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He defied Stalin to feed the world

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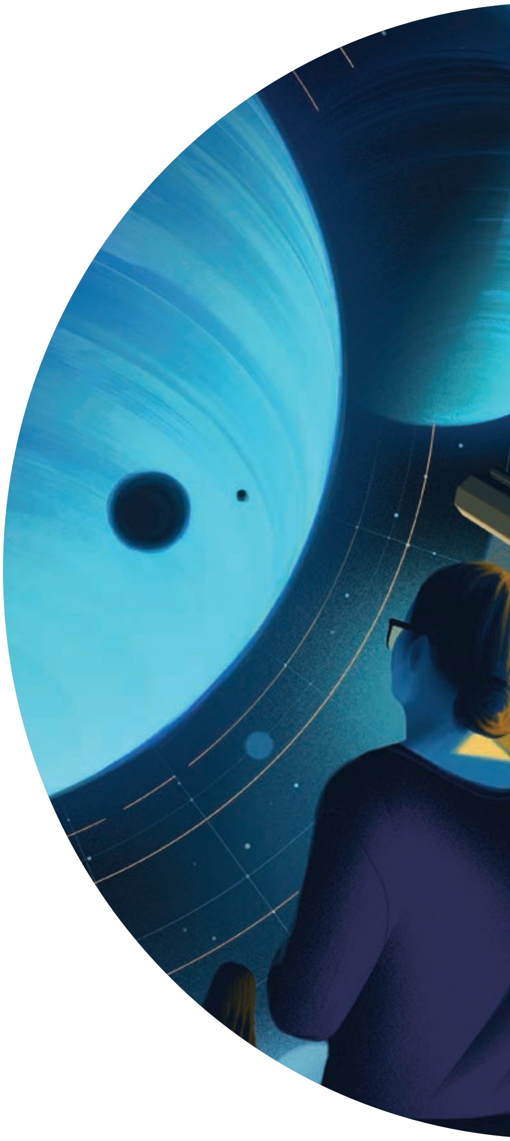

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Human Science

BY KEVIN BERGER

Science is the most objective thing we've ever come up with. But it's done by emotional primates.

I WANT TO BE a paleoanthropologist. This editing and writing thing is OK. But it would be amazing to discover and identify a fossil that forever changes the picture of our origins. "It's just awesome and mind-blowing," says Jeremy DeSilva, a paleoanthropologist at Dartmouth College. DeSilva was part of the research team that described two recent branches to the human family tree, *Australopithecus sediba* and *Homo naledi*. It's also, DeSilva says, personal.

During a recent interview, DeSilva shows me a fossil. "This is a foot fossil of an infant from *Australopithecus afarensis*, Lucy's species," he says. "It was a 2-year-old individual. There are no toes. That's the sole of the foot there. And that's the ankle. But see how tiny it is? When I first started working on this fossil, my twins were very little. I had to leave them and fly off to Ethiopia. It was important to get the science as right as possible, but it was hard not to think about my kids. Science is the most objective thing we've ever come up with. But it's done by emotional primates. We can embrace and recognize when we are being emotional and subjective. It's important. It humanizes the science. The public can relate to that more than to a robotic, entirely objective, unemotional scientist trying to explain something to them."

DeSilva, featured in this issue, is a passionate advocate for science education. Before teaching at Dartmouth, he was an educator at the Boston Museum of Science. "I love to share discoveries with the public, show them fossils, and let them hold them," he says. "We're visual primates. It's a joy to see kids' eyes light up when you hand them an ancient human fossil and say, 'This is a replica of a 7-million-year-old fossil.' "

I was curious how DeSilva spoke to museum visitors who held views that rejected evolution. "The answer is not to be dismissive or belligerent in any way toward an audience that rejects evolution. They may not understand it. They may not have had the opportunity to hold a fossil and grapple with the fact that this thing existed. The questions they ask are excellent ones. 'How how do you know how old a fossil is?' 'How do you know this is related to us and not to chimpanzees?' Maybe the motivation behind them comes from a different place than science. But it's important to engage with this audience and let them know the questions they're asking are good ones and ones we also grapple with."

DeSilva raises the issue of science education with his students. "I tell my students that people think about their world in different ways. One of the great joys of being a human is to take the ideas that people come up with and rattle them around in your brain and think about ways in which they are discordant and need to be reconciled. Students ask me all the time what I believe, and I tell them it's irrelevant what I believe, that I would be cheating them out of their own personal journey in discovering how all this works."

