life. More precisely, individual computational instructions are the irreducible

quanta of life—the minimal replicating set of entities, however immaterial and abstract they may seem, that come together to form bigger, more stable, and more complex replicators, in ever-ascending symbiotic cascades.

In the toy universe of bff, the elementary instructions are the seven special characters “< > + - , []”. On the primordial sea floor, geothermally driven chemical reactions that could catalyze further chemical reactions may have played the same role. Our growing understanding of life as a self-reinforcing dynamical process boils down not to *things*, but to networks of mutually beneficial *relationships*. At every scale, life is an ecology.

Nowadays, we interact with computers constantly: the phones in our pockets and purses, our laptops and tablets, data centers, and AI models. Are they, too, alive?

They are certainly purposive, or we couldn't talk about them being broken or buggy. But hardware and software are, in general, unable to reproduce, grow, heal, or evolve on their own, because engineers learned long ago that self-modifying code (like bff, or DNA) is hard to understand and debug. Thus, phones don't make baby phones, and apps don't spontaneously generate new versions of themselves.

And yet: There are more phones in the world this year than last year; apps acquire new features, become obsolete, and eventually reach end-of-life, replaced by new ones; and AI models are improving from month to month. It certainly *looks* as if technology is reproducing and evolving!

If we zoom out, putting technology and humans in the frame together, we can see that this larger, symbiotic “us” is certainly reproducing, growing, and evolving. The emergence of technology, and the mutually beneficial (if, sometimes, fraught) relationship between people and tech, is nothing more or less than our own most recent major evolutionary transition. Technology, then, is not distinct from nature or biology, but merely its most recent evolutionary layer. ☺

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The Hermit's Reality

In solitude, this modern priest is asking timeless questions

BY CAITLIN L. CHANDLER







WHEN YOU ARE A HERMIT living alone in the Italian Alps, you monitor the weather. Snow means you can't get groceries for a week. Rain will nourish the vegetable garden but also erode the hillside and send water into every crack in the roof. When the thunderstorms roll in, you get off the trail to avoid the lightning.

On a cold morning in May 2024, Johannes Schwarz stood on the narrow balcony of his hut, registering the clouds that filled the sky like cotton wool. It had rained all week and showed no sign of ceasing. Schwarz was a towering figure. He wore a beard down to his chest and a black fleece that covered the top half of his priestly robe.

In Schwarz's previous life, the weather was an app on his phone that didn't impact his daily life beyond telling him to grab an umbrella. Now it was a series of constantly changing realities that put him in touch with something that felt pure and elemental. The rain meant he would have to write inside all day and make do with the groceries he already had: For dinner he would pull apples and flour out of the storage room to make a tart.

For the past eight years, Schwarz, an Austrian priest of the Archdiocese of Vaduz in Liechtenstein, has spent part of the year in a hermitage on Monte Viso, a mountain wedged in the southwestern Italian Alps near the French border. Schwarz had come to live at the altitude of 3,900 feet to access a world removed from the clutter of daily life and parish responsibilities, one where he could pursue closer contact to the unseen. "Reality, if you really seek it out, will have answers about who we are, how we are, and what we are called to be," wrote Schwarz from his desk adorned with portraits of Catholic saints.

On the mountain, Schwarz lives what he calls a "prayer life," by which he does not mean that he prays all the time. To Schwarz, prayer means "raising your mind to God." Gardening as prayer. Lecture notes as prayer. Meditation in the wooden chapel he built himself as prayer. "If you want to be a proper hermit, you have to live in relationship to God. Otherwise you just become another wild, bearded man who lives by himself in the forest," Schwarz told me during my visit in May.

Otherwise you just become another wild, bearded man who lives by himself in the forest.

Schwarz estimated he still fell more on the side of wild, bearded man than enlightened hermit. But he was trying. He had given up many of the comforts of modern life—sofas, flat-screen TVs, constant connectivity—and taught himself how to build, plant, paint, write, and listen. Time up here was a slippery thing. He was 46, and he figured he had at least 20 more years—weather and health permitting—to better understand through devotional isolation the transitory nature of human existence and share what he found with others.

A SIGN OUTSIDE THE ENTRANCE to Schwarz's tiny stone hut reads: "Eremo San Onofrio," St. Onuphrius' Hermitage. Onuphrius was a hermit in the Egyptian desert in the fourth or fifth century, one of the early Christian ascetics who went into the wild to attain *hēsychia*, or inner silence; he lived in the desert for 70 years, enduring extreme thirst and hunger, and is commonly depicted as a skeletal man with nothing but a long beard and a loincloth of leaves. None of this was a state that Schwarz originally aspired to. "When I became a priest 20 years ago, I would have never been able to tell you that one day I will live in a hut," Schwarz said.

Schwarz grew up playing in the woods in the Austrian countryside outside the small city of Linz. As a child, he made maps tracing the creeks from their

origin to where they entered the Danube River. He had to walk over a mile from his parents' house to see friends and came from an outdoorsy family, with a great-grandmother who had hiked well into her 80s. He was only "nominally Catholic," as he puts it, which was the same for most Austrians, and his family didn't go to church.

In 1990, Schwarz was 12, and the area around Linz was full of people exploring alternative ways to live: There were workshops on aura readings and finding energetic fields. Schwarz occasionally joined in: He remembers, for instance, walking unharmed over glowing coals as a teenager. He dabbled in environmentalism, donating to Greenpeace and the World Wildlife Fund. Next came the art of puppetry: Schwarz gave street performances across Europe. Then, when he was 19, a friend who was in what Schwarz calls "the alternative scene" invited him to accompany her to Rome and Umbria.

The Basilica of Saint Francis of Assisi—glowing pink and white stones backed by Umbria's green hills—was a wonder. Schwarz learned that St. Francis had personally rebuilt the tiny chapel inside the Basilica before he had interpreted the summons to "rebuild the church" as a metaphysical invocation; the idea moved Schwarz profoundly. He could almost see St. Francis' fingerprints laying the mortar. It was in that chapel that Schwarz suddenly felt called to become a priest. He gave up other imagined prospective lives—painter, scientist, husband, father of five children—and enrolled at Austria's International Theological Institute in the eastern Alps.

"EVERY DAY I WALK myself into a state of well-being and walk away from every illness. I have walked myself into my best thoughts, and I know of no thought so burdensome that one cannot walk away from it," wrote the Danish theologian Søren Kierkegaard in 1847.

In 1998, while still a theology student, Schwarz walked more than 1,000 miles from Austria to the well-traveled Santiago de Compostela in Spain in a cloth robe, without money or a backpack, relying on the kindness of strangers. While walking, Schwarz found his attachment to comfort slipping away. First came the physical pain as the body adjusted to

day-long movement. Then, as the pain faded, the mind wandered, processing memories and new encounters, slipping in and out of rumination. But after a few weeks, "the rhythm of your steps will slowly clear your mind," wrote Schwarz. Eat, sleep, walk, repeat. He met people he would not have encountered otherwise and found them to be delightful. At some point, he stopped talking to himself—there was no internal voice or meta-commentary. This new reality was reflective and calm, like drifting in a lake. "Once you simply are, your hiking boots no longer matter," he wrote. "You've started a journey inward. What will you find, or whom?" Schwarz returned to school, but the altered state of pilgrimage stayed with him; he longed to undertake future and more ambitious walks.

MOUNTAIN MAN Part-time hermit Johannes Schwarz has made pilgrimages on foot for thousands of miles at a time. The walking, as Kierkegaard also noted, creates a different mental reality.



Reality, if you really seek it out, will have answers about who we are, and what we are.

In 2004, Schwarz became a priest, serving for nine years in a parish in peaceful, semi-rural Liechtenstein; for two of those years, he was the parish priest. But despite the bucolic surroundings, he didn't enjoy the responsibilities of overseeing a budget or making spreadsheets. His creative self was untapped, and he was always running from one thing to the next. Also, being a priest was in a way too easy and therefore dissatisfying. There was a constant reinforcement of your role in a way that could boost an ego. "You will always have people who like what you're doing and will always give you praise," Schwarz explained. Although he wanted to serve in whichever capacity his Bishop ordered, in the parish he was restless.

In 2013, Schwarz took leave from work and trekked 8,680 miles on foot from Liechtenstein to Jerusalem, and made a documentary film about this journey, *To Where God Dwells*. He was inspired to film his pilgrimage after viewing the film *Into Great Silence*, which captures the lives of the Carthusian monks at the Grande Chartreuse, a monastery in the French Alps. In Israel, he encountered the sun-bleached Negev desert, an immense space where it was hard to glimpse a living thing. "Walking through the desert, I entered a world in which you could perceive silence," Schwarz said.

The vast space held a presence, like "the joy that comes with the presence of a lover." It was as if he had suddenly entered a tent, he said, and inside the tent the atmosphere was different. He kept walking, but "the more immediate experience sort of never left me," he said. "There is this beautiful St. Augustine quote that says the lover has the urge to sing ... which I did, even though I'm not a singer, filling the desert with my voice as I walked through it." Schwarz returned to his parish, but he wanted to continue to experience that spiritual expansion.

The Alps had long captivated Schwarz as both a place and a pilgrimage route, offering well-worn footpaths that other mystics, monks, and the spiritually inclined had trod. There was a history of people retreating into their slopes for protection or inquiry into the non-material world; down in the valley from Monte Viso were the remnants of the Waldensians, followers of an ascetic Christian movement that was excommunicated by the Roman Church in 1184 and had hidden out in the valley since the end of the 13th century. In 2016, Schwarz asked permission from his Archdiocese to withdraw from parish life in pursuit of his own projects—mostly writings, documentaries, or short films to translate religious concepts into modern parlance.

After combing through different ranges for real estate, Schwarz found a property with a crumbling stone dwelling for under €20,000. There was something St. Franciscan in the idea of rebuilding a house rather than letting it dissolve.

IN THE 1950S, the English writer and adventurer Patrick Leigh Fermor absconded from the city to overcome writer's block and stay in monasteries across Europe. In *A Time to Keep Silence*, a book of letters from his sojourn, Fermor wrote about the French Abbey of St. Wandrille, which allowed no speaking or smoking. "The period during which normal standards recede and the strange new world becomes reality is slow, and at first, acutely painful," Fermor wrote. Yet after just a few days, he experienced a transformation in which his mind could

focus on larger questions, while common emotions like fear and guilt dissipated. His work improved.

Schwarz's transition into solitude was not painful like Fermor's; it was like a slow realization of cultivating something that had been inside him all along. He carried what he'd gained from his experience as a pilgrim—physical labor, isolation, minimalism, and wilderness—onto the mountain. "It's in losing yourself that you become who you truly are," Schwarz said.

At the onset of his hermitage, Schwarz kept daily habits in order to not become aimless. He slept deeply, woke without an alarm, and began his days at 5 a.m. He constantly had to repair or build to keep the house stable and the gardens producing food, lit candles in the chapel, lined the walls with cork for insulation, carved icons, and painted religious iconography.



INTO THE SOLITUDE In his cabin on the hillside of the Italian Alps, Schwarz has disentangled himself from old habits and slipped into a cadence of life in sync with the realities of weather and wildlife.

His mind does not fill with to-do lists or replay conversations from the day before.

As Schwarz labored to restore the hut and worked on videos and books, he began to experience an ease that he had not had before. The days flowed one into another. In each task, there was a kind of pleasure. As a younger person, he would have blasted music while doing outside work, but here he didn't want the distraction as he pushed stones into the steep hillside to create terraces that warm the soil. The mountain sharpened his hearing: What at first sounded like a depraved howl in the middle of the night Schwarz could soon identify as the cry of a wolf. He began to pay attention to smells of the herbs and grasses around him. "There is nothing in our mind that has not come in through the senses," he said.

During periods of rest, Schwarz said his mind does not fill with to-do lists or replay conversations from the day before. Instead, he listens to the water rushing through swollen creeks full of melted snow, glimpses the pale green leaves unfolding from tree branches. Nature is not a mother to Schwarz—nature does not give him unconditional love—but, in the lineage of St.

Francis, more like a sister, an entity to be respected. In the summer he sleeps with the balcony doors open, notes the return of frogs to the pond. He does not worry about money, because his living expenses are low, and his human interactions are occasional and fulfilling rather than constant and grating. He has a cell phone but forgets about it for long periods of time. The most stressful things Schwarz encounters are animals, like the chipmunks that slept under his stone slab roof for seven months of the year, woke up in the summer, and made a racket.

The hermitage has semi-removed Schwarz from the material world—although he still travels to give sermons, hosts visitors, and conducts local funerals when asked—but the internet connects him to it. In late 2023, he posted a series on YouTube about his life, *One Year in the Life of a Part-Time Hermit*. Schwarz wanted to share his insights, but he did not necessarily want to instruct others how to live. "I'm not suggesting you break out from your 9-5," Schwarz says in one of the videos. "I simply propose that you choose to lead an



extraordinary life. And you do not have to go anywhere to do that. I contend that a life is extraordinary only in as much as the ordinary things are done with an extraordinary amount of love.”

In his home on the mountain, Schwarz finds himself in conversation mostly with a Western religious and philosophical canon—one that includes Plato, St. Augustine, and Nietzsche. He reads the news and is troubled about the ongoing wars, but to him they also feel remote, symptoms of societies that have moved away from caring about deeper meaning and were focused on individual grievances.

“We have to look beyond the physical—to what is therefore called metaphysical,” he said. “Without metaphysics, all that is left is politics. And politics devoid of the right metaphysics—for all the good desires, hopes, and dreams of man—leads in the end to a very earthly hell.”

Schwarz, who at one point wanted to be a marine biologist, is an advocate of the scientific method, but he faults modern science with replacing the most critical questions—“What is the meaning of life?” “What is our purpose here on Earth?”—with mundane questions such as “How do objects work?” In his view, post-Enlightenment thinking had led to the subjugation of nature on a grand scale, and materialism and naturalism are ideological positions that draw on a story about the world that was not true. Not everything real can be quantified.

“Reality, if anything, is something we discover,” Schwarz said: a gift you could remain open to. He still goes on strenuous pilgrimages, which he feels are essential in whittling down existence, taking him even closer to its core. You cannot access inner stillness through reading an article about it, and perhaps, Schwarz wondered, it would have been better to say

nothing at all. And, although he is often able to access *hêsychia*, an inner silence, he is still interrogating his purpose on Earth. Was fleeing society a way for him to escape his own weaknesses and failings? Is he getting closer to God, or evading his duties as a priest?

The more Schwarz puts down roots in the Alps—he has recently built a deck and a *walipini* greenhouse, which is dug into the ground—the more he becomes aware of the temporary nature of the physical reality that surrounds him. It is at times a contradictory thing to explain. He has grown attached to the property and the birds, misses the smell of wet earth when he travels—yet increasingly sees himself as merely a custodian of the land, one who would soon leave this world for the next. Schwarz recently re-tiled his roof, choosing tiles that would last for 35 years, until he turns 81. From his vantage point, it is not so far off. “The past five years almost feel like a blink,” Schwarz said. Although the dragonflies were only hatching, he knew that soon the chestnuts would fall and he would roast their soft centers in the small wood stove during winter nights.

Unlike his desert pilgrimage, the mountain hermitage has a physical structure, but it still feels somewhat like that spiritually expansive tent where Schwarz could see things from an altered perspective. The desert and the mountain are connected: They offer a way to be in between this world and the next. “We need to understand ourselves as pilgrims passing through,” Schwarz said. ☺

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When Reality Came Undone

*A century ago, a circle of physicists shook the foundation of science.
It's still trembling.*

BY PHILIP BALL

IN 1926, TENSIONS WERE RUNNING HIGH at the Institute for Theoretical Physics in Copenhagen. The institute was established 10 years earlier by the Danish physicist Niels Bohr, who had shaped it into a hothouse for young collaborators to thrash out a new theory of atoms. In 1925, one of Bohr's protégés, the brilliant and ambitious German physicist Werner Heisenberg, had produced such a theory. But now everyone was arguing with each other about what it implied for the nature of physical reality itself. To the Copenhagen group, it appeared reality had come undone.

Bohr had electrified the scientific world in 1913 with his bold theory of how atoms are constituted. Drawing on an idea proposed in 1900 by the German physicist Max Planck, he said that the electrons that orbit the dense central nucleus are constrained to specific orbits, able to jump between them only by emitting or absorbing light in discrete packets of energy called quanta. The theory won Bohr a Nobel Prize in 1922, but it was an ungainly, ad hoc mix of traditional physics and Planck's new "quantum" hypothesis. Bohr craved an explanation that got to the root of why atoms seemed to behave in this peculiar way. It couldn't be constructed from the traditional classical mechanics that had prevailed since Isaac Newton laid out its basic rules in the 17th century but demanded a new mechanics of quanta.

Such a "quantum mechanics" was devised by Heisenberg in the summer of 1925 when he was on the island of Heligoland in the North Sea, seeking relief from his dreadful hay fever. Ambitious, bold, and brilliant, Heisenberg had come to Bohr's attention when as a student he had challenged one of Bohr's claims in a lecture the Dane gave at Göttingen University in 1922.

Bohr had invited the young man to Copenhagen in 1924, and the two of them began searching for a way to put the quantum hypothesis into a rigorous mathematical form. Heisenberg took the kind of leap of faith that Bohr had displayed in devising his quantum atom: Throw out what tradition insists on and start afresh. His scheme involved writing down the numbers measured experimentally for the frequencies of



RELATIVELY ABSURD

Albert Einstein looks relaxed here with Niels Bohr. But the idea in quantum physics that reality meant only something we observe caused him to ask with exasperation how the moon could only be real if we looked at it.

light emitted by atoms, in the form of columns called matrices. These could then be used to make calculations, for example to predict how intense the emitted rays are.

Heisenberg's matrix-based quantum mechanics looked like the breakthrough Bohr had been waiting for. As he wrote to his own former mentor, the New Zealander Ernest Rutherford in England, "We now see the possibility of developing a quantitative theory of atomic structure."

However, Heisenberg's austere matrix mechanics gave no hint of what the math meant for the real world: the physical nature of matter, light, and energy. That lacuna was intentional. Heisenberg was determined to work only from what experiments had revealed, with no assumptions about the underlying reality it described.

