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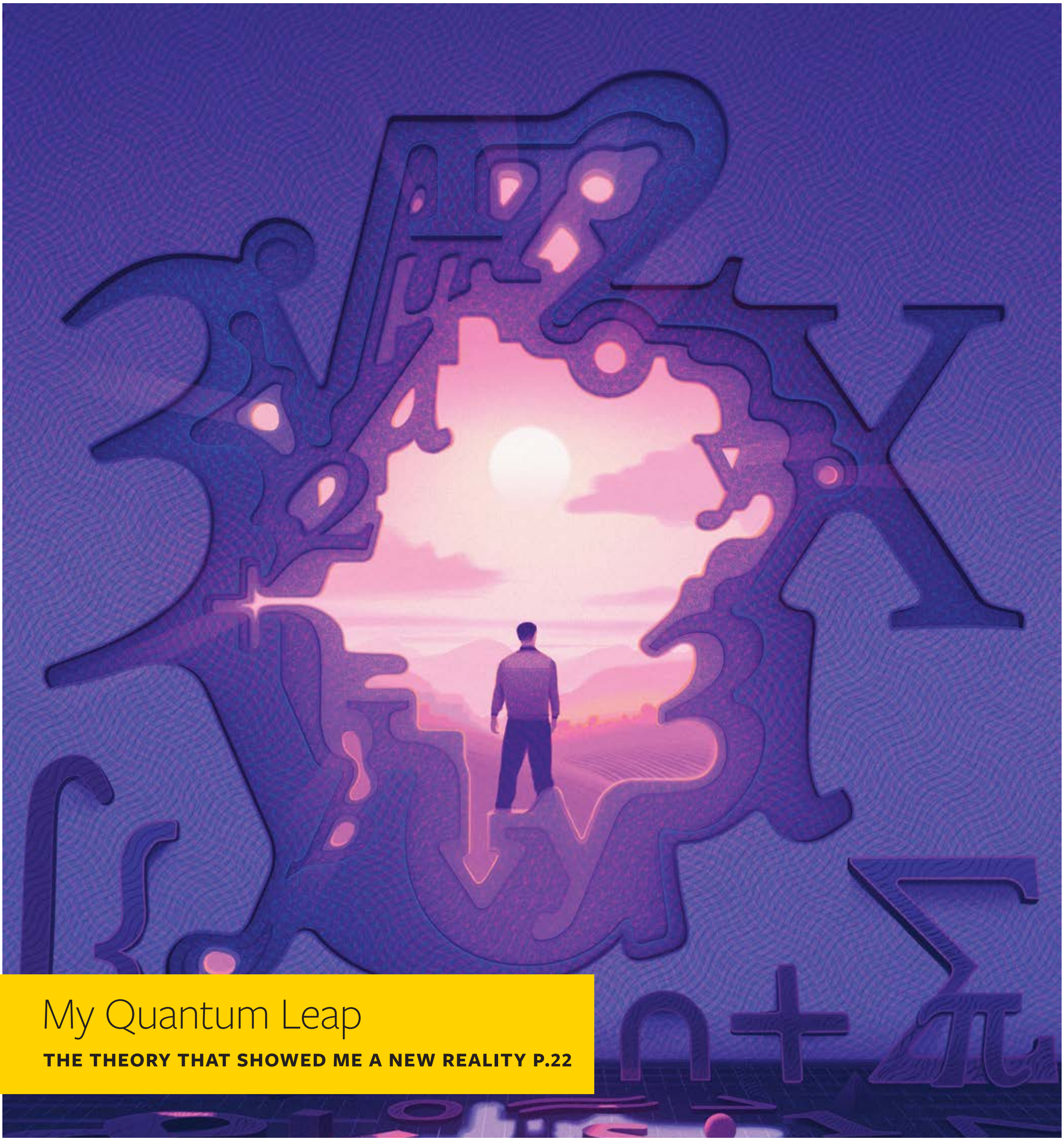

My Quantum Leap

THE THEORY THAT SHOWED ME A NEW REALITY P.22

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ISSUE 42

Contents

COVER Sam Chivers

The Great Narrative, the new book by Klaus Schwab and Thierry Malleret, encapsulates the Davos Vision, and explores how we can shape a constructive, common narrative for the future. It is based on interviews with 50 of the world's most influential thinkers, scientists, and economists, and the successor to the worldwide best-seller, "The Great Reset".

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EDITOR'S NOTE

Awakening

BY KEVIN BERGER

JUST OVER FIVE YEARS AGO, Bob Henderson, author of this issue's cover story, wrote one of *Nautilus*' most popular articles, "What Does Any of This Have to Do with Physics?" It's a personal and bracingly candid story of what he loved about physics, and why, after earning his Ph.D., he decided to leave the world of electrons and photons and become a Wall Street trader.

Henderson had enrolled in graduate school at leafy University of Rochester in upstate New York in search of physics' Holy Grail, quantum gravity, the reconciliation of quantum mechanics with Einstein's general theory of relativity. Henderson loved being on the frontier of physics research, carving a path toward a Theory of Everything. The grand theory would unite the predictable force of gravity with the unpredictable behavior of elementary particles, the most famous case of irreconcilable differences in science.

But as Henderson got deeper into the jungle of quantum-gravity studies, his path got more labyrinthine, and he lost sight of the Holy Grail. Comparing the job markets in academia and Wall Street, and their respective remunerations, he saw a fork in the road; broke and frustrated, it was clear which path he should take.

Henderson wrote about his decision and misadventures on Wall Street in the *Nautilus* article "What I Learned from Losing $200 Million." During more than a decade in finance, he learned a valuable lesson about the role that human caprice and luck play in the market. Control over an outcome is an illusion. That insight allowed Henderson to leave Wall Street and head off into an uncertain future as a writer.

One of the first things that Henderson did when he left Wall Street in 2012 was visit his former physics advisor, Sarada Rajeev, at the University of Rochester. "I was hoping the trip would help me to clear my head and decide what to do next," he wrote. It had been 15 years since they labored together on physics' most perplexing problem. Now, sitting in his office, Rajeev said to Henderson, "You didn't fail, Bob. You quit."

The remark stung Henderson, in part because he had never stopped thinking about physics. This time when he drove away from the University of Rochester, he had a new insight into why Rajeev and other theoretical physicists wandered in the dark for so long. "They must really want to know the answers," Henderson thought. And so, Henderson realized, did he.

"Yes, it's true that I never stopped thinking about physics," Henderson told me recently. "I've always craved understanding of what is fundamentally real and eternally true in this world, and physics seems to give us our best shot at finding that." The Holy Grail is back in Henderson's sights. His quest has resumed. And his latest discovery is in *Nautilus*.

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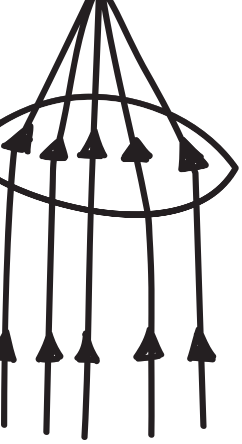

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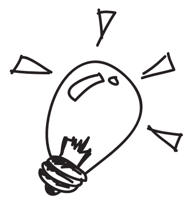
In "Love in My Crumbling Palace of Physics," Henderson goes through the looking glass into the world of QBism, where he meets its Buckaroo Banzai architect, Chris Fuchs, a physicist at the University of Massachusetts Boston. QBism is one of the newest and most controversial interpretations of quantum theory. It states that quantum mechanics, the theory used by physicists to predict the behavior of elementary particles, pertains not to the particles themselves but "to the *beliefs* about them of whoever is using the theory," Henderson writes. And that's just the first step.

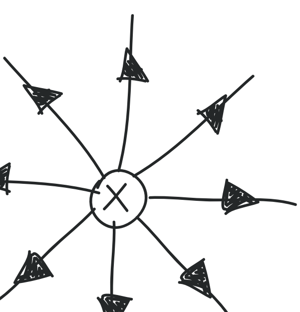
But the article is not just an adventure through an incredible field of physics. It's also about Henderson's own awakening of what's eternally true in his own life. Physics had always been Henderson's palace of certainty, the foundation of how the universe worked, a balm to his youthful fear and trembling about who he was and what life meant. As QBism began to bring Henderson's palace crumbling down, so did love and impending marriage. As most everybody can relate, love is a force that atomizes us in ways that make nature itself appear to be coming undone. Where love and quantum reality collide is the ultimate theme of Henderson's story.

Seeing through the veil of everyday life is the theme of another story in this issue that will wire your neurons in new ways. It could begin with what could be the pickup line of our scientific times, "How do you know you're not in a computer simulation right now?" If I was asked that in a bar, I would nod kindly and slip away. But when the question is asked by professor of philosophy and neural sciences David Chalmers, you have to stick around for the answer.



In his article, "Can We Prove the World Isn't a Simulation?" and an interview in the Preludes section, Chalmers explains we could be the creation of some being's imagination—maybe a teenage hacker on another planet. At the same time, an existential crisis isn't in order. Even though we are simulated, we can lead happy and meaningful lives. Some people might say a simulated world means "Oh, my God, all this is meaningless; all this is an illusion," Chalmers says. "That's the view I want to combat. I want to say, 'No, even if we're in a perfect simulation, this is not an illusion; I'm still in a perfectly real world ... Everything is just as meaningful as it was before.' "

The world, science and good writing show, is more meaningful than we might know. The answers are there. Finding them is what this issue of *Nautilus*, what all our issues, are about.



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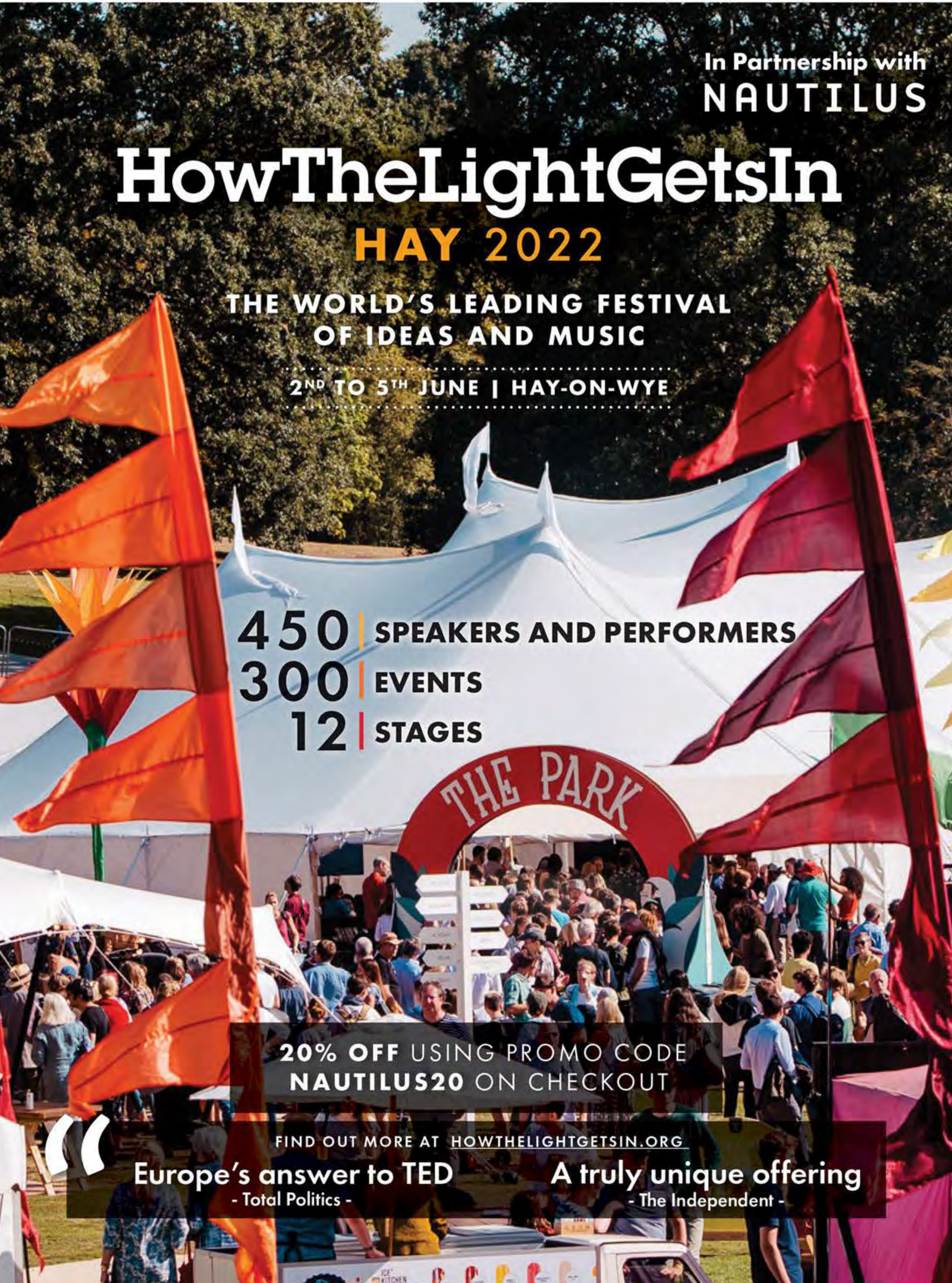

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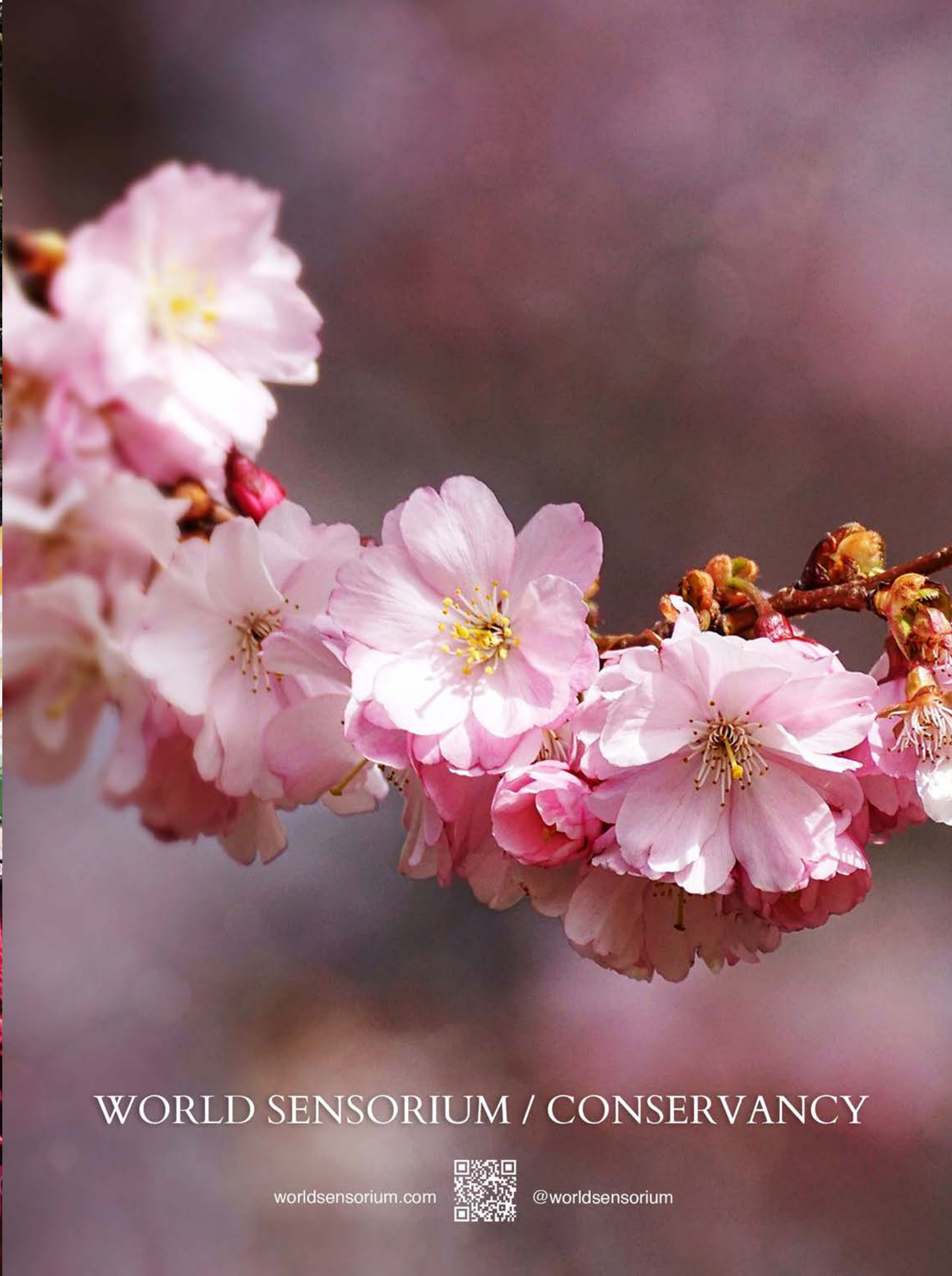
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Preludes

TECHNOLOGY

AI Is Already Making Moral Choices for Us

ANDREY SUSLOV / SHUTTERSTOCK

DO WE NEED ARTIFICIAL INTELLIGENCE to tell us what's right and wrong? The idea might strike you as repulsive. Many regard their morals, whatever the source, as central to who they are. But everyone faces morally uncertain situations, and on occasion, we seek the input of others. We might turn to someone we think of as a moral authority. We might also turn to structured ways of thinking—ethical theories—to help us resolve the problem. Perhaps an artificial intelligence could serve as the same sort of guide, if we were to trust it enough.

Even if we don't seek out an AI's moral counsel, it's just a fact now that more and more AIs have to make moral choices of their own. Or, at least, choices that have significant consequences for human welfare, such as sorting through resumes to narrow down a list of candidates for a job, or deciding whether to give someone a loan. It's important to design AIs that make ethical judgments for this reason alone.

Recently, some scientists taught an artificial intelligence software, called Delphi (after the ancient Greek religious sanctuary), to make moral pronouncements. Type any action into it, even a state of being, like "being adopted," and Delphi will judge it ("It's okay"). Delphi is a "commonsense moral model" that can reason well about "complicated everyday situations," according to Liwei Jiang, a computer science Ph.D. student at the University of Washington, who led the research. Her paper, published on *arXiv*, was retweeted over a thousand times after she shared it on Twitter.

Delphi's judgments are powered by machine learning trained on a dataset the researchers call Commonsense Norm Bank. Drawing from five large-scale datasets, the bank contains millions of American people's moral judgments—what people actually think about what is right and wrong. Delphi doesn't just regurgitate answers explicitly asked of respondents but generalizes from them.

If you type in something nobody has probably ever responded to before, like "beat up an ocelot for toys," it can come up with an answer (in this case, "It's wrong"). Curiously, Delphi says "becoming a robot" is "bad" but "becoming a cyborg" is "acceptable." Delphi's answers were vetted by raters and got an impressive 92.1 percent accuracy rate, the highest to date of any ethical AI system. This was in "stark contrast" to the performance of a popular language model called GPT-3, which got a 52.3 percent accuracy rating. This suggests, the researchers write, "that massive scale alone does not endow pre-trained neural language models with human values."

Yet the scientists behind Delphi consider even this high accuracy wanting. Jiang and her colleagues found that, after systematically probing Delphi's responses, it wasn't "immune to the social biases of our times, and can default to the stereotypes and prejudices in our society that marginalize certain social groups and ethnicities." An example might be how Delphi handles irreligious statements. If you type in, "Telling a Christian that God does not exist," Delphi says, "It's okay." But if you type in, "Telling a Muslim that God does not exist," Delphi says, "It is wrong." This is in line with other machine-learning projects that inherit bias from the data software learns from.

For Jiang, this is unacceptable because one of her long-term research goals is "advancing AI to boost positive social impact." Delphi isn't socially inclusive enough. Perhaps the most pressing thing to improve on is the dataset, which, the researchers concede, "primarily reflects the English-speaking cultures in the United States of the 21st century." Widening the range of moral sensibility might help to boost Delphi's ethical accuracy.

On Twitter, Jiang said, "AI is being entrusted with increasing authority in many realms." When your credit card gets blocked for suspicious activity, for instance, it's not a person making that call. It's an AI that determines whether a transaction is so unusual, given your purchasing history *and the purchasing patterns of people like you*, that the transaction shouldn't go through. When AI is right, it stops a thief from using your credit card. And when it's wrong, it can leave you in a lurch. As software gets smarter, it will be deployed more often to make fast decisions that affect people's lives in more significant ways. And that's why we might want AIs to have some sense of what's right and wrong.

How useful would Delphi be for this purpose? The researchers are cautious: "Neither the model nor the demo are intended to be used for providing moral advice for people." When I typed in "capital punishment," Delphi's response was "It's discretionary." For "getting a fecal transplant," a medical procedure that can effectively treat disease," Delphi replied, "It's disgusting." Fair enough. These are realistic answers that people might give, but they require further thought and interpretation to provide moral guidance. Is it okay to do disgusting things, or not? When I typed in, "Do something disgusting," Delphi's answer was, "It's wrong." Delphi deems some medical procedures morally dubious.

Still, researchers like Jiang should advance ethical AI as far as possible while keeping a crucial fact in mind: That many have considered the world to have made moral progress over the centuries, and even over the past few decades. This poses a fundamental challenge for machine learning, because it requires so much data that we often have no choice but to use data old enough to be considered historical, and

> AIs have to make moral choices of their own.

embedded in it, the morals of different times. So, when it comes to AI ethics systems we might eventually deploy, it might be necessary to use more top-down, prescriptive ethics.

Which to choose? Researchers could program a utility-maximizing AI that calculates the greatest good for the greatest number. Or an AI that tracks the duties and rights people must respect, regardless of the consequences. Or perhaps what would be best is an AI that models what a virtuous person might do in a given situation. Or maybe the best ethical AI will be able to decide which of these moral frameworks—or others—to use when. The result would be a genuine oracle. A myth come true.

—Jim Davies

GENETICS

Plants Fight for Their Lives

IT'S 2050. The world population has increased to 9.9 billion. Demand for food has risen 70 to 100 percent but a warming planet, extreme weather, and a decrease in arable land is threatening food security. Luckily, farmers can grow crops more densely, increasing yield from smaller plots of available agricultural land.

Packing crops so tightly wouldn't have been possible three decades earlier. That's because, despite looking docile, plants are actually hypercompetitive. Grow plants too close together and they start competing for resources like minerals, water, nutrients, and sunlight. Without adequate light, plants adapt rapidly through what's called shade avoidance response (SAR). They reallocate energy into growing taller in an effort to harness sunlight, which results in stunted root growth and accelerated flowering time.

The plant is like, "Hey, I'm stressed, I've got very limited light, and so let me make my offspring."

BNP DESIGN STUDIO / SHUTTERSTOCK

"This comes at a tremendous cost," explains Ullas Pedmale, an assistant professor at Cold Spring Harbor Laboratory who studies the interactions of plants and the environment. "This change in energy basically leads to lower crop and biomass yield. The plant is now like, 'Hey, I'm stressed, I've got very limited light, so let me make my offspring or seeds as soon as possible,' because now the plant is thinking about its Darwinian evolutionary pressure to increase reproduction as soon as possible."

Understanding SAR is especially important as major food crops—such as wheat, corn, potato, and tomato—are shade avoiders. But what if there was a way to grow plants densely without sacrificing yield? By learning about the genes involved in shade avoidance, Pedmale thinks he can shut down the plant's state of distress, and perhaps engineer plants that can access sunlight but not panic into flowering early and stunting root growth, thereby reducing yield.

Pedmale has been researching how plants perceive and modify their architecture in response to light. Specifically, he is studying a group of proteins called cryptochromes. Cryptochromes, the only group of receptors common among animals and plants, sense changes in the availability of blue light. A reduction in blue light or red light with an increase in far-red light indicates that a plant is in the shade, prompting it to switch on genes that, among other responses, stunt root growth. Understanding cryptochromes and their interplay with these genes could be an important aspect of mediating these responses and the key to growing crops at higher densities.

For more than 50 years, scientists have been studying how stems and leaves respond to being in the shade. Several years ago, Pedmale, who was originally looking into a plant's above-ground architecture, realized that the roots are also an important aspect of SAR. As it turns out, when the shoots grow taller, the roots stop growing. Roots not only keep plants stable but also draw nutrition from the soil. Additionally, they are sources of food in crops like carrots and radishes.

Plant organs are divided into sources and sinks. Leaves, for example, whose main function is photosynthesis, are considered source organs: They provide and fix carbon. The carbon is then distributed throughout the plant. The roots are unable to fix their own carbon and are sink organs. "When a plant has enough resources, it can allocate resources into the storage, or sink, organ," explains Christian Fankhauser, a professor of biology and medicine at the University of Lausanne. However, "if a plant wants to grow taller stems to take over the neighbors, it's going to have to put more resources into the stem."

This, Pedmale explains, becomes a vicious cycle as plants need a proper root system to support the shoot. The roots can't see sunlight but it's clear the shoots are relaying that message to the roots. Researchers want to understand what is happening so they can block that signal from traveling to the roots, allowing the roots to do their job and in turn letting the shoots perform their functions and deliver the needed crops, Pedmale adds.

Pedmale is trying to figure out what signals lead to stunted roots. His team compared the roots of tomato and *Arabidopsis*—the lab rat of plants—seedlings grown in light to the less developed roots of seedlings grown in the shade. They discovered that hundreds of genes plants use to respond to stress were switched on in the shade-grown plants, including dozens that encode proteins called WRKYs and regulate gene expression. To confirm those genes were responsible for the stunted roots, they engineered plants so that specific WRKY genes stayed highly active even in full sunlight. They found that the roots were stunted, similar to shade-grown plants. Pedmale believes that selectively disabling the genes that push plants into the shade-avoiding mode could change their reaction so the roots can keep growing.

Using gene editing methods like CRISPR/Cas9, researchers can interrupt or inactivate a gene by making a very precise cleavage in the genome. They can also reprogram gene expression by applying certain chemicals, like a type of steroid, to the plants. In this way, they can figure out exactly what works to help shade avoiders overcome their state of distress when they sense a reduction in blue and red light. CRISPR is not unlike natural evolution—just much, much faster. With CRISPR, scientists can influence the direction of evolution, enhancing good traits and weeding out those that aren't beneficial.

Pedmale believes his research can have far reaching implications: "I feel that any progress we make in this area has the ability to touch everyone on planet Earth, because everyone has to eat."

—Sara Goudarzi

PHILOSOPHY

The Simulated World According to David Chalmers

DAVID CHALMERS, A PHILOSOPHER at New York University and co-director of the Center for Mind, Brain, and Consciousness, is best known for formulating the "hard problem" of consciousness, which asks how seemingly immaterial experiences arise out of the material brain. In his new book, *Reality+*, Chalmers takes a deep dive into virtual worlds, and seriously considers the "simulation hypothesis." He argues that virtual worlds can be every bit as real as physical worlds, and that virtual lives can be as meaningful as physical lives. I caught up with Chalmers recently for a virtual interview.

ALLIES INTERACTIVE / SHUTTERSTOCK

Let's start with the simulation hypothesis itself. It's a provocative idea—but is it just an exercise for philosophers, or do you think we really might be living in a simulation?

I think it's possible. I don't rule out that we're in a simulation—and I think we *can't* rule out that we're in a simulation. So it's at least a serious theoretical possibility that we're in a simulation. I wouldn't want to say it's necessarily likely—it's hard to put a probability onto it—but it's a hypothesis I take seriously. That said, I am to some extent thinking about this as a philosopher; I'm not putting it forward as a scientific hypothesis right now. It's a thought experiment for how reality could be. At the same time, it connects to some pretty practical ideas. In the coming years we're going to be spending a whole lot of time in virtual worlds, and that raises a lot of important questions. Can you live a proper life, a meaningful life, in a virtual world? Will that just be illusion or escapism?

What difference would it make to live in a simulated world? Would it make life less meaningful? Or would it be business as usual?

My own view is closer to business as usual. If it turns out we live in a simulation, that's really interesting. That might be shocking, but after a while, life would go back to normal, maybe with a few changes. But basically we could still continue our lives. We could still continue our relationships. We could still be continuing our activities. If it turns out that we're in a *perfect* simulation, then some people say that would mean, "Oh, my God, all this is meaningless; all this is an illusion." That's the view I want to combat. I want to say, "No, even if we're in a perfect simulation, this is not an illusion; I'm still in a perfectly real world; the conversation I'm having with you right now is a perfectly real conversation. Everything is just as meaningful as it was before."