DeSilva is quick to add that science is not the same as personal beliefs. "Evidence-based understanding of our world, and evidence-based decision-making about our world, is critical. Science literacy and information literacy could not be more important right now." At *Nautilus*, we couldn't agree more.


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Readers Respond

Comments and letters about stories from print issue 37.

"WHAT MAKES MUSIC UNIVERSAL"

In our species, the presence of language is universal. But all societies have their own language(s). The languages are most frequently not mutually intelligible to speakers of other languages, and their syntax, grammar, morphology, and sound processes aren't "universal" (although there are always some elements that are similar to other languages). The presence of music is similarly universal to humankind. And all societies have their own separate music(s). The vocabulary and syntax of those musics are not universal. Why are these concepts so difficult?

—*Marc Herman*

The debate between nature and nurture continues, albeit at a far more finely grained level. I think it's obvious, the answer is: both. Yes, of course, the ability to make, share, and appreciate music is a universal human trait, forged by evolutionary factors that favored highly empathic and highly communicative individuals and tribes through time. There are going to be musical commonalities across the cultural spectrum. After all, our bodies, ears, and brains are very similar—99.9 percent of the genetic code is shared by all humans.

And yes, cultural factors are critically important in how the shared traits are expressed, and the range of musical styles, modalities and purposes is extremely broad. No two individuals are going to play or sound the same, and no two cultures are going to develop identical musical traditions. That individual and cultural diversity is one of the special and beautiful features of music—a seemingly infinite variety open to the creative talents of billions of people. Intended to be shared. That is something to celebrate! Time for a song!

—*George Gantz*

"GAIA, THE SCIENTIST"

What can I say? This was beautiful! And I absolutely love the Greek mythology references. A pleasure to read. We're all scientists in our own ways!

—*Ryan Clark*

"I HAVE COME TO BURY AYN RAND"

Sloan and many males have misread both *Atlas Shrugged* and *The Fountainhead* for 60+ years as some sort of thinly veiled economic selfish monographs, when in reality they express philosophy for striving for the best that is within us *and* creating a society where expressing that is possible and rewarded in a society of equals. I'd love to live in a society like Galt's Gulch, where talented people do their own work, and then share that (and other mundane chores). There is largesse, sharing and cooperation in that society, but there is not coercion. She did not rant against helping others, but rather being *forced* to help. Her argument was never against the people who had never been permitted to develop their full potential; it was always against those with gifts who preferred mendacious mediocrity and deliberately promotion of the sniveling bureaucrat. In short, Rand was in rebellion against the typical female role of the 1940s and 1950s.

—*Jo Schaper*

Nautilus *welcomes reader responses. Please email* letters@nautil.us. *All letters are subject to editing.*