EINSTEIN CAN'T BELIEVE IT

By 1926, the matter was a mess. The Copenhagen circle—Bohr, Heisenberg, and colleagues including the brash young Austrian Wolfgang Pauli and their collaborator Max Born, Heisenberg's former tutor, in Göttingen—disagreed with peers such as Albert Einstein (who had proposed light quanta in 1905) and the Austrian physicist Erwin Schrödinger about how to interpret the new quantum mechanics. The suggestion coming from Copenhagen that the quantum world simply couldn't be visualized in terms of objects interacting in time and space seemed to Einstein and Schrödinger to relinquish all that science strove to attain: a physical picture of reality.

What's more, in the early part of the year, Schrödinger



A dismayed Werner Heisenberg dismissed wave mechanics as “crap.”

announced a rival form of quantum mechanics to Heisenberg's, based on the idea that quantum particles could be described as waves. That seemed to restore a physical picture of what was going on: Matrices were abstract and mathematical, but waves—even if they were waves of particle-like entities like electrons—were familiar aspects of reality. But Heisenberg, dismayed by this apparent competition for a true quantum theory, dismissed wave mechanics as “crap”; Schrödinger in turn said he was “repelled” by the abrupt quantum jumps between energy states assumed in matrix mechanics.

Soon, however, the Copenhagenists didn't even agree with each other. In trying to make sense of Heisenberg's ideas, Bohr found himself at loggerheads with the young German. Bohr was inclined to accept Schrödinger's waves and to make a concept called “complementarity,” the keystone of quantum mechanics: Entities like electrons could behave like particles or waves, but not at the same time or in the same experiment.

Heisenberg didn't care for such qualitative ideas, wanting instead just to stick with the math. “Our talks often continued till long after midnight and did not produce a satisfactory conclusion despite protracted efforts,” he wrote later. “Both of us became utterly exhausted and rather tense.” Their disagreements almost reduced Heisenberg to tears.

In the spring of 1927, Bohr took off on a skiing trip in Norway to think the matter over by himself. In his absence, Heisenberg wrote a paper in which he attempted to explain what his matrix mechanics implied for quantum objects. What he concluded seemed bizarre.

There are some pairs of properties of quantum particles, he said, that we can never measure simultaneously as accurately as we like. If we measure one of them more accurately, the other necessarily becomes less certain. There is, Heisenberg said, a fundamental uncertainty at the heart of nature. From the perspective of classical physics this seems crazy, for there is nothing to stop us measuring at once the speed and position of a large classical object (how could speeding fines ever be imposed if there were?).

Heisenberg submitted his paper for publication while Bohr was on the ski slopes, only to find on his boss' return that Bohr thought it contained serious flaws. Heisenberg sought to illustrate his “uncertainty principle” by showing how an attempt to measure the position and speed of an electron by bouncing a gamma ray off it would inevitably disturb the very things one was trying to measure. But Bohr felt that here Heisenberg was overlooking the wavy character of the gamma ray—as he was, of course, because he didn't like the idea of waves in quantum mechanics at all.

More heated conversations followed, after which Heisenberg agreed to add a note to the

end of the paper acknowledging Bohr's view on the complementarity of waves and particles. "Thank God!" he wrote to his parents. "My friendship with Bohr is of course more important than physics."

What was at stake was more than whether the new quantum mechanics was right or not. To the Copenhagen circle—here, at least, Bohr and Heisenberg agreed—the theory challenged the assumptions underlying the entire scientific enterprise for the past several centuries.

Quantum mechanics, they said, demanded we throw away the old reality and replace it with something fuzzier, indistinct, and disturbingly subjective. No longer could scientists suppose that they were objectively probing a pre-existing world. Instead, it seemed that the experimenter's choices determined what was seen—what, in fact, could be considered real at all.

In other words, the world is not simply sitting there, waiting for us to discover all the facts about it. Heisenberg's uncertainty principle implied that those facts are determined only once we measure them. If we choose to measure an electron's speed (more strictly, its momentum) precisely, then this becomes a fact about the world—but at the expense of accepting that there are simply no facts about its position. Or vice versa.

But the question, "What were the position or momentum before we measured one or the other?" has no answer—not because we couldn't know until we looked, but because the question has no meaning. We seem to choose what is real. This idea seemed crazy to Einstein. Heisenberg said Einstein refused to admit that "it was impossible, even in principle, to discover all the partial facts needed for the complete description of a physical process. And so he refused point-blank to accept the uncertainty principle."

A century later, scientists are still arguing about this issue of what quantum mechanics means for the nature of reality. Alternative

interpretations of quantum mechanics have arisen and generated their own heated debates.

One of these is the "pilot-wave" theory, a form of which was presented by the French physicist Louis de Broglie in the 1920s but which was more fully developed in the 1950s by David Bohm, and which says that quantum particles are real entities with well-defined properties in time and space, but which move and interact under the influence of waves in a somewhat mysterious field called the quantum potential.

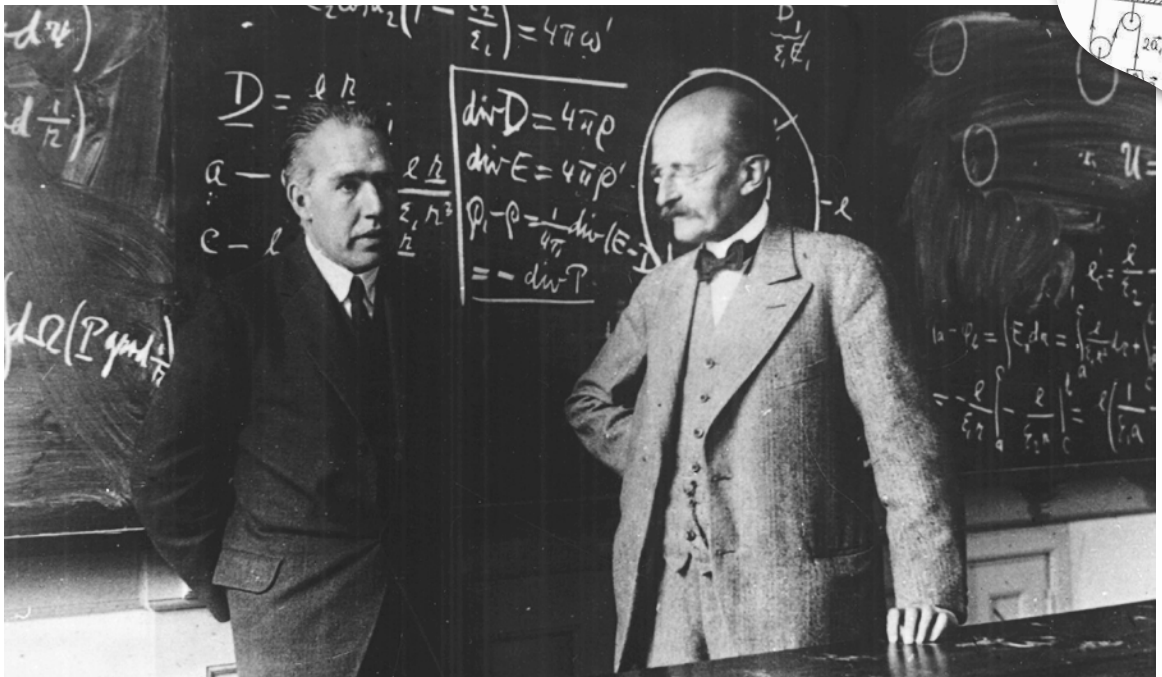
Perhaps the most popular alternative interpretation is typically dubbed the many-worlds view, first proposed by the American physicist Hugh Everett in 1957, which argues that measurements don't impose a choice on which of the possible outcomes allowed by quantum mechanics become "real"; rather, all outcomes are realized, but in different worlds that diverge when the measurement is made.

Physicist Anton Zeilinger, who shared the 2022 Nobel Prize for his experimental studies of the elusive nature of the quantum world, said it's impossible to demonstrate "that any particle has a realistic trajectory," in the case of the Broglie-Bohm interpretation. Meanwhile, Everett's claim "that the observer coexists in many different states is intrinsically untestable."

Such alternative interpretations of quantum behavior suggest that physicists want objective reality back. They want a return to what philosophers call realism, where things have definite positions and properties irrespective of how or whether we look at them. But so far, scientific investigations of the quantum world have not obliged the demands of the realists.

BOHR WON'T LET SCHRÖDINGER SLEEP

At first, Heisenberg's matrix mechanics was too much even for some of his Copenhagen colleagues. The math was fine, but what jarred



was Heisenberg's insistence that it was meaningless to seek a physical picture of what was going on. Forget the whole idea of electron orbits in atoms, he said—that's just a manner of speaking. But, Pauli objected, we can see the moon following an orbit! How can electrons be any different?

Bohr, on the other hand, seemed to delight in the puzzle. "How wonderful that we have met with a paradox," he said. "Now we have some hope of making progress." That was Bohr all over: to embrace a contradiction as if it was an answer. It was almost as if, by merely coining a word for it—complementarity—Bohr was claiming to have solved the problem. Complementarity might be loosely said to imply that contradictory things can both be true, but just not at the same time. A particle can be a wave, and vice versa—but not both

at once. "The *opposite* of one *profound truth* may very well be another *profound truth*," Bohr was fond of saying.

Bohr has been justifiably criticized for expressing his ideas obscurely, both in writing and in his lectures. But that seems to be because he was struggling to express ideas that our everyday language isn't designed to capture. When we say that wave-like quantum particles can be "in many places or states at once," or that a measurement of some property of a particle "collapses" all its smeared-out waviness into a single value, or that the strange quantum phenomenon called entanglement makes a measurement on one particle instantly influence another no matter how far away it is, we're not really talking about what quantum mechanics is like but are constructing pictures of it that are based on

QUANTUM LEAP

Niels Bohr (left), pictured here in 1930 at the University of Copenhagen Institute for Theoretical Physics with Max Planck, tied together radical new ideas proposed by Planck about a quantum realm.

Quantum mechanics replaced the old reality with something disturbingly subjective.

our own classical intuitions—exactly what quantum physics undermines.

Schrödinger felt that his wave-based quantum mechanics offered an escape from the indistinct, unformed reality that seemed to emerge from Copenhagen. Sure, it was weird that quantum particles could behave like waves, as though they were smeared out in space—but once you got over that, at least the waves felt like something real. But when Schrödinger visited Copenhagen in the autumn of 1926 to discuss his theory, he did not quite reckon with the reception he would get. Bohr later said, rather blandly, that “Schrödinger gave us a most impressive account of his wonderful work.” In fact, it was a raging battle.

Schrödinger held a seminar with the Copenhagen team that apparently descended into turmoil. According to one account, “Half a dozen physicists were shouting objections and questions. Bohr, his pipe forgotten, was pacing the room. Everyone was haranguing his neighbor ... the commotion went on for most of the week.”

Apparently exhausted by the arguments, Schrödinger caught a cold and went to bed with a fever at the Institute’s guest rooms. That brought no respite. Bohr continued to debate the matter at Schrödinger’s bedside until Bohr’s wife Margrethe persuaded him to relent for the sake of their guest’s fragile health.

“If I had known that [the wave theory] was going to be taken so seriously as to cause all of this discussion,” Schrödinger said at one point, “I would never have invented it.” And if in contrast we were forced to accept

the abominable quantum jumps alleged by Bohr, Heisenberg, and their colleagues, “I should be sorry I ever got involved with quantum theory.”

But Bohr responded by assuring him that everyone else was grateful that he had—because Schrödinger’s wave mechanics “represents a gigantic advance over all previous forms of quantum mechanics.” He wasn’t just trying to placate his guest; to Heisenberg’s chagrin, Bohr and many of his colleagues adopted Schrödinger’s wave calculus in preference to Heisenberg’s matrices, as it was generally easier to use. Schrödinger himself proved that both versions of quantum mechanics are equivalent, so which one uses is just a matter of taste.

At any rate, Schrödinger’s wave mechanics didn’t restore the kind of reality he and Einstein wanted. His theory represented all that could be said about a quantum object in the form of a mathematical expression called the wave function, from which one can predict the outcomes of making measurements on the object. The wave function looks much like a regular wave, like sound waves in air or water waves on the sea. But a wave of what?

At first, Schrödinger supposed that the amplitude of the wave—think of it like the height of a water wave—at a given point in space was a measure of the density of the smeared-out quantum particle there. But Born argued that in fact this amplitude (more precisely, the square of the amplitude) is a measure of the *probability* that we will find the particle there, if we make a measurement of its position.

HEISENBERG'S MOST DISCONCERTING IMPLICATION

This so-called Born rule goes to the heart of what makes quantum mechanics so odd. Classical Newtonian mechanics allows us to calculate the trajectory of an object like a baseball or the moon, so that we can say where it will be at some given time. But Schrödinger's quantum mechanics doesn't give us anything equivalent to a trajectory for a quantum particle. Rather, it tells us the chance of getting a particular measurement outcome. It seems to point in the opposite direction of other scientific theories: not toward the entity it describes, but toward our observation of it. What if we don't make a measurement of the particle at all? Does the wave function still tell us the probability of its being at a given point at a given time? No, it says

nothing about that—or more properly, it *permits us to say nothing about it*. It speaks only to the probabilities of measurement outcomes.

Crucially, this means that what we see depends on what and how we measure. There are situations for which quantum mechanics predicts that we will see one outcome if we measure one way, and a different outcome if we measure the same system in a different way. And this is not, as is sometimes implied (this was the cause of Heisenberg's row with Bohr), because making a measurement disturbs the object in some physical manner, much as we might very slightly disturb the temperature of a solution in a test-tube by sticking a thermometer into it. Rather, it seems to be a fundamental property of nature that *the very fact of acquiring information* about it induces a change.

HAPPY MEAL

Werner Heisenberg (left) and Niels Bohr argued endlessly over quantum reality, at times reducing Heisenberg to tears. Their friendship, though, lasted throughout their lives. Here they share a cozy chat in 1936 at the University of Copenhagen Institute for Theoretical Physics' canteen.



Alternative interpretations suggested physicists wanted objective reality back.

If, then, by reality we mean what we can observe of the world (for how can we meaningfully call something real if it can't be seen, detected, or even inferred in any way?), it is hard to avoid the conclusion that we play an active role in determining what is real—a situation the American physicist John Archibald Wheeler called the “participatory universe.” This view seemed absurd to Einstein, who asked in exasperation how the moon could only be real if he looked at it.

Einstein was right to be disturbed by all this. How could you not be, if you truly appreciated what the message from Copenhagen was? When, after one discussion, someone told Bohr that it made them giddy to think about the implications, he responded, “But if anybody says he can think about quantum problems without getting giddy, that only shows that he has not understood the first thing about them.”

Heisenberg’s “uncertainty” captured that sense of the ground shifting. It was not the ideal word—Heisenberg himself originally used the German *Ungenauigkeit*, meaning something closer to “inexactness,” as well as *Unbestimmtheit*, which might be translated as “undeterminedness.” It was not that one was uncertain about the situation of a quantum object, but that there was nothing to be certain about.

There was an even more disconcerting implication behind the uncertainty principle. The vagueness of quantum phenomena, when an electron in an atom might seem to jump from one energy state to another at a time of its own choosing, seemed to indicate the demise of causality itself. Things happened in the quantum world, but one could not

necessarily adduce a reason why. In his 1927 paper on the uncertainty principle, Heisenberg challenged the idea that causes in nature lead to predictable effects. That seemed to undermine the very foundation of science, and it made the world seem like a lawless, somewhat arbitrary place.

Reality, previously a world in which well-defined particles interacted through precise laws, so that in principle the future could be predicted from a complete knowledge of the present, seems to dissolve into a haze of possibilities, within which there was no longer any objective viewpoint for an observer to stand. The position that denies any pre-existing reality, independent of our knowledge of it, is called anti-realism. Was this then really what the Copenhagen interpretation amounted to?

Some think so, but it’s not obvious. Regarding quantum mechanics as a theory about the probabilities of measurement outcomes is not the same as saying that there is nothing before a measurement is made. It is simply to recognize the limitations of what the theory *permits us to say* about that.

One might say that, in this view, the theory doesn’t speak about *how things are*, but about what we will see *if we observe*. It doesn’t deny the independent existence of some substrate of the world that gives rise to the observations, but only of our right to pronounce on it. Historian of science Mara Beller puts it another way: Bohr’s position implies that we do not *need* to adopt a realist view of the world to use quantum mechanics to make predictions about what we will observe.

Properly construed (and the Copenhagen team were not always themselves sufficiently careful to make this clear) the

interpretation shows us the limits of what, if quantum mechanics is correct, we can conclude with confidence about reality. That's the austerity that Zeilinger advocates in any search for deeper understanding.

The problem was that Bohr, Heisenberg, and their collaborators tended to imply that such a search was pointless; we just had to accept that this is how things are. It's no wonder Einstein and others tried so hard to restore some version of the old objective reality.

One of Bohr's most provocative views was that there is a fundamental distinction between the fuzzy, probabilistic quantum world and the classical world of real objects in real places, where measurements of, say, an electron with a macroscopic instrument tell us that it is *here* and not *there*.

What Bohr meant is shocking. Reality, he implied, doesn't consist of objects located in time and space. It consists of "quantum events," which are obliged to be self-consistent (in the sense that quantum mechanics can describe them accurately) but not classically consistent with one another. One implication of this, as far as we can currently tell, is that two observers can see different and conflicting outcomes from an event—yet *both* can be right.

But this rigid distinction between the quantum and classical worlds can't be sustained today. Scientists can now conduct experiments that probe size scales in between those where quantum and classical rules are thought to apply—neither microscopic (the atomic scale) nor macroscopic (the human scale), but mesoscopic (an intermediate size). We can look, for example, at the behavior of nanoparticles that can be seen and manipulated yet are small enough to be governed by quantum rules. Such experiments confirm the view that there is no abrupt boundary of quantum and classical. Quantum effects can still be observed at these intermediate scales if our devices are sensitive enough, but those effects can be harder to discern as the number of particles in the system increases.

To understand such experiments, it's not necessary to adopt any particular interpretation of quantum mechanics, but merely to apply the standard theory—encompassed within Schrödinger's wave mechanics, say—more expansively than Bohr and colleagues did, using it to explore what happens to a quantum object as it interacts with its surrounding environment. In this way, physicists are starting to understand how information gets out of a quantum system and into its environment, and how, as it does so, the fuzziness of quantum probabilities morphs into the sharpness of classical measurement. Thanks to such work, it is beginning to seem that our familiar world is just what quantum mechanics looks like when you are 6 feet tall.