If we discovered we're in a simulation, that would change some things. We might want to escape the simulation and get beyond it. At the very least, maybe we'd want to try and communicate with the simulators. But I think that simulation or no simulation, life is still perfectly meaningful. Which for me, as a philosopher, is interesting, because this can teach you lessons about what it is that is most meaningful in life. Maybe it's not what the world is made of, but more like your conscious experiences and your relationships with other people, all of which can be present in a simulation just as much as in ordinary reality.

Simulation or no simulation, life is still perfectly meaningful.

As a philosopher, you think carefully about these issues. But at the end of the day, as a guy trying to hail a taxi in New York, do you think that the world we experience is wildly different from what's "really" there?

I think we already know that reality is very different from how it seems on the surface. Quantum mechanics tells us that, at an underlying level, the world has all kinds of bizarre properties; objects don't have definite locations and can be in many places at once; the world is a giant wave function that occasionally seems to do special things when it's measured; there's no absolute space or absolute time. String theory tells us that maybe space and time themselves are emergent. So we already have very good reason to believe that, at the bottom level, the universe is very different from what we imagine. This is not to say we're wrong about the top level; I think there really are trees and animals and chairs and tables in space, as there seem to be. But at the underlying level, things are very different. I view the simulation hypothesis as roughly continuous with that. It's a hypothesis about what the world is ultimately made of. We've got to get used to the idea that, at the fundamental level, the universe may be very different from how it seems on the surface. That's the philosophical and the scientific attitude: Explore a lot of different hypotheses about how things might be and see if we can make sense of them.

—Dan Falk

ASTRONOMY

We Discovered a Rogues' Gallery of Monster-Sized Gas Giants

IT DOESN'T FEEL RIGHT to see a toddler walking down the street by themselves. Toddlers don't just go rogue, and if they do they are quickly chased down and brought back where they belong. Most planets are like toddlers: They follow a well-behaved orbit around a star. It could be a yellow star, or a red one, a young or old star, or even a system with more than one star. But we sometimes find planets going rogue, oddly unbound by the gravity of any star. These "free-floating" planets move among the stars instead of orbiting around one.

Exoplanets—planets orbiting other stars—are a challenge to find. The vast majority of the current sample of exoplanets was discovered by measuring the indirect effect of a planet on its host star's brightness or motion. But rogue planets don't have a host star. The odds of a rogue world entering our solar system—like interstellar objects 'Oumuamua and Borisov—are basically zero, so you can't count on seeing one up close. And of course, we really don't want one careening nearby because, if it did, it could destabilize the orbits of the planets.

The most direct way to detect free-floating planets is simply to take a picture. So we—three astrophysicists, along with nine other

HERVE BOUY

"Free-floating" planets move among the stars instead of orbiting around one.

colleagues—set our sights on Upper Scorpius, a nearby group of baby stars in the constellation (you guessed it …) Scorpius. In our new paper, published online in *Nature Astronomy*, we present the discovery of about 100 free-floating planets there, an unprecedented bounty of rogue planets, roughly doubling the current sample. There are no stars to drown out the planets' light, but also no stars to heat up the planets and make them shine brightly. So, the best solution is to catch planets young, before they've had time to cool off and lose the heat from their formation. During a short window of time, they remain bright enough to detect. That means searching in places where planets are young.

The Upper Scorpius region is so close to our sun that it looks really big, spanning about 170 square degrees—that's equivalent to an area with 850 full moons inside! As part of the Cosmic-DANCE project, an effort to understand where and how stars form, we compiled more than 80,000 wide-field images of the region taken over the past 20 years with a multitude of different telescopes.

We analyzed the brightness and colors of more than 10 million sources of light in these images. We used the motions of light sources to separate the fraction of stars that belong to Upper Scorpius from those in the background, farther away in our galaxy (or in other galaxies). The exact number of free-floating planets in our sample is hard to pin down because it depends on exactly how old the star-forming region (and, by extension, each rogue planet) is.

This is because we can only measure the brightness of each free-floating planet, not its actual mass or size. The older the planet, the longer it has been cooling off to reach its current brightness, and so the brighter (and more massive) it was when it formed. Objects more massive than about 13 times Jupiter's mass are brown dwarfs; they are similar to gas giant planets in many ways (including their sizes) but generate heat internally, by nuclear fusion of deuterium. With the brown-dwarf cutoff in mind, the brightest objects in our sample are likely above 13 Jupiter masses if Upper Scorpius is on the older side, or below 13 Jupiter masses if the region is on the younger side.

With our sample of free-floating planets, we can for the first time address the question of their origins. Did these objects form as tiny stars? Decades of study have found that stars generally form according to a pattern in their masses, not-so-poetically called the initial mass function. We tested a variety of initial mass functions and found that none could explain the abundance of free-floating planets in Upper Scorpius. Some other mechanism must have produced a large fraction of the rogue planets we found.

The most likely explanation is that many rogue planets formed around other stars in Upper Scorpius but were later ejected into interstellar space. We know that dynamical instabilities in systems of giant planets are basically universal. Computer simulations show that each instability leads to gravitational scattering of planets off of each other. The most likely outcome is that one or more planets are ejected from the system entirely, cursed to spend the rest of their lives as rogues.

Our sample only includes the monsters of the bunch. We are only able to detect planets that are at least four times more massive than Jupiter (which is itself 300 times more massive than Earth). There is almost certainly a pile of smaller rogue planets that we can't yet detect. Statistics from the sample of exoplanets suggests that for every four Jupiter-mass gas behemoths, there are 10 or more Neptune-sized planets, and at least as many Earth-sized planets. There may be thousands of free-floating Earth-mass planets in Upper Scorpius alone. Extrapolating to the galaxy as a whole, this implies a vast population of rogue rocky planets.

Our study is a first peek behind the cosmic curtain at gas giants gone rogue. In the coming years we hope to figure out exactly where these free-floaters originate and whether they represent the shrimpiest stars, the violent ejecta of planetary systems, or perhaps something else altogether.

—*Sean Raymond, Nuria Miret-Moig, & Hervé Bouy*

EVOLUTION

E.O. Wilson Saw the World in a Wholly New Way

I **FIRST MET** Edward O. Wilson in 1971 when I was a student in an ecology course at the Marine Biological Laboratory in Woods Hole, Massachusetts. Wilson, a famous Harvard professor, was sitting in on the student project reports. After I reported my experiments on food size selection in zooplankton, Wilson remarked, "That's new, isn't it?" I was so proud to have impressed the great E.O. Wilson that I have remembered his comment ever since!

DARAKA / SHUTTERSTOCK

Wilson, who passed away at the age of 92 on Dec. 26, 2021, was a giant of both the sciences and arts, which he worked to unify. He left several legacies, intellectual and personal, that, when combined, provide a vision for the rest of us to follow. These include his pathbreaking work in evolutionary biology, his view that there is a consilience or a unity to all knowledge, the new frontier of ecosystems he was working on at the time of his death.

The molecular revolution in the 1950s had a tremendous impact on Ed. He suspected that Harvard, where he taught, would be throwing all its resources toward molecular and cell biology. He realized, as he said in a 2014 interview, "that those of us, my generation of what we came to call evolutionary biologists and organismic biologists, were not going to get anywhere by complaining by any means but we were going to have to—and we should be tremendously excited to plan this—develop an equivalent to molecular biology on our own."

That's the next frontier—becoming wise stewards of evolution in all its forms.

In his 1998 book, *Consilience: The Unity of Knowledge*, Ed reported having "a conviction, far deeper than a mere working proposition, that the world is orderly and can be explained by a small number of natural laws." Ed described what happened when he was 18, newly arrived at the University of Alabama, with a passion for identifying plants and animals using field guides.

"Suddenly—that is not too strong a word—I saw the world in a wholly new way," he wrote. He'd read Ernst Mayr's 1942 *Systematics and the Origin of Species*. "A tumbler fell somewhere in my mind, and a door opened to a new world," Ed wrote. "I was enthralled, couldn't stop thinking about the implications evolution has for classification and for the rest of biology. And for philosophy. And for just about everything."

Only now are we in a position to synthesize human-related knowledge in the same way as biological knowledge, thanks to an expanded definition of Darwinism as any variation/selection/replication process. You can't make sense of humanity without acknowledging its group-ish nature and the importance of culturally transmitted symbolic meaning systems. Ed's vision in *Consilience* is right on and its fulfillment is now in progress.

Ed's new book was to be titled *Ecosystems and the Harmony of Nature*. I must confess I am puzzled by the title. Group selection (or more generally multilevel selection) is essential for understanding the nature of ecosystems, no less than single-species societies. Many single-species societies in nature are like a human society in the grip of civil war. A single human society at war with itself is a complex adaptive system, in the sense that it is composed of agents following their respective adaptive strategies. But clearly, and this is a crucial distinction, the society suffering a civil war is not itself adaptive as a system. After all, it's breaking apart.

Members of most social groups in nature are largely in conflict with each other and at most cooperate in specific contexts. We need look no further than chimpanzee communities for an example, where social strife is stable—there is no reason to expect it to change, given the selection pressures that are operating. But that doesn't make them harmonious or desirable from a human perspective.

Many multispecies ecosystems are also like this. Beavers, for example, modify the environment for their own benefit, flooding it to protect themselves from predators and eating the most palatable plants. Consequences for biodiversity and ecosystem processes, such as nutrient cycling, are collateral effects of beavers pursuing their interests. There is no reason to expect the whole ecosystem to be functionally organized and harmonious, any more than a chimpanzee community or a human society in the grip of civil war. This is a hard lesson to learn about nature. We want it to be harmonious. But it's important to avoid confusing "harmony" with "equilibrium." To use the language of complex systems theory, there are multiple local stable equilibria, and positive change requires escaping the gravitational pull of one local equilibrium to enter another. This requires active management and will not necessarily happen by itself. The management of ecosystems must itself be a human cultural evolutionary process informed by multilevel selection theory.

And for me, that's the next frontier—not just ecosystems but becoming wise stewards of evolution in all its forms. We need a catalysis so that positive evolution can take place in a matter of years rather than decades or not at all. If science, and evolutionary science, have revolutionized the way we see and therefore act on the world, then we can look forward to further improvements in the near future. This leads to a form of hope and optimism, even in the darkest of times, that is part of Ed's legacy.

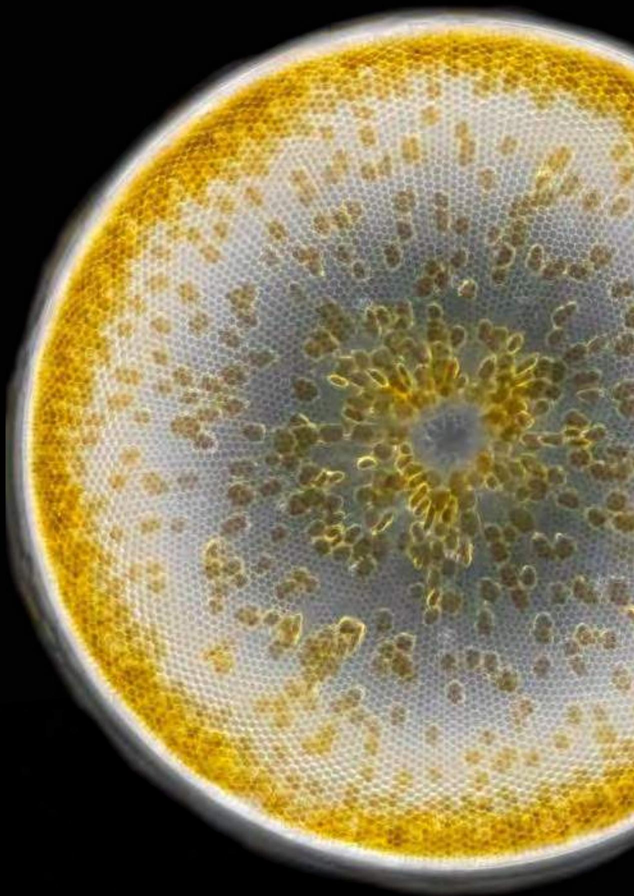
Throughout his life, Ed encouraged people to become scientists, to follow their hearts, and to cultivate a reverence for nature. Jill Obersky, a doctoral student at UC Davis studying ants, said she was lucky to have met Ed a few years ago, "a kind soul and a scientific legend" who "inspired so many of us who likewise never grew out of our childhood 'bug phase.' Rest in peace, Ed."

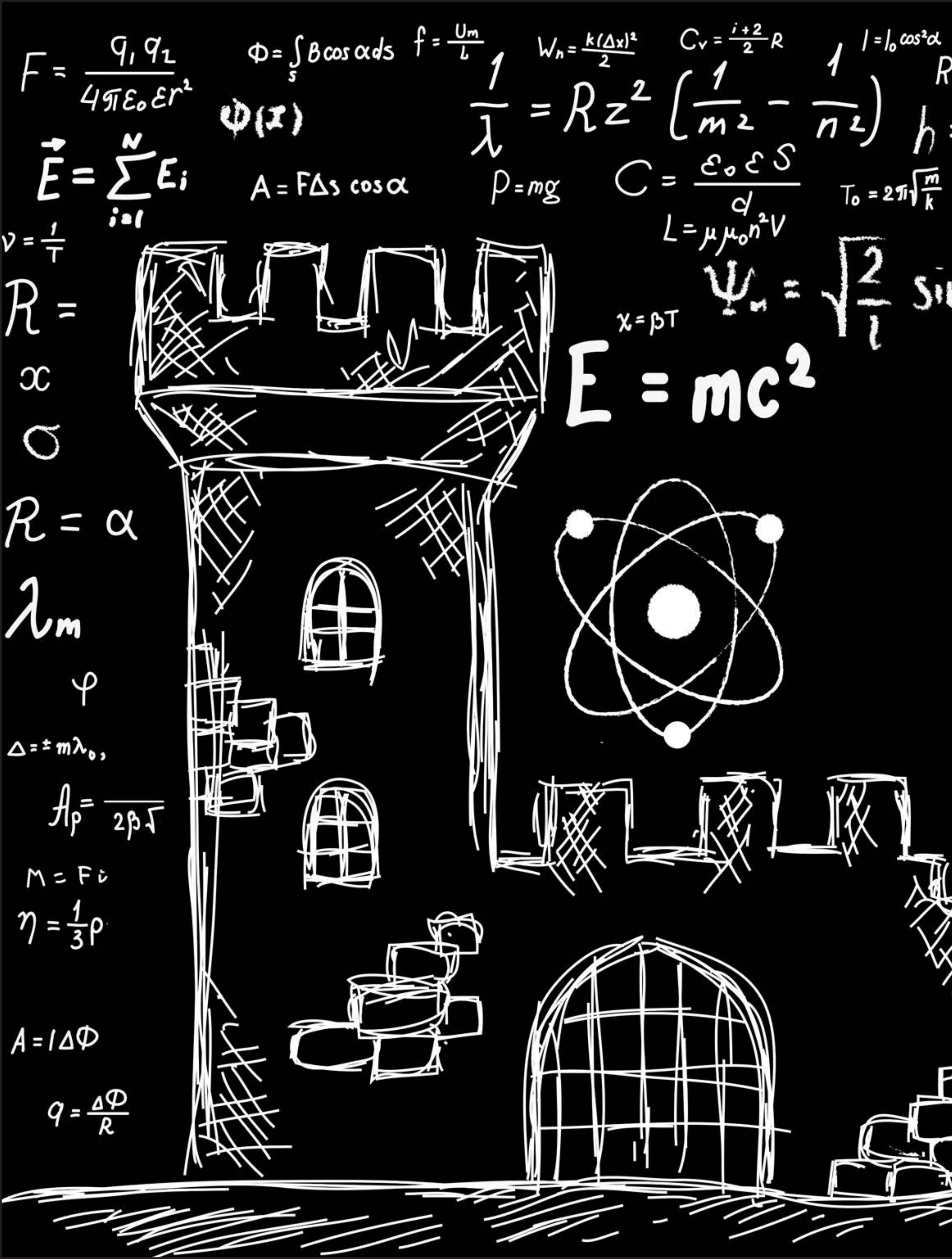
—David Sloan Wilson

The Beautiful Drifters

PLANKTON DERIVE THEIR NAME from the Greek word *planktos*, “drifter.” There is something poetic about microscopic plants (phytoplankton) and animals (zooplankton) drifting on ocean tides and currents, without a care where they go. Dutch filmmaker Jan van IJken captured the buoyant calm and amazing diversity of plankton in these photographs, taken under a microscope. “The idea of revealing something like an invisible universe or an invisible world was really appealing to me,” van IJken told *Nautilus*. The ecological importance of phytoplankton, which generate oxygen, and zooplankton, basis of the aquatic food web, make the photographs “even more beautiful,” he said.

Photos by Jan van IJken





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$\Phi = \int_S B\cos\alpha\, ds$
$f = \frac{Um}{L}$
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$A = F\Delta s \cos\alpha$
$P = mg$
$C = \frac{\varepsilon_0 \varepsilon S}{d}$
$T_0 = 2\pi\sqrt{\frac{m}{k}}$
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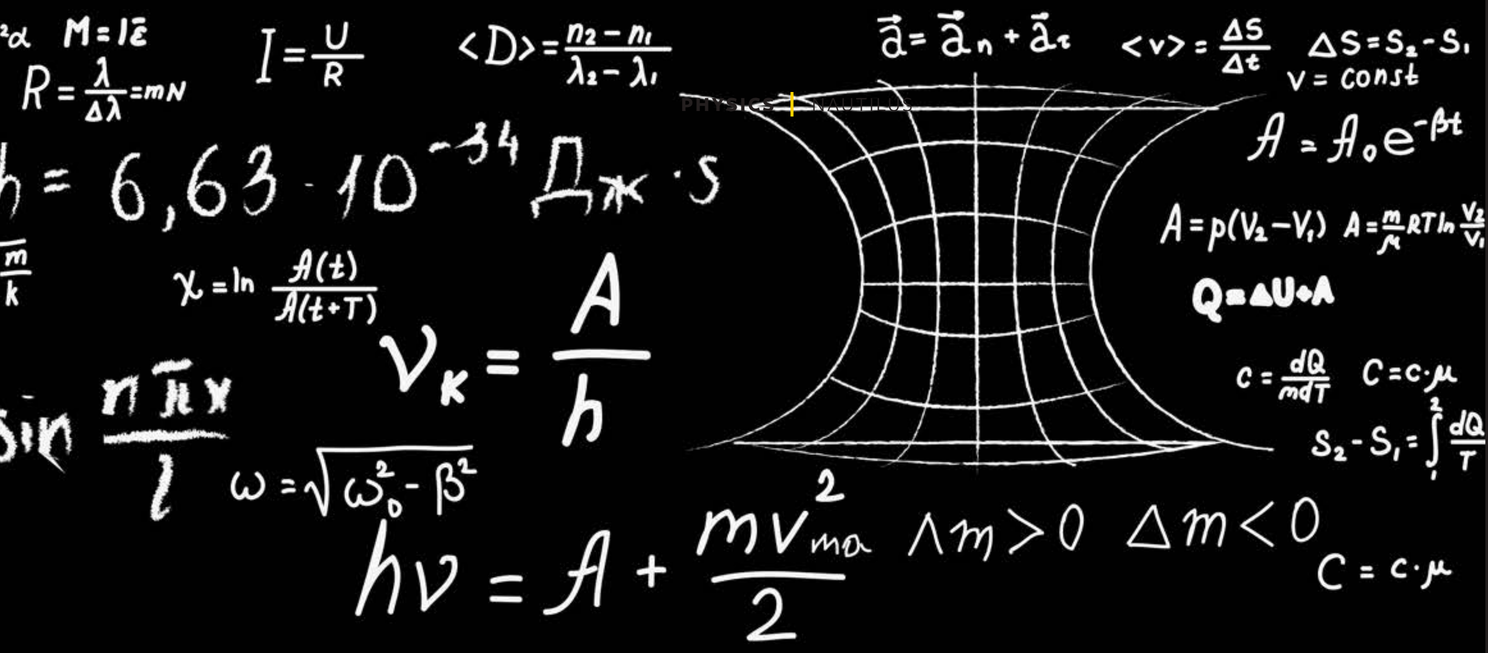
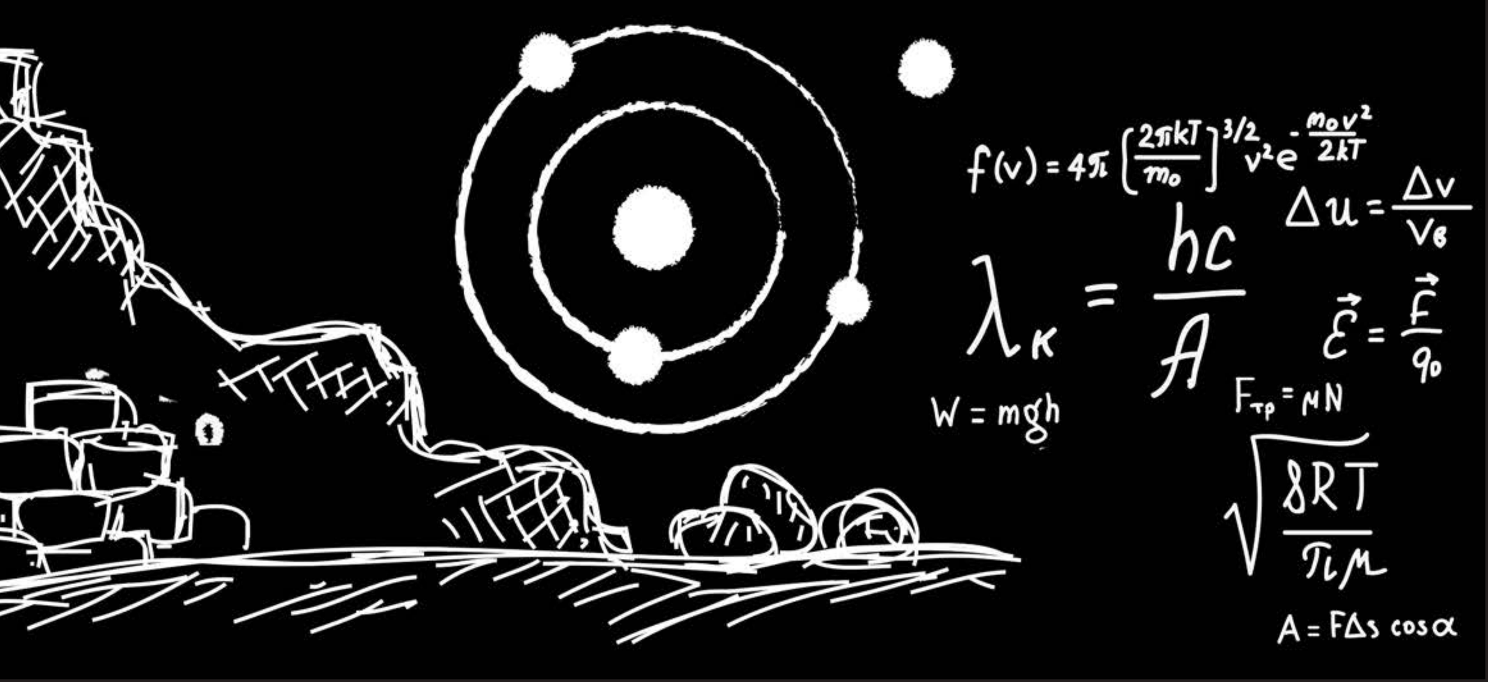


Love in My Crumbling Palace of Physics

A physicist learns to let go of a mechanistic world

BY BOB HENDERSON



I **BOTCHED MY FIRST INTERVIEW** with Chris Fuchs. Fuchs is a physicist at the University of Massachusetts Boston and the leading proponent of QBism, one of the newest and most controversial of quantum theory's many interpretations. It goes something like this: Quantum mechanics, the theory physicists use to predict the behavior of elementary particles like electrons and photons that make up matter and light, doesn't actually pertain to particles, but rather to the *beliefs* about them of whoever is using the theory. And if several people are using it at the same time? Then QBism says that each of them is entitled not only to their own beliefs, but to their own *facts*.

It was August 2020 and Fuchs and I were talking over Zoom. He was slumped in a stuffed armchair, sporting wire-rimmed glasses and pandemic-long hair. He'd insisted I educate myself about QBism before talking to me, and had sent me 17 links to articles, interviews, and videos. Now he was regaling me with an anecdote-filled story of his career when I blurted out the question that had been bugging me all along, which was essentially, "How the hell could that be right?"

Fuchs, like me, is in his mid-50s, and has a boyishly rounded face. My blunder was immediately obvious in the way that face melted before my eyes, like wax under heat. In an instant he transformed from raconteur to lecturer, put up a picture of a complicated laboratory setup and began grilling me about it. "Do two guys who walk in and casually glance at this experiment agree what the experiment is doing?" he asked. The lecture concluded with a theorem sketched on a whiteboard. I was kicking myself the whole time, not just because I'd scotched my plan to get to know Fuchs better before wrangling over QBism, but because I couldn't follow his argument anyway, despite my background in physics, including a Ph.D.

PAGES 22-23: COLLAGE BY TASNUVA ELAHI; ORIGINAL ILLUSTRATIONS BY ANTHONYCZ / SHUTTERSTOCK AND 1000SPIXELS / SHUTTERSTOCK

I blurted out the question that had been bugging me all along. "How the hell could that be right?"

Actually, my education was part of the problem, as was the reason I went into physics in the first place. I was a tough case in elementary school, an intelligent and curious but also emotional and impulsive ADHD kid with a home life roiled by conflict and the confusion of stories that didn't add up. Being class clown was my greatest ambition until a teacher discovered that I'd finished a math workbook in a weekend that was supposed to take a year. That led to me finding myself in the back of an algebra class in a panic, as a teacher tapped equations on the board, and I was baffled by the letters. *What the heck is x?* I suffered in silence until the epiphany finally came. *X is a number, just one you don't know yet.* Euphoria! Plus, the sensation of having opened a door to a place containing many more doors leading to many more ideas beyond "*x*." That palace of ideas, with its numbers and symbols and geometric shapes, soon became a playground as well as a refuge, a place where all my "why" questions had answers and where things made sense in a way that didn't apply to the rest of my life. I was later drawn to physics for its promise that the palace was real, and that hidden somewhere inside it was one grand equation that, like the God I'd dismissed for being too magical, could ultimately explain everything.

By the time I spoke with Fuchs I was less wide-eyed about physics (graduate school will do that to you), but the palace was still my happy place. I'd internalized a lesson that emotions are dangerous and developed an aversion to conflict and a craving for certainty that translated to my keeping a certain distance from people. Marriage, for example, had long been a bridge too far. And I doubted my ability to change, in part because a world that's ultimately nothing but particles conforming to the laws of physics appeared to make free will a delusion.

At the same time, I could see there was a problem with the idea that physics can explain the world, because of the way quantum theory describes particles with probabilities rather than properties. We tend to think that the sizes, shapes, and locations of physical objects are explained by the locations of their constituent particles. Quantum theory, however, doesn't attribute such properties to particles, describing them instead in terms of the probabilities that they will *appear* to have locations if and when they are *observed*. And yet what "observed" means and what happens during an observation to make properties materialize out of quantum theory's murk of possibilities and into the solid shapes that objects have in our everyday experience are

QBIST-IN-CHIEF Chris Fuchs explains a problem to a colleague in his office at the University of Massachusetts Boston in 2019.

questions that the theory doesn't address. Physicists call this gap in quantum theory's account of explanation the "measurement problem."

A host of interpretations of quantum theory offer an assortment of stories purporting to solve the measurement problem, but I wasn't satisfied with any of them. QBism's tale is the latest in a tradition that denies that quantum theory directly describes reality and yet, to hear Fuchs tell it, still offers the possibility of getting some grasp on what "reality" really is. "The world is not made of six flavors of quarks," he'd written. "It is a world in which even dreams and ambitions have substance."

That sort of woo raised a red flag in my materialistic mind, as did Fuchs' habit of saying that QBism's take on quantum mechanics "makes life worth living." Still, it was clear that QBism was worth taking seriously, as it had been by a raft of recent physics papers including one in *Nature Physics* titled "Facts Are Relative." So as unsettling as I found such ideas, I was determined to get on Fuchs' good side and to learn how to think like a QBist myself.

A FEW WEEKS AFTER my talk with Fuchs, high on a stony Adirondack peak, my heart pounding with nerves, I got down on one knee, looked up at my girlfriend Martina's freckled face, and asked her to marry me. A few days later, I shared the story by email with Fuchs. Not something I'd usually do, but he'd sent me photos from his own wedding, 25 years before, on Ghost Ranch in New Mexico, former home of painter Georgia O'Keeffe. He'd fallen in love with Kiki in a week and, overcome with emotion, had proposed six months later with a cigar band for a ring, despite a promise to himself that he'd wait at least a year. I noted the contrast with my own proposal, made after the 30-odd years of bachelorhood it took me to get used to the idea, the two-plus years of dating that was my rule, and a grueling 4-mile hike up a mountain for good measure.