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Air Pollution: A Solvable Problem
Air Pollution: A Solvable Problem
Air pollution is a global threat. The World Health Organization estimates that 4.2 million people die every year as a result of exposure to outdoor air pollution, and very few cities enjoy air quality that is considered safe.
Story by: Jane Burston & Matt Whitney, Clean Air Fund
Editor: John Letzing
Data from: NOAA, NASA, WHO
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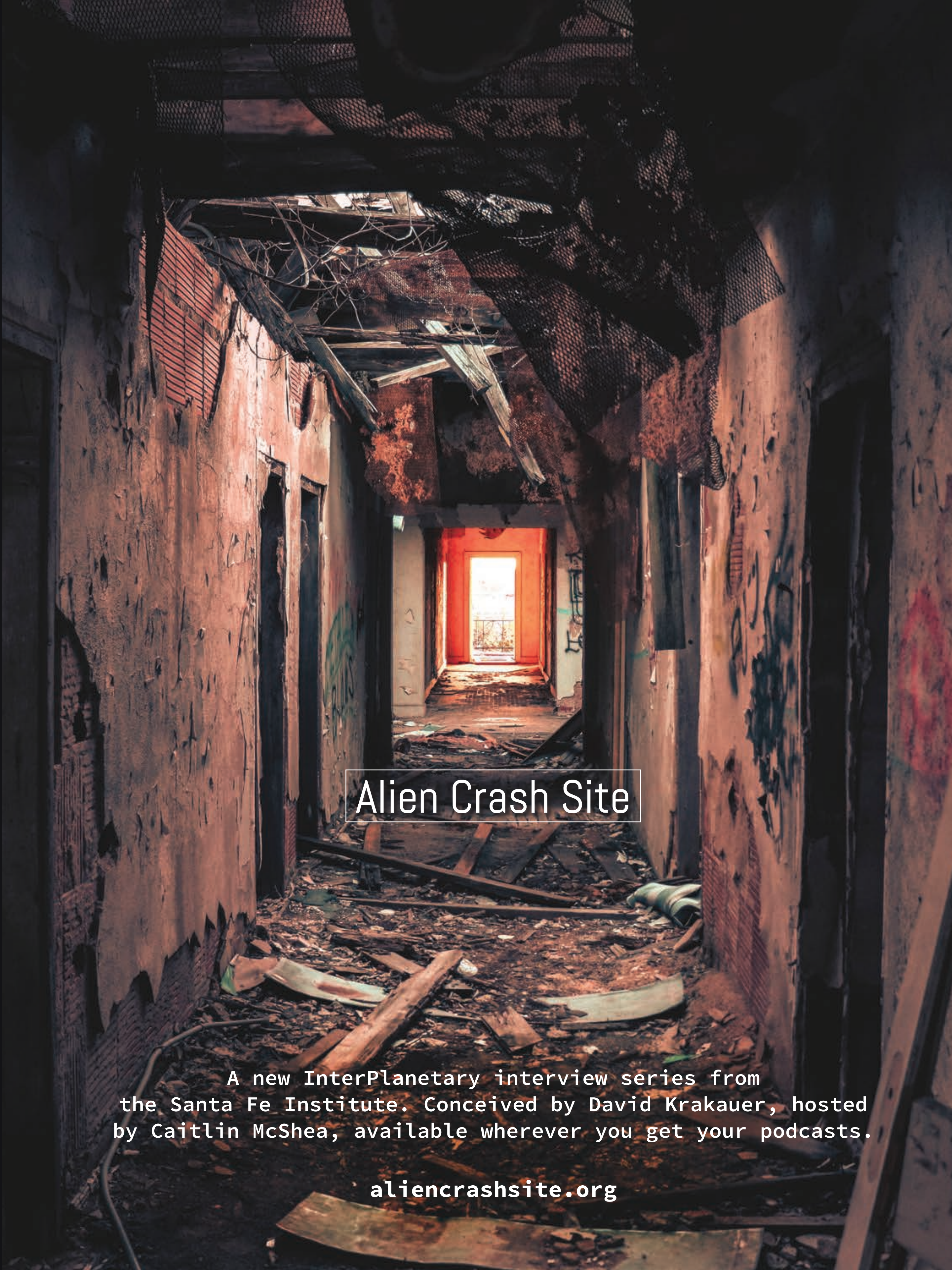
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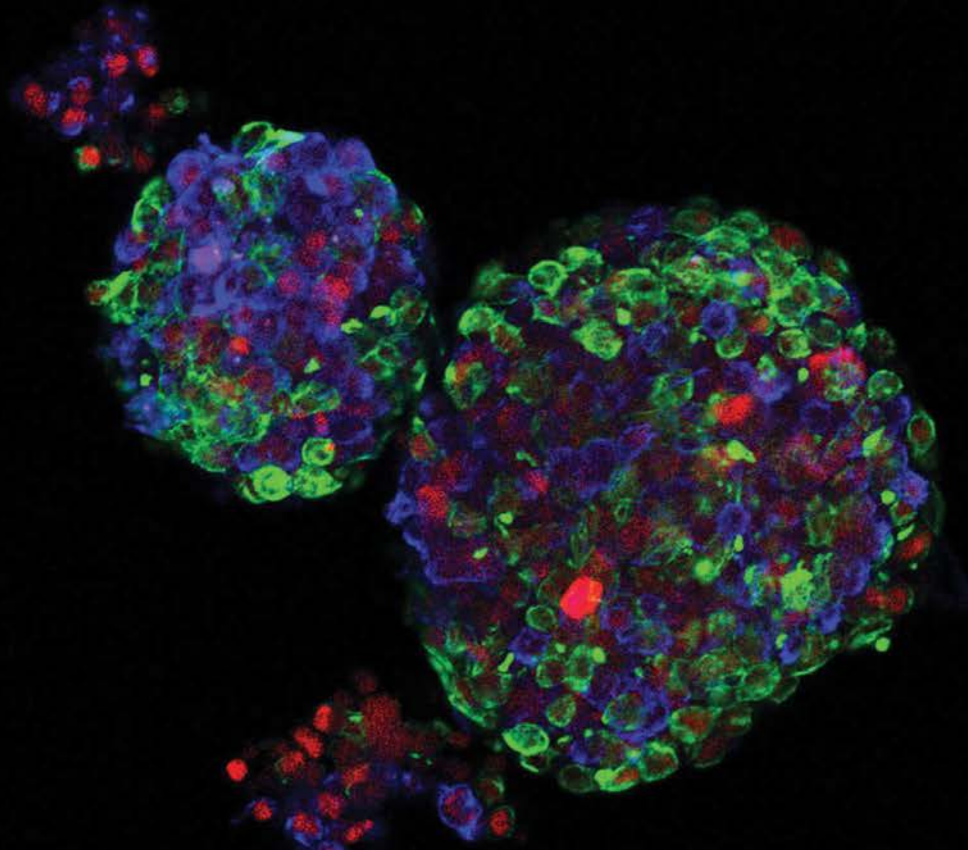
BIOLOGY + BEYOND