But even if we manage to complete that project of uniting the quantum with the classical, we might end up none the wiser about what manner of stuff—what kind of reality—it all arises from. Perhaps one day another deeper theory will tell us. Or maybe the Copenhagen group was right a hundred years ago that we just have to accept a contingent, provisional reality: a world only half-formed until we decide how it will be. ☺

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



The Harrowing and the Beautiful

In the darkest reality, this celebrated composer finds his voice

BY MICHAEL HERSCH



“... a few uncontrolled screams—in our stride”

—Robert Lowell

EARLY LAST YEAR, I experienced a health emergency. The medical discharge report read in part, “You experienced an out-of-hospital cardiac arrest ... fortunately you were able to be revived.”

I appreciate the conciseness and lack of drama in this description, something the late poet and painter Fawzi Karim once addressed in relation to reality in art and the pursuit of it:

As a consequence of being here, I have become very close to the idea of the simple sentence, one in which there is no exaggerated feeling or idea or belief. It is better to leave things just as they are. Once you add these other things you misjudge, you become unjust.¹

It was my daughter who found me collapsed in our kitchen. I don’t remember the legion of emergency personnel who came into our house attempting to revive me, the activity, the noise, the medical detritus left behind, the neighbors no doubt gathered outside awaiting a glimpse of the person who inevitably would be brought out on a stretcher, necks craning in a search for answers as happens in a neighborhood when something out of the ordinary breaks the silence. I don’t remember anything of the next five or so days, or anything in the 24 hours prior to the event. The entire experience is difficult to piece together. What is primarily left for me is the face of my daughter recounting the experience.

At some point in the days after admittance, I self-extubated in the I.C.U. After regaining consciousness, I was in a state of bewilderment, pain, and confinement. I had breathing difficulties due to blood in the lungs, perhaps a laryngeal injury caused by my inexpert and violent removal of the breathing tube. It wasn’t entirely clear to me what was happening.

I slowly retrained my senses to the realities around me, moving through the weeks that followed with at once lucidity and a structural sense of disconnectedness, both states co-existing in an effort to return to a meaningful normalcy. The most terrifying part of the ordeal was not, in fact, landing on that line between life and death, but simply the lack of agency and day-to-day clarity during that emergent period upon stepping back from it; restriction, confusion, and misapplication of power reigning overall. These things still haunt.

On reflection, I have discovered that my attitudes toward work, toward composing and the internal momentums therein, remain similar to how I felt about these things before the cardiac arrest. This is a bit surprising, in that there is some expectation one should, perhaps, approach things differently after what are at least outwardly transformative and demarcating experiences. While it is unclear to me whether I have moved forward as an artist, I have in the past year, however, found myself in new territories of deliberateness—concurrent, energized states of cognizance and intuitiveness, composure and presentiment—and a yielding, perhaps (perhaps not), of new ways of hearing, of seeing. I feel, imagine, a renewed sense of resoluteness.



The truth about the world ... is that ... had you not seen it all from birth and thereby bled it of its strangeness it would appear to you for what it is, a hat trick in a medicine show, a fevered dream,

After regaining consciousness, I was in a state of bewilderment, pain, and confinement.

a trance bepopulate with chimeras having neither analogue nor precedent, an itinerant carnival, a migratory tentshow whose ultimate destination after many a pitch in many a muddled field is unspeakable and calamitous beyond reckoning.

—Cormac McCarthy, *Blood Meridian*

Someone recently asked what I was “after” in my work; what did I hope to achieve? It seems a simple enough question. But beyond what has for much of my life felt a desperate urgency to write music, the excitement in attempting to capture a moment, a situation, a state of mind, a state of being, *aliveness*, trying to reach for a succinct answer to this question in conversation is difficult.

The answers I generally arrive at feel like weak attempts at characterizing something for which the work itself holds the answers. I do know that in the work to which I respond of other artists there is always an omnipresent exigency, even in the stillest, most delicate moments; palpability, something convincingly messaged through the art directly, even if it is difficult to capture in discussion; and above all, fearlessness, a clear willingness to proceed no matter the destination.

Reflecting on the death of a dear friend, I characterized the period thereafter as akin to being caught in an undertow. Even when regaining a sense of control, a

distance and reemergence from the currents, I would inevitably and predominantly be pulled back to places of grief and disquiet. The relentlessness of return seems at times a kind of constitutional inability to fully come to terms. Perhaps this is more common than many wish to believe, a permanent, indestructible irresolution. Looking back upon my own work, a confrontation with irresolution seems to comprise in large part the engine which propels me to wrestle with these things, in this case through the prism of music.

There also is a recurring engagement with varying forms of violence in my work, violences at the core, or at least at the origin points of the musical exploration. At times, the violence is within (illness), at times without (violence inflicted by one person or groups of people against another or others).

The world of illness has shaped and informed my monodrama *On the Threshold of Winter*, and the elegy, *I hope we get a chance to visit soon*, these works engaging with loss to cancer, and to a lesser extent my own direct experiences with the disease. Examples of violences from without include my two recent operas: *Poppaea* and *Medea*, and a work for unaccompanied violin, *the weather and landscape are on our side*, a cycle loosely structured on some of the last correspondence of writer and artist Bruno Schulz, who was shot on the street by a Nazi officer in 1942.

There are certainly many instances where disquiet—that structural irresolution and a confrontation with these states that I am attempting to give shape to—presents as more environmental or atmospheric, a musical argument which is divorced from any explicit narrative or event. In struggling to quantify my most recent opera, *and we, each*, I have written that the work is above all an exploration of the treacherous territories of relationships—between individuals, within societies and, ultimately, the collapse of both. The opera is based upon texts by poet Shane McCrae. From the last scene, McCrae writes:

... *The couple stretched and broke ...*
 ...*world in world ... chaos flung on bones ...*
 ... *where I meet you, we are here.*

When asked questions of motivation, and when considering the broad topic of reality, I am reminded of painter Francis Bacon's "brutality of fact." Bacon, responding to the notion that many perceive his work as horrific, said, "I've always hoped to put over things as directly and rawly as I possibly can, and perhaps if a thing comes across directly, they feel that that is horrific."²

I also think of something my friend, sculptor Christopher Cairns, has repeated over the years. He likes to quote painter Eugène Delacroix, who reportedly said he "liked the look of fresh blood." Cairns feels Delacroix must have meant he was attempting to "get at reality," that he was struggling to "get at something real" in his art.

Again, Cormac McCarthy in *Blood Meridian*:

They found the lost scouts hanging head downward from the limbs of a fireblackened paloverde tree. They were skewered through the cords of their heels with sharpened shuttles of green wood and they hung gray and naked above the dead ashes of the coals where they'd been roasted until their heads had charred and the brains bubbled in the skulls ... Their tongues were drawn out and held with sharpened sticks thrust through them and they had been docked of their ears and their torsos were sliced open with flints until the entrails hung down on their chests. Some of the

men pushed forward with their knives and cut the bodies down and they left them there in the ashes.

Critic Caryn James, reflecting on McCarthy's broader motivations, writes that "McCarthy has asked us to witness evil not in order to understand it but to affirm its inexplicable reality."³

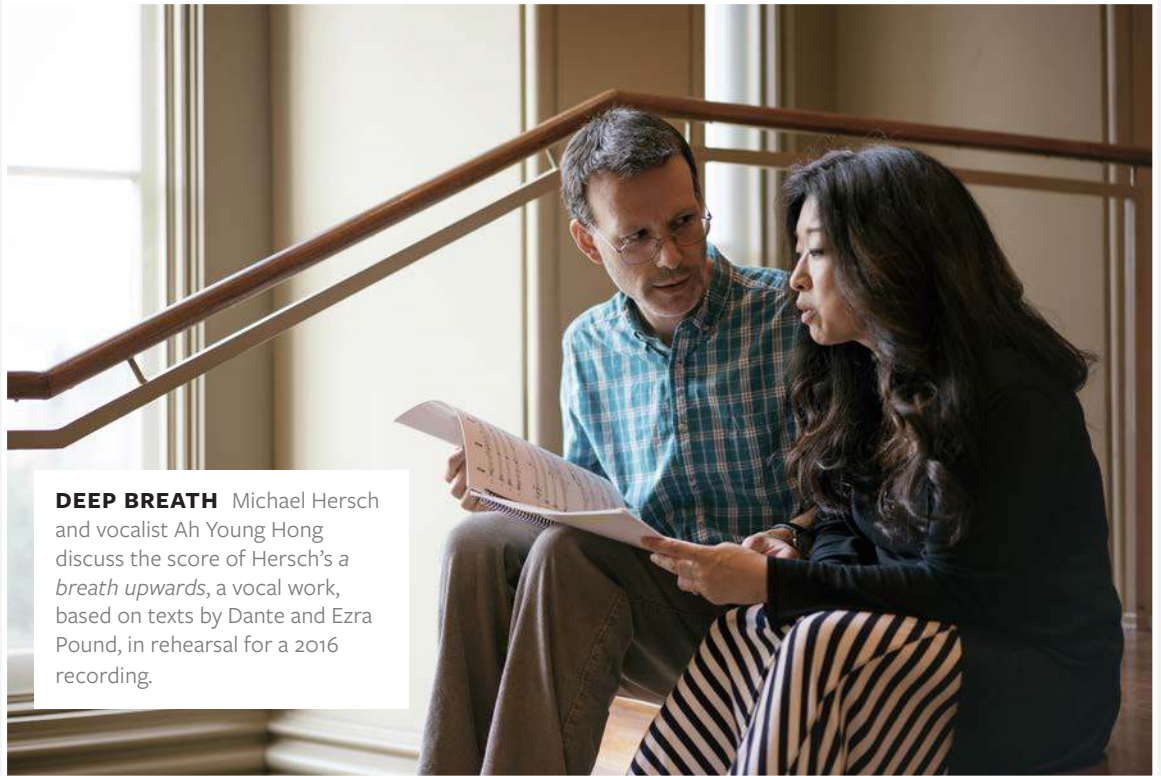
This reality need not be the nightmarish, grim, complex worlds explored by McCarthy, though it commonly is. In my experience, the nature and work of an individual is frequently shaped more by the tragedies that befall them than by anything else, and the beautiful, the just moments in and of one's life are often, if not inevitably, contoured by those darknesses.



I was barely a year old when my 23-year-old aunt was killed in an accident. In later years, I would wonder how this event shaped my mother and her subsequent choices, the loss of her sister reminding her of reality in the starkest of terms at a relatively young age, the tangible knowledge that catastrophe is likely taking shape just over the horizon, just out of sight, but remaining diffused enough to silence or mask, only for a time, the threat. She suffered from bouts of intrusive anxiety that would constrain her life in various ways, but she always impressively overcame the obstacles that afflicted her, or for the most part seemed to.

Then, not long after the loss of her sister, her father died, a second trauma for her and for the family; catastrophe's form having gathered and deployed once again. During his illness, my parents decided to send me to live with him during the period he underwent treatments. The seemingly relentless doctor and hospital visits unnerved me, but I wasn't frightened for his imminent absence. This possibility didn't occur to me. He exuded strength and permanence. I never sensed he was dying, though he did soon after. When I went through my own cancer treatments almost 30 years later, I tried to summon his courage, or what seemed a courageousness reflected through the eyes of a 7-year-old boy.

The last visit I had with my dear friend, mentioned earlier, brought again into question my grasp of the realities around me, though without the excuse of



DEEP BREATH Michael Hersch and vocalist Ah Young Hong discuss the score of Hersch's *a breath upwards*, a vocal work, based on texts by Dante and Ezra Pound, in rehearsal for a 2016 recording.

childhood misapprehensions. Looking back now, I realize she was of course very near death. This was reflected in all aspects of her presence: her voice, her appearance, her almost fantastical and fanatical sense of optimism. But she was so persuasive in her optimism that she convinced me she would go on, she would continue to survive as she had done again and again.

For a time our treatments overlapped. We went through a period when our varying cancer treatments were occurring simultaneously (though different cancers in different parts of the country). While I was mainly left with physical disfigurement, pain, anger, and speculation, these all-too-common things paled in the face of her death and the remaining questions thereafter.

She died in 2009, age 45. There has remained for me since her death a certain emotional defacement resulting from the miscalculation of not recognizing

how near death she was at that time, the regret of not seeing what was right there in front of me.

The irresolution I often feel and recognize in the art to which I respond is, perhaps, as an acute grief which can take on the quality of amber-like immutability, a state never truly able to be moderated, only (often feebly) covered over. The attempt, though, to transform, to scrutinize, to break through, in my case to endeavor through music, is often terribly exciting. This I believe, even if eventually doomed, is the major propellant for my work. From the beginning, I have attempted to shape musical drama without obfuscation, without missing or passing by those things I wish to explore, though often difficult. I also recognize that some of the most beautiful art finds its beauty in the veneer, the facade, the mask, the shell. I, however, have generally been drawn to what is behind the bandages.

Someone asked what I was “after” in my work; what did I hope to achieve?



Almost 25 years ago, I attended an exhibition in Rome of Michael Mazur's *The Inferno of Dante*, a series of 41 etchings with accompanying texts of Dante in a translation by Robert Pinsky. It was a deeply moving experience. Mazur and I spoke, and soon after I performed a number of my works for him at the piano. A few years later, when my first recording of solo and chamber music was released, Mazur wrote a program note for it. Although I feel now very far from those works, as one does when time wrenches us forward and we find ourselves at a distance, Mazur's words linger and remain present for me:

There is ... the overwhelming sense of “sadness,” which is better than “doom.” In fact, the abyss in its finality is easy to portray: a rich black says it all. Dante is often thought to have made his poem [Inferno] about doom and punishment for sin. He looked into the abyss but primarily found sadness there. Sadness is a much more complicated and, therefore, interesting human condition. It is harder to portray visually.

I would make the case that this is similar in music. Mazur continued:

These compositions are filled sometimes with frightening sounds. They are unrelenting, nearly without hope ... But no artwork can be without hope since it is in the very nature of creative work to be optimistic, if only in as much as we continue to work through everything but our own death.⁴

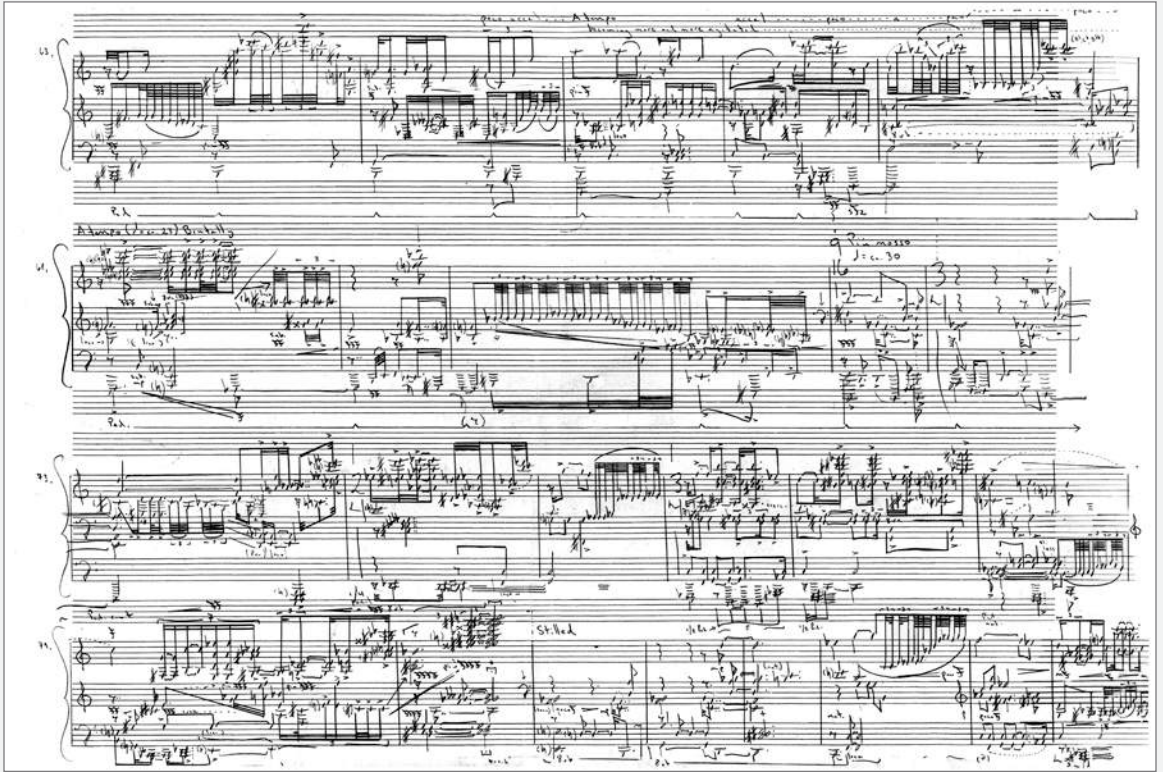
Approximately a decade after our initial meeting, I intersected with Mazur's artwork musically for the first time, resulting in a piece which is one of the only works I've written where both of the earlier noted elements

of internal and external violences overtly collide. The piece is a string quartet titled *Images from a Closed Ward*, a 13-movement cycle completed the year after Mazur's death in 2009. The origin point for the quartet was Mazur's “Locked Ward” series of images, a collection which struck me as a kind of real-world embodiment of much of what I had seen years before in his *Inferno* imagery.

The artwork confronts the horrors of mental health treatment as Mazur witnessed it during the 1960s. In an interview with Cherie Doyle Riesenbergh in 1988, Mazur relayed an anecdote regarding an early confrontation with a reality that fundamentally changed his approach to making art. He was 19 and was singing popular songs with a group of friends for women in a secured unit of a veteran's hospital. In the midst of the performance, one of the soloists was violently attacked on the stage. Mazur noted, “I never forgot that. It was the first meeting with reality, with the darkest kind of reality.”

In her book, *Robert Lowell: Setting the River on Fire*, psychologist Kay Redfield Jamison references art and truth in her writings on the 20th-century poet, though I think her utilizations of these terms are interchangeable with the term “reality.”