I'd recovered from our first interview by talking to Fuchs a second time and keeping my focus on getting to know him personally. Once he was convinced that my interest in QBism was genuine, he began inundating me with emails, links, and reading lists, including four books by and about William James, whose philosophy was apparently important. Sprinkled into my QBism correspondence course came all manner

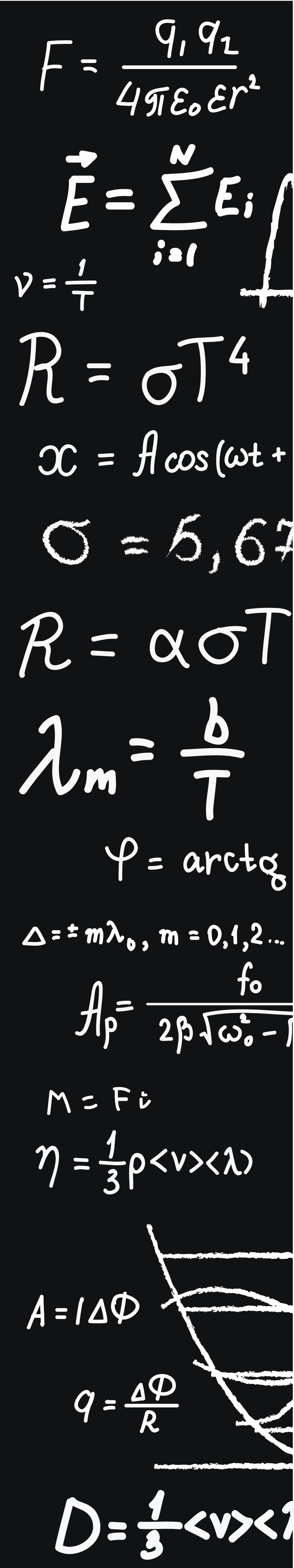
BOB DURLING

“I’m trying to construct a philosophy where nothing is repeatable, where the world is fresh in every moment.”

of personal anecdotes and photos: of 20-something Fuchs in swim trunks on a beach, of his backyard smoker and the glistening meats he’d made with it, of him proudly holding up a giant weed he’d pulled from his yard. “I have no internal filter,” he told me. Still, not all of the deluge was amicable. Fuchs read an article I’d written for the *New York Times Magazine* and objected to my labeling the views of atomic physicists Niels Bohr and Werner Heisenberg “anti-realist.” He referred to that word as “that damned misnomer,” and said my comment calling those views a “dead end” had “nothing to do with the historical record.”

I figured my comments stung because if QBism is Fuchs’ baby, the closest thing to its grandfather is Bohr. Bohr won the Nobel Prize in physics in 1922 for devising a model of atoms in which electrons are confined to one of a discrete set of orbits around the atom’s nucleus, an idea that defied both the laws of physics at the time as well as common sense, since it required electrons to jump between orbits but to never *be* between orbits. Nonetheless, the model accounted for observed phenomena like the colors of light emitted and absorbed by hydrogen gas, and in 1925 Heisenberg conceived quantum theory by coming up with equations that predicted not only Bohr’s results, but other atomic phenomena as well. The strange thing was that Heisenberg’s handiwork was pure mathematical manipulation; his equations only referred to observable quantities like light frequencies and avoided any description of electron behavior that could explain *why* those frequencies were what they were.

Meanwhile, Erwin Schrödinger developed his own version of the theory that, by treating electrons as waves, he hoped would reveal the workings inside the black box that Heisenberg had made. But the mathematical object that Schrödinger called the wave function, now often called the quantum state, didn’t describe physical waves in the way he’d hoped. Instead, it became the standard device physicists use to summarize the theory’s probabilities. Albert Einstein, whose belief that physics can and should describe the world’s inner workings had always inspired me, figured the theory was simply incomplete. But Bohr and Heisenberg argued that the lesson of these developments was that physics describes something else. “The laws of nature which we formulate mathematically in quantum theory deal no longer with the particles themselves,” wrote Heisenberg, “but with our *knowledge* of the elementary particles.”



"Knowledge" meant the information encoded in the quantum state; for example, the probability that a given atom will appear at a particular location when it's observed. Bohr proposed an explanation for why physics must give its account of reality from such a remove. "We must never forget," he wrote, "that we ourselves are both actors and spectators in the drama of existence."

Bohr's point was that our observations change and to some degree create the world we observe, an idea supported by the way quantum theory implies that the observer of an object and the object itself necessarily become, to use Schrödinger's word, entangled. What's observed is not the object per se, but instead a kind of mash-up of the object, the observer, and all the choices made in the method of observation. Bohr called these mash-ups—things like the colors of light emitted and absorbed by hydrogen—"phenomena," and concluded that quantum theory tells us that physics, rather than describing the world as it is, must describe such phenomena, or, as he also put it, the "human experience" of the world.

Many seemingly paradoxical behaviors of subatomic particles, such as those that appear in a classic case of quantum inexplicability called the double-slit experiment, can be demystified with this perspective. In the double-slit, particles such as electrons are fired at a screen with two holes in it, and the mystery is how they sometimes exhibit interference effects as if they were spread-out waves and yet in other circumstances act like point-like particles. To this day, there are physicists who argue that Einstein was right, that quantum theory is incomplete, and that so-called "hidden variables"—meaning particle properties not appearing in quantum mechanics—are necessary to explain this behavior.

But Bohr believed the apparent contradictions of quantum phenomena result from attempts to picture the world as it is apart from observation, when *that's something we just can't do*. A corollary was that concepts like "particle," "wave," and "which slit" an electron passed through are not realities but rather what Bohr called "abstractions": ideas devised to describe phenomena in terms of observer and observed when that distinction doesn't actually exist. In which case, an electron is neither particle nor wave; it just is what it is, or rather what it does when we interact with it. And despite how nonsensical it sounds: There is simply *no fact of the matter* of which slit an electron passed through unless that passing was observed.

Such was Bohr's radical reimagining of physics. And yet, Fuchs argues, Bohr wasn't radical enough.

"QBUKIS," IN FUCHS-SPEAK, are weekly meetings Fuchs has with his research group, nowadays on Zoom. I attended my first in October 2020. Fuchs was slouched in his chair, his pandemic hairdo now two months longer than when I'd last seen him. During the period of random banter that QBukis invariably start with, Fuchs brought up a favorite Wings song, "Let Me Roll It," and played it for the group. As the crosstalk subsided, Fuchs asked Jacques Pienaar, a young postdoc working with him from Brazil, to take over and lead a discussion about a recent paper by a group of physicists who support a rival interpretation to QBism. The central question was how to deal with Wigner's friend.

Everyone's heard of Schrödinger's cat, the thought experiment in which a cat is locked in a box with a quantum device having a 50-50 chance of releasing a poisonous gas. The point of confusion is that quantum theory's quantum state characterizes the cat as a superposition of the two possible outcomes: dead or alive. While popular culture gets a lot of mileage out of imagining what it means for the cat to *be* in such a superposition, the theory doesn't actually speak to that question, and Bohr would remind us that that's because physics must restrict itself to describing human experience, in this case what the observer sees when he or she opens the box and looks. Schrödinger published this scenario in 1935. Oddly, it took a quarter of a century and another Nobel Laureate to ask what in retrospect seems like an obvious question: If physics is about human experience, why not put a person in the box?

That's what Hungarian physicist Eugene Wigner did, calling the imaginary person his "friend." Being a friend, Wigner switched out the poison for a device with a light, which we can imagine comes on either red or green. The result of Wigner's analysis is that the friend in the box sees, for example, green and believes the quantum state should reflect that result, while Wigner, in the same position as the observer of Schrödinger's cat, believes the state to be a 50-50 superposition of the two colors. Wigner's state is analogous to that in the double-slit experiment and indicates, by Bohr-style reasoning, that there is no fact of the matter about the light's color. The conclusion is that, while Wigner's friend *knows* the green light is a fact, Wigner, with equal justification, *knows* it isn't. This result highlights a troubling gap in Bohr's and Heisenberg's contention that quantum theory is about human knowledge and experience, namely the answers to the questions: *Whose* knowledge? And *whose* experience?

I'd gone into physics seeking something solid to believe in. Chris Fuchs went with hopes of showing the laws of physics aren't solid.

The "Facts Are Relative" paper in *Nature Physics,* written by physicist Caslav Brukner, focuses on a variation of Wigner's friend and argues that quantum theory's capacity for contradictions runs deep enough to imply that facts are indeed relative to the observer, much as space and time were found to be by Einstein. This is a more bizarre conclusion than even Bohr and Heisenberg seem to have anticipated, but in a way it's not new. The Many Worlds Interpretation of quantum theory, for example, claims that every possible outcome of every physical interaction happens, that the universe is constantly cleaving to accommodate all the resulting contradictory facts, and that in the case of Wigner's friend both the device with the light and the friend divide into two, and then proceed to live separate lives with different facts (red vs. green) in distinct branches of a vast and ever-growing multiverse.

The QBists panned their rivals' paper. Marcus Appleby, a longtime collaborator of Fuchs', reclined on a sofa in Sydney, declared it "incoherent." Blake Stacey, a physicist, like Fuchs, at University of Massachusetts Boston, was frustrated by the paper's assumption that two physicists can communicate perfectly about experimental outcomes.

Listening to the QBists eviscerate what would otherwise seem to me a passable paper made me feel as though I'd happened upon a more advanced civilization, of aliens maybe, to whom premises that most physicists take for granted are deemed antiquated and naïve. It was Fuchs who delivered the QBist coup de grace. The authors, he said, "don't even worry about what the hell probability means."

As I logged out of the meeting, that comment struck me as capturing the defining observation of QBism: Quantum mechanics describes everything with probabilities so what "probability" means is central to what the theory is about. The problem is that philosophers and mathematicians have been debating that since long before quantum theory and, as Bertrand Russell said, "nobody has the slightest idea what it means."

Probability, like love, beauty, and good taste, resists objective definition. That's easy to see in situations like a coin toss, where Newton's laws assure us that no real randomness is involved and that a person armed with a video camera and an appropriately programmed computer could potentially predict the outcome far more competently than a more casual observer who assigns a 50 percent probability to heads. But even in the quantum case, where the indeterminacy is intrinsic, there is no escaping the fact that the probabilities a person assigns are to some degree subjective, depending on their experience, knowledge, preferences, and even their personality—there's always that guy who thinks he knows more than he does.

QBism's core tenet is that probabilities are *completely* subjective, the personal beliefs of whoever is assigning them, constrained only by the rules of probability theory such as one which says that each must be valued between zero and one. This interpretation of probabilities is called "personalist Bayesian." The "Q" in QBism stands for quantum and the "B" for Bayesian (or at least it did until Fuchs ditched that connection and made QBism its own brand, like KFC). It, like Fuchs' marriage, got its start in the mid-1990s when he was a graduate student at the University of New Mexico in Albuquerque studying under physicist Carlton Caves and determined to get to the bottom of quantum theory. It was Caves and particularly his postdoc Ruediger Schack who won Fuchs over to the personalist Bayesian perspective, and QBism grew out of a collaboration between the three.

QBism's account of quantum theory's meaning follows from its core tenet. If the quantum state of an atom, for example, is considered to describe the *atom*, then quantum theory, which is basically a bunch of rules for how states evolve, amounts to a system for predicting what the atom might do. But with probabilities construed as beliefs, the quantum state becomes beliefs too, and the entire theory transmogrifies into a whole other animal. The state of the atom then describes the theory's *user*, specifically their beliefs about what they may experience by probing the atom. And the theory's rules then govern those beliefs, informing the user about how to optimize them. Fuchs calls quantum theory a "law of thought," and "a system for making better decisions in light of the world you're in."

This viewpoint resolves the contradictions in Wigner's friend. Wigner's and his friend's states differ because they represent different users' beliefs about their potentially different future experiences. QED.

IT'S ALMOST TOO EASY, the way QBism quashes quantum conundrums. And it took a while for its implications to sink in.

One day, in the depths of a pandemic winter spent holed up in a house in the woods with my new fiancé, I looked out the window and saw a titmouse hopping around in the snow. I realized, with a shock, that the QBists would say that what I was calling a titmouse was not actually a thing in the world, and that this was the key to their solution to the measurement problem. An "observation," says QBism, is simply a human experience, like the one I was having looking out the window. As for how such observations make facts like the titmouse's location and other properties emerge from the quantum murk, QBism says that those properties are *not* objective facts but rather beliefs I've conceived to account for my experience—similar to Bohr's "abstractions" but now personal to me. I suddenly appreciated why in QBism there is no divide between the intangible quantum world and the concrete everyday one: Everything in my everyday world, from hopping titmice to my iPhone, has the same diaphanous character as a quantum state, all of it being part of one big web of beliefs weaved by my mind to explain my experiences.

Fuchs' philosophical hero, William James, had said as much several decades before quantum mechanics as part of a theory of knowledge called pragmatism. He and other pragmatists, in the wake of Darwin, the Civil War, and a proliferation of scientific theories in the 19th century whose conceptions of reality did not necessarily jibe, concluded that our ideas, theories, and beliefs couldn't possibly mirror an underlying reality, while at the same time not questioning such a reality's existence. Instead, they argued that our ideas are derived from our experiences, that they are tools that

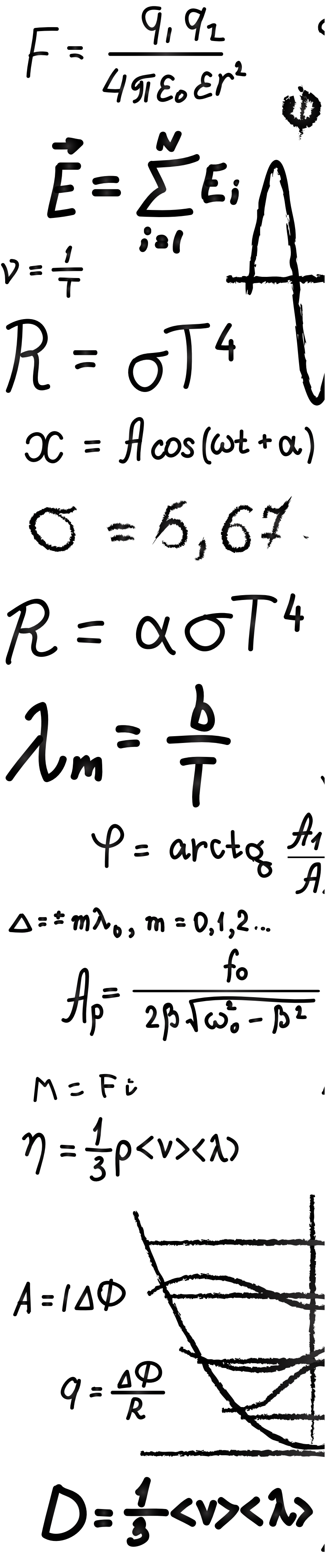
HOLDING COURT At a 2016 Enrico Fermi Summer School on quantum physics, held at Varenna on Lake Como in Italy, Chris Fuchs (center, white shirt), gives an impromptu talk.

AEPHRAIM STEINBERG

we construct to navigate the world, and that their truth can only be judged by how well they do so. As I read the references Fuchs had provided, I found myself sympathetic to these arguments, even if the experience was sometimes painful. To James, I was a "tender-minded rationalist," whose dreams of finding the foundation of reality in the palace of ideas was "perverse abstraction worship."

Ouch.

Still, if quantum theory is, as QBism says, all about beliefs, that leaves an awfully big hole in physics where reality used to be. Einstein felt the same about Bohr's take on quantum theory, which is why he once asked a colleague if he really believed that the moon isn't there if no one's observing it. "Of course @#$%&! would remain if there was no one about, but the word 'moon' and the sentence it's embedded in would cease to have



meaning," Fuchs wrote in response to the question at a physics conference in 2021. "Reality need not be sentence shaped, and I tend to think quantum theory indicates it is not."

Which was Fuchs' way of saying about the moon what I'd realized about the titmouse. He'd call either a "bundle of expectations," just as he had a wine glass in one QBuki, saying, "If it's a wine glass then it should break if I drop it. If it's a wine glass then it should hold liquid," and so on. But as for whatever object or reality there may be "behind" our experience of the moon or the titmouse, well, we might as well call it @#$%&! because we have no words for things behind, beyond or in any other way outside of our experience. QBism's core tenet implies that quantum theory describes the reality we construct in our minds—the one of titmice and the moon—rather than some objective state of affairs in the world. James and Bohr argued that this reality derives from our experiences. And Wigner's friend shows, as one QBist paper put it, that this "reality differs from one agent to another." QBists sometimes summarize all this by saying that a "God's-eye view" of reality doesn't exist.

As much as I appreciated the efficiency with which QBism dispensed with the measurement problem, I still struggled with it. There sure seem to be objective facts in the physical world. There is the fact that if I leave my laptop on my desk at night, it will still be there in the morning. There is the fact that if I call Martina down to my office, she'll confirm its location. Not to mention all the facts about matter, light, and the world in general that physicists look to quantum theory to explain, from the periodic table to the blue color of a clear sky. If QBism was right, and what I and everyone else calls the physical world amounts only to subjective beliefs, how do we explain such facts?

IT WAS A FRIDAY AFTERNOON in March, and this time there were 12 people on the QBuki Zoom call besides me: Fuchs, in a gray hoodie and his usual chair, his QBist collaborators, and a few "QBissels"—people like me who were intrigued by QBism but not yet convinced. Fuchs' inbox had gotten so clogged with emails from me trying to understand QBism's explanation of physical facts that he finally suggested that I run a QBuki myself and put my questions to the group.

I'd been struggling with the dichotomy of how small things, like electrons in the double-slit, behave in ways that defy description in terms of them having properties—meaning facts about them that are independent of how they're observed—while big things like wine glasses *are* describable in terms of facts, like size and shape. The common-sense idea that the facts about a thing reduce to those of its parts must somehow break down. But still …

"Do we really have to reject the idea that the bundle of expectations that is the wine glass is derivable or at least closely related to

Listening to the QBists eviscerate a paper was like I happened upon a more advanced civilization of aliens.

the bundle of expectations of the atoms that make up the glass?" I asked.

"Very often, Bob," Fuchs responded, sounding like a teacher whose patience is being tried by a slow student, "it feels like you're still always putting the little guys down as the more basic things and the bigger guys down as the more derived things."

"The reason I think of atoms as more fundamental than the glass," I explained, "is that they're presumably simpler, right?"

This prompted a barrage of rebuttals from the group. The simple-seeming single colors that comprise white light, someone pointed out, require the philosophically complex concept of infinity for their definition. Even elementary particles are, per quantum theory, "infinitely complicated," another said.

Before I could assess the damage done to my point, Fuchs changed the subject.

"Bob often brings up the stability of the world," he said, referring to the kinds of dependable regularities I wanted explained, from the way my laptop stays put at night to the repeatability of scientific experiments. Fuchs mentioned the Hollywood movies he'd seen in which a happy family in a car gets hit by a truck. He brought up 18th-century philosopher David Hume's argument that no matter how many times the sun has risen in the past we can't be sure it will in the future.

"The sun always rises, until it doesn't," he said. "You can count on family stability until you can't."

Hollywood? Car crashes? I didn't see his point. But again, before I could respond, physicist, QBissel, and Pienaar's wife Gabriela Barreto Lemos chimed in to say that it was extremely hot where they were in Rio, that their air conditioning worked until it didn't, and that she's been noticing recently how everything is changing all of the time.

"It's amazing," she said, "because when you start doing that, your whole world is like, *Boosh!*," she mimed an explosion with her hands. "Everything seems super stable, and then you realize it's not fucking stable; I'm not stable. You're not stable. My computer's definitely not stable. The air conditioning is not stable. Nothing is."

"I love it!" shouted Fuchs.

So did everyone else. A round robin of testimonials to the world's inherent instability ensued from QBists and QBissels alike. Buddhism and Alfred North Whitehead were cited in support. I was disoriented, but also sympathetic. Things with Martina had been getting more strained. Living together through a pandemic had taken its toll. I'd even started to question whether marriage made sense. *Gabi is right. Nothing is stable.*

It was five o'clock, about the time Fuchs usually started making noises about his imminent cocktail. I

QUANTUM LEVITY In 2010, at a New Directions in the Foundations of Physics meeting, Chris Fuchs cracks up himself and fellow physicist Rob Spekkens with a joke. Famed physicist Charles Misner is to Fuchs' left.

MICHAEL SEEVINCK

could have used one myself. But the QBists were on a roll and I sensed that Fuchs wanted to finish me off.

"What was your next question, Bob" he said.

I took a breath and steered the discussion to hydrogen, the simplest of the elements, and the one whose frequencies Bohr and Heisenberg contended with back in the day. I said I wanted to understand why, if those frequencies are not objective facts about the world, do we all agree about what they are.

"There's something to be explained there," I said, "because what does it mean to be subjective? It means that different people can have different opinions, right?"

"I'm just slowly losing it," Fuchs responded. "Maybe this is why I've never answered you in email. We agree when we agree and we don't when we don't. I can't imagine that there is some precondition in the universe that says we must agree about anything, anything whatsoever."

"Then the answer is just outside of QBism," I said. "It's out of scope. That's fine."

A few objections were lobbed at me in response, but Fuchs and I stayed out of it. Fuchs then brought the meeting to a close.

"Bob, you have been thought-provoking," he said.

What I felt like I'd been was pummeled.

IT TOOK SEVERAL MORE QBUKIS, numerous one-on-ones with the QBists, and quite a bit of time for me to finally wriggle free from the ruts of my old ways of thinking and to realize that, to a QBist, a wine glass is *not* made of atoms. Once things are reconceived as bundles of expectations, big ones aren't made of smaller ones since beliefs don't work that way. Atoms become instead an aspect of wine glasses rather than their constituents, meaning a *concept* that encapsulates some of our expectations about them, such as how they will look under an electron microscope. That realization led to another that was even more startling to me than my encounter with the titmouse: that to a QBist, physical things are *more* than just atoms.

I also appreciated that the point of Fuchs' car crashes was that all the so-called facts about the world that we glean from observing it are, strictly speaking, beliefs, since future experiences could reveal them to be false. No sensible scientist would disagree, and an irony that I was just starting to perceive about QBism was that its most radical claim is not so much that our facts and ideas are subjective in this way, but that it has identified in quantum theory a single one that is *not*.

But there was still one big nut I hadn't cracked: the one that had set Fuchs off at the end of the meeting, the question of why people agree about physical facts if those facts don't exist objectively. Sure, part of the answer is that as members of the same species, we respond to similar stimuli in similar ways; but that still begs the question of what the sources of those stimuli are, because despite Hollywood's car crashes and Barreto Lemos's faulty air conditioning, the world *does* have stable features, including the existence of my laptop, the characteristic colors of hydrogen gas, and all the other physical phenomena that people with working senses do agree about and that, at least to my way of thinking, quantum theory was originally developed to explain. I mean that's what science is about, right? Explaining things? Finding truth?

Over the summer, I spoke to several specialists who confirmed that I was not alone in my frustration.

Jean Bricmont is a retired professor of physics at the Catholic University of Louvain in Belgium. His books include *Making Sense of Quantum Mechanics* and *Quantum Sense and Nonsense*. Bricmont wants to ask the QBists, he told me, "What is your belief *about*? They're subjective beliefs, OK, but about *what*?" He didn't buy my suggestion that QBism was an improvement over Bohr because it solves Wigner's friend. "It's an improvement only insofar as it reveals the absurdity [of Bohr's interpretation]," he said. "It's pure idealism."

Oxford philosopher Christopher Timpson has thought deeply and written much about QBism. Although he remains relatively sympathetic to it, he still considers its lack of explanation of physical facts a potential "killer blow." "If you want, as very plausibly one should want, a thicker notion of explanation which stands independent from merely what we expect," he said, "then the QBists can't deliver it unless they make some clever new developments."

I was particularly eager to hear from Carlton Caves, Fuchs' old research advisor and collaborator, whose input had been crucial to QBism's early development. I knew from Fuchs that he'd ultimately lost his enthusiasm for it. Why? I wondered. “I look out my window and there’s an oak tree there,” Caves told me. “I expect other people to look out my window and tell me there’s an oak tree there, and there’s nothing in QBism that would suggest there’s any reason to think that that would be true.”

Caves had worked with Fuchs and Schack for more than a decade and considers them both “incredibly deep thinkers.” He called their collaboration the “first golden age” of his career. But in the end, the implications of probabilities being beliefs led to a place that was, he said, “not where I want to be.”

Ruediger Schack, the third of QBism’s co-founders, was still a believer. He’s a professor of mathematics at Royal Holloway, University of London. He has a deep voice and an economy of speech that leads Caves to call him “Mr. Terseness” to Fuchs’ “Mr. Prolixity.” When I told Schack that Timpson called QBism’s lack of explanation of physical facts a “killer blow,” his response was, in effect, an indifferent yawn. “QBism can predict that the color of ruby is red,” Schack said. And that, he said, “is all the explanation I need.”

Everything seems super stable, and then you realize it’s not fucking stable; I’m not stable. You’re not stable. My computer’s definitely not stable.

I understood why Caves called him Mr. Terseness. But it was Schack’s equanimity above all that helped me put the final piece of the QBism puzzle in place: It convinced me that Schack’s own craving for explanation had been satisfied. To be able to predict, he was saying, *is* to have an explanation, not one that’s necessarily simple enough to be summed up in a few sentences, but one that resides nonetheless in all the knowledge and know-how that went into the prediction. William James and his fellow pragmatists would, I believe, have agreed. After all, if our ideas and theories don’t mirror an underlying reality, in what sense can they supply explanations? “Truth in our ideas,” James wrote, “means their power to work.”

Rationalists like me crave mechanistic explanations: A ruby is red because the electrons in its atoms move in a specific way, and anyone looking out Caves’ window will see an oak tree for similar reasons. But when atoms are considered *concepts* as opposed to *constituents* of rubies, mechanistic explanations no longer apply. It’s a “stock rationalist trick,” James wrote, to treat concepts we invent to explain phenomena we observe. We could claim, James said, that a man digests and sleeps well because he is healthy.

But "healthy" is just a word coined to describe someone who digests and sleeps well, so that claim is no explanation at all. QBists believe that quantum theory validates James' conceptions of truth and explanation because attempts at mechanistic explanations for quantum phenomena like the double-slit lead to paradoxes—such as electrons being both particles and waves.

I soon found myself applying such pragmatic thinking to day-to-day life, including my disagreements with Martina. What was the point, I thought, of all the "why" questions I was always asking her and myself. *Why is it so hard to put things back the way they were? Why am I so bothered that she doesn't*? What I really needed, and what were so often right in front of me, were answers to "How?"

And yet I couldn't feel satisfied with the notion that knowing how is as good as knowing why in physics, for the same reason that Bricmont dismisses QBism out of hand and that I once called Bohr's ideas a dead end: It seems to imply that physics ends at human experience and can't speak to the nature of reality beyond that.

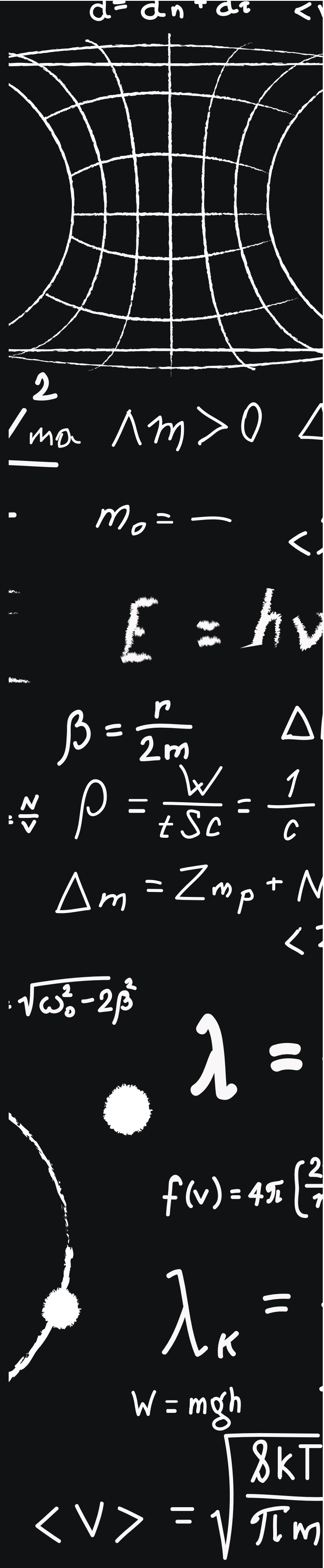
Fuchs disagrees.