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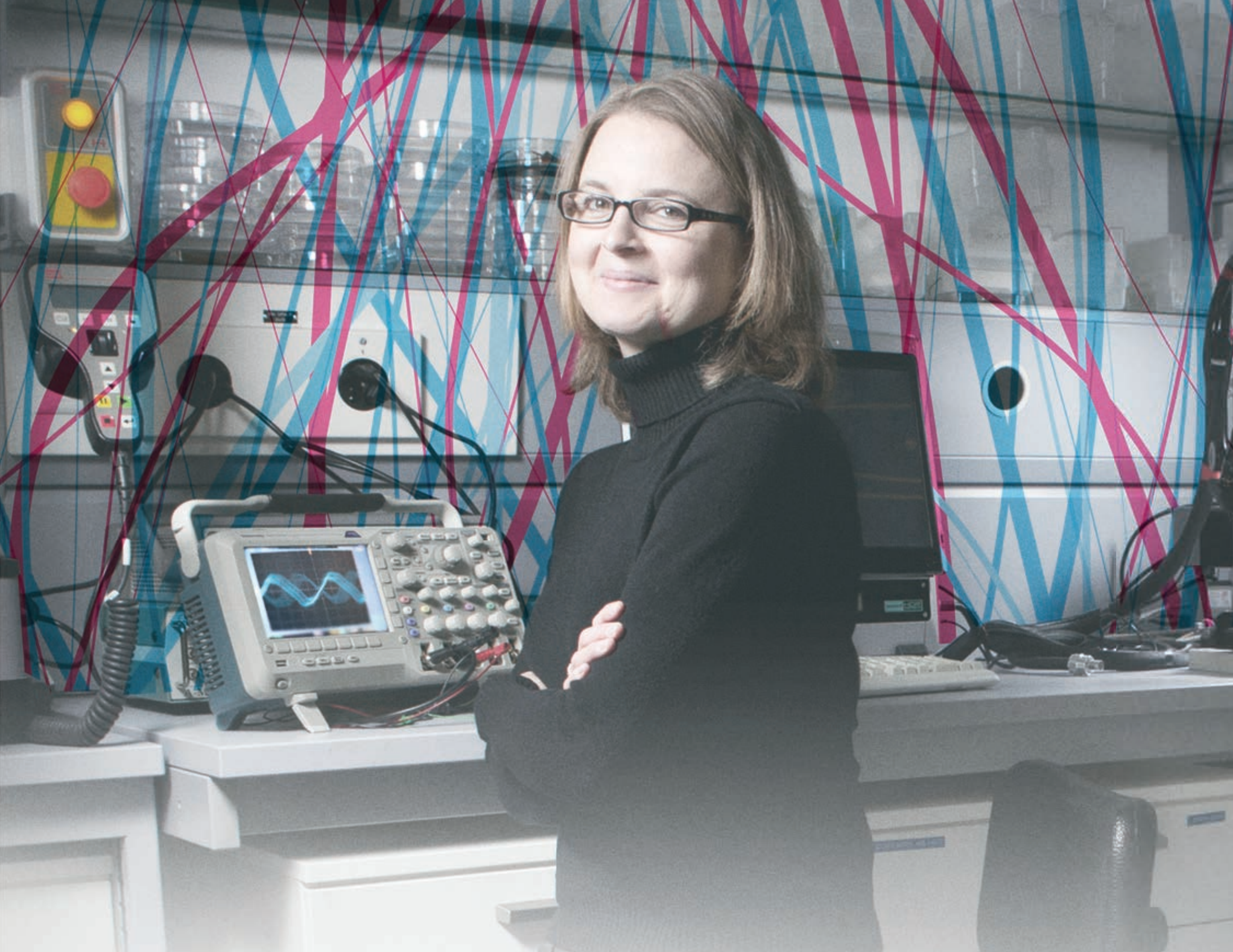

Professor **Stéphanie Lacour** holds the Bertarelli Chair in **Neuroprosthetic Technology** at the École Polytechnique Fédérale de Lausanne, based at Campus Biotech in Geneva. A pioneer in the field of soft bioelectronic interfaces, her lab's focus is on designing devices that have mechanical properties close to those of the host biological tissue so that wearable and implantable man-made systems become truly biointegrated.