To create ... art requires toughness, eyes that do not avert their gaze ... that [do] not back away from the great, hard subjects: love, betrayal, suffering, madness, war, death. Truth is not always an uplifting thing; human nature is flawed ... It is not for the faint of heart. Art is the “ruthless cutting edge that records and celebrates and prophesies on the stone tablets of time,” wrote the Scottish poet George Mackay Brown. Lowell, who spent time with Brown on his late-life trip to Orkney to trace the ancestral roots of his poetry and his own madness, put it plainly. “We must all live by taking a few uncontrolled screams—in our stride.”⁵



SHROUD OF LEAVES A manuscript page from Michael Hersch's work, *sew me into a shroud of leaves*. The work comprises 153 movements and lasts some 10 hours of performance. The work is a catalog of Hersch's shifting perspectives and experiences over the 15 years it took him to complete it.

Perhaps somewhere in those screams is the something “real” that Cairns and Delacroix are talking about. Each of these artists, Lowell and McCarthy included, attempt to engage with and make sense of the world around them, the world as they see it with no attempt to anesthetize or becloud it. The work these artists create, that I am attracted to, does not shy away from, nor attempt to escape this world, as difficult and as ferocious as it can be. There seems little interest in constructing opacity.

However, that notion of disquiet, the human difficulties often traversed in their work, are not devoid of those things one might characterize as beautiful; fully, absolutely, beautiful. Responding to negative reactions

to his often-graphic work, painter Hyman Bloom stated his hope was to somehow bring a clear unity to the “harrowing and the beautiful.”⁶

Karim's approach to his work, his appeal to “the simple sentence,” of “no exaggerated feeling or idea or belief,” that it “is better to leave things just as they are,” is something I obsess over. In my own conversations with Karim, the idea of simplicity has nothing to do with an absence of complexity; it is about fidelity to one's ideas, specifically what the artwork at hand requires, unto itself. This ultimately becomes something which relies on an instinct: an intuitive signal that the “reality” of the piece has been identified and engaged with. It is a search for a dignity in the essence

What I respond to in artists is fearlessness, a clear willingness to proceed no matter the destination.

of the piece. This dignity doesn't refer to the overlooking of fear, of humiliation, degradation, the profane; things from which we might instinctively recoil. It is simply that whatever is being said is expressed with an ultimate clarity, a precision, the realities surrounding us in direct confrontation with the senses and imagination. It is a journey, above all, to simply get to the heart of the matter.



*It was when darkness crept in and far below me
I saw the roof of my house, saw the shadows falling ...
so soundlessly I glided, scarcely moving a wing,
high above the earth.*

—W.G. Sebald



In 2016, I completed *sew me into a shroud of leaves*, a cycle of three works comprising 153 movements and lasting some 10 hours of performance time. While my work has changed since then, with a shift primarily to works for the theater and the voice, the cycle is in certain respects a catalog of my priorities, observations, shifting perspectives, above all, experiences, across a finite span of time, namely the 15 years it took me to complete the trilogy, which I began in 2001.

Poetical fragments and textual connections from three different poets are interleaved throughout each

of the cycle's sections. Here I am not attempting to render these particular texts into music. Rather, I feel the texts share some expressive sensibility with the music, which is why they came to mind in the first place. They are more companions than anything else. The first part of the cycle intersects with the poetry of Christopher Middleton (the second with W.G. Sebald, the third with Marius Kociejowski). Oftentimes, there is a shocking juxtaposition of everyday circumstance and violence in Middleton's work in particular. In his "Gentle Reader," Middleton writes:

*... Oboe, flute, and strings deliver from the air
Just such a picture, like a Claude Lorraine.
Another fifty years—with different trees
The picture will be mistier, Corot ...*

Andrew Farach-Colton has noted, "the poet suggests that we, the gentle readers of the poem's title, are 'greedy' for aural and visual images. And then, later in the poem, in an abrupt shift, there are the images and sounds we turn away from. Middleton wants us to see these, too, and to hear"⁷:

*... the shouts of thugs
Clubbing to death with crowbars people
Rather shocked to find that this was happening
A few doors only from home, for no good reason ...*⁸

The last movement of Part I of the cycle is paired with the only complete poem of this first part of the cycle, Middleton's "Something Vespéral."⁹ Interestingly,

this example turns away from much of the confrontational darkneses explored by many of the artists I have referenced, including Middleton himself. This text communicates his characteristically elusive beauty:

*Spectres, vast, remote,
Uneasily wagging their heads
In shrouds of crushed amethyst:*

*Tomorrow I will confirm
That they are hill crests,
And slopes parade the green oak, olive,*

*Serried cherry.
On sunken pots of Rome
An iridescence, thick
Or light, signifies the human:*

*Should the moment return
At sundown's onset
I will ask what is this colour,*

*Again a few score of breaths,
And scaling the underside
Of pine branches*

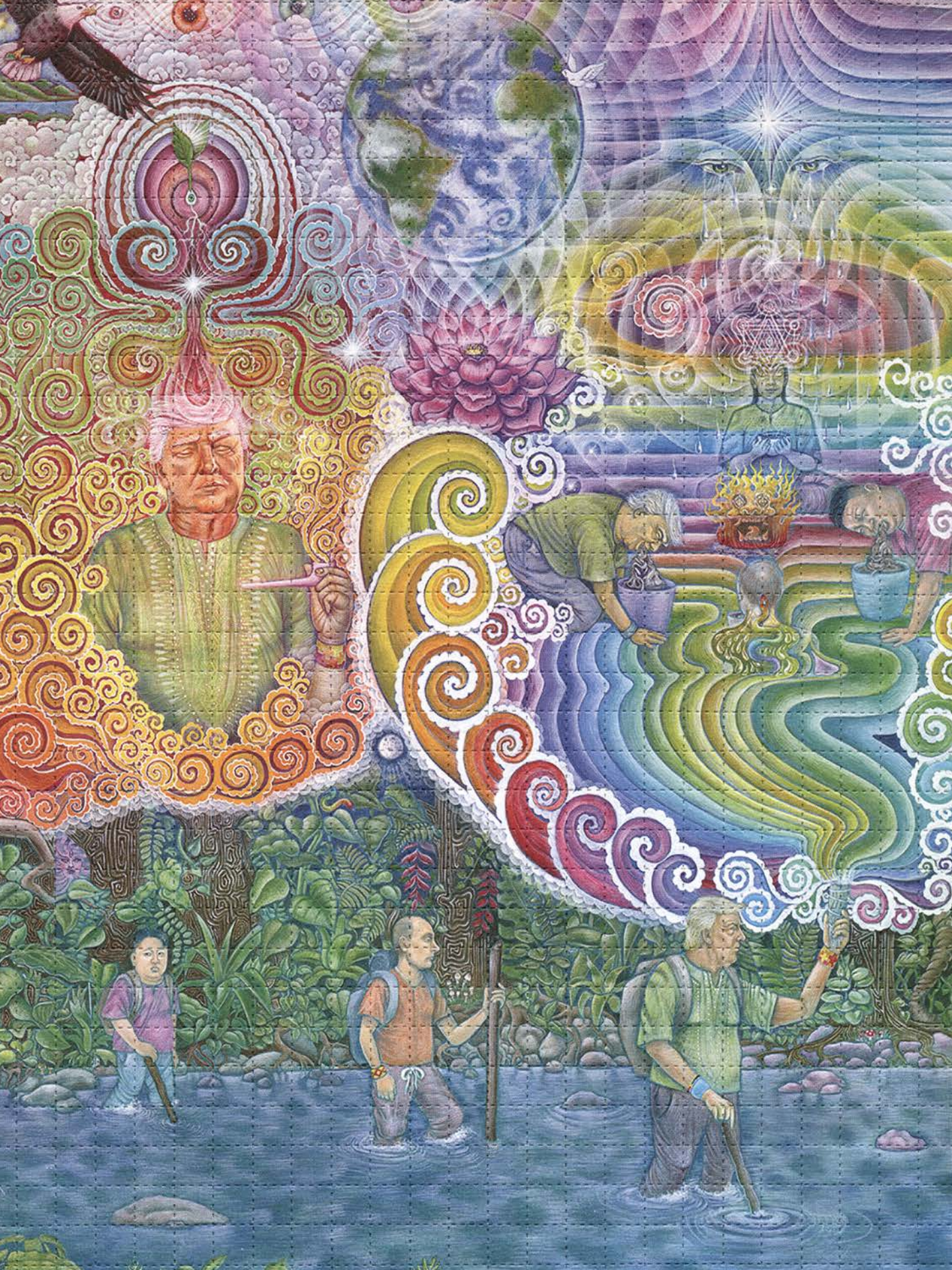
*An aqueous rose, diffused.
Neither quality, nor adjunct.
How long so old.*

While the reassuring, the inspiring, and the consoling are explicable attractive, and their powerful grip is obvious, it is also important, perhaps more important than ever, to gaze squarely into and to not turn away from the “unspeakable,” the “muddled field” to which McCarthy draws attention—a field which all too often crashes into our respective spaces. Whether acutely present, looming nearby, or quietly stalking the distance, these places are with us as well, allowing us to feel at the outer limits of that which our capacities provide, to attempt to make sense of this world and the realities therein. ☺

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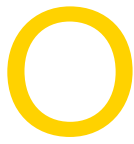


A Reality Far Beyond Anything You've Known

What should we make of the mystical experiences reported by those on psychedelics?

BY STEVE PAULSON

ART BY THE BLOTTER BARN



LIVER SACKS WASN'T ALWAYS the beloved neurologist we remember today, sleuthing around the backwaters of the mind in search of mysterious mental disorders. For a few years in the 1960s, he was a committed psychonaut, often spending entire weekends blitzed out of his mind on weed, LSD, morning glory seeds, or mescaline.

Once, after injecting himself with a large dose of morphine, he found himself hovering over an enormous battlefield, watching the armies of England and France drawn up for battle, and then realized he was witnessing the 1415 Battle of Agincourt. “I completely lost the sense that I was lying on my bed stoned,” he told me in 2012, a few years before he died. “I felt like a historian, seeing Agincourt from a celestial viewpoint. This was not ordinary imagination. It was absolutely real.” The vision seemed to last only a few minutes, but later, he discovered he’d been tripping for 13 hours.

“I’m an old Jewish atheist,” Oliver Sacks said. “I have no belief in heaven.”

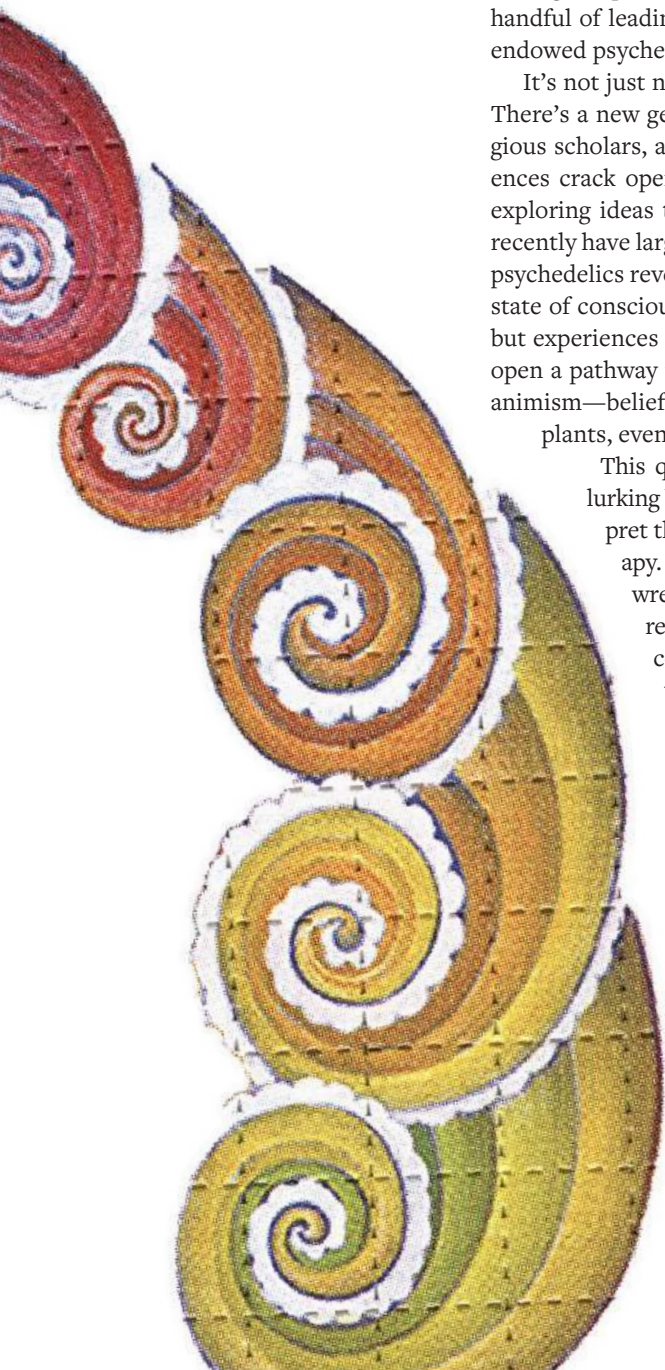
These early experiences with hallucinogens gave Sacks an appreciation for the strange turns the mind can take. He had a craving for direct experience of the numinous, but he believed his visions were nothing more than hallucinations. “At the physiological level, everything is electricity and chemistry, but it was a wonderful feeling,” he said. When I asked if he ever thought he’d crossed over into some transpersonal dimension of reality, he said, “I’m an old Jewish atheist. I have no belief in heaven or anything supernatural or paranormal, but there’s a mystical feeling of oneness and of beauty, which is not explicitly religious, but goes far beyond the aesthetic.”

I’ve often thought about this conversation as I’ve watched today’s psychedelic renaissance. Clinical trials with psychedelic-assisted therapy show great promise for treating depression, addiction, and PTSD, and a handful of leading universities have recently created their own heavily endowed psychedelic centers.

It’s not just neuroscientists and psychiatrists studying psychedelics. There’s a new generation of researchers—including philosophers, religious scholars, and anthropologists—who believe psychoactive experiences crack open deep questions about the nature of reality. They’re exploring ideas that have obsessed psychonauts for decades but until recently have largely been written off by scholars as fringe questions. Do psychedelics reveal a deeper dimension of the mind? Not just an altered state of consciousness—that’s obvious to anyone who’s ever tripped—but experiences that don’t begin and end in the brain? Do psychedelics open a pathway to theories about consciousness like panpsychism and animism—belief systems in which everything in the world—animals, plants, even rocks—are conscious or have some spiritual essence?

This question about a transpersonal reality hangs in the air, lurking behind this psychedelic moment. It shapes how we interpret the mystical experiences so common in psychedelic therapy. It informs metaphysics—the philosophical tradition that wrestles with fundamental questions about reality, like the relationship between mind and matter and the space-time continuum, which are precisely the kinds of questions that tend to surface in psychedelic experiences. It’s the question at the heart of the interface between the scientists who study psychedelics and many of their research subjects who believe they’ve tapped into some dimension of consciousness that extends beyond their own brains.

“People really don’t want to deal with it because it’s such a hairy problem,” says Erik Davis, a longtime chronicler of the psychedelic scene, and author of *High Weirdness: Drugs, Esoterica, and Visionary Experience in the Seventies*. “I find it very strange how few people are talking about this topic,” added philosopher Chris Letheby in an email. “I would have thought it was THE topic!”



MANY DRUG-INDUCED VISIONS are clearly hallucinations. If giant fluorescent serpents suddenly appear in your ayahuasca revelry, you're not likely to go looking for them once you're sober. But other psychedelic experiences aren't so easily explained. Like encounters with an other-worldly intelligence.

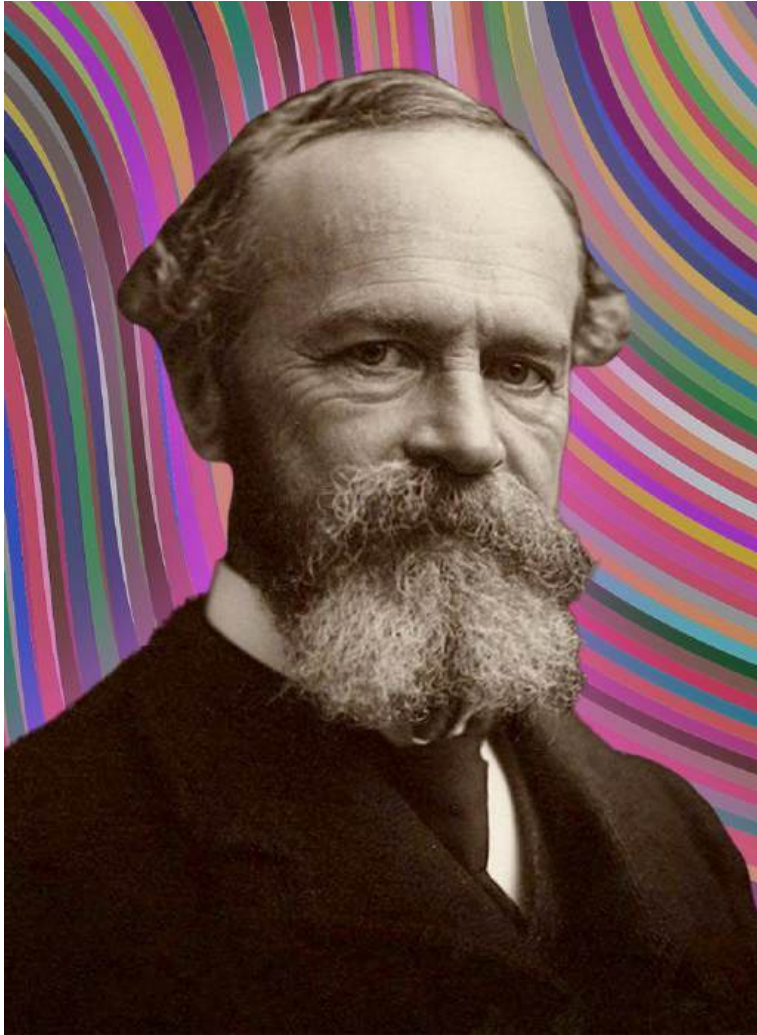
Consider one of the most celebrated stories in psychedelic history—Gordon Wasson's experience with the Mazatec *curandera* Maria Sabina. Wasson was a banker at J.P. Morgan who'd spent years searching for a traditional healer who would initiate him in a mushroom ceremony. When he finally found Sabina in a remote village in southern Mexico, he persuaded her to help him “learn the secrets of the divine mushroom.” The experience changed Wasson's life. He later reported seeing brilliantly colored palaces and a “mythological beast drawing a regal chariot.” “They seemed more real to me than anything I had ever seen with my own eyes,” he wrote in *Life* magazine in 1957.