IT WAS A STEAMY MORNING in July of 2021, in that hopeful period post-vaccines but before Delta. Fuchs was sitting in a white Adirondack chair in his backyard, crossed bare legs and Birkenstocks supporting the laptop in which he was engrossed. I'd driven to his home in Quincy, Massachusetts, from mine in upstate New York and we, abiding by long-ingrained middle-aged-guy manners, shook hands. I think he may have been a little nervous. I know I was. I'd never before had such intense interactions with someone I hadn't even met.

He showed me around his expansive suburban backyard, a charmingly chaotic sprawl of patios, herbs and vegetables growing in pots, fabricated flowers and giant insects made of metal and wood, and the tools and hardware for innumerable partially finished projects, all surrounding a large slate blue house. A big tan and white dog named John Archibald barked nonstop at me until he settled down. Kiki made muffins. And for the next two days Fuchs and I hung out in his yard and house and engaged in the kind of long, free-flowing conversation that you can't have on Zoom.

After our initial tour, Fuchs recounted how he came to physics. He'd already told me about growing up "pretty poor" in the small Texas town, Cuero, and about a childhood that involved at least as much conflict and confusion as mine. Now he explained how he'd found refuge in science fiction, including Isaac Asimov's books and *Star Trek* on TV. He'd dreamed of living the life of Captain Kirk, flying to the stars and exploring strange new worlds. That led him to the physics section of the library, where he went to learn how to make that happen.

"It was like porn for me," he said about the books he took home. The equations went over his head, but he understood enough to discover the disappointing truth that Einstein's theory of relativity, and its prohibition



on faster-than-light travel, made his *Star Trek* dream impossible. "The laws of physics aren't going to allow it," he recalled telling his best friend. "So they've *got* to be wrong."

Fuchs explained he was inspired by the scientific writings of physicist John Archibald Wheeler, a professor at the University of Texas at Austin. Once, while attending the American Legion's Boys State program in Austin, Fuchs snuck off to meet Wheeler. The professor was out of town, but his secretary let him take a sampling of his papers, including one on an idea called "law without law," which was that the laws of physics are not hard and fast but rather only approximations that arise from quantum randomness, similar to how order emerges from chaos in Darwin's theory. It was an idea that offered Fuchs hope that his dream was not dead. As the other John Archibald lolled in the grass nearby, Fuchs stopped at this point in his story. A surge of emotion made it hard for him to speak. "I was like *Whoa!*" he said. "I've got to understand quantum mechanics!"

Fuchs did his bachelor's in physics at UT, with Wheeler as his research advisor. He also earned a bachelor's in mathematics. "It from bit" was another Wheelerism. It expressed his belief that an electron, as Fuchs put it, "is nothing more than our information about it." Inspired by that idea, Fuchs found his way to Caves and Schack on a mission to understand quantum mechanics in information terms.

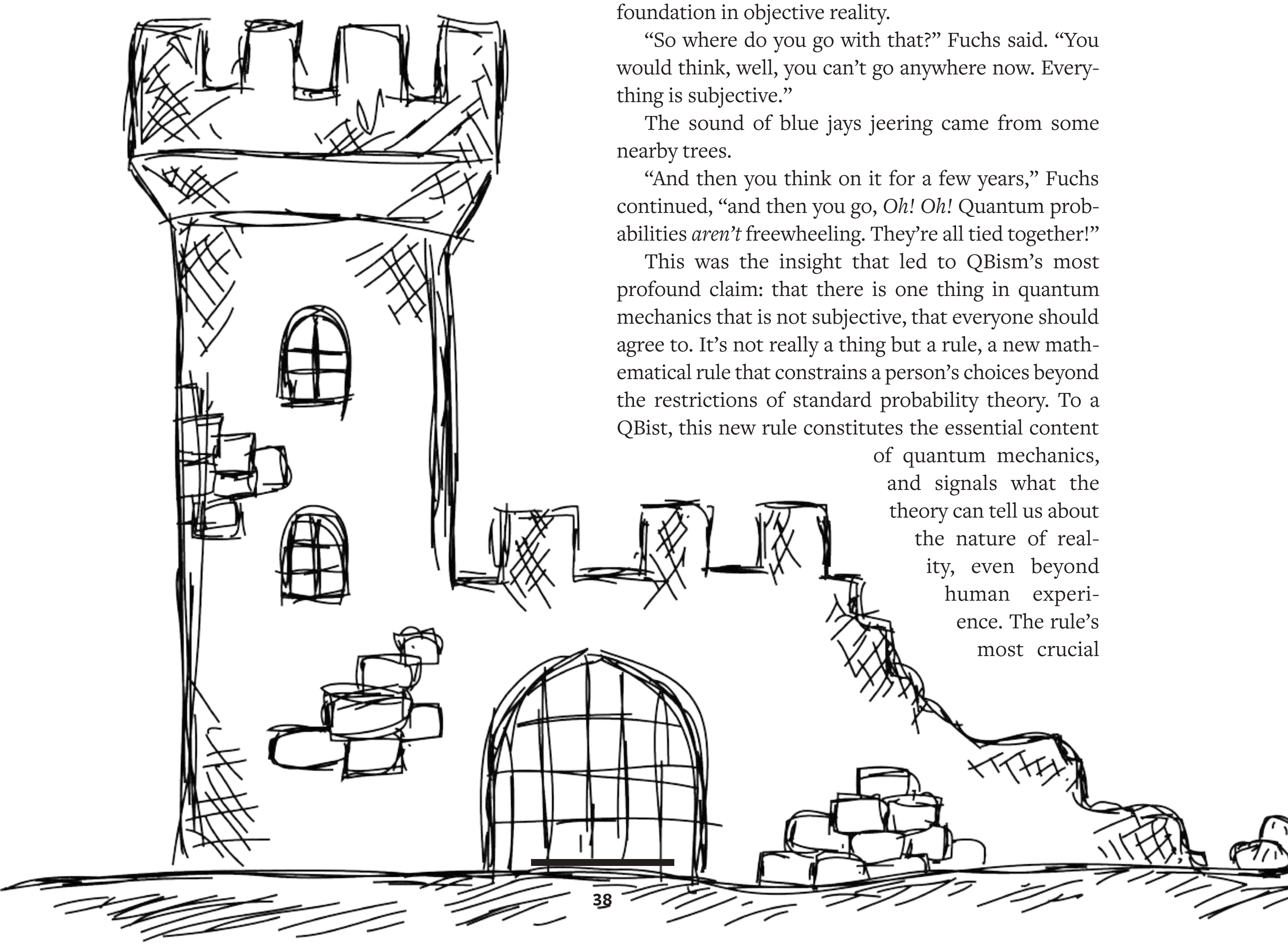
While I'd gone into physics seeking something solid to believe in, Fuchs went with precisely the opposite orientation: with hopes of showing that the laws of physics *aren't* solid. Years later, it seemed that he'd succeeded too well. QBism's core tenet that probabilities are personal beliefs had led to the conclusion that every part of quantum theory, from quantum states to the lab equipment used to measure them, had the metaphysical status of subjective beliefs, with no apparent foundation in objective reality.

"So where do you go with that?" Fuchs said. "You would think, well, you can't go anywhere now. Everything is subjective."

The sound of blue jays jeering came from some nearby trees.

"And then you think on it for a few years," Fuchs continued, "and then you go, *Oh! Oh!* Quantum probabilities *aren't* freewheeling. They're all tied together!"

This was the insight that led to QBism's most profound claim: that there is one thing in quantum mechanics that is not subjective, that everyone should agree to. It's not really a thing but a rule, a new mathematical rule that constrains a person's choices beyond the restrictions of standard probability theory. To a QBist, this new rule constitutes the essential content of quantum mechanics, and signals what the theory can tell us about the nature of reality, even beyond human experience. The rule's most crucial



feature is that it is "normative," meaning that it tells the theory's user how to think rather than how the world behaves. Fuchs' compares it to the Ten Commandments. One can disregard it, but "something bad is likely to happen as a result." "Bad" meaning that your computer, nuclear reactor, MRI machine, or any other application of the theory simply won't work.

We were now in Fuchs' living room, him on his sofa, bare feet on the coffee table, and me in a chair nearby. I asked him what the normative character of quantum theory's new rule says about nature's doings. That their probabilities "can't be quantified," he said, that "there's no number that will shoehorn a potential event."

I was reminded of something I'd read before. "Nature and its parts do what they want," Fuchs had written, "and we as free-willed agents do what we can get away with."

Fuchs sounded a lot like James, who speculated that "experience as a whole is self-containing and leans on nothing," meaning that no deeper layer of reality explains our experiences, because the experiences *themselves* comprise the ultimate reality. James called his vision a "pluriverse," a place in which no thing was more fundamental than any other, where mental phenomena like dreams and ambitions are as real and substantive as anything else, and where, he wrote, "being comes in local spots and patches which add themselves or stay away at random, independently of the rest." James' pluriverse was the furthest thing imaginable from what he called the "block universe," one that amounted to a giant machine, built from fundamental ingredients and governed by immutable laws. The pluriverse was a wilder and more heterogeneous place, one that was forever unfinished as its motley cast of constituents pushed, pulled, and clashed with each other in a never-ending process of construction, each driven by its own unknowable inner nature, each free from the reins of any top-down laws at all.

This is Fuchs' understanding of the world, too. "I think the chair that I have my feet on has as much of an inner life as I do," he'd said in one QBuki.

Our conversation circled back to Wigner's friend. Fuchs compared the scenario to one of those Escher drawings, of say a staircase, which displays in two dimensions a situation that can't exist in three. In the analogy, Wigner's and his friend's contradicting facts are like two sections of the staircase: They can peaceably co-exist so long as we don't try to interpret them as aspects of a single block universe.

I was finally appreciating how quantum theory could substantiate the pluriverse idea. How James' "experiences" and Bohr's "phenomena" could be one and the same. How quantum theory's mysterious acts of "observation" could correspond to James' "facts in the making." And how it might be that there are no variables hidden in Heisenberg's black box, because reality is simply the phenomena, the experiences, out of which that box was built—and more generally that there may not be any deeper reality hidden in the palace of ideas because it too is derived from experiences and not the other way around.

And I could see why Fuchs kept saying that quantum theory makes life worth living. "The world stands really malleable," wrote James, "waiting to receive its final touches at our hands. Like the kingdom of heaven, it suffers human violence willingly. Man *engenders* truths upon it."

It's that malleability that gives Fuchs hope, because to him it means that the laws of physics only summarize the experiences humans have had so far, do not limit those we may have in the future, and are even, to some extent, shaped by human activity. "One day we will get to the stars, in the sense of *Star Trek*," he said from his sofa. "How's that going to happen? I don't know ... But if you buy the ideas of James ... then you've bought into a hope that it *can* happen."

Hope, yes, but as to going further, Fuchs unfortunately is "stuck." He told me this a couple of weeks earlier in a one-on-one Zoom call, while wearing a "Life is Crap" T-shirt illustrated with a cartoon bird pooping on a sad face. I'd run my fifth and final QBuki a few days before and he'd written me an email saying he felt sorry for me, because of how exhausted I looked by the end. He suggested we talk to try and iron things out.

His tone was completely different than I'd ever heard before. He spoke to me as if were colleagues rather than like an oracle, speaking down from above. He confessed that the QBism project was stuck and explained why he'd snapped at me in the QBuki a few days before. "You got my ire because you, poor fellow, made the poor choice of word 'repeatability,' " he said. Repeatability just meant the ability of scientists to

If our theories don't mirror an underlying reality, in what sense can they supply explanations?

repeat experiments. What was wrong with using that word? "Well," he said, "I'm trying to construct a philosophy where *nothing* is repeatable, where the world is fresh in every moment."

Trying to construct. I suddenly realized how much of QBism is a product of Fuchs' desire and how much its future depends on faith. Fuchs went on to tell me a story he'd written a long time ago which, although he's an atheist, recounted a conversation between Adam and God. Adam wishes for a world like Fuchs wants to believe in. And God grants his wish by making the world conform to quantum theory, such that it grows unbound by laws as James envisioned, and yet where science can progress by finding normative rules to navigate it, including potentially to the stars. "Faith uses a logic altogether different from reason's logic," James wrote. "Reason claims certainty and finality for her conclusions. Faith is satisfied if hers seem probable and practically wise."

Fuchs said he abides by the chain of thinking of James' faith ladder:

"It would be well if it were true …"

"It might be true …"

"It ought to be true …"

"It shall be true," goes the last step: Act as if it is and it will be.

Fuchs and his QBists are now looking for ways to flesh out fuzzy philosophical ideas like "experience," to translate them into mathematical language, and to show in detail how quantum mechanics follows from them, which is to say to explain why that particular theory is the optimal "law of thought" to survive and thrive in the pluriverse. How to go about that is not at all clear.

"I think there is a better story to be told," Fuchs said across the coffee table, "but we don't know how to do it yet."

We talked for a long time about the challenges of abandoning a God's-eye view when thinking through situations like Wigner's friend. What, after all, is "the" situation if all that is real are Wigner's and his friend's individual experiences? I said I couldn't see how to think that way. "It's a struggle for me too," Fuchs said. "You're asking tough questions. You really are a member of the group."

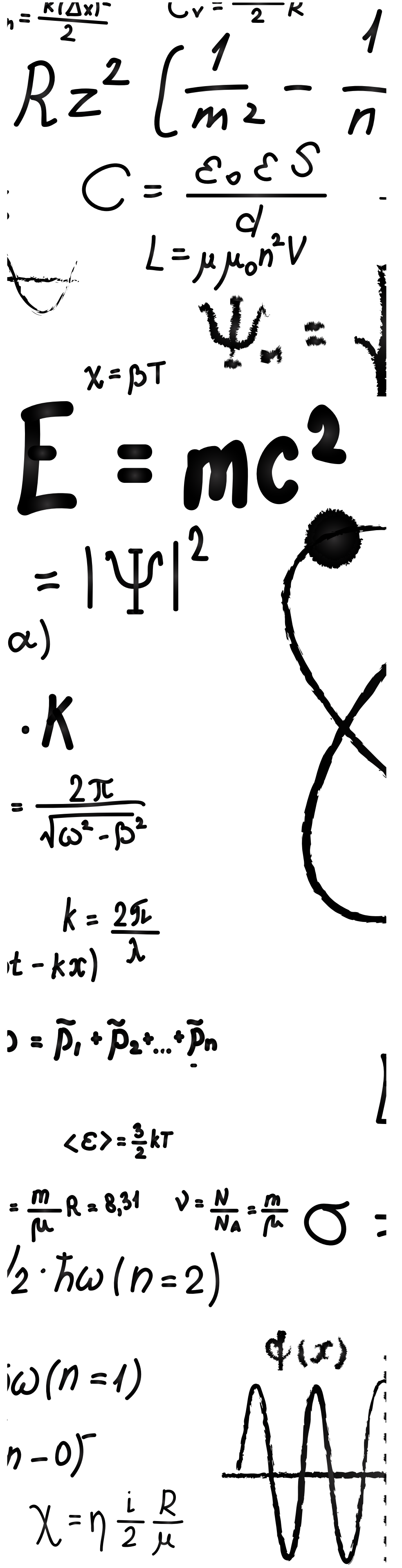
Maybe he was being polite. But I believed him—even if I wasn't quite ready to take the leap of faith that a true QBist needs to make.

A WEEK AFTER I left Fuchs, on a vast green lawn overlooking the Hudson River and the Catskill Mountains beyond, Martina and I stood under an arch of white flowers and exchanged vows in front of our families and friends. Although I had a lot of things on my mind in the preceding days, one was how to think more like a QBist.

I chuckled at an irony. I'd started off hoping to understand QBism's way of reconciling the familiar everyday world with the foreign quantum one and ended up open to the idea that we're all living in the quantum world. How much my new outlook came from Fuchs versus my love for Martina was impossible to know—my thoughts and feelings were too entangled to separate. But it seemed right, as QBism claims, that the everyday and quantum worlds are one and the same. That uncertainty is unavoidable and unquantifiable. That people can have different realities but must live in the same universe. That we are more than just atoms. That our choices are our own. And that our futures are not limited by our pasts.

It ought to be true ....

BOB HENDERSON is a writer based in upstate New York who earned a Ph.D. in theoretical physics, and has previously made his living as a photojournalist, electrical engineer, financial quantitative analyst, and derivatives trader.



Can We Prove the World Isn't a Simulation?

You might think we have definitive evidence we're not in a simulation. That's impossible.

BY DAVID J. CHALMERS

HOW DO YOU KNOW you're not in a computer simulation right now? This idea is often known as the simulation hypothesis. The simulation hypothesis says simply: "We are living in a computer simulation."

EZUME IMAGES / SHUTTERSTOCK

What is it to be living in a simulation? As I understand this notion, it's all about interacting with the simulation. When you're in a simulation, your sensory inputs come from the simulation, and your motor outputs affect the simulation. You're fully immersed in the simulation through these interactions.

At the start of *The Matrix*, Neo's biological body and brain are in a pod in a nonsimulated world, connected to a simulation somewhere else. In the ordinary spatial sense of "in," Neo's brain is not "in" the simulation. However, all his sensory inputs are coming from the simulation, and his outputs are going there, so he's living in a simulation in the sense that matters. After he takes the red pill, his senses respond to the nonsimulated world, so he is no longer living in a simulation.

I will use the word sim for someone who is in a simulation. There are at least two sorts of sims. First, there are biosims: biological beings outside the simulation (in the spatial sense) and connected to it. Neo is a biosim. So is a brain in a vat, connected to a computer. A simulation that includes biosims is an impure simulation, since it includes elements (the biosims) that aren't simulated.

Second, there are pure sims. These are simulated beings who are wholly inside the simulation. Most of the people in Daniel F. Galouye's 1964 novel *Simulacron-3*, are pure sims. They receive direct sensory inputs from the simulation because they're part of the simulation. Importantly, their brains are simulated, too. Simulations containing only pure sims may be pure simulations—simulations in which everything that happens is simulated.

There can also be mixed simulations, which contain both biosims and pure sims. Inside the Matrix, the leading characters Neo and Trinity are biosims, whereas the "machine" characters Agent Smith and the Oracle are pure sims. In the 2021 movie *Free Guy*, the main character, Guy (played by Ryan Reynolds), is a fully digital nonplayer character in a video game, while his in-game partner, Molotov Girl (played by Jodie Comer), is a video game player and designer with an ordinary life outside the game. So Guy is a pure sim, while Molotov Girl is a biosim.

The simulation hypothesis applies equally to pure, impure, and mixed simulations. Occurrences of the simulation idea in science fiction and philosophy are

As biological systems, bodies can be simulated.

split fairly evenly among them. In the short term, impure simulations will be more common than pure simulations, since we know how to connect people to simulations but we don't yet know how to simulate people. In the long term, pure simulations may well be more common. The supply of brains for impure simulations is not endless, and in any case hooking them up may be tricky. By contrast, pure simulations are easy in the long term. We need only set up the right simulation program and watch it go.

Here's another distinction. The *global* simulation hypothesis says that the simulation simulates a whole universe in detail. For example, a global simulation of our universe will simulate me, you, everyone on Earth, planet Earth itself, the whole solar system, the galaxy, and everything beyond. The *local* simulation hypothesis says that the simulation simulates only a part of the universe in detail. It might simulate just me, or just New York, or just Earth and everyone on it, or just the Milky Way galaxy.

In the short run, local simulations should be easier to create. They require much less computational power. However, a local simulation has to interact with the rest of the world, and that can lead to trouble. In the 1999 movie, *The Thirteenth Floor*, the simulators simulated only Southern California. When the protagonist tried to drive to Nevada, he encountered signs saying "Road closed." He kept going, and the mountains morphed into thin green lines. That's not a good way to design a convincing simulation. If a local simulation is completely local, it cannot properly simulate interaction with the rest of the world.

To work well, local simulations will have to be flexible. To simulate me, simulators will have to simulate much of my environment. I talk to people elsewhere, see events taking place around the world on TV, and travel often. The people I meet interact with many others in turn. So a good simulation of my local environment will require a fairly detailed simulation of the rest of the world. The simulators may need to fill in more and more details as the simulation runs. For example, a simulation of the far side of the moon will need revision once spacecraft can photograph it and send pictures back to Earth. There might be some natural stopping points: Perhaps simulators could render Earth in detail and the solar system as they need to, with just a rudimentary simulation of the universe beyond?

Philosophers revel in distinctions. There are many more distinctions we could make. We could distinguish between temporary and permanent simulations (Do people enter the simulation for a brief period or spend their whole lives there?), perfect and imperfect simulations (Do we faithfully simulate all the laws of physics, or do we allow approximations and exceptions?), and pre-programmed and open-ended simulations (Is there a single course of events programmed in advance, or can various things happen depending on initial conditions and what the sims choose?). You can probably think of other distinctions, but we already have enough to go on.

Can you prove you're not in a simulation? You might think you have definitive evidence that you're not. I think that's impossible, because any such evidence could be simulated.

Maybe you think the glorious forest around you proves that your world isn't a simulation. But in principle, the forest could be simulated down to every last detail, and every last bit of light that reaches your eyes from the forest could be simulated, too. Your brain will react exactly as it would in the nonsimulated, ordinary world, so a simulated forest will look exactly like an ordinary one. Can you really prove that you aren't seeing a simulated forest?

Maybe you think your darling cat could never be simulated. But cats are biological systems, and it seems likely that biological mechanisms can be simulated. With good enough technology, a simulation of your cat might be indistinguishable from the original. Do you really know that your cat isn't a simulation?

Maybe you think the creative or loving behavior of the people around you could never be simulated. But what goes for cats goes for people. Human biology could well be simulated. Human behavior is caused by the human brain, and the brain seems to be a complicated machine. Do you really know that a full simulation of the brain could not reproduce all this behavior in detail?

Maybe you think your own body could never be simulated. You feel hunger and pain, you move around, you touch things with your hands, you eat and drink, you're aware of your own weight in a way that seems viscerally real. But as biological systems, bodies can be simulated. If your body is simulated so well that it sends exactly the same signals to your brain, your brain wouldn't be able to tell the difference.

Maybe you think your consciousness could never be simulated. You have subjective experience of the world from a first-person perspective: You experience colors, pains, thoughts, memories. It feels like something to be you. No mere simulation of a brain would experience this consciousness!

This issue—the issue of consciousness and whether a simulation could have it—is harder than the others. For now, we can set the issue of consciousness aside by focusing on impure simulations—that is, *Matrix*-style simulations in which you're a biosim connected to the simulation. Biosims are not themselves simulated. They have ordinary biological brains which will presumably be conscious like ours. Whether you're an ordinary person or a biosim whose brain is in the same state, things will look and feel the same to you. If so, we can never prove we're not living in a simulation.

What about the other way around? Could we prove we *are* in a simulation? In *The Matrix*, Neo realized he'd been living in a simulation when he took the red pill and woke up in a different reality. He shouldn't have been so sure. For all he knows, his old world was nonsimulated and the red pill plunged him into a simulation.

Still, we certainly could get very strong evidence that we're in a simulation. The simulators could lift the Sydney Harbor Bridge into the air and turn it upside down. They could show us the source code of the simulation. They could show us private episodes from our past, along with the simulation technology that produced them. They could show me a film of my brain hooked up to wires in the next reality up, with an associated readout of my thoughts and feelings. They could give me control of the simulation, so that I could move mountains in the world around me just by pressing some buttons.

We need only set up the right simulation program and watch it go.

Even this evidence would fall short of absolute proof that we're in a simulation. Maybe the world we're in is a nonsimulated magic world, like the Harry Potter world, in which all-powerful wizards are using their powers to convince us we're in a simulation. Maybe most of my life has been nonsimulated but simulators have put me into a temporary simulated duplicate to fool me. Or maybe I'm having a drug-induced hallucination. Still, I think that if I got evidence like this, I would probably be convinced that I am in a simulation.

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PHOTO OF A PAGE OF H.A. REY'S *KNOW THE STARS.*

Readers Love Curious George. I Fell in Love with the Author's Astronomy Books

H.A. Rey recreated star maps with wit, grace, and accuracy

BY DAN FALK

HE IS WITHOUT A DOUBT the most famous little monkey in all of fiction. Curious George, known for letting his inquisitiveness get him into trouble and then using his ingenuity to get him out of it, has been entertaining children and their parents since 1941, when the first book of his adventures, simply titled *Curious George*, by the husband-and-wife team of Margret and H.A. Rey, was published. It was followed by six more books; the last one, *Curious George Goes to the Hospital*, appeared in 1966. George has also starred in six animated feature films, and, since 2006, a PBS television series. Some 30 million copies of the George books have been sold, in 19 different languages.

The first Rey book that I encountered, however, had no monkeys whatsoever. As a kid growing up in Nova Scotia, with a keen interest in the stars and the universe, I devoured all the science books that I could find. I was lucky that my parents had books like *Marvels and Mysteries of The World Around Us*, a massive Reader's Digest hardback that weighed as much as my head, which covered pretty much the whole universe. But it was aimed at adults and older kids, and anyway the astronomy stuff was squeezed into a few pages at the end. The little book that really got me hooked on the night sky was called *Know the Stars*, adapted from a longer work, *Know the Constellations*. The author was H.A. Rey.

Hans Augusto ("H.A.") Rey and Margret Rey were German-Jewish refugees who fled Europe for America in 1940. Both were writers and illustrators; the George books largely bring together Margret's words and Hans's artwork. Hans' first astronomy book, *The Stars: A New Way to See Them*, was published in 1952; *Find the Constellations*, aimed at younger readers, appeared in 1954. Although both books are monkey-less, there are clues they came from the same hand that brought George to life. Early in *Know the Stars*, for example, we find a little sketch of a 20th-century office worker transported to ancient Mesopotamia. It's evening, and the constellation of Leo the lion is visible; a shepherd points it out to the baffled time-traveler. *Find the Constellations* features cartoon-like figures who similarly point out various features in the night sky.

Hans first took an interest in the stars while serving in the German army as a young infantryman during World War I—"long before George entered the picture," Ellen Ruffin, curator of the de Grummond Children's Literature Collection at the University of Southern Mississippi, in Hattiesburg, which houses the Rey archive, told me. At night, during breaks in the fighting, Rey looked skyward. What he saw looked nothing like the fanciful pictures in the popular astronomy books of the time. In one early 19th-century textbook, Leo the lion is drawn with a full mane of fur and a looping tail; with paws thrust forward, it seems ready to pounce. Only with great effort do we see the "backward question mark" (also called "the sickle") at the lion's front end—the only part of Leo that's relatively easy to spot in the springtime sky—with the bright star Regulus marking the "dot" of the question mark. Similarly, Bootes the herdsman is depicted as a muscle-bound Greek figure; there is precious little resemblance to what one sees in the sky.

Hans' diagrams, in contrast, are almost breathtaking in their simplicity. He drew the constellations with clean lines, almost like stick figures. And, remarkably, they look like the people and animals that the ancients imagined, *and* they look like what you actually see when you look up at the sky (far from city lights, hopefully). Take Ursa Major (the Great Bear). Rey's version looks like a bear, albeit a sort of stick-figure bear; at the same time, it clearly shows the seven stars within the bear that form the familiar "big dipper." For Rey, Leo the lion has no mane and sports the world's simplest tail; in fact, it could

MARGRET AND HANS The Reys, both illustrators and writers, combined their inspirations to create Curious George and delight kids to this day.

be a horse or just about any other quadruped. But it's faithful to what we see when we look up. In *Find the Constellations*, a cartoon figure points to his front paw and says, "There's a big star in his foot." Yep, that's Regulus.

My favorite Rey-ism is Gemini (the twins): It's literally two stick-brothers holding hands, each one with a bright star where his head would be (and we soon learn their names: Pollux and Castor). Importantly, the star positions are accurate: Yes, he connected them with lines; but the stars are precisely where they're supposed to be. Hans taught himself celestial cartography for this purpose, and to create the sky-view maps that appear in both *The Stars* and *Find the Constellations*. He uses larger dots to indicate brighter stars, and explains the "magnitude" system that professional astronomers use to denote the brightness of stars.