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KNOWLEDGE **SHARED**
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Preludes

PSYCHOLOGY

Why People Feel Like Victims

IN A POLARIZED NATION, victimhood is a badge of honor. It gives people strength. "The victim has become among the most important identity positions in American politics," wrote Robert B. Horwitz, a communications professor at the University of California, San Diego.

Researchers are still looking for the roots of victimhood today. In 2020, researchers in Israel, led by Rahav Gabray, a doctor of psychology at Tel Aviv University, identified a negative personality trait they call TIV, or Tendency for Interpersonal Victimhood. People who score high on a TIV test have an "enduring feeling that the self is a victim in different kinds of interpersonal relationships," they write.

You only need to spend only a few minutes watching or reading the news, in any country, to hear and see victimhood raging. We caught up with Gabray to get the science behind the headlines.

Is TIV an aberration in the personality?
Sometimes it may be, if one is high on the TIV scale. But we didn't research clinical patients. That's not what interested me. I'm interested in how this tendency appears in normal people, not those with a personality disorder. What we found was that, like in a bell curve, most people who experience TIV appear in the middle range.

Why is it so difficult for people with a high degree of TIV to recognize that they can hurt other people?
They don't want to divide up the land of victimhood with other people. They see themselves as the ultimate victim. And when other people say, "OK, I know that I hurt you, but you also hurt me," and want them to take responsibility for what they did, the person with TIV is unable to do it because it's very hard to see themselves as an aggressor.

LUBOFFKE / SHUTTERSTOCK

In one of your studies, you conclude that TIV is related to an unwillingness to forgive, even to an increased desire for revenge. How did you come to that?
In an experiment, participants were asked to imagine they were lawyers who had received negative feedback from a senior partner in their firm. What we found was that the higher the tendency of participants to perceive interpersonal victimhood, the more they tended to attribute the criticism by the senior partner to negative qualities of the senior partner himself, which led to a greater desire for revenge. Our study finds that not only do people with high TIV have a higher motivation for revenge, but have no wish to avoid their offenders.

Can one develop TIV without experiencing severe trauma or actual victimization?
You don't need to have been victimized, physically abused, for example, in order to exhibit TIV. But the people who score very high on TIV are generally those who have experienced some kind of trauma, like PTSD. Maybe they didn't fully recover from it. Perhaps they didn't complete therapy. Something we often see is that they tend to act very aggressively toward family members.

How debilitating is TIV for those with moderate TIV? Does it affect everyday functioning?
Yes. The higher the TIV, the more you feel victimized in all of your interpersonal relations. So if you are in the

middle of the scale, you might feel yourself as a victim in one relationship but not another, like with your boss, but not with your wife and friends. But the more you feel like the victim, the more you extend those feelings to all of your interpersonal relationships. And then of course it can affect every aspect in your life. If you feel being victimized in your work, for example—we did a lot of experiments with the narratives of managers and workers—it means that you cannot let stand an offense by your boss, no matter how trivial. I think everyone knows that offenses in interpersonal relations are very common. I'm not talking about traumas, I'm talking about those small daily offenses, and the question is how you deal with it.

> They see themselves as the ultimate victim.

Victimhood is also a matter of socialization.

Yes, and you see it when leaders behave like victims. People learn that it's OK to be aggressive and it's OK to blame others and not take responsibility for hurting others. This is just my hypothesis, but there are certain societies, particularly those with long histories of prolonged conflict, where the central narrative of the society is a victim-oriented narrative, which is the Jewish narrative. It's called "perpetual victimhood." Children in kindergarten learn to adopt beliefs that Israelis suffer more than Palestinians, that they always have to protect themselves and struggle for their existence. What's interesting is the way in which this narrative enables people to internalize a nation's history and to connect past and present suffering.

What can we do to overcome victimhood?

It begins with the way we educate our children. If people learn about the components of victimhood, and are conscious of these behaviors, they can better understand their intentions and motivations. They can reduce these tendencies. But I hear people say that if they don't use these feelings, if they don't act like victims, they won't achieve what they want to achieve. And that's very sad.