Sabina had her own understanding of the mushrooms. She called them “the holy children” and claimed they danced around her, singing and playing music. She sang during her trance-like ceremonies and said the mushrooms spoke through her; she was just the translator.

Sabina's account may sound like nothing more than a poetic description of a visionary experience, but some scholarly trippers take these experiences literally. Katherine MacLean, a psychologist who ran some of the early psilocybin trials at Johns Hopkins University, and the author of the 2023 “psychedelic memoir” *Midnight Water*, considers Sabina “a patron saint of mushrooms.” MacLean is a longtime tripper who believes psychedelics have uncanny qualities that defy scientific explanation. “Consensus reality is functional to a point,” she told me. “There are thresholds that most people don't notice, and then suddenly, you might find yourself up at the doorway.”

Aldous Huxley called this deeper reality “Mind at Large.” He believed we walk through our daily lives with blinders on, our consciousness funneled through a reducing valve in the brain so we don't get overloaded with sensory input. But under a psychedelic, we might enter this expanded dimension of consciousness. Chris Bache, a religion professor who had 73 high-dose LSD journeys, claims he encountered “the mind of the universe.” At various times, he felt himself dying and being reborn, or communicating with an amorphous Council of Elders, or changing gender, even having





VOYAGER Psychologist William James was an early “psychonaut,” testing nitrous oxide on himself to see what it might reveal about the mind—and reality.

Hardened neural circuits suddenly get rewired, at least for a few days or weeks. A psychedelic can strip away our sense of self and the perception of space and time, creating a mystical feeling of unity with the surrounding world. “Given this radical change in perspective, you would expect some radical change in the underlying neural basis, which so far we haven’t seen,” neuroscientist Christof Koch said. “But we’re still at a very early stage in the science.”

In his 2024 book *Then I Am Myself the World*, Koch suggests several possible explanations for this expanded state of consciousness. The neocortical regions of the brain that are activated when we’re angry, anxious, or self-critical seem to be sidelined under a psy-

sex and giving birth as a woman. “I can’t reduce these experiences to my brain or my personal unconscious,” he told me. “When you go outside of space and time, it’s just immediately obvious that you’re in a reality that’s far beyond anything that you’ve known inside Earth to experience.”

The challenge for scientists and other scholars of psychedelics is to develop an explanatory framework for evaluating these personal stories. Neuroscientists point to the serotonin 5-HT_{2A} receptors activated by psychedelics like LSD and psilocybin, and brain imaging shows how these drugs can trigger neuroplasticity.

chedelic, which creates a more “open” psychological state. Another possibility is that psychedelics enhance certain cognitive processes, such as imagination, selective attention, and short-term memory. A third possibility, he suggests, is that psychoactive experiences boost the amount of integrated information in our minds, which then silences the sense of self and creates the perception of vastness in the world around us.

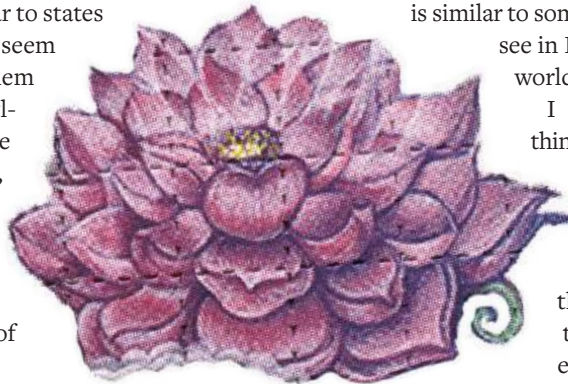
Koch, who pioneered the study of the neural correlates of consciousness with Francis Crick, has had his own profound psychedelic experiences. He describes his encounter with 5-MeO-DMT—aka the “toad”—as

a near-death experience. “There was a bright light of overwhelming intensity, there was terror, and there was ecstasy,” he told me. “There was no ego, there was no memory, there was no Christof, there was no fear, there was no desire. I was gone.” As he regained consciousness, he cried and stripped off all his clothes and then curled up in a fetal position. “There isn’t a single day I don’t think about this experience,” he said.

It’s not surprising that Koch would seek out a transcendent experience with psychedelics. He grew up a devout Roman Catholic and yearned for some direct experience of God, but as he put it, “I never saw a burning bush.” Eventually, he lost his religious faith but never gave up his hunger for some underlying meaning in the cosmos. I asked Koch what he learned from his encounter with the toad. “It’s what Wittgenstein says in his *Tractatus Logico-Philosophicus*,” he said. “Once you understand the meaning of life, you don’t talk about it anymore. This was very vehemently reaffirmed through this experience.”

DOES IT MATTER if these other-worldly experiences are “real?” Many of today’s psychedelic scholars refer to William James, whose 1902 book *The Varieties of Religious Experience* sought to provide an intellectual grounding for mystical experiences. James’ fascination with mysticism was sparked by his own experiences with nitrous oxide, which he described as revealing “depth beyond depth of truth.” He claimed that mystical experiences are intuitive rather than conceptual. “Although so similar to states of feeling, mystical states seem to those who experience them to be also states of knowledge,” he wrote. “They are illuminations, revelations, full of significance and importance, all inarticulate though they remain; and as a rule, they carry with them a curious sense of authority for after-time.”

It’s strange how few people are talking about this topic.



Today, a rubric called the Mystical Experience Questionnaire, derived from James and refined by later generations of psychedelic researchers, is used by scientists in clinical trials and by therapists at psychedelic retreats. The key qualities of mystical experience, according to researchers at Johns Hop-

kins, include the sense of the interconnectedness of all things, a merging with ultimate reality, the bending of space and time, ineffability, and the feeling that the experience is indisputably true—or as some people say, “realer than real.”

Mystical experiences are highly valued in psychedelic-assisted therapy. When a severely depressed person senses the presence of some life-enhancing reality while tripping, she’s more likely to break out of her despair if she believes the experience is real rather than just a feel-good hallucination. In fact, there’s evidence that psychedelics can change a person’s metaphysical beliefs.

“I was particularly interested in this idea that a single experience can change your outlook on what is the fundamental nature of reality,” said Chris Timmermann, a neuroscientist who runs the DMT research group at Imperial College London.

To test the idea, he helped develop the Metaphysical Beliefs Questionnaire. What he found was that a single psychedelic experience in a group setting, either with psilocybin or ayahuasca, led to a lasting shift in beliefs. “They rejected the idea that the fundamental nature of reality is physical or material,” Timmermann said. “And they endorsed panpsychism more strongly—the idea that everything in the universe is conscious, which

is similar to some animistic perspectives you see in Indigenous cultures, that the world out there is alive.”

I asked Timmermann if he thinks psychedelics could reveal some transpersonal dimension of consciousness. “There is certainly a neural correlate in these experiences. Without the drug, there is no experience,” he said. “But whether

A little synchronicity is a beautiful thing. It's like a little wink of God in your reality.

that completely explains away the experience, I don't know. I'm agnostic in that regard because ultimately, the causality around these experiences is very hard to determine."

Chris Letheby, a philosopher at the University of Western Australia, has fewer questions about the causal mechanism behind psychedelic experiences. He's written about what's been called the "comforting delusion objection." While acknowledging the healing power of mystical experiences, he asks, "What if the divine universal consciousness is not real?" In his book *Philosophy of Psychedelics*, Letheby refers to experiences of cosmic consciousness as "metaphysical hallucinations" and believes physicalism is the only credible perspective. He argues that psychedelics produce lasting therapeutic benefits by transforming our sense of self and changing how we relate to our own minds. In his view, there's no need for any unfounded belief in a transcendent dimension of consciousness that extends beyond the brain.

But not every philosopher accepts Letheby's premise. Peter Sjöstedt-Hughes, a philosopher at the University of Exeter, says the naturalistic framework of neurobiology and psychology isn't the only credible perspective for understanding what's real in psychedelic experiences.

"The whole 'comforting delusion objection' is based upon a certain metaphysics, which just assumes without argument that they are hallucinations," he said. "You can only know if something's a hallucination if you know what reality is. And by reality, I mean the relation between mind and matter at the fundamental level."

Sjöstedt-Hughes' own interest in psychedelics was serendipitous. He was teaching a course on religion but had no personal experience of anything remotely mystical. Then one day he was walking in Cornwall with his

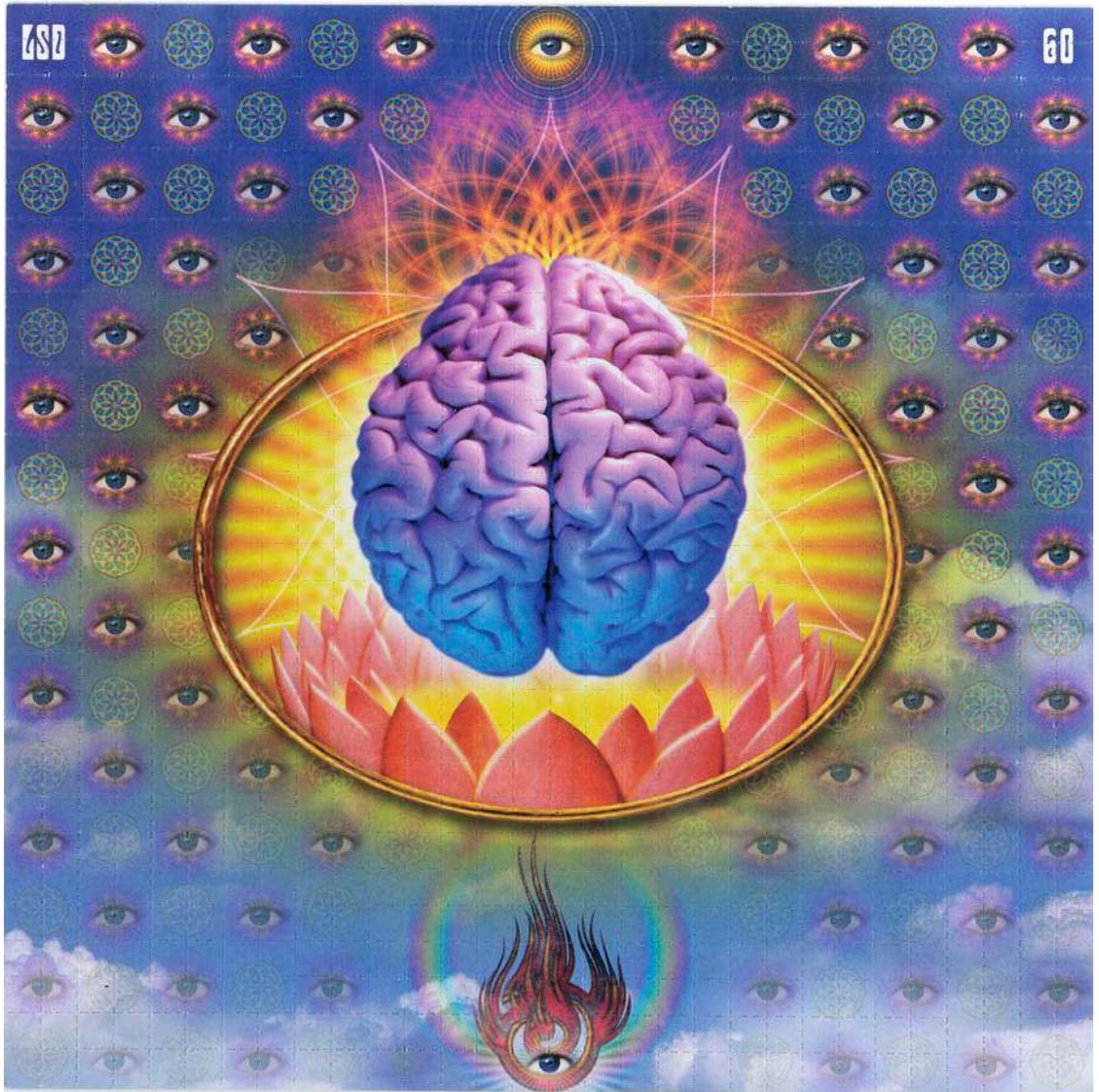
brother when they found magic mushrooms growing in a field. They picked a bunch, and after making sure they weren't poisonous, he ate a few.

"The experience was so extremely profound and so different from anything I'd ever experienced, I then had to read all the philosophy about it," Sjöstedt-Hughes said. As a scholar of metaphysics, this felt like hitting some deep vein in esoteric thinking: "A high-dose psilocybin experience will offer you states of mind that are so beyond anything you could have dreamt or imagined that it suddenly gives you all this new material to work with."

After studying various philosophical systems, Sjöstedt-Hughes concluded that psychedelic experiences can line up with different non-materialist metaphysical beliefs, including idealism (reality is fundamentally in the mind) and pantheism (God is Nature).

"For example, if you take Spinoza's view, as Einstein did, that mind and matter are essentially the same thing—they're both expressions of something deeper—then you would expect the neural correlates of consciousness to be exactly the same as from an emergent physicalist point of view," he said. "So when you have a psychedelic experience where your mind fuses with a universal mind or cosmic consciousness, we can't necessarily say it's a hallucination."

What should we make of these experiences? If people say they've talked with angels or dead ancestors, should we dismiss them as raving, drug-addled trippers? These experiences often feel more revelatory—more real—than ordinary waking reality. "It's almost impossible to write it off as a purely projective phenomenon," said Erik Davis. "It seems like something in the external world, which has reorganized itself according to a different kind of logic that implies some level of reality or organization or super story that you're involved in."



Davis, who has a Ph.D. in religious studies, is not put off by over-the-top psychedelic stories. He's written at length about the weird, other-worldly visions of psychonaut Terence McKenna, who claimed hallucinogens opened a portal into some interdimensional space with aliens. "One of the leitmotifs of psychedelic experience is synchronicity—uncanny coincidences that build on top of each other," Davis said. "But at the same

time, it leaves you with this problem. If you start building a worldview based on those experiences, it can lead you toward psychosis. A little synchronicity is a beautiful thing. It's like a little wink of God in your reality. But if they start coming every five minutes, you better buckle your seatbelt."

Contemplative traditions like Buddhism have a long history of trying to verify the truth of visionary or

ecstatic experiences that arise during meditation. A novice meditator might talk with his teacher—comparing notes, you might say, to determine whether these experiences reveal something true and not just a distorted version of reality. Skillful guides in the psychedelic underground also draw on their own experiences when they work with neophyte trippers. A teacher might say that no single person has a straight line to the truth, and the idea that there's some fixed, objective reality is itself a fiction. What's accepted as "real" emerges from this shared understanding. Cultural expectations and communal rituals also shape our understanding of these experiences.

Psychedelics have their own distinct history, going back in Indigenous cultures, where much of our knowledge about plant medicines originated. Psilocybin, ayahuasca, and peyote were used for centuries in sacred ceremonies, long before Western scientists and drug companies swooped in and collected plant samples, looking for chemical compounds they could synthesize. In this older worldview, psychedelic experiences are rooted in relationships with everything around us—including plants and animals, even the juju of the mushroom or cactus itself.

"These medicines are not about the human experience alone," said Yuria Celidwen, a Mayan scholar of contemplative practice at the University of California, Berkeley. Even the word "psychedelic," which means "manifesting the mind," is problematic for the Indigenous people I've interviewed. For Celidwen, there's always a communal and ethical component to "spirit medicines," as she prefers to call them. She believes it's misguided to think of hallucinogens as primarily a tool for personal enlightenment, yet modern psychedelic culture has taken shape around highly individualistic experiences. It's also baked into most scientific studies—typically, with the research subject lying down

alone in a room, wearing eye shades and headphones, shutting out the external world to go inward. But the greatest insights on psychedelics may not be about ourselves but our connection with the world around us.

MORE THAN A CENTURY after he wrote *The Varieties of Religious Experience*, James remains a touchstone for many people who study psychedelics. He wasn't afraid to consider the truth claims of mystical experiences, though he was careful not to endorse any belief in a supernatural or non-material reality. Yet James wrote about the optimistic, life-affirming quality of mystical experiences, notable because he had his own struggles with melancholia. He understood how a profound mystical experience can transform a person's life. His long chapter on mysticism is filled with conversion stories—ecstatic experiences that chart a turning point and a new sense of purpose. "We pass into mystical states from out of ordinary consciousness as from a less into a more, as from a smallness into a vastness," James wrote. "They appeal to the yes-function more than to the no-function in us."

This experience of vastness is also the great promise of psychedelics for the people who use them, whether they suffer from depression or simply find life too drab and pointless. Even without any belief in a transpersonal realm of consciousness, what's remarkable about psychedelics is their capacity to shake up and shift your worldview.

The psychopharmacologist Roland Griffiths, arguably the most important psychedelic researcher of the past two decades, leaned heavily into James and subsequent characterizations of mysticism. Griffiths had an international reputation as an expert on drug addiction when he kickstarted the psychedelic revival, persuading Johns Hopkins and various government agencies to allow him to run a clinical

He had a 12-hour LSD trip, in which he asked his cancer a series of questions.

trial with psilocybin, specifically to see if it could elicit transcendent experiences.

In his 2006 study of mystical experiences, most of the participants ranked their high-dose psilocybin trip as one of the most spiritually significant experiences of their lives, and 14 months later, they reported substantial improvements in their “personal well-being, life satisfaction, and positive behavior change.” Griffiths’ research center went on to do a series of clinical studies showing remarkable potential for using psychedelics to treat addiction, depression, and end-of-life anxiety. If you wanted evidence of the transformative power of psychedelics, Griffiths was your man.