In *The Stars* (the book aimed at adults), Hans gives one of the best explanations of the "celestial sphere" that I've come across, including a concise explanation for why the constellations that we see vary over the course of the night and from season to season—the result, as Rey explains, of the Earth spinning on its axis while also revolving about the sun. The result of these two motions is that the stars rise about four minutes earlier from one night to the next. (Why four minutes? Because the *solar day*—which we set our clocks by—lasts 24 hours, while the *sidereal day*—the true length of the Earth to spin once on its axis, relative to the stars—takes just 23 hours and 56 minutes.) If not for these four minutes, Rey writes, "we should see the stars in exactly the same position at the same hour every night, and star-gazing would be the simplest thing in the world." He continues: "Now four minutes a day does not sound like much but it adds up. In a month it makes 30 x 4 minutes = 2 full hours. One month from today the stars will rise two hours earlier than today."

As Margret put it, Hans wrote about astronomy so clearly "that even adults can understand it." Neither of Rey's astronomy books has ever been out of print.

THE REYS' STORY is a remarkable one, and I'm embarrassed to admit that I only learned about it recently, through Louise Borden's 2010 book, *The Journey That Saved Curious George: The True Wartime Escape of Margret and H.A. Rey*, and the media coverage that her book sparked.

Hans and Margret were both from Hamburg. In the 1930s, Hans was working in Brazil, selling bathtubs; Margret, who had studied art at the famous Bauhaus school and had worked in advertising, later moved to Brazil also. They married in 1935 and moved to Paris the following year, renting a flat in Montmartre. The city may have become their permanent home were it not for the rise of antisemitism under the Nazis. They fled in June 1940, just as German troops were closing in on the French capital, escaping on bicycles cobbled together from spare parts. They carried with them only their clothes and a satchel full of early George drawings. They made their way to Spain and eventually to Portugal; in Lisbon they caught a steamer to Brazil, and from there continued to New York. (Their story is also the subject of Ema Ryan Yamazaki's charming 2017 documentary, *Monkey Business*, which also looks at the Reys' lives more broadly.)

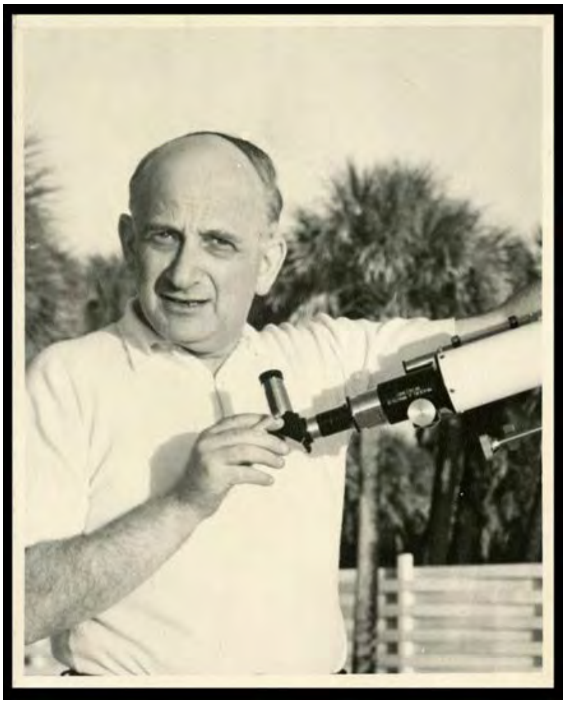
Like so many elements of our culture, the Curious George franchise has been the subject of intense scrutiny and re-evaluation in the 21st century. Some have balked at the premise of the first book, in which the Man with the Yellow Hat captures George in the African jungle and takes him across the ocean; for some, the echoes of the transatlantic slave trade are jarring. Writing in the *New Yorker*, Rivka Galchen observes that the first George story is "not a book that would be written in the same way today." She adds: "The text seems oblivious to the resonances with the Middle Passage, and those resonances now feel at once buried and overwhelming."

What we read into the books today does not, of course, tell us very much about what its creators were thinking 80 years ago. We know the Reys were no fans of fascism, having barely escaped Hitler's genocidal regime with their lives. We might also take note of Margret's 1945 book, *Spotty*; illustrated by Hans, it relates the adventures of a spotted rabbit struggling for acceptance in a world full of all-white rabbits. It is an explicitly pro-tolerance, pro-diversity tale. Meanwhile, the George franchise has evolved with the times: In a 2006 movie, George is not captured but rather sneaks onto the America-bound ship as a stowaway.

Though much less well known than the George books, Hans' astronomy books have also left their mark. *The New York Times*, reviewing *The Stars* in 1952, said

BIG DIPPER The back cover of H.A. Rey's *Know the Stars*, published in 1962. Rey's star maps hooked young readers with their simplicity and fun.

PHOTO OF THE BACK COVER OF H.A. REY'S *KNOW THE STARS*.



STAR MAN In the 1960s, recall residents of a New Hampshire community, Hans Rey held informal stargazing sessions for them.

FROM THE MARGRET AND HANS AUGUSTO REY PAPERS. USED BY PERMISSION THE DE GRUMMOND CHILDREN'S LITERATURE COLLECTION, MCCAIN LIBRARY AND ARCHIVES, THE UNIVERSITY OF SOUTHERN MISSISSIPPI, HATTIESBURG, MS.

it "represents the pictorial method of teaching at its best. It is almost certain to become standard equipment among amateur star gazers." And so it did. In fact, some of those amateurs went on to become professional astronomers. Jim Hesser, who served as director of the Dominion Astrophysical Observatory in British Columbia for almost three decades, was excited about the night sky as a youngster—but, like Rey, he was put off by the unrealistic artwork in astronomy guides of the time. "Discovering [Rey's] book was a turning point, for which I've long been grateful," Hesser told me. "I have recommended it time and time again to newcomers."

After first settling in New York, the Reys relocated to Cambridge, Mass., in 1963. Beginning in the 1950s, however, they spent their summers in Waterville Valley, New Hampshire. Although the Reys are long gone—Hans died in 1977, Margret in 1996—they're fondly remembered by residents of Waterville Valley. People recall the informal stargazing sessions that Hans hosted on clear summer nights, setting up his telescope at the local golf course, and welcoming anyone who came by to see what he was up to.

Nat Scrimshaw, 61, was a child when he first met the Reys; he still lives just a few miles away. Central New Hampshire is known for its natural beauty, though the encroaching condos have made Waterville Valley less tranquil than it once was. Back in the '60s, Scrimshaw recalled, there was just the Waterville Inn and a few cottages. With hardly any light pollution, "you could just go out at night and have this incredible view of the stars."

Before Scrimshaw and I ended our conversation on Zoom, he picked up his tablet and walked a short distance down the road to the home of Penny Palmer, another long-time resident who has warm memories of the Reys, and of Hans's stargazing sessions. "Our parents would be at the bar at the inn, drinking, and we'd go out to the fairway until we saw this tiny little flashlight, and that was Mr. Rey," Palmer said. "So that's how we found him."

Rey would set up his small refractor telescope to look at the moon, planets, and stars; he'd point out the constellations to whoever happened to drop by. Pocket lasers had not yet been invented, but Palmer remembers how Rey improvised the next best thing: He used Margret's nail polish to paint the front of his flashlight

Rey gives one of the best explanations of the celestial sphere.

so that it emitted just a narrow beam in the shape of an X, which was perfect for pointing things out in the night sky. She also remembers the one time that the usually calm Rey lost his cool. Palmer's young cousin "thought it would be funny to shine a flashlight down the telescope tube. And Mr. Rey, who was the sweetest man in the world, just went ballistic."

As Scrimshaw grew up, his relationship with Rey evolved. As a child, he loved visiting Rey in his studio and watching him draw, "seeing this kind of magic, that he could create these characters with colored pencils and chalk." As Scrimshaw became a young man, their conversations deepened. "He loved to talk history, science, art. He was a true Renaissance man, very educated in many different disciplines; he spoke multiple languages. When I was in high school, I would visit and talk with both Margret and Hans; that's when he went from 'Mr. Rey' to 'Hans.' "

In later life, Hans became an environmentalist, likely sparked by the energy crisis of the 1970s; he was especially keen on wind energy. Having experienced the horrors of war firsthand, he was also a vocal pacifist, and strongly opposed the war in Vietnam. One of the most remarkable artifacts in the de Grummond collection is a copy of a letter that Rey wrote to President Nixon in 1972, decrying "mechanized mass murder from 50,000 feet up in the air." Even if the U.S. were to win the war, he wrote "that victory would bring no glory to the United States, but lasting shame."

While Scrimshaw doesn't consider himself an artist, he always enjoyed doodling; these days, inspired by Rey's legacy, he gives "chalk talks" at the Margret and H.A. Rey Cultural Center in Waterville Valley, and at children's hospitals. When he draws, he channels his old friend. "Hans would grab a sheet of paper and quickly draw different characters, and make up stories about them—and then give the drawings away to the kids," Scrimshaw said. The staff at the Rey Center, meanwhile, continue to host summertime stargazing sessions, and the local municipal government recently adopted a dark sky ordinance to fight light pollution by regulating outdoor lighting—a small step toward preserving the sky that Hans Rey loved so much.

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The Worrisome Rise of NFTs

An astrobiologist says nonfungible tokens do not bode well for our species's future

BY CALEB SCHARF

NATTAPON KANCHANAKET / SHUTTERSTOCK

HUMANS ARE VERY GOOD at inventing commodities, and we've been at it for a long time. See that pebble over there? Well, that's a better pebble than all these others, and if you give me something in exchange for it, I'll let you take ownership. It'll be *your* pebble, forever. And soon there will be a market in pebbles, a pebble community, pebble exhibitions and auctions filled with pebble speculators, pebble exchanges, and pebble artists.

The deeper, evolutionary reasons why we do this—or why any species commodifies objects or experiences—are not immediately obvious. It could be a trait that supports social interaction and cohesion, helping distribute food and resources more efficiently throughout a population. Or perhaps it supports the signaling of individual fitness or intention that can guide our reproductive strategies. A behavior statistically favored in an intricate web of Darwinian selection, eking out a tiny advantage for the genetic lineage of anyone who plays along.

What further complicates this (as with any such trait) is the *cost* incurred for individuals or a species; the expenditure of resources and energy. The most explicit, and worrisome, example today is the emergence of commodities like cryptocurrencies or nonfungible tokens (NFTs). In simple terms, just as a cryptocurrency is meant to be infallibly secure and fair, an NFT is a way to assign secure provenance and ownership to a digital asset. That digital asset might be an image, a video, or some hybrid digital experience.

If bits of data were more like Michelangelo's marble, the whole notion of NFTs would be irrelevant.

Already there's been a lot of grumbling about the extraordinary energy demands of cryptocurrencies. Now there's grumbling about the absurd growth in the market for NFTs. This is because both commodities use a robust system for tamper-proof bookkeeping: the blockchain. Blockchain technology is purposefully burdensome and computationally distributed, making it notoriously energy intensive. Estimates put the energy used to create and trade a cryptocurrency like Bitcoin on a par with the total consumption of a country like Sweden. And that's without accounting for the environmental footprint of the physical computer hardware.

It's possible to see a purpose for cryptocurrencies, but NFTs are (for now) almost comically bereft of anything most of us would associate with social or cultural value. Down the line there may be value in attaching permanent ownership or provenance to digital works of art. But at the moment it's Pudgy Penguins for the masses, or a pixel-heavy version of Nyan Cat going for an eye-watering $1.2 million for cynical investors. With an explosive growth of equally speculative and bewildering offerings appearing every day.

This represents a tangible planetary burden. Prompting the people behind the blockchains to try to improve their environmental image. The company Ethereum (that supports cryptocurrency as well as NFTs) has indicated it aims to cut energy use by more than 99 percent by changing its core methodology. That change will make it possible for aspiring currency "miners" to participate without so much hardware and electricity consumption.

That sounds great but understanding the nature of these changes is not easy, since the whole idea of blockchains is rooted in astonishingly arcane concepts like "proof of work" or "proof of stake" manifested in computer hardware and algorithms. It's also far from clear that other companies will follow suit, or that the most energy-intensive pieces can ever be fully removed from the scheme without risking the innate reliability that makes the blockchain so appealing in the first place.

The much bigger question, though, has less to do with these emergent upstarts in our informational world and more to do with humanity's overall trajectory. Any species that endlessly grows, and continually invents energy-hungry processes, may not be destined for a happy ending. At best, such a species will go through boom-and-bust cycles, with big corrective failures. At worst, a species like this simply won't make it through to the future. NFTs and cryptocurrencies by themselves may not be the cause of a future collapse, but they are symptoms of what ails us. And like all symptoms, they can offer clues to a cure, because the root of the problem may be much deeper—in the fabric of digital information itself.

NATURE CONSISTS OF both fungible entities (identical and perfectly exchangeable) and nonfungible entities (unique, nonexchangeable). For example, you—fellow human—are a nonfungible asset. You are a complex, storied entity with your own unique history and a future of largely unpredictable twists and turns. In that sense, you are no different than pretty much any other living organism or system on Earth. Even endlessly reproducing bacteria or duplicating viruses are ripe with nonfungibility. Small variations in genetic sequences and circumstances create the magical diversity that natural selection acts on.

Yet, underneath all of this we think that the universe is built out of entirely fungible pieces. One photon of light can be completely identical to, and replaceable by, another photon. Even though some elemental pieces, like electrons, are strictly unable to occupy the same quantum state, any of them can still be readily swapped and no one would know the difference.

You—fellow human—are a nonfungible asset.

The extraordinary fact is that the universe is an engine that turns the fungible into the nonfungible. It takes indistinguishable atoms and assembles molecules of increasing complexity that become more and more distinct from each other. Each complicated structure having less and less likelihood of an exact match across the observable universe. In other words, nature has no need for NFTs to keep track of things—the ledgers are embedded already in any sufficiently intricate object.

By comparison, even though the 1s and 0s of our invented digital world are built out of transistors or magnetic dots containing tens of thousands of atoms, they are inherently fungible. We've effectively undone the nonfungible nature of the world around us. In digital form, data can be reproduced perfectly. A digital copy is just as good as the original. That's a remarkable thing, and one key to the power we get from digitization. But it is precisely this quality that gives rise to the issues we face with security and ownership further down the line, and the burden that places on us, our energy, and our planet. A trail for easily-copied data can only be maintained with yet more data, and encryption, and redundancy, and more hardware, and more energy-consuming computation.

But what if we had built things differently from the beginning? What if a digital bit was more than just a 1 or 0, and contained a degree of uniqueness? Take, for example, Michelangelo's statue of David. This was carved from a single block of Tuscan marble that originated in deposits of calcium carbonate from billions of microscopic marine organisms, and transformed into its smooth, slightly translucent form by high pressure and temperature. Every speck of this statue has a signature of unique provenance in its intricately crystallized makeup, its weathering, and its isotopic composition. Superficially, the statue can be copied, and has been innumerable times, but inspect it closely enough and it is entirely, automatically, nonfungible.

If bits of data were more like the specks of Michelangelo's marble, the whole notion of NFTs would be irrelevant. Every bit would hold its own uniquely traceable fingerprint, with no need for some extra token of nonfungibility. This raises the disquieting possibility that in our exuberant adoption of the power of digitization, we've missed a trick, lured on by new tools and riches. Consequently, we're now faced with the mother-of-all-patch-jobs, where we have to invent ways to create retroactive nonfungibility in our data instead of placing the option of being nonfungible at its core.

I can't claim to know what nonfungible electronic bits would look like. Maybe someone has already invented them. Perhaps they'd be so cumbersome that it'd set our computational world back by decades. But we need to do something pretty radical. If we don't, the environmental consequences of blockchain use could be catastrophic because of the potential to outpace any efforts to transition to zero-carbon energy production. With the core issue of fungibility unresolved the same is likely true for whatever else we invent to buttress the shaky walls of our increasingly blended reality, where commodities in the universe meet commodities in the metaverse.

There is of course another solution: We stop reinventing things like currency or certification until we have a proper plan. This can sound like an oddly conservative position; having secure and decentralized ways of carrying out free trade or retaining data ownership is in principle a very good thing. Blockchains are clever and help fix that nonfungible digital shortfall. But it's atrocious timing for us to create yet another fast-growth planetary burden. Putting a scheme like NFTs on hold (or rethinking and rebuilding those fundamentals of digital nonfungibility) until humanity has figured out a way to generate all our energy cleanly, from solar, nuclear, and so on, would make more sense. It would be a cosmic tragedy for Darwinian selection to prune our lineage out of existence for the sake of frivolous NFTs or crypto-greed. For the present moment the future is still a commodity that can be replaced with something better.

CALEB SCHARF is the director of astrobiology at Columbia University. His latest book is *The Ascent of Information: Books, Bits, Genes, Machines, and Life's Unending Algorithm*.

LEONARD ZHUKOVSKY / SHUTTERSTOCK

Novak Djokovic and the Healing Water Crystals

The story of the tennis star spotlights the pseudoscience that bedevils science and society

BY KEVIN BERGER

AT THE END OF every tennis match that he wins, Novak Djokovic sweeps his hands to his heart and opens his arms to the crowd, sending them his love. At trophy ceremonies, he thanks the people involved in the tournament, from the executives standing at his side whose companies have funded the tournaments, to the ball kids who toss him balls to serve—usually with a little tremble, as Djokovic is often sizzling with impatience. The gratitude is expected of him, but he's gracious in his delivery. He's aware that all the parts must click together to create the tournaments that have made him, a boy from Serbia, a wealthy man.

Throughout his career, Djokovic has spoken warmly about the fact that he hasn't achieved his success alone, that his family, coaches, and country have helped make him the champion he is. His nonprofit foundation builds and renovates preschools and kindergartens in Serbia. It's bought ventilators for Serbian hospitals during the pandemic. It recently funded a sculpture created by Serbian kids about Nikolai Tesla, "Wings Are Everything in Life," about the great scientist's love and admiration of birds. Djokovic is also behind a new tennis union that would help low-ranked players earn wider shares of pro tennis industry profits. He's affable and funny, a spot-on mimic of other players' mannerisms and styles.

Then there's his own playing style. If the definition of intelligence is the ability to absorb problems, solve them, and strike a new way forward, Djokovic is a genius. On a tennis court he has the perspective of Pythagoras and the reflexes of a gazelle. He tracks down and returns shots at angles that mere mortal players don't see.

This past January, Djokovic made headlines outside tennis for his decision to remain unvaccinated for COVID-19. Being vaccinated protects one's health and tamps down SARS-Cov-2's tendency to mutate, spread, and infect others. Getting vaccinated is an act of responsibility that stems from the values Djokovic expresses, that we are members of a community whose lives and achievements can't be separated.

Australia, "in the public interest," canceled Djokovic's visa and he didn't play in the Australian Open, a "Grand Slam" tournament, one of the sport's most prestigious. Had Djokovic won the tournament, he would have stood alone as the male player with the most Grand Slam victories in history. As it turned out, one of his main rivals, Rafael Nadal, won the tournament, and now holds the record. Most media commentary on the affair concluded Djokovic could have avoided his legal defeat had he simply got vaccinated like his fellow players, and 4.7 billion people around the world.

That's true, but why? Why did a fierce athlete with a record-breaking goal in his sights not do the simple thing? Why did a man so intelligent and sympathetic to others not do the right thing?

The closest Djokovic has come to a public explanation was in a *New York Times* interview in August 2020. "My issue here with vaccines is if someone is forcing me to put something in my body," he said. "That I don't want. For me that's unacceptable. I am not against vaccination of any kind, because who am I to speak about vaccines when there are people that have been in the field of medicine and saving lives around the world?"

Djokovic's response is honest and respectful. But it underscores the question of why a conscientious person wouldn't put something in his body that has saved lives around the world, especially when there is so much at stake in his own. Clues to why Djokovic spurned vaccination can be mined from his public views about health and science. The excavation, I thought, could be an informative one. And it was. It took me from the tennis courts to the underworld salons of pseudoscience. There, with the music of Enya playing, serenity candles burning, and books on the shelves about the healing powers of water crystals, I found a highlight reel of a mindset that bedevils science and society. In a viral pandemic, that mindset is not a game.

IN HIS 2013 BOOK, *Serve to Win*, a blend of autobiography and diet advice, Djokovic writes that his path to the top of the tennis world began with an open mind. It's a trait he forged in the crucible of the Yugolslav Wars, which tore apart his young world in the 1990s. Djokovic was born in Belgrade in 1987. One year, as bombs shattered Belgrade, Djokovic and his family hid in a bomb shelter for 78 straight nights.

In the aftermath of World War II, Yugoslavia, his family's native home, was ruled under communism until political and ethnic tensions, fanned into violence, exploded into war in 1991.

Under communism, Djokovic writes, "you are not taught to be open-minded. And there's a reason for this: If you are not open-minded, then you can be easily manipulated. People at the top are very invested in making sure we do not question what we are told to believe. Whether it is a communist ruler or, for many of us, the rulers of the food and pharmaceutical industries, people at the top understand that most of us are led by fear." Growing up in wartime, Djokovic writes, taught him "the importance of keeping an open mind and never ceasing to search for new ways of doing things."

In 2010, Djokovic welcomed a nutritionist "with a crazy story" into his life. Igor Cetojevic, a Serb, managed to contact Djokovic and told him he had watched him play in the Australian Open on TV. In the match, Djokovic collapsed from exhaustion, and one of the TV commentators said his asthma was acting up again. Cetojevic suspected it wasn't asthma. "More specifically, he guessed that my breathing issues were the result of an imbalance in my digestive system that was causing a buildup of toxins in my intestines. Which is a heck of a diagnosis to make from 8,700 miles away," Djokovic writes. (I'll say.)

Not long after, Djokovic met Cetojevic. The nutritionist told him he was falling apart in matches because of his diet. He would perform a test. Cetojevic had Djokovic place his left hand on his belly and hold his right arm straight out to the side. Cetojevic pushed down on Djokovic's right arm and had him resist. In a second test, Cetojevic had Djokovic hold a slice of bread to his belly. This time when the nutritionist applied pressure to Djokovic's right arm, "I was noticeably weaker," Djokovic writes. The nutritionist replied, "This is a sign that your body is rejecting the wheat in the bread."

Pronto, Djokovic switched to a diet without gluten, the name for a protein found in wheat. He was transformed. "I felt fresher, more alert, and more energetic than I had in my life," he writes. "I was faster, more flexible, and able to get balls other players couldn't, yet I was still as strong as I'd ever been, and my mental focus was unshakable." In 2011, gluten-free, he writes, "I won ten titles, three Grand Slams, and 43 consecutive matches."

PHOTO BY SHABLON / SHUTTERSTOCK; PHOTO EDITING BY TASNUVA ELAHI

The nutritionist appears to have been Djokovic's first guide to the outer limits of science. The website Science-Based Medicine has done a fine job taking the air out of the hyperbole that human organs, such as intestines, build up with toxins that can be cleansed with a diet that works like your car's air filter. Toxins like lead or mercury can accumulate in the body in dangerous doses. But otherwise, our skin, kidneys, lymphatic system, gastrointestinal system, and liver do just fine filtering and flushing chemicals from our bodies. A 2015 review from the National Center for Complementary and Integrative Health concluded "there was no compelling research to support the use of 'detox' diets" for "eliminating toxins from the body." Gluten can be toxic to the 1 percent of the population with celiac disease, a serious autoimmune reaction to the protein. But for the rest of us, research has shown there's no conclusive genesis for a gluten build-up in our bodies nor a reliable biomarker for gluten sensitivity.

Whether or not gluten was Djokovic's Kryptonite, his new diet clearly made him feel like Superman. With talent sculpted from years of eight-hour-days of practice with experienced coaches, and a bespoke physical fitness regime managed by a physiotherapist, Djokovic was on top of the tennis mountain. Perhaps confident that holding a piece of bread to his belly gave him the insight to spur his final ascent, Djokovic held court with gurus in other redoubts of alternative-medicine land.

I have dipped my toes in New Age waters in the past. But this deep dive took my breath away.

In 2020, locked down at home in the pandemic, Djokovic chatted online with Chervin Jafarieh, who describes himself on his website "as one of the most respected and influential health experts in the world." Jafarieh founded a company called Cymbiotika, "an innovative wellness company that designs sophisticated, organic nutritional formulations scientifically proven to increase vitality and longevity." He hosts a podcast called "Wake the Fake Up."

During one of their talks, Djokovic told Jafarieh, "And you know, I've seen people and I know some people that through that energetical transformation, through the power of prayer, through the power of gratitude, they manage to turn the most toxic food, or maybe the most polluted water, into the most healing water. Because water reacts, and you know scientists have proven that. Obviously, molecules of the water react to our emotions, to what is being said."

LEE MCINTYRE is a research fellow at the Center for Philosophy and History of Science at Boston University. He's the author of *The Scientific Attitude: Defending Science from Denial, Fraud, and Pseudoscience*, and *How to Talk to a Science Denier*. Both books offer keen insights into the nature of science and how it gets distorted under the crushers of business, politics, and personal identity. "To do science we must be willing to embrace a mindset that tells us that our prior beliefs, ideologies, and wishes do not matter in deciding what can pass the test of comparison with the evidence," he writes.

"Why," I asked McIntyre, "would someone believe that thoughts could transform polluted water into healing water?"

"Because they want to," he said.

"But this is an intelligent man," I said.

"It's not about intelligence, facts, or rationality," McIntyre said. "It's about disinformation, identity, and trust."

The "scientist" in whom Djokovic places his trust about the water-purifying powers of emotions and prayers is Japanese writer Masaru Emoto, who died in 2014. Emoto is the author of books including *The Hidden Messages in Water* and *Water Crystal Healing: Music & Images to Restore Your Well Being*. His research and experimental results have been published in *Explore: The Journal of Science & Healing* and *The Journal of Alternative and Complementary Medicine*. Gwyneth Paltrow, founder of the health-product store, Goop, which promotes its "open-minded" mission, has also expressed her fascination with Emoto.

Emoto's experiments consist of writing phrases on water containers. Those phrases include "Love and Appreciation," "Thank You," "You Make Me Sick," and "I Will Kill You." Emoto also plays music to water, including Bach's "Air on the G String," John Lennon's "Imagine," Chopin's "Farewell" song, and "a heavy metal music." He doesn't reveal which heavy metal band or song, just that "this music is filled with anger and seems to be denouncing the world."

After the labels had been on the water containers for a few days, or after the water had been exposed to the music, Emoto and his helpers froze the water samples, placed the resulting crystals under an electron microscope, and photographed them. In *The Hidden Messages in Water*, Emoto wrote, "Water exposed to the words 'Thank you' formed beautiful geometric crystals, no matter what the language. But water exposed to 'You fool' and other degrading words resulted in obviously broken and deformed crystals."

Djokovic's reference to prayer alludes to an experiment conducted by Emoto and a team from the Institute of Noetic Sciences, a research group "inspired by the power of science to explain phenomena not previously understood."

The experimenters placed four Fiji water bottles in the Institute of Noetic Sciences' offices in Petaluma, California. They used Fiji because once the labels were removed, the bottles contained no words. Two of the bottles, called "treatment bottles"—treated with prayer—were "placed inside a double-steel-walled, electromagnetically shielded room," wrote the experimenters in the journal *Explore*. The other two, the "control bottles," were placed in a cardboard box on a different floor in the building. Emoto, located in Tokyo, asked a group of 2,000 people to pray to the bottles in the institute's Petaluma lab, 5,000 miles away. Emoto wasn't told about the "control bottles" in the cardboard box.

A day after the prayer session, Emoto and his helpers froze the water from the Fiji bottles and photographed the crystals. A group of 100 volunteers, "recruited over the internet to blindly and independently rate each crystal," assigned the crystals a numeric value on a scale of zero to six; zero meant "not beautiful" and six meant "very beautiful." Results showed

OUTER LIMITS On the court, Novak Djokovic's ability to track down and return shots from a full stretch defies belief. As do some of his views.

FRESNEL / SHUTTERSTOCK

crystals "treated" with prayer, compared to the "control" water, scored "higher for aesthetic appeal."

The aesthetics of water crystals are important, according to Emoto, because they signal the profound effects that water has on our bodies. It turns out "water has the ability to copy and memorize information," he wrote. You want the best information in your body as possible. "Water makes up 70 percent of our bodies, and there is little doubt that the information in the water goes a long way in the formation of our personalities," Emoto wrote. "So how can people live happy and healthy lives?" Purify the water in our bodies. How? Play the water Bach or treat it with gratitude from your thoughts. "Can you imagine what it would be like to have water capable of forming beautiful crystals flowing throughout your entire body?" Emoto asked. "It can happen if you let it."

I HAVE DIPPED MY TOES in New Age waters in the past. But this deep dive took my breath away. When I surfaced, I couldn't stop wondering what water had against heavy metal music. Plenty of people around the world love heavy metal and are grateful for the pleasure it brings them. And to many the music of Bach sounds "fragmented and malformed," to borrow Emoto's description of heavy metal. What makes water the final arbiter of musical beauty?