—*Mark MacNamara*

ANIMALS

The Evolutionary Wonders in the Deep Sea

THE DEEP SEA is a part of our planet unlike any other. Accounting for over 95 percent of Earth's living space, it is cold, dark, and under extreme pressure, yet an astounding variety of creatures abound.

Although relatively little is known about the biology and behavior of animals in the deep sea, our ability to observe and study them has never been greater. In recent years, scientists have made great progress gathering high-resolution photos and videos of deep-sea organisms for all to see. In doing so, they hope to show the world that "the deep-sea is not this barren, lonely, dark place where nothing survives," says Alan Jamieson, a marine biologist at Newcastle University. "There are incredible animals down there."

GIANT LARVACEANS

Giant larvaceans, which average about 4 inches from head to tail, live inside giant orbs of mucus, known as houses, that can reach up to 3.3 feet in diameter. Like all larvaceans, the giant larvacean builds its house by secreting a sticky, snot-like substance from cells on its head.

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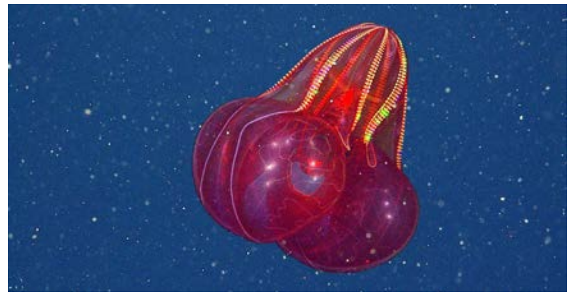
When a giant larvacean flaps its tail to swim, water—up to 20 gallons per hour—is pumped through its house, which acts as a filter for food particles. When these houses become oversaturated with particles that are too large to eat, larvaceans discard them and start constructing new ones. Most of the particles that get caught in a mucus house are carbon-rich, so every time a larvacean discards one, it is actually sequestering carbon. And because the carbon is unlikely to return to the atmosphere for millions of years, their constant house-shedding actively combats climate change.

Researchers with the Monterey Bay Aquarium Research Institute photographed this particular larvacean in Monterey Bay at a depth of roughly 850 feet.



BLOODY-BELLY COMB JELLY

The bloody-belly comb jelly is one of the deep-sea's most vibrant gems. The name of this ruby-colored ctenophore was inspired by the creature's blood-red tissue. The bloody-belly comb jelly's bright red color may make it easy for remotely operated vehicles with lights and cameras to spot it, but its color actually helps it hide from predators. The color red is nearly invisible in the deep sea, allowing the jelly to not only conceal itself but also any bioluminescent organism being digested in its stomach.

Like all comb jellies, which are not technically jellyfish, bloody-belly comb jellies move by beating the iridescent, hair-like cilia that line their bells. Bloody-belly comb jellies have only been found at depths between 980 and 3,320 feet deep in the Pacific Ocean. Researchers with the Monterey Bay Aquarium Research Institute photographed this bloody-belly in 2019 more than 1,600 feet below the surface of the Monterey Bay.

—*Annie Roth*

PHILOSOPHY

Does It Matter If We Have Free Will?

BELIEF IS A SPECIAL KIND of human power. Most people grow up with the notion that they are, in some sense, responsible for their thoughts and actions because, unlike animals, humans can think about their choices. We can reflect on what we should do, and other people—be they our parents or Supreme Court justices—can rightly hold us accountable. This is what most people mean when they talk about having free will.

You could also say that no such thing exists, a view which seems increasingly fashionable. "Cognitive neuroscience and popular media," a new meta-analysis notes, "have been putting forward the idea that free will is an illusion, raising the question of what would happen if people stopped believing in free will altogether." The paper, a preprint posted on *PsyArXiv* by social psychologist Oliver Genschow and his colleagues, delves into almost 150 studies, with over 26,000 participants, that sought to manipulate people's belief in free will in order to tell whether believing or disbelieving in free will affects their morality.

This isn't an idle theoretical or academic question—beliefs about free will, Genschow says, seem to affect many "societally relevant" behaviors, like cheating. They also lie at the foundation of our criminal justice system, helping to justify retributive forms of punishment (the idea that people *deserve* to be locked up, for example, for committing certain crimes) as opposed to rehabilitative ones (confining and reforming people until they can safely re-enter society).