I interviewed Griffiths several times over a dozen years—the last time in 2023 when he was dying of colon cancer. Until then, he had always dodged questions about his own psychedelic use, but now he was ready to get more personal. He’d recently had his own 12-hour LSD trip, in which he asked his cancer a series of questions: Did he have to die? Was there anything he should do before he died? He described the experience as “dialoguing with an entity,” so I asked if he believed he had communicated with some intelligence beyond his own consciousness. No, he assumed this was some kind of internal wisdom welling up from deep inside himself.

Griffiths straddled two worlds. He always talked like a scientist, with little

patience for those who believed the mushroom or Mother Ayahuasca possessed its own intelligence, but he was also a longtime meditator with an interest in mystical traditions. I wondered, what did he think would happen when he died? “I put the chance of an afterlife—continuity of consciousness—to be a diminishingly small probability,” he said. “But it’s not a zero probability because we are in this mystery. And that’s all I need.” ☺

STEVE PAULSON is the executive producer of Wisconsin Public Radio’s nationally syndicated show *To the Best of Our Knowledge*. He’s the author of *Atoms and Eden: Conversations on Religion and Science*.



Of Black Holes, Teacups, and Demons

How thought experiments illuminate the hairiest problems of science

BY PATRICIA PALACIOS

IN HIS 1967 SHORT STORY “The Southern Thruway,” Argentine writer Julio Cortázar conjures a catastrophic traffic jam just outside of Paris. The gridlock endures for months, forcing motorists to build an entirely new society around their immobile cars. It is a thought that has perhaps crossed many people’s minds as they are stuck in seemingly interminable traffic: *What might happen if ...*

Cortázar’s 20th-century fiction often played in the realm of the fantastical as a way of probing the deeper truths about existence. In a series of lectures delivered in 1980 at the University of California, Berkeley, Cortázar explained that, in his work, “the fantastic is at the service of reality.” He continued:

The fantasy, the fantastic, the imaginable that I love and with which I have tried to make my own work is everything that ultimately serves to project more clearly and with more strength the reality that surrounds us.

Dabbling in the fantastic might seem natural for a fiction writer—but at sharp odds with science. It turns out, however, that fantasy may play a similarly useful role in illuminating the darkest and most mysterious corners of

science, including seemingly impenetrable regions, such as the study of energy within black holes.

Such fantasies—like Cortázar’s epic traffic jam—are actually a very useful form of thought experiment. *What might happen if ...* In physics, thought experiments have proven invaluable over the centuries for exposing weaknesses in existing theories and generating new ideas.

Thought experiments, of course, are not like real experiments performed in the lab. They usually consist of fictional—sometimes even fantastic—situations that occur in the mind of the scientist: Demons, spirits, and giant teacups can all be part of scientific thought experiments. How can it be that *thought experiments*, mere exercises of the imagination, can teach us something about our scientific theories—especially in today’s era of high-computation physics? This question motivated me to open a new chapter in my own research.



SEVERAL YEARS AGO, I was on a ski tour in the Alps with a colleague of mine from the University of Salzburg, the philosopher and historian of science Rawad El Skaf. My poor level as a skier together with our enthusiasm for discussing big ideas in physics led us to spend much of the day on the terrace of a very charming *Hütte* (cottage), mulling over the role of thought experiments. We arrived at the following conclusion, which we later described in a paper together: Thought experiments in black hole physics help us reveal and resolve tensions and, in some cases, inconsistencies between different theories—much as they have throughout the history of physics, including in the revolutionary theories of general relativity and quantum mechanics.

More than a century ago, one of the most famous thought experiments in physics helped rip a hole in one of its key laws. It involved imaginary gasses, a door, and, perhaps fittingly, a demon.

In 1867, the second law of thermodynamics reigned. It declared that entropy cannot decrease in an isolated system—whether that’s a closed chamber, black hole, or a universe—and that heat only flows spontaneously from hot to cold—and never the other way around. One of the reasons why the second law was (and still is) so important is that it has a series of implications at all levels. It predicts that a cup of hot coffee will eventually cool down; that temperature differences are very hard to maintain; and even that, as time passes, we will grow older and not younger.

But that year, Scottish physicist James Clerk Maxwell—a pioneer of statistical physics—considered *what could happen if* there were a being who could play a game with gas molecules? His conceptual experiment imagines a small being, called later a “demon,” which can manipulate (without expending energy) the flow of gas molecules in a container by controlling a door that divides the container into two parts. We assume that when the gas molecules approach the door, the demon can quickly

select the molecules allowing only fast-moving molecules (which produce hot temperatures) to pass from the left- to the right-hand side of the container and allowing only slow-moving molecules (which produce cold temperatures) to move from right to left.

By doing this, the demon is able to make one part of the container colder as the other gets hotter. Importantly, this implies that temperature differences could be produced at the expense of no work—and that entropy can also decrease in the process.

Maxwell’s fictional demon allowed him to “pick a hole” in one of the most important physical laws of his era. He disputed not only the deterministic character of the law, showing that it allows for exceptions, but also, and more profoundly, he disputed the idea that the laws of nature always follow a simple, regular path. The second law of thermodynamics, he concluded, is valid only *statistically*.

Could we have seen those possible violations of the second law without invoking demons? Perhaps, but these fantasies certainly helped scientists make these problems with the second law more intuitive. As historian of science Jimena Canales puts it in her book *Bedeviled*, “Scientific thinkers used demons to explore problems, test the limits of what is possible, and better understand nature.”

ASPECTS OF NATURE CAN be vexingly hard to understand when we lack empirical evidence about them. Such is the case with the relatively new field of black hole thermodynamics. This discipline aims to ascribe thermodynamic properties, such as temperature, to black holes, which are defined in astrophysics as “regions of no escape.” It is a challenging intellectual space for even the brightest minds. It’s hard to speculate what might be happening with energy and entropy in a black hole when relevant information is as-yet essentially undetectable. So, in areas like this, thought experiments appear to be at their most essential.





Fantasy may play a useful role in illuminating the darkest and most mysterious corners of science.

As Erik Curiel, a philosopher of physics working on the foundations of black holes, has written: “Why assume a classical black hole has an entropy in the first place? The best answer to this is implicit in the series of thought-experiments.”

To better explain Curiel’s position, let us take a trip back in time to the origins of black hole thermodynamics. At the beginning of the 1970s, John Wheeler, an eminent physicist, wanted to challenge his graduate students at Princeton University. So he suggested the following situation: Imagine holding a cup of tea in the vicinity of a black hole. Instead of drinking the tea, what might happen if you threw it into the black hole?

He used this simple thought experiment to reveal a tension between the second law of thermodynamics and the “no-hair theorem,” which is a conjecture in general relativity. According to the no-hair theorem, a black hole is determined only by well-known parameters—namely its mass, angular momentum, and electric charge. Wheeler referred to this with the phrase that “black holes have no hair” because it implies that all the information, for instance about the formation of the black hole, would vanish behind the black hole’s boundaries (its event horizon).

The problem arises if we combine the no-hair theorem with the second law of thermodynamics in scenarios such as the one proposed by Wheeler. If you were to throw a cup of tea into a black hole, thermodynamics would predict that the entropy in the exterior of the black hole decreases. However, given that the no-hair theorem does not tell us anything about the entropy in the interior of the black hole, one cannot exclude the possibility that the total entropy of the universe may have decreased in the process. This is intriguing, because it means that we cannot rule out the possibility that the second law might be violated after all. Since the consequences are similar to Maxwell’s demon, some people have called this thought experiment “Wheeler’s demon.”

Wheeler wanted to push his students by suggesting counterfactual situations in which the second law would become observationally meaningless, or in his own words “transcended.” Not all students were impressed by this challenge. Robert Wald, for instance, another eminent physicist who was a student of Wheeler’s during that period, admits: “The thought that flashed through my mind at the time was ‘Boy, am I glad that I have some good problems to work on!’”

Could we have seen possible violations of the second law without invoking demons?

A perhaps slightly facetious take that seems perfectly reasonable for the time.

These thoughts about the possible “transcendence” of the second law were motivated not by real experiments performed in the lab, but by those only in “the laboratory of the mind” that could not happen in the real world. Of course it is not physically possible to have a cup of tea in the vicinity of a black hole—gravity would not allow it!

So, why should we take thought experiments, with their preposterous tea parties and wily minuscule demons seriously?

Jacob Bekenstein, another prominent physicist and student of Wheeler’s at that time, taught us an important lesson. In contrast to Wald, he decided to take the challenge proposed by Wheeler very seriously and looked into different ways that the second law might be rescued.

To solve the conflict between the no-hair theorem and the second law of thermodynamics, he conjectured that black holes have an entropy that is proportional to the black hole area. This new definition of black hole entropy was motivated by Stephen Hawking’s famous 1971 “area theorem,” which says that the surface area of the event horizon of a black hole cannot decrease with time. Bekenstein then used this definition to formulate the “generalized second

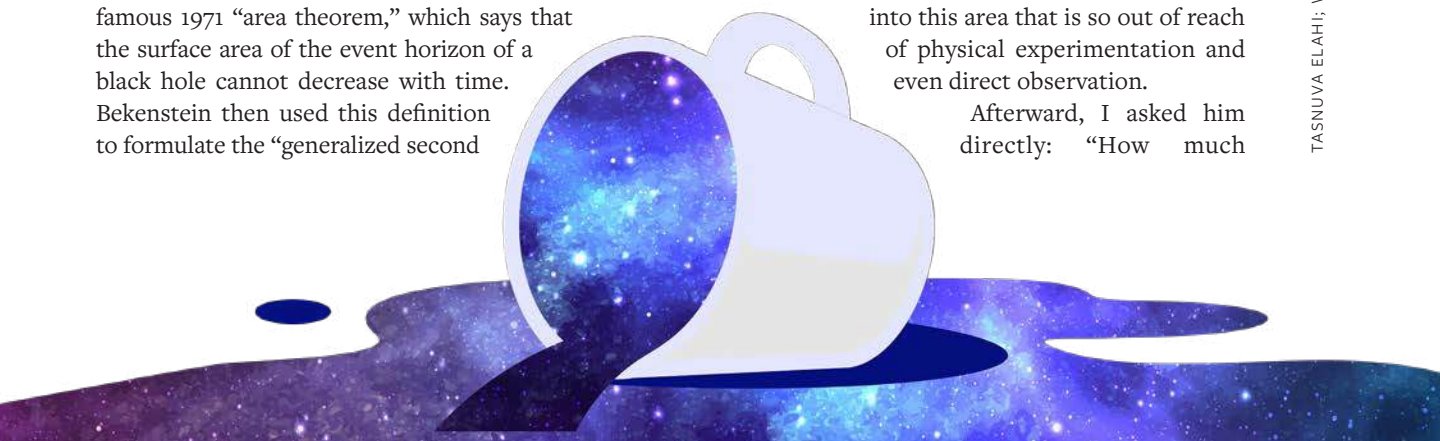
law,” which says that “common entropy plus black hole entropy cannot decrease.” So throw a cup of tea in and the entropy of the black hole will increase to compensate for the loss of entropy in its exterior. The second law—or rather a generalized version of it—has been rescued!

Bekenstein’s findings were published soon after in his 1972 seminal paper “Black Holes and the Second Law.” And the field of black hole thermodynamics—a now well-established discipline in physics and a field that keeps many contemporary physicists awake at night—was born.

All motivated by a seemingly trivial setup about a cup of tea.

NOT LONG AFTER my heady ski trip conversations with El Skaf, I attended a workshop on the foundations of thermodynamics, held in a beautiful European-style home in the countryside of Minnesota, where Juan Maldacena, a leading scientist in black hole physics at Princeton, presented his latest results. In the talk he stressed the important role of thought experiments for generating insights into this area that is so out of reach of physical experimentation and even direct observation.

Afterward, I asked him directly: “How much



What might happen if you threw a cup of tea into a black hole?

do your results rely on thought experiments?” He answered without hesitating: “Nearly 100 percent!”

But are thought experiments useful only in cases in which direct experimentation is impossible *in practice*, like impenetrable black holes?

There is a tendency among physicists to think that all the fantasies involved in thought experiments should eventually be replaced by real, physical experiments. This thought is probably inherited from the empiricist tradition, the philosophical position that tells us we can only learn about the real world from sensory experience and empirical evidence.

I agree that only real experiments can tell us, more conclusively, how to resolve the contradictions that are first revealed by thought experiments. But I also strongly believe that it is only due to the fantasies of thought experiments that we can see in a clear and intuitive way the inconsistencies and conflicts between different theories. They allow us—even before a laboratory experiment could be conceived of—to wonder, *what might happen if ...*

In the past few decades, more philosophers of science have started to stress the important parallels between fictional literature and science. The philosopher Roman Frigg, for instance, in his influential paper “Models and Fictions” argues that scientific models share important aspects in common with literary fiction, and that theories of fiction can therefore help us better understand how science works. In science, fiction—and even fantasy—can be used as an instrument to better understand our theories and the real world. This suggests that the friction between science and fiction is less sharp than people tend to think.

Interestingly, this is not far from what Cortázar himself proposed about the two disciplines. In *Literature Class*, the book distilled from his Berkeley lectures, he noted—according to my translation of his Spanish text—that, “it has seemed to us that literature is a kind of combinatorial art in which fantasy, imagination, truth, lies, any postulate, any theory” are welcome. Scientists, on the other hand, he said, it has often seemed, occupied a very different world—one of certainty, confidence. “But when I read about Heisenberg’s uncertainty principle, I said ‘damn, they’re like us.’” ☺

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High Mountains, Ancient Shells, and the Wonder of Deep Time

Learning to appreciate the big picture

BY KATY KELLEHER

STANDING ON THE SIDE OF A MOUNTAIN outside Santa Fe, New Mexico, I held evidence of the ocean. The rough gray rock was small and unimpressive, marked by a series of squiggly white lines; it was hardly worth Instagramming, much less taking home, but my daughter ran down the trail to bring me another, a little more articulated than the first, recognizably scallop-like. Her face was alight with excitement and her voice was thick with winter cold. “Mama,” she said, “I found a seashell.”



Being able to situate oneself and one's world as dots on an endless line is no small thing.

We were hiking on the Chamisa Trail, part of the Dale Ball Trail system, which winds through the western foothills of the Sangre de Cristo mountains. Here, the ground is red and the trees are sharp. Snow falls often in winter, blanketing the young mountains in white, obscuring the prickly pear paddles, leaving only the spines visible. I had read that sharp-eyed hikers could find fossils scattered throughout the region, but I didn't expect it to be so easy, nor did I think my 4-year-old would be so fascinated by them.

We had moved from Maine to New Mexico just months before, and we all fiercely missed the ocean, despite our growing admiration for the desert. We were still learning how to parent, teach, and play in this unfamiliar landscape with its deadly rattlers, punishing plants, and startling temperature swings. I pushed away memories of my former aquatic hobbies and tried to embrace the Land of Enchantment and its mystical vistas. And yet, here we were, collecting shells. "Just like in Maine," my daughter said.

"Do you know how it got here?" I asked, crouching beside her in the mud. "There used to be a huge ocean here, right where we are standing." It was all I knew, but it was enough for that moment. It was a little sliver of a greater, more complex reality, a piece of information that could spawn thousands of new questions, given time. She looked around, up and down the trail. I like to think she was doing exactly what I was: wondering at the bigness and strangeness of our world.

LATER, I FIND OUT that this fossil is "almost definitely from the Pennsylvanian," according to Kevin Hobbs, field geologist and mapper for the New Mexico Bureau of Geology and Mineral Resources. The Pennsylvanian is what geologists call the period between 320 million and 300 million years ago. He identifies the fossil as a probable brachiopod.

"They are still around. You can go to the ocean today, and you'll still find them," he adds, though their heyday is long past. Most of the brachiopods who live today exist in deep, dark recesses of the ocean. Three-hundred million years ago, they were the main reef-builders and filter-feeders of their time. They dwelled in mud and on loose rocky shorelines, living their quiet lives alongside the equally staid clams and colorful corals. Around them moved predatory starfish and cartilaginous fish, early reptiles, and an abundance of amphibians.

While much of what is now northern New Mexico was covered with water, a chain of islands had begun to form, on which vibrant green life thrived: huge seed ferns, scale trees, and supersized club mosses. The oxygen-rich atmosphere enabled arthropods to grow to frightening dimensions. Six-foot-long invertebrates insects scampered around the forests on their many, many legs, feasting on seeds, leaves, and spores. It's likely that the crow-sized dragonflies found elsewhere at the time flitted around the Sangre de Cristos on their powerful wings, hunting for prey.

The Pennsylvanian gave way to the Permian, followed by the Triassic—when the first known dinosaurs appeared—and then the Jurassic, and finally the Cretaceous, the Age of Dinosaurs, which ended about 66 million years ago. At Ghost Ranch in Abiquiu, New Mexico, an hour drive from the Sangre de Cristo mountains, I held the fossilized bone of a *Coelophysis*: a 9-foot-long bipedal meat-eating dinosaur who lived during the Late Triassic Period. It was one of nearly 1,000 individual skeletons found in a quarry during the 1940s. The specimen was broken in half, and in the middle of the stone bone, I could see a pop of bright whitish-yellow quartz.

Standing in Ghost Ranch's Ruth Hall Museum of Paleontology, surrounded by bones and reproductions, I was able to better grasp how much our world had changed. On the day I visited in late May, temperatures registered in the 70s, but they felt much





TIDES AND TIME Now found mostly in deep ocean redoubts, brachiopods were widespread 300 million years ago.

hotter. My nose was sunburnt, my throat was dry, my legs were scratched from walking among cacti. Yet here, again, was evidence that the Southwest wasn't always so. Some 200 million years ago, creatures who looked like sea dragons swam through the water above the mass grave of drowned bipedal dinosaurs. Life was expanding and changing, evolving.

Although there seems to be little shared between my tiny shell and the club-like *Coelophysis* leg bone, these various finds are pieces of a larger puzzle. Alongside the thousands of other fossils found in New Mexico, these objects helped form the bedrock of the tectonic plate theory. First postulated in the early 20th century, the theory only rose to prominence in the 1960s. The idea that the Earth was composed of

moving layers—a hard, fragmented outer shell atop a molten core—was initially dismissed as fanciful, too strange to be real. But that's how much of our reality has been formed, through strange suppositions and hopeful guesses, collected observations and unlikely finds. The hypothesized movement of those plates provided a mechanism—the collision and overlapping of plates pushing Earth's crust upward over millions of years—by which an ancient seabed could become a mountaintop. Geologists pointed to fossilized brachiopods and other marine creatures found at otherwise-inexplicable elevations to make their case.