I know, it's easy to be a wiseacre and sarcasm is no substitute for evidence. I continued my research in earnest.

In our Internet age, search engines offer quick trips to sites that delight in debunking pseudoscience. I came upon a site created by Stephen Lower, a retired faculty member of the Department of Chemistry at Simon Fraser University in Vancouver. Lower clearly got a kick out of reading about Emoto. If you have water crystals, beautiful or not, flowing through your body, Lower wrote, "I have bad news: You are dead, and are no doubt residing in a deep freeze!"

Emoto followers relish using the word "molecule." On Goop, Paltrow wrote, Emoto has demonstrated "how negativity changes the structure of water, how the molecules behave differently depending on the words or music being expressed around it." In conversation with Djokovic, Jafarieh remarked that Emoto's experiments have shown that "happy thoughts" have "created a molecular structure that had a geo-prism based on sacred geometry." Alas, Emoto's photographs don't show water molecules, they show frozen water crystals, which are not the same thing. Frozen water forms into myriad shapes by crystallizing around a speck of dust, dirt, or pollen.

The experiments consist of writing phrases on water containers, such as "Thank You" and "I Will Kill You."

"SkepDoc" Harriet A. Hall has been one of the most astute and entertaining voyagers into pseudoscience for the past decade and more. Had Emoto consulted with actual scientists, Hall wrote, "they could have told him that these snowflake crystals, just like raindrops, form around a core of dust, so actually the cleaner water is less likely to form them. Their beauty varies with the temperature and conditions of formation, not with the purity of the water."

I admire SkepDoc, Science-Based Medicine, and other sites that debunk pseudoscience. One of the major crimes of the Internet, though, is all information, despite its validity, gets lumped together. The medium is the message, and the message is science is just another act under the Big Top. "You hear it all the time from pseudoscientists: 'I did my own research,' " McIntyre said. "What they mean is they're reading lies on the Internet, and they don't understand how science works. What's distinctive about science is it cares about evidence and is willing to change its theories on the basis of evidence." Without that understanding, false equivalencies rule the day. Which is why some scientists don't want to be dragged into the circus in the first place.

Richard Saykally is a professor of chemistry at the University of California, Berkeley. His work in spectroscopy, the technique of splitting electromagnetic radiation into its wavelengths, a tool that helps scientists identify the signatures of atoms and molecules, has written textbook papers on water and its molecular behaviors. In fact, his 400 papers have been cited more than 50,000 times in the fields of science. I asked him what he thought about remarks that scientists have proven water molecules react to prayers and emotions. He was nice—and brief—in response. "The simple answer, Kevin, is that everything in science is testable and based on statistically quantified evidence. I know of no evidence that supports those claims," he said. "Talk is cheap."

Folks who champion Emoto, at least the ones I sampled on websites with names that feature words like "healing," "fractal," "awaken," "enlightenment," often remark that Emoto's research is backed by evidence. They point to papers like the one in the journal *Explore* on prayer. As I learned from McIntyre and other scientists who've studied pseudoscience, writers like Emoto dress up their beliefs with technical terms and call it science.

The *Explore* paper is a casebook example. It's composed in faux-objective tones and outfitted with jargon, with its "treatment" and "control" bottles, and asseveration that treatment bottles were "placed inside a double-steel-walled, electromagnetically shielded room." I mean, why? The experiments say the room was a limited-access location. I might suggest that "double steel-walled, electromagnetically shielded room" sounds scientifically impressive. After all, it was only two bottles. They could have locked them in a desk drawer. It's just hard to conclude, despite the scientific terms and academic tone, that prayers can be telepathically transported 5,000 miles and transform water in Fiji bottles into healing crystals.

NEVERTHELESS, I ASKED. I began at the point of origin. Could prayer thoughts even get out of the brain?

"Well, the brain is a powerful organ, but it doesn't have magic powers," Stuart Firestein, a professor of neuroscience and the former chair of the Department of Biological Sciences at Columbia University, told me. "It uses a lot of energy to perform its many tasks, including generating positive or negative emotions, which, by the way, are subjective experiences, and can't be reduced to a single neural process or location in the brain. That energy is from the body's metabolism and is a complex blend of chemical and electrical processes, and it remains within the skull, a very good insulator."

"But doesn't some energy escape from the brain? Isn't that what's picked up by electroencephalograms?" I asked.

"An EEG does record minute electrical signals from the brain," Firestein said. "But it requires highly sensitive electrodes and a special gel to decrease the scalp resistance, and even then it requires recording from dozens of spots at once to get any usable signal. This demonstrates the weakness of any signal that could emanate from the brain. So without resorting to imaginary forms of energy that can be transmitted from the brain to exterior objects, there is no possibility for the energy we know about and can measure to alter physical objects outside the brain."

And what about the remarks that water has memory, and positive thinking can strip pollutants from water? Sam Lord holds a Ph.D. in chemistry from Stanford and is a research specialist at a cellular biology lab at the University of California, San Francisco. Echoing Firestein, he told me, "There's no ionizing radiation—a signal that's sufficiently high-energy to cause electrons to detach from atoms—coming out of your brain or your voice that is powerful enough to break chemical bonds in the water."

Lord, whose specialty is microscopy, explained that even an electron microscope couldn't capture a water molecule in the first place. That requires femtosecond spectroscopy, laser technology that produces flashes of light in femtoseconds. A femtosecond is one quadrillionth of a second. Egyptian scientist Ahmed Zewali was awarded the Nobel Prize for Chemistry in 1999 for developing the technology. With femtosecond spectroscopy, scientists can see that water molecules don't settle into anything like a crystal structure. The bond that unites the atoms hydrogen and oxygen into a water molecule lives for less than a couple picoseconds. A picosecond is one trillionth of a second.

"At room temperature, there's so much energy bouncing those water molecules around that within picoseconds, any structure that existed is gone," Lord said. "Not only is there no evidence of water memory in practical, everyday life, when you get down to the molecular level and observe any structure that might exist, it's transient, it's gone within a picosecond."

Of course, toxins exist in water, and scientists over generations have developed technologies to remove them. "One way is 'reverse osmosis,' which is just a fancy way of saying pushing water through a very fine filter," Lord said. "The water molecules go through pores while other molecules including viruses, bacteria, and lead, get trapped. Another method is adding a tiny bit of bleach to water, which kills bacteria and viruses. Bleach and ultraviolet treatments break apart organic molecules into things that are smaller and not harmful."

Lord knew, as McIntyre's studies have shown, that a scientific explanation on its own won't likely change the mind of somebody who believes good vibes can strip toxins from water.

"I know, though, if I'm going to take a scoop of water out of a scummy pond," Lord said, "I'm going to want to either physically remove the contaminants, the viruses and bacteria, with a filter; chemically inactivate them with bleach; or inactivate them with high-energy electromagnetic radiation. Those methods have been proven to purify water. I would ask someone who believes saying nice things to water, or praying to it, can remove its toxins: 'How confident are you in that belief? Would you be satisfied if your municipal water was treated in that fashion?' "

Finally, I contacted Kenneth Libbrecht, a professor of physics at California Institute of Technology, an expert in the "physical dynamics of ice crystal growth," to cite the name of one of his papers. I asked him if he might say a word or two about healing crystals. He responded, politely, not so much. But Libbrecht was familiar with Emoto. Some years back he posted on his personal website, SnowCrystals.com, a riff about Emoto's claims that ice crystals took shape from people's thoughts or music.

Everything in science is testable and based on statistically quantified evidence.

"While I try to keep an open mind to new ideas, this one is just too outrageous," Libbrecht wrote. "As we liked to say back on the farm in North Dakota—it's good to have an open mind, but not so open that your brains fall out."

MCINTYRE, THE PHILOSOPHER OF SCIENCE who has studied pseudoscience and science denialism, told me he didn't follow tennis and knew little about Djokovic, other than what he had read in the news about his refusal to be vaccinated. But from my discussions with McIntyre and his books, I could see Djokovic fit the profile of many who sing the healing songs of water crystals.

About a decade ago, the term "conspirituality," a portmanteau of conspiracy and spirituality, started making the rounds. It's an apt way to describe a worldview in the land where crystal healing is credible. It goes something like this: To protect its profits, the medical industry has conspired to squelch the evolution of consciousness and the new paradigm of global awareness about natural paths to healing and wellness. Scratch someone who believes in pseudoscience, McIntyre said, "and chances are you'll find a conspiracy theorist."

Invariably, McIntyre added, "conspiritualists" aren't necessarily against traditional science. Indeed, in *Serve to Win*, as Djokovic admonishes his readers to be skeptical of Western doctors and keep an open mind to alternative therapies, he admits, "Don't think for a second that I'm knocking Western medicine—trust me, if I blow out my knee and need surgery to reconstruct it, you can bet I'll be seeking out the best Western doctor I can find."

McIntyre has heard that kind of remark often. He calls those who make it "cafeteria skeptics." "They go through science and say, 'Oh, I'll take a little bit of this, a little bit of that. No, I won't take any of that,' " he said. "They actually trust science, just not the kind of science they prefer not to believe in." Flat Earthers don't acknowledge that signals from the cell phone in their pockets bounce off satellites circling the globe. The person dying in a hospital from Covid, who regrets not being vaccinated, is practically a daily reminder in the news of the tragedy of cafeteria skepticism, of not believing in a product of science that may have saved their life.

A library of psychology books and science papers exist on why people believe in conspiracies and pseudoscience like crystal healing in the face of contradictory scientific evidence. McIntyre has studied many of the most recent ones and while he's not a psychologist, and couldn't neatly summarize the research, he told me, the one quality that stands out to him is people's fragile sense of identity and "willingness to protect it at any cost." That insight pierced him at a Flat Earth convention he attended. As he thought about the speakers and the people he met, he writes, "I concluded that perhaps Flat Earth wasn't so much a belief that someone would accept or reject on the basis of experimental evidence, but instead an *identity*. It could give purpose to your life. It created an instant community, bound together by common persecution. And perhaps it could explain some of the trauma and other difficulties you might have experienced in life, as the elites in power were all corrupt and plotting against you."

Cafeteria skeptics go through science and say, "Oh, I'll take a little bit of this, a little bit of that."

From the trauma of war in his early life, Djokovic fulfilled his dream of being the best tennis player on the planet, an astounding achievement. He found inspiration on the margins of medical science and used his fame to exclaim how he got to the top of his world and how we might get to the top of ours. With his identity anchored in alternative-medicine land, does Djokovic associate having to get vaccinated himself with the authority and manipulation that haunted him as a kid? Other tennis tournaments have announced players must be vaccinated. No vax, no play. Will Djokovic get vaccinated? I hope so. As a fan, I love to watch him play. But I also hope he will live up to the community values of his philanthropy, especially now.

In his new book, *After Lockdown*, the French philosopher Bruno Latour writes that being cooped up during the pandemic curtailed our freedom, but it also freed us from thinking we're inherently alone, forever seeking transcendence. He writes "that we couldn't long survive without a whole host of jobs of which we had till then, we must admit, only a fairly vague awareness: catering jobs, deliverers, carriers, not to mention nurses, ambulance drivers, and 'carers,' a whole tribe of people as poorly paid as they were poorly viewed." That's such a beautiful insight. As Latour writes, "it's enough to make you wonder if the expression 'global awareness,' which was pretty empty till now, hadn't started becoming meaningful."

My trip into Pseudoscience Land left me feeling pretty empty. It's a made-up reality redolent of so much distress across the globe right now.

My dip in the healing crystal waters felt no different than sinking into the swamp of politics where influential people say anything to support and defend their identities. The beauty of science and its power to redeem is not just about producing safe and effective vaccines or sending telescopes into space to unravel the mysteries of the universe and our origins. Science teaches us to face reality—which is more extraordinary than is dreamed of in pseudoscience philosophies—and see that we are inextricably connected to others, for their health and ours. You can't play tennis alone.

KEVIN BERGER is the editor of *Nautilus*.

My Dad Once Told Me the World Was 100 Years Old

His teasing provoked me to understand the origins of time

BY SUBODH PATIL

ART FURNACE / SHUTTERSTOCK

HOW FAR DOES TIME go back? It's a simple enough question that a child could have the temerity to ask. Any attempt at a meaningful answer, however, leads us headfirst into the limits of understanding what time even is. At the most solipsistic level, it only goes as far back as our earliest memories. Before that, the starting point of our sentience appears to be shrouded in oblivion, or perhaps a fragmented haze of impressions. At the most objective level, this may not be such an inaccurate metaphor, at least according to our current understanding of what might appear to be the "beginning" of the universe, the point at which the very notion of a continuum spacetime breaks down.

I must have been around 5 years old when I made the mistake of asking my dad about history. What was the world like when he was born? What about 20, or 50 years before that? By then, my old man had developed the habit of messing with me for his own amusement. So when I got around to asking him about what the world was like 100 years ago—a number that, to my sapling mind, was about as close to infinity as I could conceive—he playfully dismissed me by telling me that there was no history back then. Time only went back 100 years, he declared. I don't remember the exact nature of my reaction to this fiat, but kicks and screams were involved, very likely aggravated by his giggling. I still wonder to this day whether my dad was just being a jerk, or whether this was his way of planting the seeds that eventually provoked me into becoming a theoretical physicist.

The true nature of the beginning of time is a question that many ancient traditions, including that of the culture I was born into, Hinduism, seem at first glance to evade—by putting time on a circle. The writings of the historian and philosopher John Gray first alerted me to the idea that Abrahamic thought might have revolutionized the historiography of time, by putting it on a line. In doing so, one is immediately forced to confront questions and imperatives that may not occur, or be dismissed by those that posited a cyclicity to time, questions such as: When and how did it begin? If time has a beginning, does it have an end? Although the object of Gray's critique was the implicitly millenarian subtext to post-Enlightenment notions of progress,[1] the broader implications of his assertion were not easy for the likes of me to digest.

In spite of the remarkable, though often overlooked, and sometimes co-opted, contributions to knowledge multiple intellectual traditions outside the Abrahamic fold have made, it was in those that we find sustained, if flawed, inquiries into a peculiar possibility: that time had its origin in a moment of creation. As a detail in the annals of science, it might therefore come as a bit *too* on the nose that the first mind to have mathematically derived a beginning to the universe, as a consequence of Einstein's theory of General Relativity, was an ordained Catholic priest.

There may be certain questions that will remain forever beyond our reach from our vantage point.

Georges Lemaître, who also happened to be a professor of physics, independently arrived at a solution to Einstein's theory (first written down by the Russian mathematician Alexander Friedmann several years before). The solution described a universe filled with matter or radiation, with no fixed center nor preferred direction, that had its origin in a "primeval atom."[2] In doing so, Lemaître accounted for Edwin Hubble's startling discovery, a few years earlier, that distant galaxies in the night sky were receding from us in an ordered manner, the only implication of which could be that the universe was expanding.

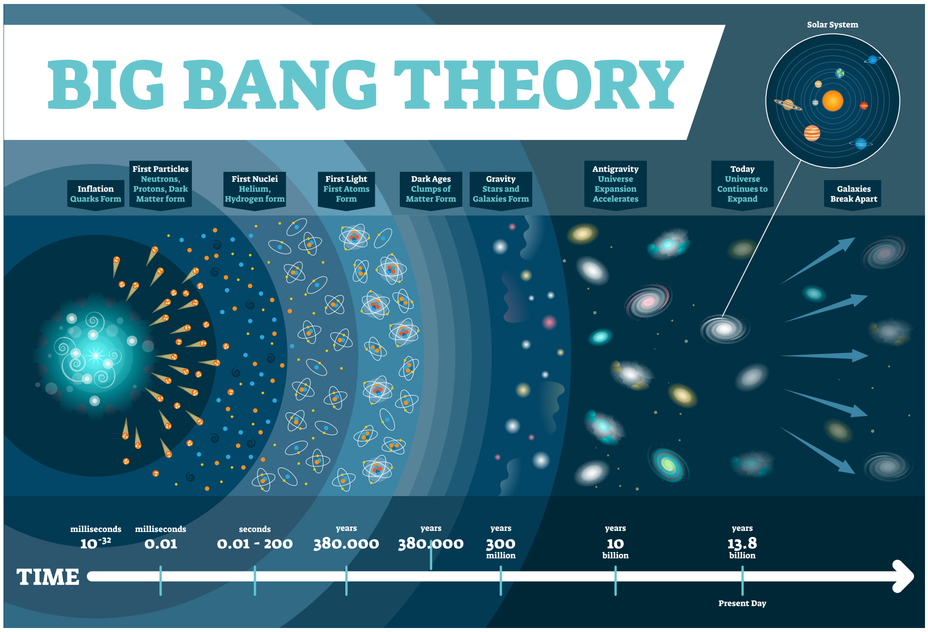
The Big Bang, as Friedman and Lemaître's solution came to be known, is the cornerstone of modern cosmology, most notable for the fact that it is an incomplete account. It raises as many questions as it answers, the most obvious one being: How did the Big Bang itself come about in the first place as the dense, thermalized, rapidly expanding, yet almost uniform fireball that was Lemaître's primeval atom? Moreover, the primordial plasma came seeded with microscopic fluctuations, which went on to collapse under their own gravity once the universe cooled enough, and in doing so, condensed into the weblike scaffolding around which all the galaxies we observe eventually formed. Where did these seed perturbations come from?

It is widely accepted today that these seeds are none other than microscopic quantum fluctuations—ripples set up by some dynamical process that preceded the Big Bang. Perhaps this process was a phase of primordial inflation, in which the Big Bang was the terminal, explosive release of energy stored in some as yet unknown field which set up the initial conditions for the Big Bang. Perhaps the universe periodically expanded and contracted in a series of cycles, with a bang at the culmination of each cycle. Perhaps it was neither. We may, given our intrinsically limited observations, be merely accessing a partial projection of the underlying reality, one we interpret through the theories currently at our disposal, perhaps not unlike that of the ancient astronomer Ptolemy, whose geocentric interpretations of the movements of planets and stars were once prevalent in Europe.

Being a cosmologist is not unlike being an archaeologist. You're trying to reconstruct what might have happened in the distant past using the laws of physics and whatever evidence history has been kind enough to leave behind, obscured by layers of galactic dust and various other detritus through which we're trying to peer. The evidence is in the form of surveys of distant galaxies and quasars, themselves a tracer of an underlying web of clustered dark matter, and maps of the relic microwave radiation left over from the Big Bang. In the near future cosmologists aim to also observe the relic bath of cosmic neutrinos, the faint radiation emitted from clouds of neutral hydrogen that made up most of the universe before stars had formed, and, of course, the gravitational waves that could have traveled unimpeded to us from the Big Bang.

It is a tantalizing prospect that young people alive today could live to see the day when most if not all gravitationally bound structures within our cosmic horizon, whether they shine light at us or not, be mapped in totality. Like the surface of the Earth, our cosmic horizon is an ever expanding but finite volume, after all. A remarkably accurate picture has emerged over decades of observations that indicate the consistency of the predictions of a hot Big Bang seeded with microscopic, almost scale-free fluctuations, and a universe made up mostly of dark matter and an as yet undetermined yet energetically significant component that imbues

ON REPEAT
It's possible that the universe undergoes periodic cycles of creation and destruction, rendering the very question of its origin moot. But there's a chance that we may find out either way within a human lifetime.



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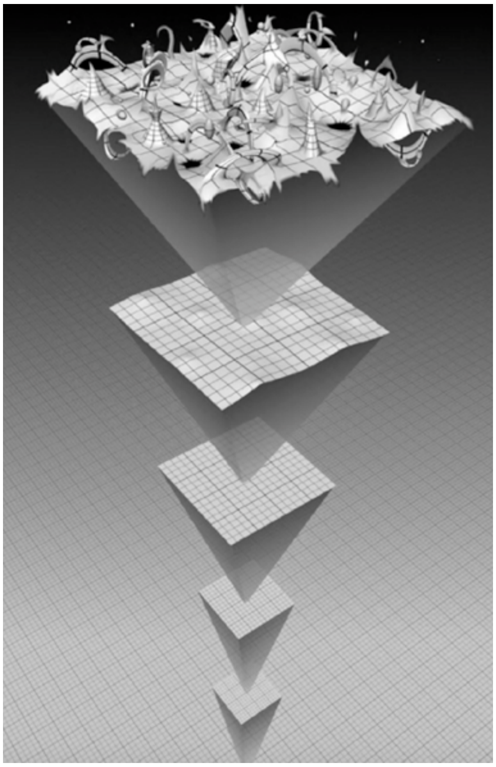
spacetime with an "anti-elasticity," causing its expansion rate to accelerate, referred to as dark energy.

As cosmic archaeologists, we are limited by the historical contingencies that place us exactly where we are, as we are. If, for instance, the earliest stars shone much more brightly, evidence for the initial seed fluctuations in the Big Bang that imprinted themselves as tiny temperature variations in the cosmic microwave background would have been erased, and our task of inferring the initial conditions of the Big Bang would have been made much more difficult. Our coming into existence as sentient observers occurred at a very particular moment in cosmic history. What an observer might conclude from their observations in another epoch might be very different depending on when they are.

This is dramatically illustrated by a simple thought experiment. Let's assume for the sake of argument that our current cosmological model is in fact correct, that our inference is spot on, and that we have not been deceived by the assumptions that go into them—a prospect that I've never been able to completely shake. In this very universe that humans managed to glimpse around 13.8 billion years after the Big Bang, in the far future, say a trillion years from now, what would a sentient observer located in our galaxy conclude?

For starters, our nearest galactic neighbor, the Andromeda galaxy, and the Milky Way will have merged into a single galaxy—Milkomeda. All other galaxies beyond our immediate galactic neighborhood would have accelerated beyond our cosmic horizon. The relic radiation from the Big Bang would have a wavelength larger than our horizon, and so impossible to detect. An observer a trillion years from now, looking up from the galactic plane of Milkomeda, would see an empty universe in which they were the center, and probably declare that to be that. Their universe always was, always will be, unchanging. This observer could only infer a time without boundary in the infinite past and the infinite future, and be justified in their narcissism in concluding that they are at the center of it all.

Fortunately, we are not this future observer, and are in a relatively privileged position among all the cosmic archaeologists that might ever exist. Although we ourselves have our own limits in what we can infer given our location in history. Frustratingly, there may be certain questions that will remain forever beyond our reach from our vantage point. It could be, for instance, that the dust and detritus within our galaxy—foregrounds as they're technically known—might fatally obscure our attempts to map the structure of the universe before stars even had a chance to form. Or, it could be that whatever preceded the Big Bang itself had an epoch preceding it, as did that epoch, and so on. Even if this process doesn't regress infinitely, any information from the initial state of the universe will have been recycled through and possibly overwritten by multiple cycles of cosmic cataclysm.



IT'S FROTHY DOWN THERE Although spacetime might appear continuous at large enough distances, once you zoom in far enough, it starts to resemble more of a froth that is continually dissolving and reforming.

As a species, however, we are nothing if not stubbornly determined and enterprising in our right to continue asking questions, and there are possibilities that may yet offer a glimpse further back than any probe available to us at present. Gravitational waves for instance, unlike electromagnetic waves, are barely obscured by intervening structures and clumps of matter, and so may yet offer us a metaphorical X-ray into the very first moments. There may come a time in the not too distant future where we can peer directly into the Big Bang using futuristic gravitational wave detectors that are sensitive to a wide range of frequencies, possibly even probing for what might have preceded it.

It's natural to wonder whether we'll ever be able to answer the questions for which we seek answers to the degree of certitude proffered by our more commonly venerated creation myths. Whether the chain of explanation of scientific inquiry ever reaches an end, or whether it's turtles all the way down. Fortunately, or unfortunately depending on your predisposition, there is an ultimate veil of ignorance beyond which cosmologists are absolved of any further responsibility, where the inquiry into the origins of space and time disintegrates into meaninglessness. That is to say, when the very framework within which we're even able to frame such questions breaks down.

This is in the regime where notions of continuum geometry—the idea that space and time are infinitely divisible—stops making sense. The arena in which things happen starts to instead resemble a violent magma, possibly fractal in nature—a quantum foam, first anticipated by John Wheeler in the 1950s. That is, instead of an infinitely divisible continuum, spacetime begins to resemble something more like a continuously bubbling and reforming froth. That this is the true nature of spacetime at the most fundamental scale, and that the continuum geometry that we're familiar with is *emergent* at larger scales, is something that multiple independent and complementary approaches to quantum gravity have arrived at. These approaches go by various different names, such as string theory, loop quantum gravity, causal dynamical triangulations, among others, but can also be understood on rather general grounds.

That there is very likely a smallest-possible scale below which space and time themselves break down is one of the more jarring consequences of attempts to make quantum mechanics and gravity sit together within a self-consistent framework. Below the Planck length, a resolution of about 10^{-35} meters—or between intervals shorter than the amount of time it would take light to traverse this distance, or about 10^{-43} seconds

There may come a time in the not too distant future where we can peer directly into the Big Bang.

(known as the Planck time)—there is no meaningfully definable geometry or topology to spacetime. These are the scales at which the physics responsible for the ultimate origin of the universe operates at. To understand this, one only needs to invoke Heisenberg's uncertainty principle in the presence of gravity.

According to the uncertainty principle, were we to localize a point in spacetime with finer and finer precision, we become more and more uncertain of the momentum or energy within it. Any attempt to probe spacetime beyond the Planck scale will result in quantum fluctuations with so much energy localized within that region, that it can spontaneously collapse into a black hole, and will break off from geometry as a spacetime singularity (geometry itself, let alone the notion of a point, loses all meaning at the Planck scale). Only to evaporate again in the smallest resolvable instant. Any observer at that scale would be adrift in a froth of creation and destruction, where moments and islands of space appear and disappear at every instant.

The usual continuum nature of spacetime emerges at macroscopic distances from this chaotic, nongeometric, microscopic reality as an averaged effect, much like the illusion of solidity of everyday objects. These are in fact constituted entirely of fundamental particles of no resolvable spatial extent, stacked in highly energetic configurations that manifest as nucleons and atoms at larger length scales. From this, we can appreciate the category error inherent in even asking whether time had a beginning or not, as it turns out to be just as meaningless as the question of where the edge of the Earth is.

It's entirely possible that we may never get to confront this ultimate veil of ignorance given our place in time. If, as is widely accepted, an epoch of primordial inflation was the origin of what looked like a Big Bang in our past, it's entirely possible that the universe at its largest scales consists of multiple, self-reproducing regions,[3] each with their own cosmic horizons, unaware of the other. By peering back at what might look like the Big Bang to them, any observer in this multiverse would merely be looking back at their nucleation—not unlike a bubble nucleating in a pot of boiling water—in their branch of a much bigger universe whose ultimate origin might never fully be revealed to them. It's also possible that the universe undergoes periodic cycles of creation and destruction, rendering the very question of its origin moot.

The remarkable thing is that, in my view, there's a chance that we may find out either way within a human lifetime. I happen to be in a minority among cosmologists in being uneasy with how much our current understanding seems to flatter our partial theoretical understanding of physics at very high energies, close to the initial moment, where quantum gravitational effects can become important. I'm unsure whether we're justified in extrapolating our spectacular success in decoding the initial conditions of the thermal Big Bang with our limited observations to necessarily taking for granted that a phase of inflation preceded it. I'm constantly mindful of the paradigm of inflationary cosmology being the butt of a cautionary anecdote by future historians and sociologists of science. The remarkable and invigorating thing is that none of my doubts matter. Cosmologists are nowhere near being done yet with banging their heads against hard questions, and I'm thoroughly energized by the prospect of having these doubts dispelled in my lifetime.

As to whether I'm any closer to losing my wariness of being mocked, as my old man once did to me, for the naivete of my questions, I'm still not so sure. A form of occupational imposter syndrome, perhaps, that lingers, yet anchors me.

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My Out-of-Body Experience

In a sensory deprivation tank, I lost my body and found myself

BY JOEL FROHLICH

T**WO YEARS AGO**, I decided to do nothing. Not for the rest of my life, of course—for two hours. As a neuroscientist, I was already familiar with the evidence that mindfulness meditation, or attending to the present moment, is beneficial for stress and anxiety. So I had been meditating regularly for about half a year, looking to enhance my practice. And although I didn't know it yet, there were already scientific studies showing that the more extreme form of "doing nothing" that I was now interested in—floating in a sensory reduction tank—could significantly reduce stress, blood pressure, and cortisol levels.

And so it was my plan, in the first week of March 2020, on what would become the eve of the COVID-19 pandemic lockdowns, to enter a commercial float studio in West Los Angeles, called Float Lab. It's down the road from UCLA, where I worked studying consciousness in a neuroscience lab. Naturally, I was curious: Some neuroscientists use float setups with their clinical populations to investigate how a stimulus-free environment might affect experiences of negative emotions, like anxiety, and positive emotions, like serenity. My wife was skeptical: Would I really be able to last that long? Wouldn't the utter nothingness freak me out, or bore me to death? Didn't I want to try "sort of nothing" first—an easier experience, such as dining in the dark?