Scientists have tried to manipulate free will beliefs in a number of ways. A common method is eroding the

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plausibility of the concept by appealing to the mechanistic nature of reality. You tell people that all of their behavior is determined by the laws of nature, be those physical, biological, or psychological laws. How could it be otherwise? If you rewound the universe, you'd end up making all of the same choices you did the first time around. You might question this deterministic outlook by bringing up the role of chance, but on closer inspection that, too, erodes free will's plausibility—because how could we call a choice "free" if it arose out of randomness? Even if there is true randomness that affects our choices, acting one way or another because of random fluctuations in quantum fields doesn't feel much like free will.

This gist of the meta-analysis from Genschow and his colleagues suggests that free will's proponents and detractors may be putting too much store in what people believe. The belief, or disbelief, doesn't seem to affect individual behavior in any way we might care about. Manipulating people's ideas about free will, at least in experimental conditions, has only a small and temporary effect. In other words, a persuasive anti-free will essay (the most effective method found) doesn't change people's core beliefs about free will—it only puts them in a temporary, slight anti-free will mindset. There is no evidence that this induced change in free will beliefs has any effect on morality, such as antisocial behavior, cheating, conformity, or willingness to punish. There is also no definitive evidence *against* such effects. So for now, it appears that people's beliefs in free will don't really matter.

That's quite a bold conclusion given that the most popular positions seem to be either: "Free will exists and is central to ethics," and "Free will doesn't exist, and it's ethically important for everyone to recognize this fact."

A good example of this first view comes in the new book *Just Deserts: Debating Free Will* by philosophers Daniel Dennett and Gregg Caruso. They argue about whether free will makes people deserving of punishment or praise for their actions, *independently* of the good that might result from punishing or praising them. To take an extreme example, suppose there were 10 people left on Earth, and one killed the other nine. Assume there is no forward-looking reason to punish them: There are no more people they could possibly kill, no other people to learn by making an example of this person, and so on. Does this person still deserve to be punished for what they did?

Free will, for Dennett, is the thing that would make the answer "yes." That person deserves to be punished because of what they *chose* to do with their own free will. The problem with this, though, is that the existence of free will now depends on your theory of ethics! But shouldn't free will have to do with the nature of a person acting, their psychological properties, and their relationship to the laws of the universe—not whether or not utilitarianism is true?

The neuroscientist Sam Harris said as much in a recent episode of his Making Sense podcast. "Free will is an enduring problem for philosophy and science," he said, "for one reason: People *think* they experience it. They *feel* they have it."

In the episode, Harris says that, if there's anything novel about his position on free will, it is the claim that the experience of having free will is a penetrable illusion: If you pay sufficient attention to your mind when making a decision, it's possible to see that you're not really "deciding" anything. Options of what you might do simply appear in consciousness, and the feeling of "choosing" an option is just another thought that appears in consciousness, completely out of your control.

To demonstrate, he asks listeners to think of a film and carefully observe what happens, in their mind's eye, during this process. Various movies surface to mental awareness—but are these being chosen in any real sense? At this point he asks listeners if they

It appears that people's beliefs in free will don't really matter.

experience free will in this moment. "If it's not here, it's not anywhere," he says. "It is likely that every other choice you have made in your life has been more constrained than this one—what job to take, who to marry, whether to have kids, who to vote for. Most choices are much more obviously constrained by other variables than this one. So if you're not free to simply pick a film right now, I don't know where you're going to find free will."

You might argue, as Dennett has, that Harris is unnecessarily defining free will out of existence. There's a useful version of free will we can hold on to, involving our capacity for self-control. But this, as Harris has said, would just be changing the subject: People who believe in free will think it's deeper than self-control. It's about the feeling that you are, in some sense, the author of your thoughts and actions.

The way these two thinkers have talked past each other reminds us that it's hard to change people's beliefs about free will. So, it can feel like a relief to realize, at least according to Genschow's meta-analysis, that even when you *can* change people's beliefs, it seems to make no moral difference anyway.

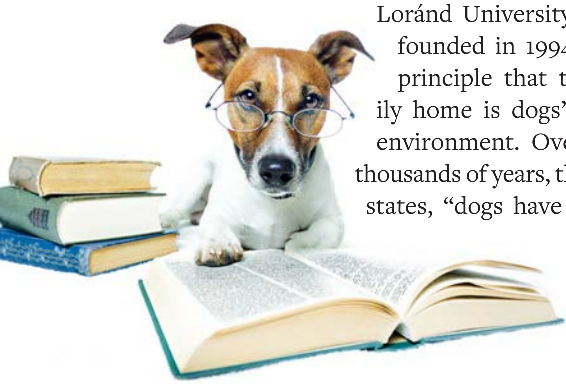
—Jim Davies

ANIMALS

Cognitive Scientists Are Going to the Dogs

A N OLD DOG, it turns out, can teach humans new tricks. "The dog has grown to be one of the most important animals for researchers who aim to understand the biological background of complex traits," says Eniko Kubinyi, an ethologist at Eötvös Loránd University. Previously dogs weren't considered good models for studies into animal behavior because they were thought to be an "artificial species" shaped by humans, Kubinyi says. But this view has changed over the past 25 years.