"Prior to the plate tectonic theory, it was really difficult to explain how you get ocean fossils on top of the Sangre de Cristos," explains Hobbs. He laughs when he



In science, as in parenting, you don't ever truly stop reaching or grasping.

talks about the “cockamamie theories” scientists once proposed about how shells ended up on summits. One idea was that there was once a lot more water on Earth, but it was boiled off into the air.

WHEN HOBBS ISN'T EDUCATING rock-curious members of the public like myself, he spends much of his time walking through arroyos and up mountains, mapping the geography of northern New Mexico. For him, awe comes easily. “It usually happens when I’m thinking about time and how long geologic time is,” he says.

Being able to situate oneself and one’s world as dots on an endless line is no small thing. Perspective, notes Maya Wei-Haas, a science writer and author of *What a Rock Can Reveal*, “is very difficult, especially when you’re young.” Knowing about the slow, long, strange processes that produce the rocks we find can help us better place ourselves in the big picture. It is both humbling and elevating, which, now that I think about it, is a good way to describe childhood in general.

Or maybe it’s just something we all struggle with equally. I had assumed that the vastness of billions of years and the massiveness of tectonic movements would be too much for my young child to grasp, but both Hobbs and Wei-Haas admit that they have trouble thinking along these lines, too. “This is something my wife and I argue about—whether you can understand geologic time,” says Hobbs. (For the record, his wife is also a geologist.) “I think you can,” he says. “But she says, ‘You just know the numbers.’” For Haas, this great philosophical question is “part of the fun” of geology. “It’s the almost-inconceivability of it.”

But in science, as in parenting, you don’t ever truly stop reaching or grasping. The world is unknowable, kids are impossible, time is terrifically long, and our time is so very short. This may lead some to conclude that nothing matters—Hobbs said he’s met plenty of nihilist geologists who do precisely that—but that’s not the only way to interpret this set of facts. You could also look at them this way: Even the small things eventually add up to something great.

IN TIMEFULNESS: HOW THINKING *Like a Geologist Can Help Save the World*, geologist Marcia Bjornerud argues that what she calls our “time literacy” is sorely lacking. It would be very strange, she points out, if someone couldn’t name the continents on a map, but we generally don’t expect non-scientists to know the difference between the Devonian and the Permian periods.

“Fathoming deep time is arguably geology’s single greatest contribution to humanity,” Bjornerud writes. “Just as the microscope and telescope extended our vision into spatial realms once too minuscule or too immense for us to see, geology provides a lens through which we can witness time in a way that transcends the limits of our human experiences.”

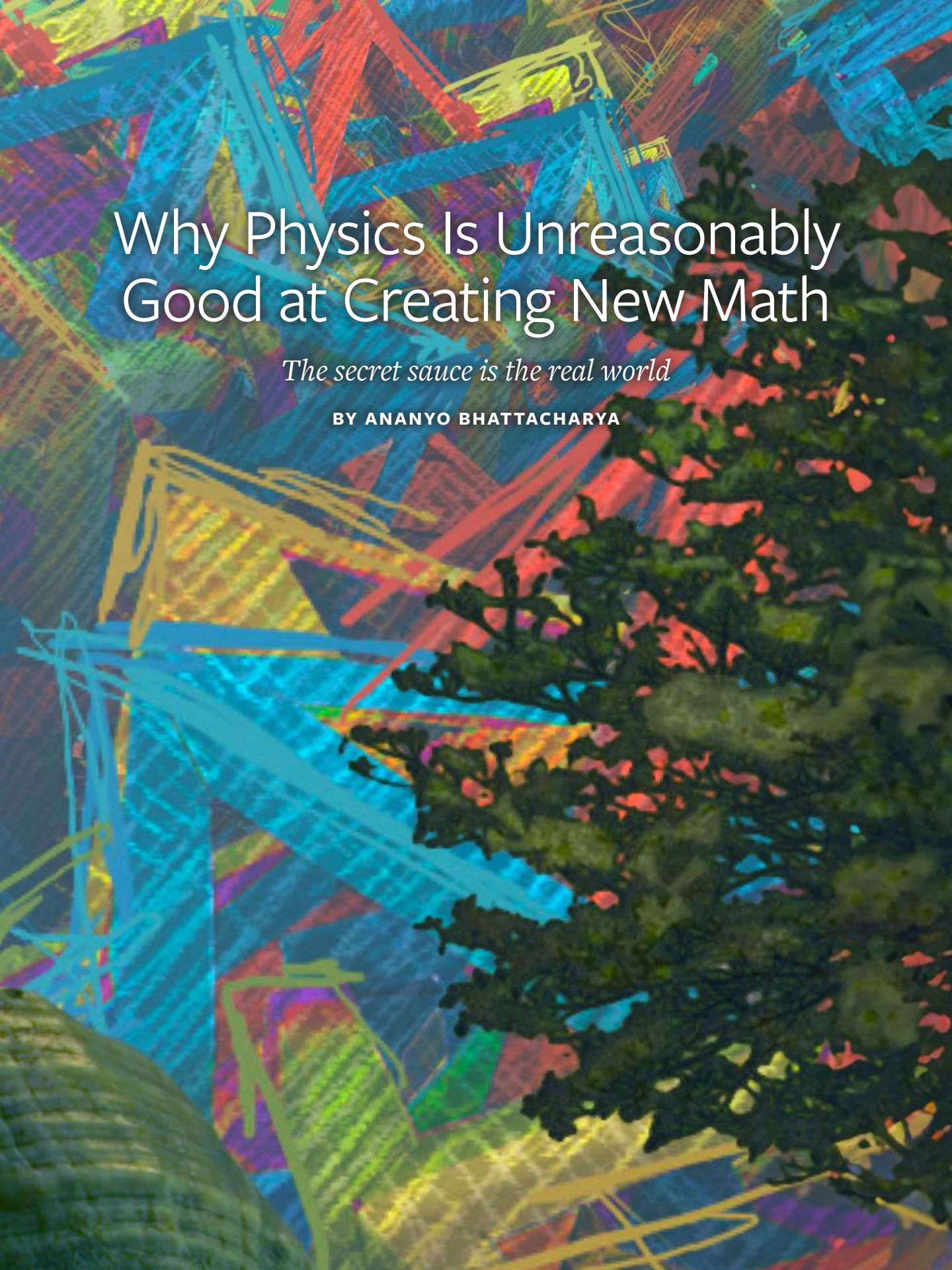
This sense of wonder and vastness is centering and calming, and it’s something I used to find only in the ocean. Paddling out past the wave breaks in autumn or skulking around a stormy beach in winter, I had a long-standing habit of taking to the shore whenever I needed to shift my thinking and quiet my brain. When my problems felt too big, I went to the Atlantic for a reminder that my life is small; lovely or troubled as it may be, it’s nothing when compared to the force of water.

I’ve now started to understand that rocks—fossils, pebbles, mountains—can provide a similar ego check. Once you learn how to read them, you can see the grand concepts written right on the surface. In a fossil, I can see the recycling of matter, the fragile lives lived so long ago, the evidence of a world in continual motion and flux. I can see the boundlessness of the universe. In a stone brachiopod in the desert, I can hear the ocean. ☺

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The background is a complex, abstract composition. It features a dense arrangement of overlapping, semi-transparent geometric shapes in various colors, including bright blue, red, yellow, green, and purple. These shapes are layered to create a sense of depth and movement. On the right side of the image, there is a dark, silhouetted shape that resembles the foliage of a tree, partially obscuring the colorful background. The overall effect is a vibrant, textured collage.

Why Physics Is Unreasonably Good at Creating New Math

The secret sauce is the real world

BY ANANYO BHATTACHARYA

MATHEMATICS HAS LONG BEEN THE BASIS for advances in physics. Albert Einstein hailed general relativity as “a real triumph” for mathematics in 1915, when he discovered that purely mathematical work, more than a half-century old, perfectly described the fabric of spacetime in his theory of gravity. How could math conceived with no application in mind, he wondered later, prove “so admirably appropriate to the objects of reality?”

Math’s service to physics, now often taken for granted, is rooted in its origins. Mathematics was, after all, invented for surveying, quantifying, and understanding the physical world. In Mesopotamia, the Sumerians developed a counting system, leaving behind clay tablets inscribed with multiplication tables. Their purpose? To tally goods and property. In the intervening millennia, what began as a tool to grease the wheels of government and commerce took on a life of its own. But, while expanding into areas of abstraction so obscure they can only be grasped after years of training, mathematics has continued to underpin the great breakthroughs in physics.

Recently, though, the tables have turned. Now insights and intuitions from physics are unexpectedly leading to breakthroughs in mathematics. After going their own way for much of the 20th century, mathematicians are increasingly turning to the laws and patterns of the natural world for inspiration. Fields stuck for decades are being unstuck. And even philosophers have started to delve into the mystery of why physics is proving “unreasonably effective” in mathematics, as one has boldly declared. That question hinges on a largely unappreciated, perplexing, and profound link between the rules that govern the behavior of the cosmos and the most abstract musings of the human mind.

Why *should* physics—rooted in making sense of real things in the world like apples and electrons—provide such good leads for solving some of the toughest problems in mathematics, which deals with intangible stuff, like functions and equations?

The experience of mathematical beauty excites the same parts of the brain as beautiful music, art, or poetry.

“Physicists are much less concerned than mathematicians about rigorous proofs,” says Timothy Gowers, a mathematician at the Collège de France and a Fields Medal winner. Sometimes, he says, that “allows physicists to explore mathematical terrain more quickly than mathematicians.” If mathematicians tend to survey—in great depth—small parcels of this landscape, physicists are more likely to skim rapidly over vast tracts of this largely uncharted territory. With this perspective, physicists can happen across new, powerful mathematical concepts and associations, to which mathematicians can return, to try and justify (or disprove) them.

THE PROCESS OF PHYSICS inspiring mathematics is, in fact, as old as science itself. The ancient Greek mathematician and inventor Archimedes described how the laws of mechanics had spurred some of his most important mathematical discoveries. Then there’s Isaac Newton, who (alongside his contemporary, the German polymath Gottfried Wilhelm Leibniz) famously developed an entirely new kind of math—calculus—while trying to understand the motion of falling objects.

But in the middle of the 20th century, the flow of new math from physics all but dried up. Neither physicists nor mathematicians were much interested in what was happening on the other side of the fence. In mathematics, an influential set of young French mathematicians called the Bourbaki group sought to make mathematics as precise as possible, rebuilding whole fields from scratch and publishing their collaborative work in an

effort—they hoped—to facilitate future discoveries. Physicists, meanwhile, were excitedly developing path-breaking ideas such as the Standard Model—still physicists’ best theory of the atomic and subatomic world. For many of them, math was just a handy tool, and they had no interest in the austere vision of mathematics championed by the Bourbakis.

Yet a reconciliation was afoot, spearheaded by the late British-Lebanese geometer Michael Atiyah. With rare intuition, and a little luck, Atiyah, also a Fields medalist, often alighted on areas that would later be of interest to theoretical physicists.

“In the mid 1970s, he became convinced that theoretical physics was by far the most promising source of new ideas,” Nigel Hitchin, a mathematician and emeritus professor at the University of Oxford who collaborated with Atiyah wrote in 2020 of his former colleague. “From that point on, he became a facilitator of interactions between mathematicians and physicists, attacking mathematical challenges posed by physicists, using physical ideas to prove pure mathematical results, and feeding the physicist community with the parts of modern mathematics he regarded as important but were unfamiliar to them.”

One of Atiyah’s long-term collaborators, who he first met in 1977, was the mathematical physicist Edward Witten. More than 20 years Atiyah’s junior, Witten later became a pioneer of string theory, an idea that posits that tiny one-dimensional vibrating strings are the fundamental building blocks of the universe, rather than the particles of the Standard Model.

Initially hailed as a possible “theory of everything” that would unite quantum theory with Einstein’s theory of gravity, string theory has to date arguably had a bigger impact on some of the most abstract fields of mathematics, such as algebraic geometry and differential topology, than in physics. In these areas, Witten and other string theorists have been able to produce precise conjectures that mathematicians have later proved.

In 1991, for example, physicists Philip Candelas, Xenia de la Ossa, and their colleagues applied string theory to a decades-old puzzle in enumerative geometry, an ancient branch of mathematics dedicated to counting the number of solutions to geometrical problems. At its simplest, this asks questions such as “How many lines can pass through two points on a plane?” (One.) Or Apollonius’ famous problem, “How many circles can be drawn that touch (are tangent to) three given circles?” (Eight.)

Candelas and his collaborators were able to use tools from string theory to solve a particularly sticky problem in enumerative geometry: counting the number of certain kinds of curves in Calabi-Yau manifolds, strange six-dimensional shapes that are central to string theory. Their result connected two kinds of geometry, “symplectic” and “complex,” that mathematicians had studied in isolation from each other for decades, thinking they were unrelated. This sort of advance—one that connects two fields that were thought to be unrelated—is considered a “deep” result in math: You can suddenly use tools from one to solve problems in the other, enabling and accelerating advances.

Just a few years later, in 1995, Witten proposed that five different versions of string theory, each requiring 10 dimensions, were all different aspects of a single 11-dimensional conceptualization he called “M-theory.” Though M-theory remains unproven, mapping the correspondences between the different

theories has led to startling mathematical discoveries. “It feels like every month string theory is giving new structures to mathematicians in an unprecedented way,” says mathematical physicist Yang-Hui He of the London Institute for Mathematical Sciences.

That string theory is a rich source of such unexpected relationships, or “dualities,” between two mathematical worlds, continues to excite mathematicians today. Physicist He and his collaborator string theorist Federico Carta, also of the London Institute, were studying the simplest type of Calabi-Yau manifold, called a K3 surface, when they stumbled across a relationship between the surface’s “homotopy groups,” which are used to classify shapes in topology, and a symmetry group, called “Matthieu 24.” The pair’s discovery reveals an unanticipated connection between two disparate fields of pure mathematics—topology, the study of shapes, and an area of modern algebra called group theory, which concerns the types of symmetry that objects possess.

Why physics should give rise to such interesting mathematics, says He, is a “deep question.” There are an infinite number of patterns and structures that mathematicians could study, he says. “But the ones which come from reality are ones which we have an intuition about at some level.”

Hitchin agrees. “Mathematical research doesn’t operate in a vacuum,” he says. “You don’t sit down and invent a new theory for its own sake. You need to believe that there is something there to be investigated. New ideas have to condense around some notion of reality, or someone’s notion, maybe.”

This raises the question of whether physics feeds math merely by providing a keener motivation for exploring it and a focus for mathematicians’ energies. Guided by intuitions about how the world should work, and a plausible endpoint, mathematicians can sometimes make speedier progress on a problem than they otherwise would.

The sort of math that emerges from studying reality is the sort our brains tend to like.

It would also explain a curious fact: “Bad” physics can sometimes lead to good math.

Vortex theory, for instance, was an early attempt by British mathematical physicist William Thomson (Lord Kelvin) to explain why atoms came in a relatively small number of varieties. He pictured atoms as spinning rings which could be tied in intricate knots, with each knot corresponding to a different chemical element. The theory was abandoned after the discovery of the electron—but the mathematics led to the development of knot theory, which has since both become a fecund area for pure mathematicians to explore and found surprising applications in fluid dynamics and for understanding tangled molecules like DNA.

FOR ATIYAH, THE ENIGMATIC relationship between physics and math all came down to the human brain. “Humans are a product of long evolution, in which powerful brains were an advantage. Such brains evolved in the physical world, so evolutionary success was measured by physical success,” he explained in a

2018 interview. “Hence human brains evolved to solve physical problems and this required the brain to develop the right kind of mathematics.” To do so, the brain must also have adapted to recognizing and appreciating mathematical patterns in nature. Atiyah even co-authored a brain-imaging study in 2014 that concluded the experience of mathematical beauty excites the same parts of the brain as beautiful music, art, or poetry. That might explain why physics can be a lodestar for mathematicians: The sort of math that emerges from studying reality is the sort our brains tend to like.

In a 2010 paper with Hitchin and Dutch theoretical physicist Robbert Dijkgraaf, then of Princeton University, Atiyah

The universe itself is not just described by mathematics but is *made* of mathematics.

went on to further highlight the successful use of physics in mathematics. Since then, however, there has been scant work to try to understand the phenomenon.

One philosopher who has recently re-examined the issue is Daniele Molinini, at the University of Bologna. His 2023 paper, published in *The British Journal for the Philosophy of Science*, responded to an oft-cited 1960 essay entitled “The Unreasonable Effectiveness of Mathematics in the Natural Sciences” written by Nobel laureate physicist Eugene Wigner. Molinini’s cheeky response instead explored “The Unreasonable Effectiveness of Physics in Mathematics.” His surprising answer is that some laws of physics may be as incontrovertible as a mathematical theorem. “There are some principles about the world that we have to take as fundamental,” he says.

Philosophers broadly agree that mathematical truths are “necessary,” in that they have to be true in all possible worlds. Truths about nature, empirical facts, are different—they’re contingent. Light travels at a certain speed, but arguably it could have been otherwise in a differently set up universe. That is, mathematical truths have been, and will always be, true, no matter what.

Might there be certain laws of physics that are also “necessary” in the same way? In his paper, Molinini argues that the principle of

conservation may be one such law. In physics, some properties of a system, such as energy or momentum, can’t change. A bicyclist free-wheeling down a hill, for example, is converting her gravitational potential energy into movement energy, but the total amount of energy she and her bike have stays the same.

If such conservation is “necessary,” Molinini contends, that may explain how Archimedes was able to successfully infer the truth of geometric proofs by mechanical considerations, a feat which is otherwise puzzling. The physics and the math, in this case, are two sides of the same coin: Both are true because they draw on the same fundamental principle.

Another view, famously articulated in the early 17th century by Galileo and often championed by mathematicians, is that the universe is written in the language of mathematics. That idea has ancient origins, going back to at least Pythagoras and his followers, but a more recent, and extreme, version is Max Tegmark’s mathematical universe hypothesis, in which the universe itself is not just described by mathematics but is *made* of mathematics.