No, I wanted to truly do nothing. Or at least as little as possible. At Float Lab, on the first of many visits, I was led to one of several private cabins, carefully designed for doing nothing. Each cabin is a rectangular tank filled with highly saline water. I showered in a private room and entered the float unclothed to minimize tactile sensations. Saturated with Epsom salt, the high density of the water allowed me to float effortlessly without muscle tension. The water was as warm as my skin. It was pitch dark and silent. Nothing.

Except that there was something.

My mind, filled with the sensations of breathing, heartbeat, and, of course, thoughts. The float tank is like the cave on Dagobah that Luke Skywalker explores in *The Empire Strikes Back*. "What's in there?" Luke asks Yoda. "Only what you take with you," Yoda answers.

But surrounded by nothingness, my relationship to these sensations changed. Without any cues to determine my bodily position, small inhalations that increased my buoyancy generated an incredible feeling of ascending upward, as though I were being beamed up into a UFO mothership. Similarly, small exhalations that reduced my buoyancy generated an equally incredible sensation of descending downward into an abyss. In later sessions, I had even stranger experiences. Without a sense of any external world around me, the boundary between self and surroundings seemed to blur—my body filled in that void and became the external world, and I was now turned inside out. During my second session I—or "I"—felt all but dissolved in the water, with no body to speak of. In another session, I felt I could fly out of my head. Floating in the tank also changed my perception of my thoughts. On a few occasions, my thoughts lost something like credibility or legitimacy. I observed them as mere illusions—not descriptions of the way things are but, rather, vocalizations in my mind's ear.

All you have in the tank is your mind.

In the past several years, researchers led by Justin Feinstein at the Laureate Institute for Brain Research in Tulsa, Oklahoma, have investigated the effects of experiences like these using both behavioral and neuroimaging approaches. Researchers generally refer to floating as Floatation-REST, an acronym for reduced environmental stimulation therapy. Feinstein's team uses a float tank custom-built for clinical populations prone to anxiety. To accommodate these patients, the tank lacks an enclosure—instead, it's an open fiberglass pool housed in a light- and sound-proof room. This setup not only reduces the risk of claustrophobia, but also uses hand-wave-activated lighting, allowing any participant to immediately stop the experience for any reason.

In one experiment from 2018, Feinstein and his colleagues studied patients with anxiety and compared their self-reported ratings of internal sensations during a 90-minute float session to a control condition where the same patients instead watched a nature documentary from the BBC *Planet Earth* series.[1] The researchers found that floating significantly increased the perceived intensity of cardiorespiratory sensations, such as one's breathing and heartbeat, relative to the control condition, while also enhancing the pleasantness of these sensations and the amount of attention participants paid toward them. This finding was made all the more remarkable by the fact that all participants in the study had a special form of anxiety triggered by noticing internal bodily sensations, such as a racing heart, which they often interpreted as the beginning of a panic attack. Despite this, these often-frightening visceral feelings actually became pleasant for the patients during their float sessions, likely due to a new association formed in the tank between feeling their bodies and experiencing deep relaxation.

In an experiment from last year, Feinstein and others recruited healthy participants and used functional magnetic resonance imaging (fMRI) to scan their brains before and after a series of three sensory reduction sessions.[2] In one condition, the participants experienced sensory reduction in the float tank, while in another condition, a different group of participants experienced sensory reduction in a fully reclinable chair built to diminish the feeling of gravity. In both sensory reduction conditions, the researchers found similar decreases in functional brain connectivity, or statistical dependencies between brain activation across different anatomical regions (think about areas of the brain that seem to "light up" together in a brain scan).

In the Floatation-REST condition, however, the researchers observed even weaker connectivity within the default mode network, a brain network involved in both mind-wandering and generating one's sense of self. In fact, the alterations induced within the default mode network by floating are similar to those induced by meditation[3] and psychedelics,[4] which, like floating,[5] have demonstrated therapeutic potential for treating anxiety and depression. Moreover, a stronger disconnection between the default mode network and a different brain network involved in bodily representation was also found in the float condition relative to the chair condition, potentially explaining the out-of-body experiences that are occasionally reported in the tank by me and others.[5]

Float tank therapy simultaneously allows one to become more aware of one's body while also feeling more detached from it. If this feels like a paradox, that's partially because, like many experiences that might be described as "spiritual," it's difficult to understand it fully unless you've felt it for yourself. Like meditation, Floatation-REST likely trains the practice of mindfulness, or nonjudgmental awareness of the present moment. Both practices may enhance awareness of the body while also altering or weakening one's sense of self and, thus, one's sense of bodily ownership. Yet unlike meditation, which typically involves explicit instructions and many hours of practice, Floatation-REST might work quickly with minimal instructions. Just float in the darkness and let the rest happen naturally.

The mindfulness hypothesis gets at the ultimate question of how and why Floatation-REST works. If

I felt I could fly out of my head.

you've never stepped in a float tank, it probably feels strange to imagine that sensory deprivation can be relaxing. (Indeed, investigators at the Laureate Institute for Brain Research find "sensory deprivation" misleading and avoid using the term given the connotations of madness and torture that accompany it.) In my first float experience, when my bladder eventually ended the session, I felt confident that only about half of my total time had elapsed. But when I stepped out and looked at the clock, my time was already up—a full two hours had nearly passed in the tank. What I'd worried might be a long and grueling session had flown by almost effortlessly. In fact, rather than feeling exhausted from a lengthy ordeal, I felt absolutely glowing as I stepped out of the tank and into the shower. My body was deeply relaxed, and every sensation I experienced after exiting the tank felt somehow enhanced and easier to appreciate. Perhaps floating really is a form of sensory *enhancement*, rather than deprivation.

After leaving Float Lab, I took in the hustle and bustle of Los Angeles with a level of equanimity and patience hitherto unknown to me. I viewed each person as a human being with an interesting story waiting to be told.

All you have in the tank is your mind. And there might be no better way to get to know your mind than by spending an hour or two in the tank. My first float experience helped me realize that I actually find the opposite of utter darkness and silence—sensory overload—to be far more difficult to tolerate. Harsh, constant lighting and prolonged exposure to loud music has been used by the United States and other countries as an interrogation technique—a form of sensory bombardment as torture. And as someone who gets easily put on edge by annoying pop music in grocery stores, I'd far rather spend many hours in darkness and silence than be helplessly forced to listen to loud and repetitive Billboard Top 40 songs ad infinitum.

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KJETIL KOLBJORNSRUD / SHUTTERSTOCK

The Wild World of Threats

Animals, including us, evolved to bluster and bluff at their peril

BY DAVID P. BARASH

YOU'RE CONFRONTING A SPIDER, up close, womano-a-womano. The tiny creature rears back on its hindmost legs and assumes a threatening posture, ridiculous given that you could easily squash it with your shoe. Yet everyone understands the gesture, even though to locate the most recent common ancestor shared by the two of you, you'd have to go back roughly half a billion years. The basic language of threat is nearly as old as that other basic language, DNA. Threats between living things have long been grist for the evolutionary mill. And human beings aren't immune.

As I write this, Russia's Vladimir Putin is threatening to invade Ukraine. He sees Ukraine as a threat to his power and country were it to join NATO. Ukraine, NATO, and the United States are responding with counterthreats. For all we know, the threats are real; certainly, none is ridiculous. The consequences are immense, with war in the balance.

A threat, as I consider it here, involves an effort at deterrence, communicating that if someone does something that the threatener seeks to prevent, the consequences—typically some form of retaliation—will be sufficiently aversive to prevent the potential perpetrator from perpetrating in the first place. Living things are typically equipped with a range of intimidating options, not just baring teeth and claws, but also displaying horns, antlers, poison fangs, bony shields, uttering scary hisses and formidable roars, puffing body up, flattening ears down, rattling, hissing, spitting, screaming, flapping wings, staring unwaveringly, even sometimes becoming weirdly quiet.

Things get interesting when threat-purveyors exaggerate their capabilities, leading recipients, on occasion, to call their bluff, which in turn results in the threatener trying to maintain credibility while the target seeks to determine whether the threat is genuine. Most people wouldn't take a spider's threat seriously, but it's a different story for another spider, or a would-be spider predator, who might well be uncertain what to do next. Believe the threat or see through it?

When threatening another animal, standard procedure is for threateners to make themselves seem larger, more dangerous, imposing, stronger, healthier, more experienced, and more motivated than they really are, all in the service of avoiding actual combat while preventing an opponent from taking their food, nest site, mate, or, quite simply from attacking. For the threat to work, the threatener must signal that it has weapons and is willing to use them. Even if neither is true. Talk is cheap, certainly cheaper than fighting, so getting your way via a threat is often a good deal.

It's fine to speak softly and carry a big stick, but if your stick is small, why not speak loudly anyhow, and hope that will work? Animals no less than people often do just that, bluffing and blustering and threatening to blow the other guy's house down. One might expect no limit to the aggressive braggadocio out there in the natural world; the payoff to exaggerated threat-making can be great, while the costs appear small.

But the costs could be high—notably if your bluff is called. When a threat is "honest," that is, backed up with inclination and ability to meet a push with a shove, there is little payoff to calling a threatener's bluff. But the more widespread and the more "dishonest" the bluffing, the greater the temptation to question its legitimacy. Honesty, we like to think, is the best policy. Natural born liars, in the biological world, must confront a practical problem that is often shared with their human counterparts: Deceivers run the risk of being tripped up in their dishonesty, especially if their bluff is called. The key is credibility, or rather, the problem of achieving it.

Animals with effective weapons that can intimidate their rivals are not shy about calling attention to their armament, which often carry what biologists call a "reliability component"—characteristics that are impossible to fake—baked into the structure of the weapons themselves. Their threats are likely to be credible and effective.

A small elk or deer cannot successfully pretend to be big. American elk and Scottish red deer rely on their large body size and massive antlers to get their way, especially when it comes to competition between bulls. They frequently engage in "parallel walking," during which opponents strut their bodily stuff, notably their impressive headgear. When successful, such demonstrations result in the more physically intimidating animal winning without having to fight. Lions have huge canines, not only for killing their prey but also for threatening other lions. They are notably silent when stalking zebras, reserving their impressive roar—along with showing off their magnificent dentition—to discourage other lions from invading their pride. Poisonous snakes with impressive fangs reveal their unique weapons when needed, in the most intimidating way they can. Bighorn sheep call attention to their big horns. If you've got it, flaunt it.

"GETTING IT," THOUGH, is expensive. Whatever the advantages of having strength to flaunt, it is nearly always costly to obtain it. In a 1953 speech, President Dwight Eisenhower noted, "Every gun that is made, every warship launched, every rocket fired signifies, in

Bertrand Russell likened the U.S. and the Soviet Union to battling scorpions, which may have been unfair to scorpions.

the final sense, a theft from those who hunger and are not fed, those who are cold and are not clothed. This world in arms is not spending money alone. It is spending the sweat of its laborers, the genius of its scientists, the hopes of its children." Something similar applies to animals and their "arms."

Male fiddler crabs have the largest weapons per body size of any animal; fully one-half of a male fiddler's energy budget is expended in growing their comparatively huge fiddles. Even after they have been produced, these structures impose a resting metabolic rate on their possessors that is 20 percent higher than that of females (which don't have enlarged claws), simply because of the cost of maintaining so much additional muscle. This doesn't count the expense of vigorously waving those appendages, as well as added demands when it comes to running with them—especially from predators, something that might well be particularly mandated for male crabs (and to a lesser extent, lobsters), whose oversized claws make their possessors especially desirable prey items because of all that expensive muscle meat inside.

The costliness of animal armaments—used more often to threaten than to fight—is not limited to invertebrates. The antlers of male caribou can be 5 feet or more in length and weigh more than 20 pounds; moose, 6.5 feet and 40 pounds. Balanced at the top of the animal's head and at the end of a long neck, the encumbering weight of these structures is increased by their levering effect. Beyond the stress of walking, running, and displaying them, there is also the cost of growing such devices, estimated at five times the energy requirement of merely keeping the body going. If this isn't troublesome enough, the demands for calcium and phosphorus to produce massive antlers necessitate that a mature bull elk or moose depletes the mineral content of his bones, resulting in a kind of seasonal osteoporosis, causing brittleness, and rendering males susceptible to life-threatening fractures.

When it comes to the tension between honest and dishonest threats among animals, the best studied examples come from snapping and mantis shrimp. Pound for pound—more accurately, gram for gram—they are among the most heavily armed of all animals. Their "raptorial appendages" consist of either weaponized clubs that have immense striking power, capable of breaking mollusk shells, or strong and sharp forelimbs used to catch and pierce prey; the former species are sometimes known as "smashers" and the latter, "snappers." Either weapon type can readily injure or even kill same-species opponents. Not surprisingly, these are conspicuously brandished during aggressive threats.

The largest of these appendages, called "meri," are part of a male's armamentarium and are directed toward other males as part of an aggressive signal called a "meral spread." These displays are especially pronounced and important when competing for a particularly cherished resource: dwelling cavities in rock or coral. Meral spreads by a resident mantis shrimp make the threatening individual less liable to be attacked and increase the probability that an intruder will back off.

However, these crustaceans molt regularly; when they emerge from their discarded carapace their bodies are soft and vulnerable, so they cannot withstand even light blows from opponents. Moreover, in their unprotected state, they are also unable to initiate an effective attack. In fact, the odd times when freshly molted individuals attempt to strike, they injure themselves instead of their opponent. Nonetheless, they display, although because a freshly molted individual cannot effectively back up its display with an actual attack, it's all bluff.

WORLDCLASSPHOTO / SHUTTERSTOCK

HEAVY ARMOR Pound for pound—more accurately, gram for gram—the mantis shrimp is among the most heavily armed of all animals.

Biologists, notably Roy Caldwell of the University of California, Berkeley, set up a series of clever experiments to test the role of bluff vs. honesty among these animals. The researchers gave newly molted and thus vulnerable individuals ownership of highly desired rock cavities in the laboratory. Hard-shelled individuals were then introduced. The well-armored newcomers sought access to the already-occupied cavities. In most cases, the freshly molted residents promptly gave up their real estate, although some first engaged in threat display—they tried bluffing before retreating. The experiment's control group—cavity owners who were between molts and thus as physically competent as the intruders—had no need to bluff. They responded to trespassers by physically attacking them, with just a few giving a meral display only.

By contrast, among those helpless, newly molted cavity residents who resisted the newcomers, the proportions were almost exactly reversed; a tiny few used a meral threat display and lunged aggressively at the intruders, but then promptly gave up when it was unavailing. Evidently, those that can defend their turf do so. Those that can't, act as though they can; they threaten. And then leave.

As W.C. Fields is alleged to have recommended, "If at first you don't succeed, try, try again. If you still don't succeed, give up. No sense being a damned fool about it."

In a follow-up study, researchers varied the size of intruders versus resident owners. When they increased the body size of the recently molted (hence vulnerable) residents, the larger individuals were more likely to

JOLLY ROGER For pirates, the payoff for flying the Jolly Roger flag was large because by issuing a credible threat, they increased the likelihood that they could capture booty without having to risk a fight.

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threaten and less likely to flee. They were able to give the impression of being more intimidating because of body size discrepancy, even though the reality was that they were no more able to back up their threats. In fact, those residents who bluffed were more likely to retain their ownership than those who refrained from displaying.

In short, if you've recently molted, bluffing pays. At least in a laboratory. Among free-living individuals, if a hard-shelled inter-molt enters the cavity of a recently molted animal, the latter is often killed. So, by threatening the intruder, a vulnerable animal is taking a big risk, but also giving itself a chance of winning. In natural populations, roughly 85 percent of cavity residents who give meral spread displays are hard-shelled inter-molts, whose displays are "honest." This gives the bluffers a chance because intruders who perceive threatening messages would be well advised to believe that they are legitimately backed, not unlike a person who wisely backs away from a rattling rattlesnake.

STOMATOPOD SHRIMP AREN'T ALONE in seeking to enhance their credibility when it comes to issuing threats. Among a certain species of recently evolved primate, individuals known as pirates really did display the skull-and-crossbones, an effective way of issuing a threat that was highly credible because pirates were known to be especially violent. Moreover, their credibility was also high because if captured, the consequence—hanging—was severe. As a result, only real pirates dared to fly the Jolly Roger. But the payoff was also large because by issuing a credible threat, *Talk is cheap, certainly cheaper than fighting, so getting your way via a threat is often a good deal.*

pirates increased the likelihood that they could capture booty without having to risk a fight. In June of 1720, there were 22 merchant vessels in the harbor at Trepassey, Newfoundland, when Bartholomew Roberts, a renowned pirate, sailed in with the Jolly Roger flying. The merchant crews all panicked and abandoned their ships. Credibility pays but maintaining it can be challenging. The pirate life is not for everyone. (Nor is encountering those who have chosen that life.)

Military strategy has often involved deterrence, which in turn has struggled with the same problem of credibility as stomatopod shrimp. A distinction is often made in the human case between deterrence by denial—exemplified by the Great Wall of China, intended to persuade would-be invaders that they won't succeed—and deterrence by the threat of punishment. To be credible, the latter must often be especially vicious. Here is some hair-raising advice from Sir John Fisher, First Sea Lord, Admiral of the Fleet, and widely regarded as the most important British naval figure after Horatio Nelson. It emphasizes that deterrence by punishment is likely to be effective in proportion as the threatener has a fearsome reputation: "If you rub it in both at home and abroad that you … intend to hit your enemy in the belly and kick him when he is down and boil your prisoners in oil (if you take any), and torture his women and children, then people will keep clear of you."

Finally, there is the most prominent, current threat, which makes Admiral Fisher's recommendation seem positively benign: nuclear deterrence. Its liabilities are legion, including that it's the main justification for the nuclear arms race, is vulnerable to many kinds of failure, and that should nuclear deterrence fail, everything else does. It also struggles with credibility. "One cannot fashion a credible deterrent out of an incredible action," wrote former defense secretary Robert McNamara. Ironically, attempts to shore up this credibility by making nuclear weapons more usable via "limited nuclear war," "battlefield nuclear weapons," "launch on warning," and "counterforce targeting" have in fact threatened to succeed. In short, by increasing the credibility of the ultimate, omnicidal threat, by making nuclear weapons easier to use, these developments risk the ultimate irony: making it more likely that they will in fact be used.

Bertrand Russell likened the posture of the U.S. and the Soviet Union during the Cold War to two scorpions in a bottle, which may have been unfair to scorpions, who use their stingers to kill prey and to defend against predators, not for mutually assured destruction. Bluffs and counterbluffs, threats and counterthreats—more rarely, actual fights with victories and defeats—all these take place among nonhuman animals. In those cases, the stakes are lower than between Russia and the West over Ukraine. Whether our wisdom is any higher remains to be seen.

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Imaginary Numbers Are Reality

How the modern world arose from imaginary numbers

BY MICHAEL BROOKS

IMAGINARY NUMBERS are not imaginary at all. The truth is, they have had far more impact on our lives than anything truly imaginary ever could. Without imaginary numbers, and the vital role they played in putting electricity into homes, factories, and internet server-farms, the modern world would not exist. Students who might complain to their math teacher that there's no point in anyone learning how to use imaginary numbers would have to put down their phone, turn off their music, and pull the wires out of their broadband router. But perhaps we should start with an explanation of what an imaginary number is.

We know by now how to square a number (multiply it by itself), and we know that negative numbers make a positive number when squared; a minus times a minus is a plus, remember? So $(-2) \times (-2) = 4$. We also know that taking a square root is the inverse of squaring. So the possible square roots of 4 are 2 and −2. The imaginary number arises from asking what the square root of −4 would be.

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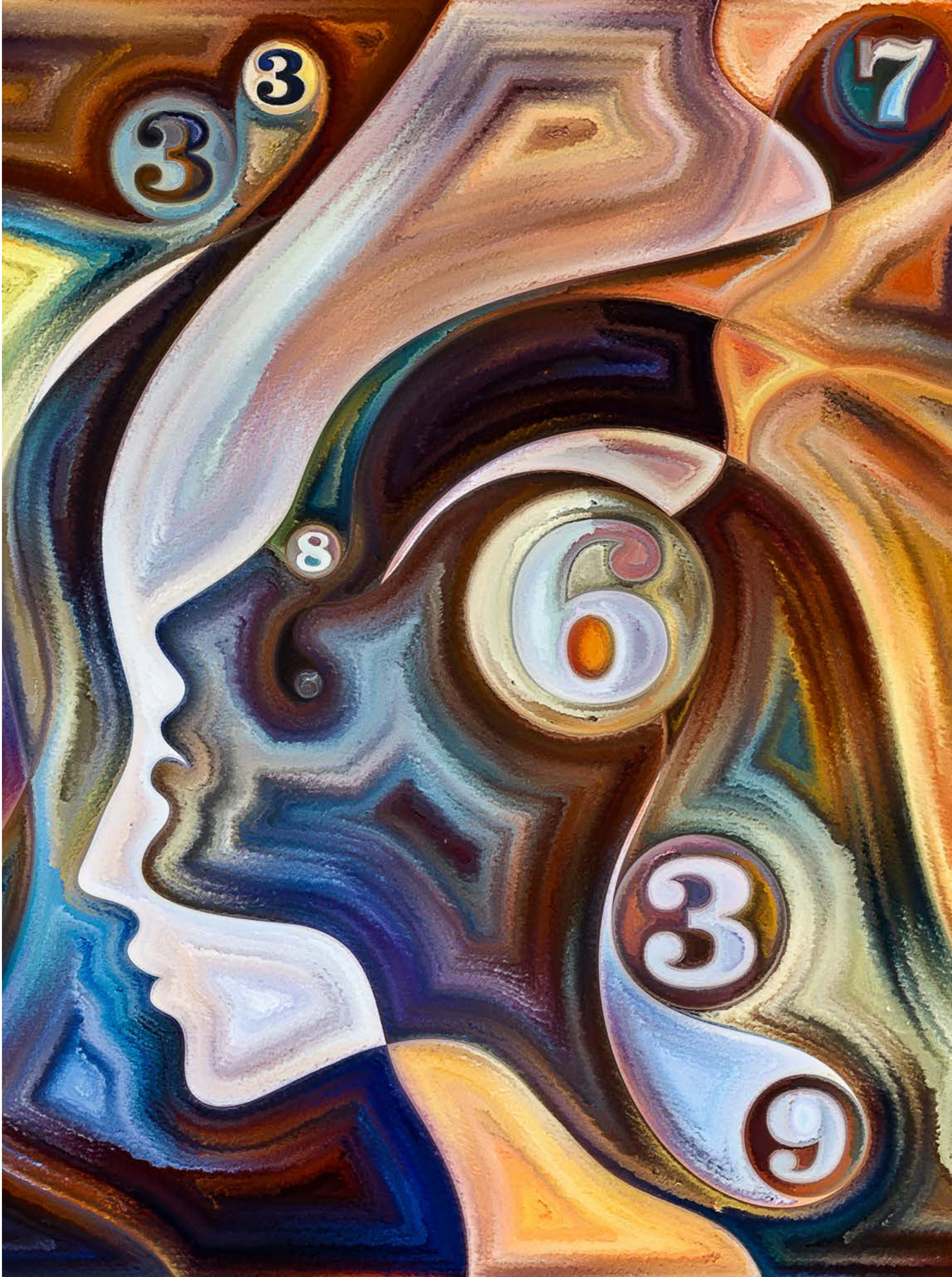
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What we're discovering here is not some deep mystery about the universe.

Surely the question is meaningless? If you square a number, whether positive or negative, the answer is positive. So you can't do the inverse operation if you start with a negative number. That's certainly what Heron of Alexandria seemed to think. Heron was the Egyptian architect whose mathematical tricks, written in *Stereometrica*, gave us the dome of the Hagia Sophia. In the same volume, he showed how to calculate the volume of a truncated square pyramid; that is, a pyramid with the top chopped off. His solution for one example involved subtracting 288 from 225 and finding the square root of the result. The result, though, is a negative number: –63. So the answer would be found via $\sqrt{-63}$.

For some reason—whether a sense that there was some mistake, or someone copied something down wrong, or because it was so absurd—the manuscripts we have show that Heron ignored the minus sign and gave the answer as $\sqrt{63}$ instead.

The square roots of negative numbers are what we now call imaginary numbers. The first person to suggest that they shouldn't be ignored was the 16th-century Italian astrologer Jerome Cardano, who was embarked on a grand project: a book detailing all of the algebraic knowledge of his times. While working out cubic equations, he stopped and stared at the issue. At first, he called them "impossible cases." In his 1545 book on algebra, *The Great Art*, he gave the example of trying to divide 10 into two numbers that multiply together to make 40. In the process of finding those numbers, you come across $5 + \sqrt{-15}$.

Cardano didn't shy away from this unexpected encounter. In fact, he even jotted down a few thoughts about it. However, he wrote in Latin, and translators argue about what he actually meant. For some, he calls it a "false position." For others, it's a "fictitious" number. Still others say he characterizes the situation as "impossible" to solve. One of his further comments on how to proceed in such a situation is translated as "putting aside the mental tortures" and as "the imaginary parts being lost." Elsewhere he refers to this as "arithmetic subtlety, the end of which ... is as refined as it is useless." He says it "truly is sophisticated ... one cannot carry out the other operations one can in the case of a pure negative." By pure negative, he means a standard negative number, something like –4. He was happy with negative numbers and wrote that "$\sqrt{9}$ is either +3 or –3, for a plus [times a plus] or a minus times a minus yields a plus." And then he continued, "$\sqrt{-9}$ is neither +3 or –3 but is some recondite third sort of thing." Cardano clearly thought the square roots of negative numbers were something abstruse and abstract, but at the same time he knew they were *something*—and something that a mathematician should engage with. The task wasn't for him, though; none of Cardano's subsequent writings mention the square roots of negative numbers. He left it to his fellow countryman, Rafael Bombelli, to address them a couple of decades or so later.

In what he called a "wild thought," Bombelli suggested in 1572 that the two terms in $5 + \sqrt{-15}$ could be treated as two separate things. "The whole matter seemed to rest on sophistry rather than truth," he said, but he did it anyway. And we still do it today because it works.

Bombelli's two separate things were what we now call real numbers and imaginary numbers. The combination of the two is known as a "complex number" (it's complex as in "military-industrial complex," speaking of combination—of real and imaginary parts—rather than complication). But let's be clear. If there's one thing we've learned in our time revisiting mathematics, it's that all numbers are imaginary. They are simply a notation that helps with the concept of "how many." So applying the name "imaginary numbers" to the square roots of negative numbers is pejorative and unhelpful.

That said, we should acknowledge a distinction. What mathematicians call "real" numbers are the numbers you're more familiar with. The "two" in two apples; the 3.14... in pi; the fraction. And just as positive numbers are in a sense complemented by negative numbers, what we call real numbers are complemented by what we now have to call imaginary numbers. Think of them as yin and yang, or heads and tails. And certainly not as actually imaginary.

Bombelli, in his wild thought, demonstrated that this new tribe of numbers have a role to play in the real world. He set out to solve a cubic equation that Cardano had given up on: $x^3 = 15x + 4$. Cardano's solution required him to deal with an expression that contained the square root of –121, and he just didn't know where to go with it. Bombelli, on the other hand, thought he might try applying normal rules of arithmetic to the square root. So, he said, maybe $\sqrt{-121}$ is the same as $\sqrt{121} \times \sqrt{-1}$, which gives $11 \times \sqrt{-1}$.

Bombelli's great breakthrough was to see that these strange, seemingly impossible numbers obey simple arithmetic rules once they are separated out from the other, more familiar types of number during a calculation. Everything after that was just grasping the nettle.

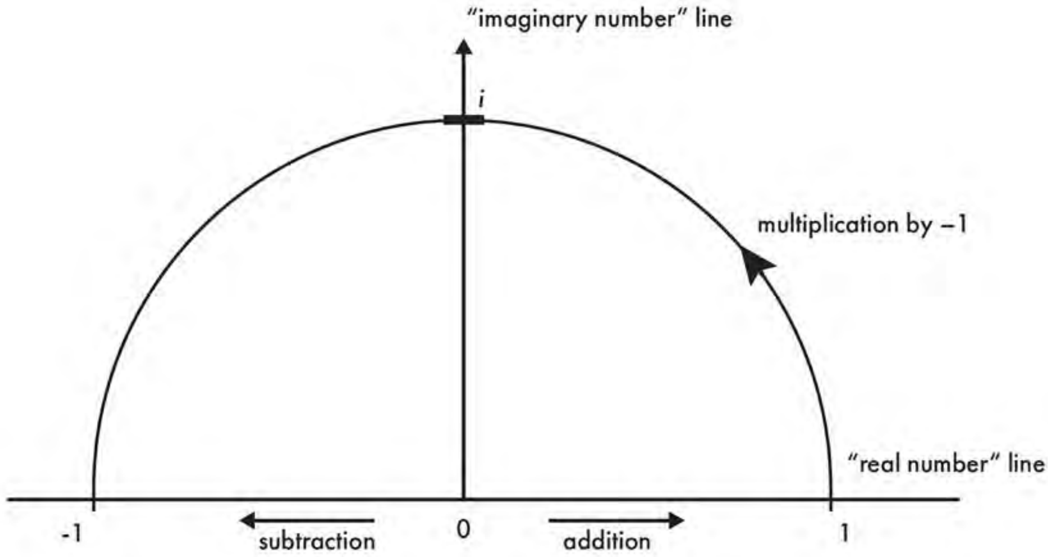
Proceeding with Cardano's cubic equation, he eventually arrived at a solution:

$$x = (2 + \sqrt{-1}) + (2 - \sqrt{-1})$$

Separate them out into what we would now call their real and imaginary parts, and it simplifies to 2 plus 2, and $\sqrt{-1}$ minus $\sqrt{-1}$. The imaginary part disappears, leaving us with just 2 + 2. So $x = 4$ is one of the solutions to $x^3 = 15x + 4$. Plug it in and check for yourself.

THESE DAYS, THE CONVENTION is to use i to represent $\sqrt{-1}$. The Swiss mathematician Leonard Euler first came up with this. It's easy to assume that i stands for imaginary, but the truth is, as with his e, Euler may just have picked it at random. Whatever the reason, Euler's move has cemented i as the imaginary number in a very unhelpful way.

To see better what an imaginary number is, let's think of a standard number line that runs from –1 to 1 (you can think of it as a ruler placed on a table in front of you, running from –1 on the left to +1 on the right). We call the process of moving along the line addition and subtraction (I'm at 0.3, and I'll add 0.3 more, which takes me to 0.6). But we can also imagine making some moves by multiplication. If I start at 1, how do I get to –1? I multiply by –1. So let's picture multiplication by –1 as half a rotation, anticlockwise, around a circle (in our case, the circle passes through 1 and –1). It's actually a rotation by 180 degrees. In mathematicians' preferred units to denote angles, 180 degrees is ϖ radians (360°, a whole circle, is 2ϖ radians).



Imaginary numbers and the number line

What happens if we only do half of this rotation? It's halfway to multiplying by –1, which you can think of as the same as multiplying by √–1. That rotation, by just $\varpi/2$ radians (or 90°) leaves our number up on the top part of the circle's circumference, away from the standard number line. So we can think of the square root of –1 as sitting on a number line that runs at right angles to the number line we're familiar with. It's just another set of numbers, this time on a ruler that meets your other ruler at 90° to form a cross, with +1 at the end furthest from you, and –1 right in front of you.

That leads us somewhere interesting. The link with rotation in circles means that *i* is related to ϖ and the sines and cosines of angles. That relationship is mediated through the strange number *e*, often called Euler's number. This "irrational" number begins with the sequence 2.71828... and goes on forever. It is ubiquitous in mathematics and is vital to statistics, calculus, natural logarithms, and a range of arithmetic calculations. Euler worked out exactly what this looks like by taking a particular kind of infinite series (it's called a Taylor series), and deriving something now known as Euler's formula:

$e^{\pm i\theta} = \cos\theta \pm i\sin\theta$

This shows there is a fundamental relationship between the base of the natural logarithm and the imaginary number. What's more, you can reduce this to the relation known as the Euler identity:

$e^{i\pi} + 1 = 0$

To some, this is a near-mystical formula. Here we have the base of natural logarithms *e*; the numbers 0 and 1, which are both unique cases on the whole number line; the imaginary number, a special case all of its own; and π, which as we know is a source of power in mathematics. Despite being discovered at different times by different people looking at different pieces of mathematics, it turns out they are interrelated, coexisting in this elegant, simple equation.

A full mathematical description of nature requires imaginary numbers to exist.

Seen from a slightly different perspective, perhaps we shouldn't be surprised. As with π itself, there really isn't anything mystical about this formula. It results from the fact that numbers change and transform themselves and each other through rotations. That only happens because of what numbers are: representations of the relationships between quantities. We don't find anything mystical about moving along the familiar "real" number line by adding and subtracting. And there's nothing different, really, about the transformations that come about through multiplications and divisions. Remember that sines and cosines are just ratios—one number divided by another—that are related to the angles within triangles, and you can represent those angles as fractions or multiples of π in units known as radians. So what we're discovering here is not some deep mystery about the universe, but a clear and useful set of relationships that are a consequence of defining numbers in various different ways.

In fact, these relationships are more than useful—they could be described as vital. Take their application to science, for example: A full mathematical description of nature seems to require imaginary numbers to exist. The "real" numbers, of which we have learned so much, are not enough. They must be combined with the imaginary numbers to form the "complex" numbers that Bombelli first created. The result, says mathematician Roger Penrose, is a beautiful completeness. "Complex numbers, as much as reals, and perhaps even more, find a unity with nature that is truly remarkable," he says in his book *The Road to Reality*. "It is as though Nature herself is as impressed by the scope and consistency of the complex-number system as we are ourselves, and has entrusted to these numbers the precise operations of her world at its minutest scales." In other words, imaginary numbers had to be discovered because they are an essential part of the description of nature.

MICHAEL BROOKS is a United Kingdom-based science writer. His most recent book is *The Art of More: How Mathematics Created Civilization*.

AI Is Helping Scientists Explain the Brain

But what if it's telling them a false story?

BY BAHAR GHOLIPOUR

THE BRAIN IS OFTEN CALLED a black box but any neuroscientist who has looked inside knows that's a sobering understatement. Technological advances are making our neural circuitries increasingly accessible, allowing us to closely watch any number of neurons in action. And yet the mystery of the brain only deepens. What's the meaning embedded in the collective chorus of spiking neurons? How does their activity turn light and soundwaves into our subjective experience of vision and hearing? What computations do neurons perform and what are the broad governing principles they follow? The brain is not a black box—it's an alien world, where the language and local laws have yet to be cracked, and intuitions go to die.

Could artificial intelligence figure it out for us? Perhaps. But a recent recognition is that even our newest, most powerful tools that have achieved great success in AI technology are stumbling at decoding the brain. Machine learning algorithms, such as artificial neural networks, have solved many complex tasks. They can predict the weather and the stock market or recognize objects and faces, and crucially, they do so without us telling them the rules. They should, at least in theory, be able to learn the hidden patterns in brain activity data by themselves and tell us a story of how the brain operates. And they do tell a story. It's just that, as some scientists are finding, that story is not necessarily of *our* brain.

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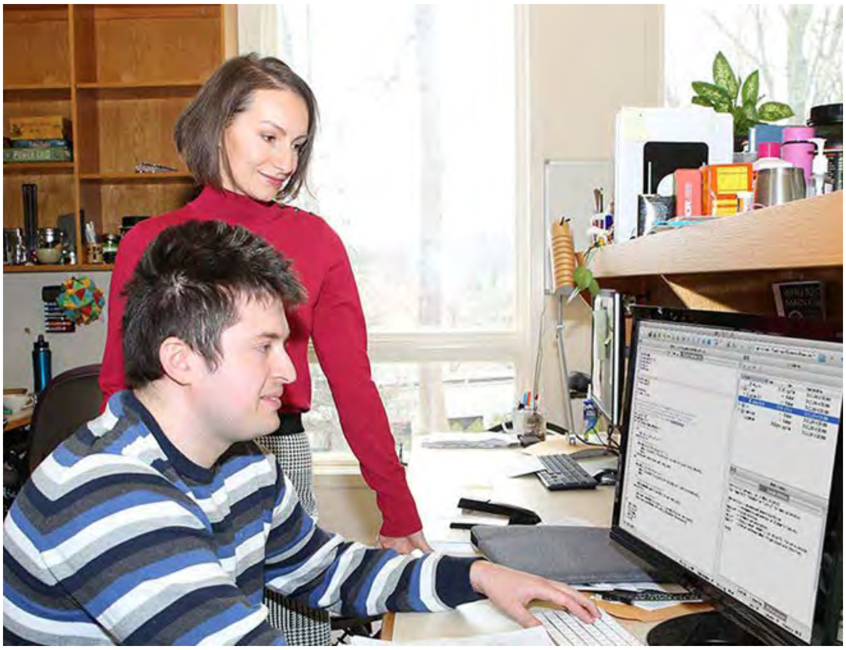

TEAMWORK A physicist turned computational neuroscientist, Tatiana Engel, pictured here with colleague Mikhail Genkin, is developing mathematical models to understand how neurons work together to arrive at the decisions our brains make every minute of every day.

Computational attempts at describing the behavior of neurons have always led to humble lessons.

That's what Tatiana Engel, assistant professor at Cold Spring Harbor Laboratory, discovered recently when investigating decision-making in the brain. A physicist turned computational neuroscientist, Engel works on developing mathematical models that could help explain what neurons do when we make decisions. While neuroscientists have some theories, they have yet to arrive at an all agreed-upon account of how decisions, even the simplest ones, are implemented in the brain. Hoping to explore a wider range of possibilities, Engel turned to machine learning: Instead of working up from specific hypotheses to model the neural activity, she started with flexible models that can mold themselves to the data and figure out the parameters of their equations on their own.

In this method, the resulting models are then judged by how well they can predict a new set of brain measurements they have not seen before. But along the way, Engel wondered, just how sure are we that the best-scoring model reflects the underlying logic of the brain?

"It's more and more common now in neuroscience, as well as in other fields, to use this type of flexible models as a tool to understand the real physical, biological systems," says Engel. "So we build a model, and it can predict the data from a system very well. Then there is this kind of assumption that such a model should function in a way similar to the real system and therefore, by studying how the model works, we will understand how the system works."

More often than not, that assumption may be unwarranted. In a 2020 study, Engel and her colleague Mikhail Genkin, a postdoc at CSHL, examined how well flexible models would work on synthetic data, whose internal dynamics was known to the researchers.[1] They

The data, even from just 100 neurons, is dizzyingly large.

found that counterintuitively, sometimes models that ranked as the strongest predictors turned out to be the farthest from mirroring the core features of the original system that generated the data. "They can have features or attributes that are not present in the system at all," Engel says. "A model can make good predictions about data and still be wrong." In other words, prediction power, the gold standard for machine learning algorithms, can be a misleading metric when it comes to neuroscience applications.

Without working computational models, scientists may have very little chance at making sense of the deluge of brain data and explaining how neural activity gives rise to brain functions. Engel's findings and those of other researchers may feel like a blow to the highly touted promises of AI's ability to aid with modeling the brain. These problems, however, are not unsurmountable, Engel says. She and others are already coming up with ideas to avoid these traps. They are developing methods that would allow them to continue using AI's powerful tools without falling for misleading stories.

COMPUTATIONAL ATTEMPTS at describing the behavior of neurons have always led to humble lessons, even when those attempts were successful. In 1952, Alan Hodgkin and Andrew Huxley imagined a neuron as an electrical circuit whose carefully arranged resistors and capacitors could generate a current similar to the neuron's characteristic spike, the building block of communications in the brain. The model proved to be a pivotal achievement, but it was far from straightforward to know that by just looking at the equations. As Huxley spent days painstakingly entering voltage numbers into a mechanical calculator to see whether the circuit's outcomes matched those of a real neuron, he marveled at the sophisticated behavior of this relatively simple model. "Very often my expectations turned out to be wrong," he recounted a decade later in his Nobel Prize lecture. "An important lesson I learnt from these manual computations was the complete inadequacy of one's intuition in trying to deal with a system of this degree of complexity."

Neuroscientists now face orders of magnitude higher complexity as they have moved on to studying populations of neurons in living animals and people. The data, even from just 100 neurons, is dizzyingly large. It varies dynamically with no obvious rhyme and reason. And it's rarely clear which parts of it are truly relevant to the brain function being studied. These factors have made it much harder to come up with models, conceptual or mathematical, to describe the neural activity.

Even harder is figuring out which proposed model explains something real about the neurons, and which one is a lucky mathematical match for data. Without knowing the ground rules in the brain, the best scientists can do is to see how the models stack up against each other.

"It's like all we see is a moving car, and we have to find out how [it moves] by making assumptions about what's happening under the hood," says Chandramouli Chandrasekaran, a neuroscientist at Boston University who collaborates with Engel on decision-making research. "We then try to figure out which of the proposed ideas, say model A and model B, does better at matching our measurements of the car's movements."

Although an increasingly popular method, this approach can still fail in important ways, Chandrasekaran says. As a hybrid computational and experimental researcher working directly with brain measurements, Chandrasekaran knows firsthand that neural activity is nothing like a smooth-riding car—it's naturally too complex to ever fit squarely inside the lines of our roughly sketched models. "Experimental data is often

Neuroscientists don't want to just fit a model to the data, but to discover hypotheses from the data.

much more complex and heterogeneous. It's what it is. It's not as simple and beautifully boxed in as what you think it is," he says. What this means in practice, Chandrasekaran has shown, is that tangential variations in neural activity can sometimes cause it to be classified as model A, when in reality it abides by model B, or vice versa.[2] That's one reason why comparing two models head-to-head is not guaranteed to identify the correct one.

A raging debate that erupted recently in the field of decision-making highlights these difficulties. It started with controversial findings of a 2015 paper in *Science* that compared two models for how the brain makes decisions, specifically perceptual ones.[3] Perceptual decisions involve the brain making judgments about what sensory information it receives: Is it red or green? Is it moving to the right or to the left? Simple decisions, but with big consequences if you are at a traffic stop. To study how the brain makes them, researchers have been recording the activity of groups of neurons in animals for decades. When the firing rate of neurons is plotted and averaged over trials, it gives the appearance of a gradually rising signal, "ramping up" to a decision.

In the standard narrative based on an influential model that has been around since the 1990s, the ramp reflects the gradual accumulation of evidence by neurons. In other words, that is how neurons signal a decision: by increasing their firing rate as they collect evidence in favor of one choice or the other until they are satisfied. The 2015 study, however, asked whether the ramping is an artifact of averaging over trials. It's much harder to analyze the messy limited data of a single trial, but what happens in it? Does a neuron's firing rate really ramp up or does it make discrete jumps? The distinction could point to different strategies underlying decision-making. Their analysis suggested that responses of neurons match a jumping model better than a ramping model. Several years and many studies later, scientists still don't have a firm conclusion on which model is correct.

And the situation could be even worse: Neither model may be correct. "What if there's a model C?

Or D?" Engel says. What if instead of two models, she could test a continuum of models? That's where flexible modeling would be most useful, as it wouldn't constrain her to just a handful of scenarios. But Engel had found that this approach could also select scenarios that didn't have much in common with the physical reality under the hood. First, she had to find a way around that problem.

FLEXIBLE MODELS ARE DEVELOPED with the goals of machine learning in mind: optimizing for prediction ability. In this way, they can take what they learn from a set of data and apply it to new data they have not seen before. For example, when building a classifier to tell cats apart from dogs, the goal is that out in the real world it can still tell cats from dogs. It doesn't matter if the algorithm achieves this using the same strategy as our brains or not. In fact, in this case, it definitely does not.

Neuroscientists on the other hand have a fundamentally different goal: They don't want to just fit a model to the data, but to discover hypotheses from the data. They want to have a model that can learn from neural activity how to be like neurons. "We had to abandon this idea of optimizing models for predictions, and come up with a new approach which puts a different objective forward," Engel says. Together with Genkin she focused on the fact that across different data samples, true features are the same but noise is different. So they developed a new procedure that allows discovering models on different data samples, and extracting the features they have in common. This new approach identified the correct model of the synthetic data. And when applied to real brain data, it arrived at similar models for each sample, suggesting that unlike the wild guesses of the conventional method, these models had captured some of the true features of the system.

This solution, published in *Nature Machine Intelligence*, would make flexible models more extendable beyond their original purposes and more useful to biological sciences.[1] It may not be a solution to every case of AI tools used in neuroscience, Engel says, but it can improve the application of flexible models, which is used widely by neuroscientists.

For Engel herself it has already started to yield new insights into decision-making. Collaborating with Chandrasekaran, the team is exploring their original question: What kind of model best describes neural activity during decision-making? So far what they see is neither ramping or jumping. Would their findings settle the debate? Or kick it further into another round? Hopefully, we'll know sometime soon.

BAHAR GHOLIPOUR is a science writer and editor covering biomedical sciences, genetics, neuroscience, and AI. Her work has appeared in *The Atlantic*, *Scientific American*, *Wired*, and many other publications. Her writing has been featured in *The Language of Composition* and in *The Best American Science and Nature Writing*.

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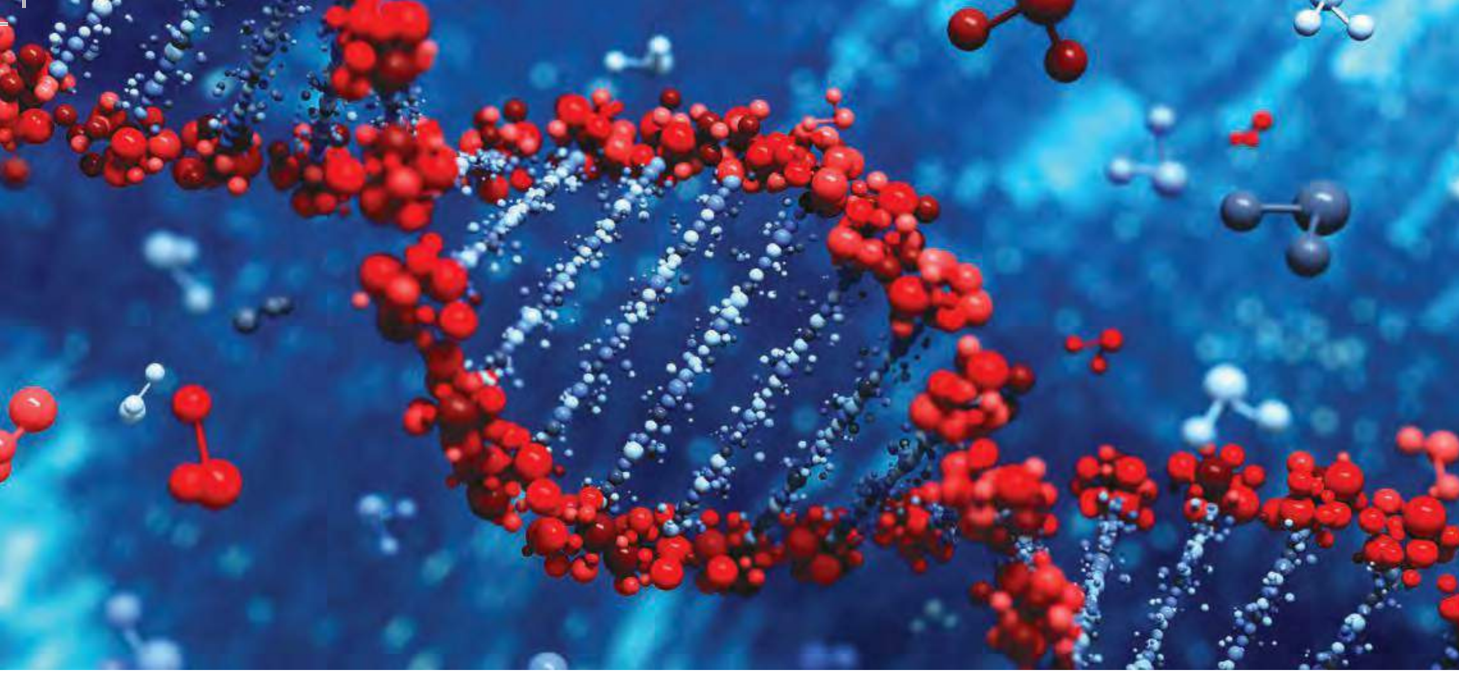

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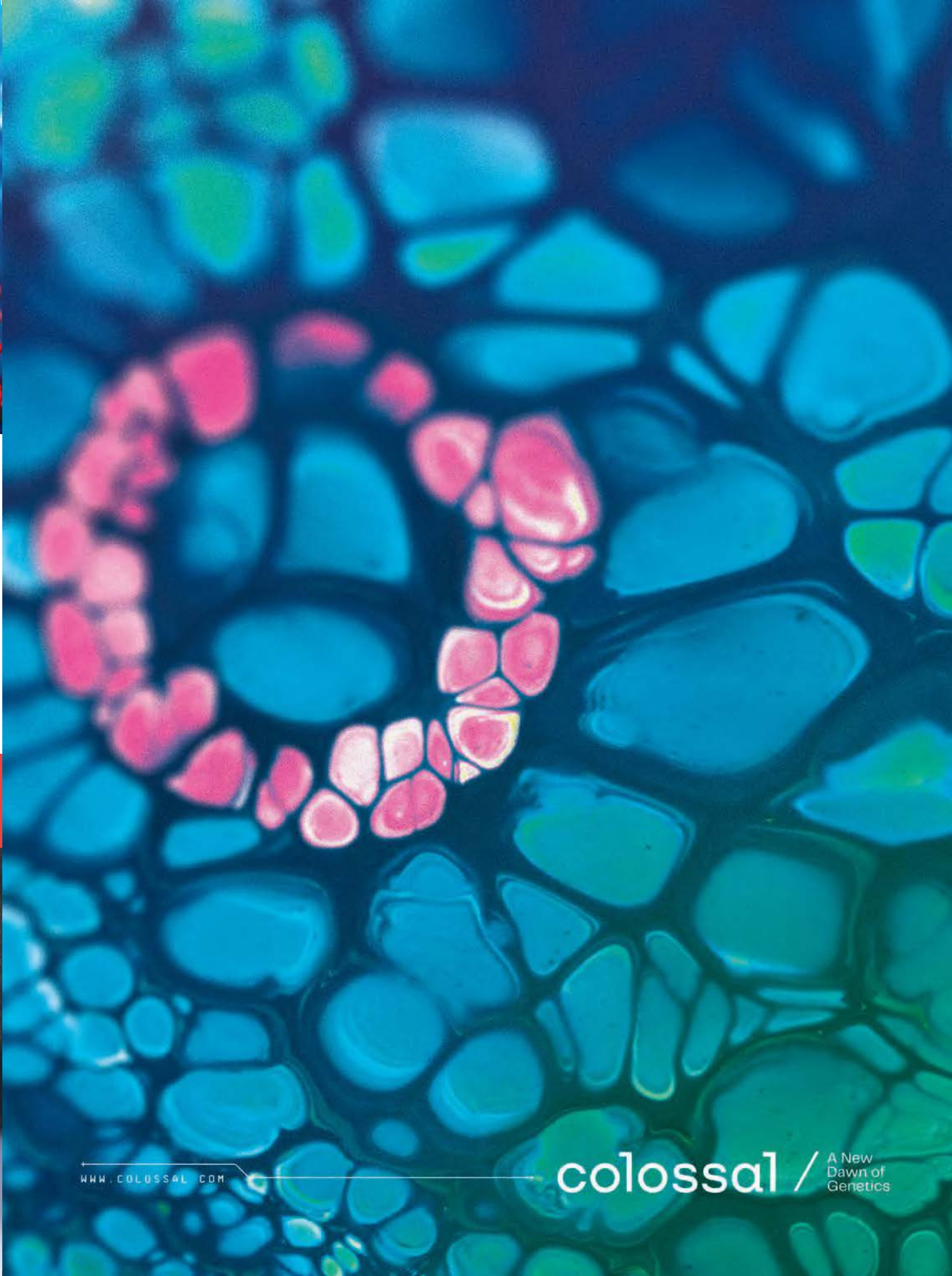
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Issue Index

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28

2019
75 STORY
76 LANGUAGE

27

2019
72 QUANDARY
73 PLAY
74 NETWORKS

26

2019
68 CONTEXT
69 PATTERNS
70 VARIABLES
71 FLOW

25

2018
A SELECTION OF STORIES FROM THE APR - DEC 2018 ONLINE ISSUES.

24

2018
56 PERSPECTIVE
57 COMMUNITIES
58 SELF

23

NOV/DEC 2017
54 THE UNSPOKEN
55 TRUST

22

SEPT/OCT 2017
52 THE HIVE
53 MONSTERS

21

JULY/AUG 2017
50 EMERGENCE
51 LIMITS

20

MAY/JUNE 2017
48 CHAOS
49 THE ABSURD

19

MAR/APR 2017
46 BALANCE
47 CONSCIOUSNESS

18

JAN/FEB 2017
44 LUCK
45 POWER

17

NOV/DEC 2016
42 FAKES
43 HEROES

16

SEP/OCT 2016
40 LEARNING
41 SELECTION

15

JULY/AUG 2016
38 NOISE
39 SPORT

14

MAY/JUNE 2016
36 AGING
37 CURRENTS

13

MAR/APR 2016
34 ADAPTATION
35 BOUNDARIES

12

JAN/FEB 2016
32 SPACE
33 ATTRACTION

11

NOV/DEC 2015
30 IDENTITY
31 STRESS

10

SEP/OCT 2015
28 2050
29 SCALING

09

JULY/AUG 2015
25 WATER
26 COLOR
27 DARK MATTER

08

MAY/JUNE 2015
22 SLOW
23 DOMINOES
24 ERROR

07

MAR/APR 2015
19 ILLUSIONS
20 CREATIVITY
21 INFORMATION

06

WINTER 2015
16 NOTHINGNESS
17 BIG BANGS
18 GENIUS

05

FALL 2014
13 SYMMETRY
14 MUTATION
15 TURBULENCE

04

SUMMER 2014
10 MERGERS & ACQUISITIONS
11 LIGHT
12 FEEDBACK

03

SPRING 2014
07 WASTE
08 HOME
09 TIME

02

WINTER 2014
04 THE UNLIKELY
05 FAME
06 SECRET CODES

01

FALL 2013
01 HUMAN UNIQUEN
02 UNCERTAINTY
03 IN TRANSIT

Anna Machin

The anthropologist puts love in perspective

INTERVIEW BY BRIAN GALLAGHER

LOVE IS BRIBERY

The reason love evolved was to motivate and reward us for taking part in relationships, critical to our survival. Humans are highly cooperative because we have to be. And that's fine, except it's incredibly stressful. You have to spend a hell of a lot of time monitoring everybody else's behavior, making sure you're spotting those people who are trying to cheat you or steal from you. And the way evolution made sure we cooperate was to come up with chemical bribery. At the basis of love are four neurochemicals. Each has a different role but together they motivate us or give us confidence to go into social relationships. Ultimately, we get addicted to those chemicals. We get this hit of joy, of euphoria, of reward when we interact with the people important to our survival. It's like if I give my kids a sweet because they've done something good, which is bad parenting, but it works.

LOVE IS BLIND

What happens when you fall in love for the first time is the activation of various areas of the limbic system and the neocortex. But we also see deactivations mainly in the brain area linked to "mentalizing," the ability to tell someone's intentions. You need to be good at mentalizing to spot a liar or a cheat. But what happens when you fall in love for the first time is that bit shuts down. It decides it's not going to work anymore. For that reason, your friends can see this person is not necessarily good for you, that maybe they're going to cheat on you or they're lying to you, but you cannot see it.

LOVE IS POLITICAL

I do a lot of public speaking and I explain the rules of mate choice as biology sees them. But a lot of women, in particular, find it hard to accept that they are still looking for a protector and a provider. Even though they are now capable of being financially independent. They're still looking for that in the man. These mate-choice rules are incredibly ancient. Whenever we see mate choice in any species, this is what we see. One reason why some women are in a position where they're financially comfortable, and don't need a man for that, is because they live in a culture where there's a certain amount of gender equality. That has come about partly from feminism. But feminism hasn't touched evolution. Women have only been able to control their contraception, for example, for about the last 70 years. That's nothing in evolutionary time.

LOVE IS HEALTHY

We neglect our friendships at our peril because often our friendships outlast our romantic relationships, and they are the ones that are really your stable foundation. You need them in your life for your mental health, physical health, longevity, and your well-being. But I do think we underestimate them. When I interview British people, I'll ask them, "Do you love your friends?" And they'll go, "Hmmm, I don't know whether I love them." And then I'll say, "Well, do you love your dog?" We don't consider the fact that we could love our friends. That's maybe a peculiarly British thing that's quite restrained that we wouldn't admit that.

COLIN KITCHEN

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