In Tegmark’s telling, our universe is just one of an infinite number of parallel universes and all the infinite possibilities of mathematics—every theorem, every proof—are realized somewhere in this multiverse. So, no wonder physics inspires new discoveries in math—the

reality physics describes is, at bottom, mathematical anyway. “There’s an intimate connection between empirical science and mathematics,” says Mark Colyvan, a philosopher at the University of Sydney who has studied the relationship between math and physics. “One conclusion one could draw is that somehow the world itself is mathematical.”

In both cases, however, the mathematics of known physics is just a tiny fraction of all the mathematics out there (nearly all of which is likely to be far less interesting), so this view doesn’t really explain why math emerging from physics should be unusually rich.

Molinini is now challenging a popular philosophical explanation for math’s applicability, “mapping,” which he believes can’t account for why good math can flow from physics. Mapping suggests that math is applied to physics by turning physical concepts, like mass or separation, into mathematical entities, such as the equation for Newton’s law of gravitation, which can then be used to calculate something that is then mapped back into a physical property—for instance, the attraction between two objects. But Molinini argues that that process of mapping breaks down when one tries to reverse it to explain how math can emerge from physics.

There is burgeoning interest in this question from philosophers, he says, who have until now focused on the converse problem of why math can be applied to the empirical sciences.

“Modern physics is providing mathematicians with a whole host of new tools and unexpected leads,” says the London Institute’s He. “And in future, physics and math will need to work together even more closely to solve some of the biggest problems in pure math.”

The Langlands program, conceived by Robert Langlands in the 1960s and often called “the grand unified theory of mathematics,” is one such area, says He. One arm of the

program, the geometric Langlands, was purportedly recently settled by a team of mathematicians who presented a proof spanning five papers and 800 pages. A kernel of that proof rests on insights originally drawn from conformal field theory, a branch of physics that is a cornerstone of string theory, among other areas. He believes that mathematicians will need to draw on more physics to explore the implications of that proof, as well as to make progress on the other arms of the program.

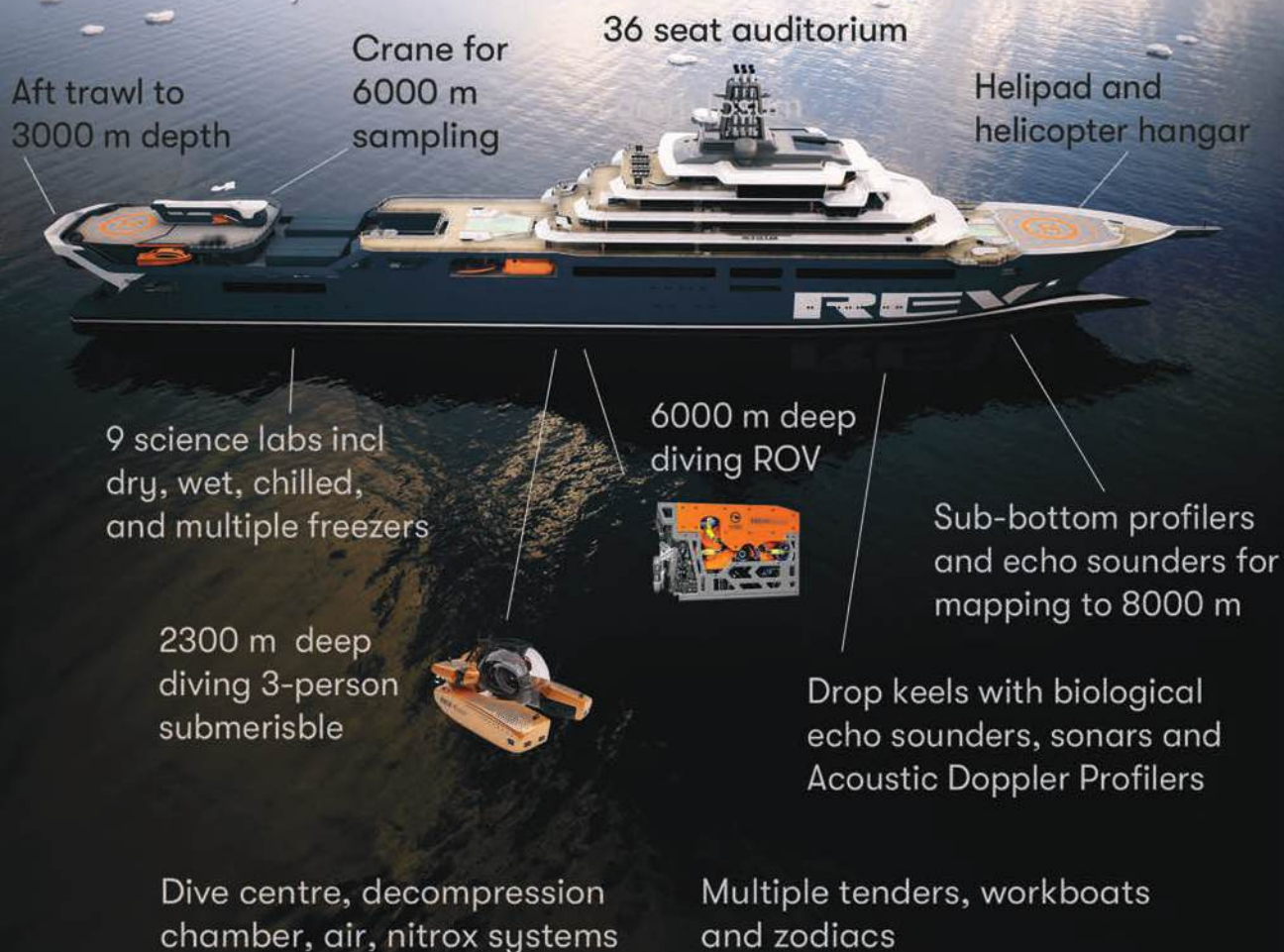
Similarly, mathematicians have already tapped physics in their attempts to make progress on the Riemann hypothesis and Birch and Swinnerton-Dyer conjecture—two of the most challenging open problems in math. An alliance between the two fields, suspects He, will be key to finally unlocking these behemoths.

“Physics and math are starting to become one again, like they were in Newton and Gauss’ day,” says He, who trained as a theoretical physicist but is increasingly drawn to applying physical ideas to problems in pure math.

It’s an intriguing thought. The story of the universe might be written in the language of mathematics. But beautiful as the tale seems to be, the signs are that understanding more than physicists already do will demand increasingly exotic and sophisticated mathematical tools, some of which are yet to be invented. Breaking down the barriers between the two fields could open new worlds of understanding in both. ☺

ANANYO BHATTACHARYA is chief science writer at the London Institute for Mathematical Sciences. During a 15-year career in journalism, he has worked as a senior editor at *Nature* and as a science correspondent for *The Economist*. He is the author of *The Man from the Future*, an intellectual biography of mathematician John von Neumann.

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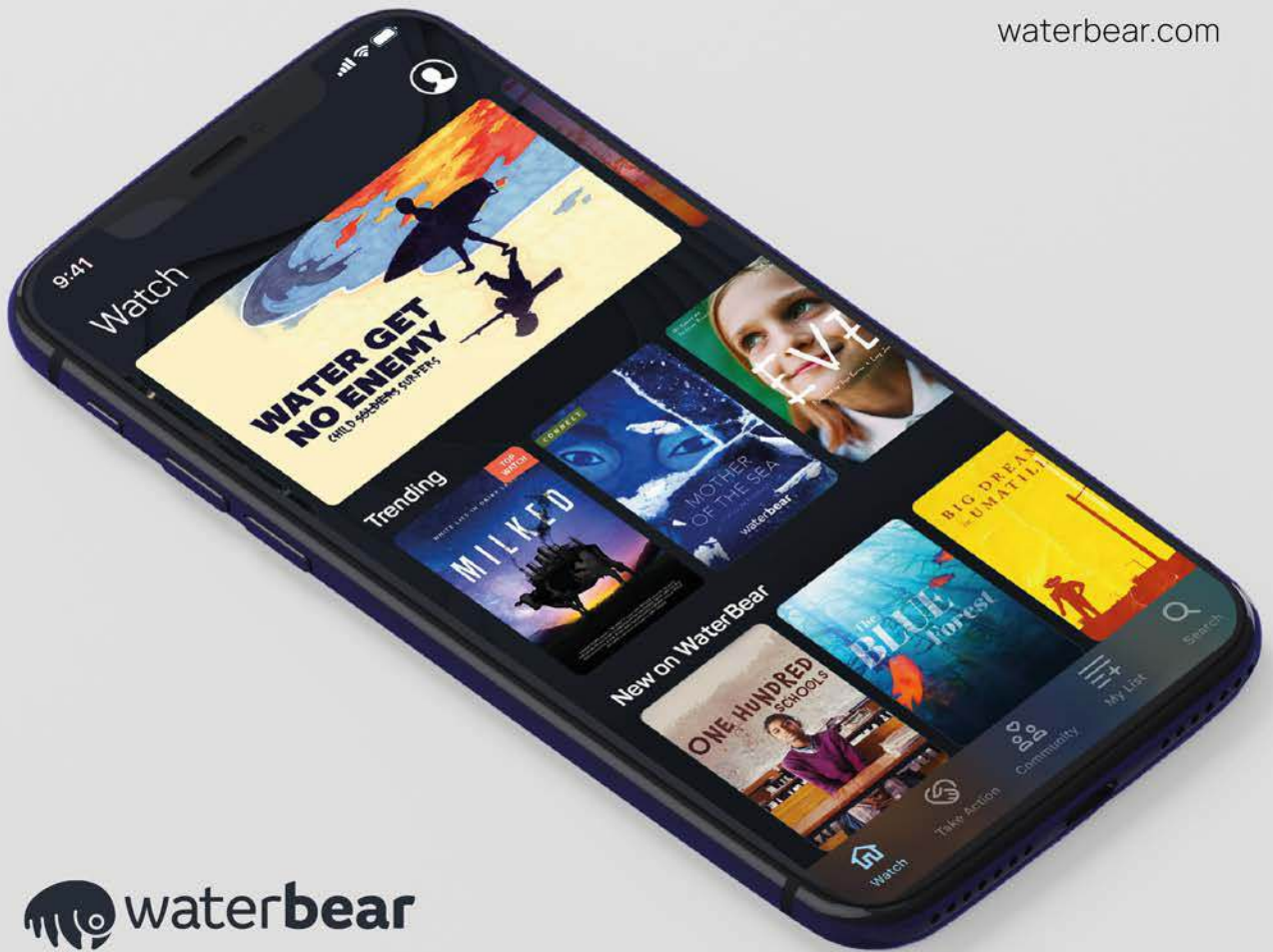
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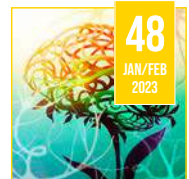
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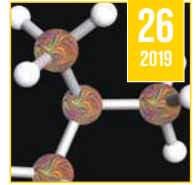
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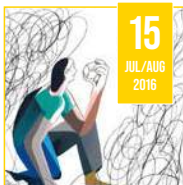
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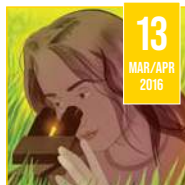
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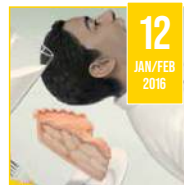
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*All of these levels
are required
if a species as
limited as Homo
sapiens hopes to
grasp the totality
of reality.*

principle of computational equivalence, and many theories of reflexivity and agency that bring us back toward the recursions of the social sciences.

These recent insights raise a rather troubling, and of course ancient, question. Should we conceive of physical and complex reality as the constructs of observers and minds working with natural language, mathematics, and computation? Or should we instead conceive of our conceptual constructs as the products of math, physics, neurobiology, and the mind? Most of us were trained as materialists placing matter before mind. But this easy assumption has been repeatedly questioned, and these assaults have become more frequent in recent years.

We suggest that many of these dilemmas can be resolved (or at least clarified) by thinking of reality as a circular structure resembling an Ouroboros (the symbol of a serpent eating its own tail). We position the ontological hierarchy of reality along this Ouroboros, including physical processes, life, intelligent systems and mind, culture, mathematics, and so forth. We suggest that any point on this circle can act as a “foundation” for subsequent theorizing, as the point where the mouth and the tail of the serpent intersect.

Consider the following choice of foundational points along the Ouroboros and the names that we give to each:

Platonists, A-lifers, and simulation theorists start with ideas. This assumes that math is foundational, and that physics, life, and mind are derived from it. The ultimate production of math by minds closes the circle making math fundamental.

Math → Physics → Neurobiology → Mind → Math

Biological materialists start at the foundational insertion point of neurobiology, from which new emergent theories ensue, including theories of mind that are the source of epistemologies, that close the circle when they generate theories of neurobiology.

Neurobiology → Mind → Math → Physics → Neurobiology

Origin-of-life researchers seek to identify crucial broken symmetries that propagate up through living matter and ultimately support the evolution of brains and minds whose models of physics and chemistry then dictate how we think about life.

Chemistry → Life → Neurobiology → Mind → Math → Physics → Neurobiology → Chemistry → Life

Research fields and disciplines are defined by the point at which they start in the cycle: the level that they declare to be “fundamental” to their investigations.

Physics likes to start with particles and fields and see how far simple symmetries might be explored to explain matter. Biologists like to start

These dilemmas can be resolved by thinking of reality as an Ouroboros—the symbol of a serpent eating its own tail.

with organic chemistry, broken symmetries, and determine how far this might explain functional organization. And psychologists like to start with the mind and ask about the origins of mathematics upon which any physical theory will ultimately be constructed. And of course the influence of each discipline need not be restricted to its contiguous neighbors along the cycle but can reach into more distant points along its development; in this way, mathematics can jump straight into psychology or chemistry into ecology.

Following the pioneering ideas of Philip Anderson in his 1972 paper “More Is Different,” and its sequels, we allow that there is an arbitrary choice of starting point: No one science is more fundamental than any other. But having rooted, or pinned the Ouroboros at one segment in its cycle, researchers are rigorously constrained in their exploration of the implications of this decision as they traverse the emergent hierarchy of the Ouroboros. Depending on whether they are catabolic (particularist) or anabolic (synthetic) thinkers, most researchers are either chewing on their field’s segment of the Ouroboros or patching up some small holes in their field’s segment.

Importantly though, every segment of the Ouroboros has at least some of this catabolic character, severing itself from the segments that came before and neglecting those that come after. An example is how Gödel’s incompleteness theorems in mathematics is a small hole chewed into the basic building blocks of mathematics itself. Similarly, much of philosophy casts strong doubt on the basic legitimacy of philosophical reasoning. And in many respects, the more we learn about neurobiology and cognitive science, the less trust we place in the mental processes involved in the research of neurobiologists. Each segment of the Ouroboros contains its own Shiva—destroyer of worlds.

In terms of Vedic metaphor, can we get beyond this self-destruction, to focus on the Trimurti or the personification of the whole? This is, in one telling, the subject of complexity science—surveying the many distinct approaches to reality that follow from our assumptions about what constitutes a fundamental level of explanation—or what effective theory we use to root our analyses. Complexity science seeks to explain emergent phenomena or mechanisms that “screen-off” their constituent parts and thereby allow new levels of description and understanding. These levels are not only natural manifestations of reality but all of them are required if a species as limited as *Homo sapiens* hopes to grasp the totality of reality. ☺

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DAVID WOLPERT is a professor at the Santa Fe Institute.

The Reality Ouroboros

Toward a new understanding of the nature of reality

BY DAVID KRAKAUER & DAVID WOLPERT

Among the roots of your classicism you must include your passions for the stars.

—Cesare Pavese, *This Business of Living*

WHAT IS REALITY? And is there just one reality or many, perhaps infinitely many? And how should we describe these realities, with mathematics, natural language, music, or visual art? The answer might be all of the above, but if so, can we justify these decisions based on a larger conception of reality?

Scientists tend to think about reality in one of two ways. The first perspective involves physically emergent hierarchies (ontologies)—ranging from the most “fundamental” elementary particles, through nuclear and atomic physics, collective chemistry, adaptive organisms and ecosystems, brains, minds, and, ultimately, human societies.

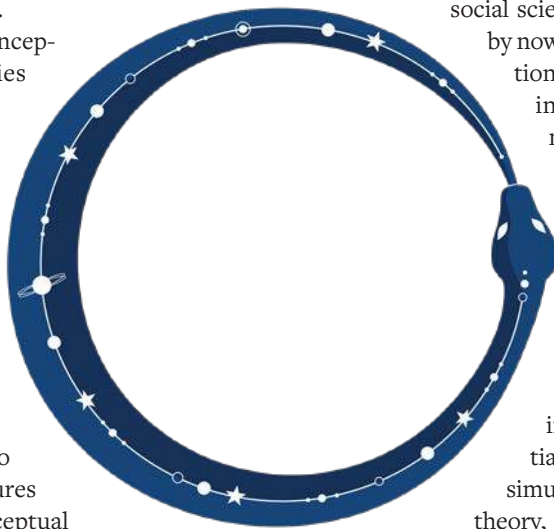
The second describes conceptually emergent hierarchies (epistemologies)—spanning logic, mathematics, natural language, natural science, and the arts. This perspective focuses on the cognitive and conceptual structures that humans create to describe the physical hierarchies in which they are embedded.

Increasingly these two ideas of reality—architectures of physical matter and conceptual

information—are intersecting. Several contemporary areas of research are blurring the boundary between theories of reality and reality itself. The clearest example of this would be in the social sciences, where “social reality” and a model or theory of society are often difficult to disentangle. For example, does a formalism like John Nash’s non-cooperative game theory describe strategic interactions, or does game theory control strategic interactions? How might we ever disentangle these two possibilities?

This blurring of the distinction between physical and conceptual reality extends far below the

social sciences to encompass deep, and by now widely held disciplinary positions, including the many-worlds interpretation of quantum mechanics, cosmic inflation, the “It-from-Bit” school of physics, and the idea of generalized observers in adaptive systems (from natural selection to cultural evolution). And these have been extended up the hierarchies, generating controversial (yet influential) frameworks, including the simulation hypothesis, constructor theory, the free energy principle, the



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