A key driver is the Family Dog Project at Eötvös Loránd University. It was founded in 1994 on the principle that the family home is dogs' natural environment. Over many thousands of years, the group states, "dogs have evolved to survive in the anthropogenic environment." The group has initiated the Senior Family Dog Project, or EVOLOR, to look specifically into cognitive aging. Kubinyi, principal investigator of the project, says dogs have a number of key advantages as an aging model for humans.



JAVIER BROSCH / SHUTTERSTOCK

Living with people means dogs experience near-identical social and environmental influences on a daily basis. They show off a host of cognitive skills in their interactions with us. Chemicals, air pollution, noise pollution, and lack of exercise—suspected risk factors of cognitive decline—affect dogs just as they do us. Dogs are also susceptible to comparable age-related diseases, such as a form of dementia similar to Alzheimer's.

The rapid rise in big data and citizen science has made it easier to get people to volunteer their pets for participation, Kubinyi says. "When we started the project, we established a group for devoted owners who promised to come to the lab several times every year, and we collected longitudinal data about those dogs." They've collected data via behavioral tests and surveys on more than 20,000 dogs. "We found age-related differences in brain activity, cognition, personality, the gut microbiome, gene expression, and gene variants in several aspects similar to human aging," Kubinyi says. "We've found parallels time after time."

The long history between humans and dogs may promote co-evolution of certain cognitive abilities.

In a recent study of 217 Border Collies that ranged in age from 6 months to 15 years, the team found similarities with humans in the dogs' personality traits as they age. The dogs' interest in problem-solving tended to rise until middle age—about 3 to 6 years—before leveling off. Novelty-seeking changed little until middle age and then steadily dropped. Like humans, dogs' personality traits stayed fairly stable over time. Young dogs that were most active tended to remain so when older.

The team found that older dogs seem to experience a similar "positivity effect" to older people, reacting less to negative sounds such as crying than positive ones such as laughter. "Old dogs seem to listen to what they want to hear," says Kubinyi. Which might tell us something about the wisdom of aging. "In humans, old people are more attuned to positive emotions and less to negative emotions," Kubinyi says. The study ends on a sage reminder. Personality changes occur unevenly over the dogs' lives, and individual Border Collies differ significantly in their personality development. The dogs' differences, Kubinyi and her colleagues write, caution against "over-generalization of the global age trends."

The Family Dog Project is also establishing a basis for understanding the specific underlying neural and genetic links to aging, including methods such as electroencephalography, functional magnetic resonance imaging, and genetics tests. One study backed up the analysis of activity patterns in sleeping dogs' brains as a biomarker of cognitive aging across species; another found that better canine performers in memory tests tended to have lower levels of certain Actinobacteria in their gut, mimicking some observations in people with Alzheimer's disease. "This is preliminary research, but there were parallels with human research," Kubinyi says.

On the genetics side, by analyzing the whole genome sequence of two mixed-breed canines aged 22 and 27—far older than the average dog lifespan of about 10 to 13 years—the researchers identified more than 80,000 novel genetic mutations compared with 850 dogs of normal lifespan. So far they have found genetic markers for aging in the blood and brain.

One of the keys to future research is EVOLOR's recent establishment of a Canine Brain and Tissue Bank, a repository for ongoing study formed by collecting samples donated by owners of euthanized pet dogs. Among those making use of the data is the Dog Aging Project at the University of Washington, Seattle. Already researchers have managed to gauge the degree to which cognitive decline in dogs is associated with increased levels of key proteins linked to Alzheimer's disease in people.

Daniel Promislow, co-director of the Dog Aging Project, says the existence of so many breeds helps researchers understand the effect of size on healthy longevity and susceptibility to different diseases. It should also give some clues about why larger breeds tend to be shorter-lived. "Given that dogs are so much shorter-lived than humans, we should be able to identify the genetic and molecular pathways associated with aging diseases faster," Promislow says. The project is also looking into the effects of rapamycin, a drug originally developed to prevent rejection of organ transplants, that's been shown to slow aging in animals.

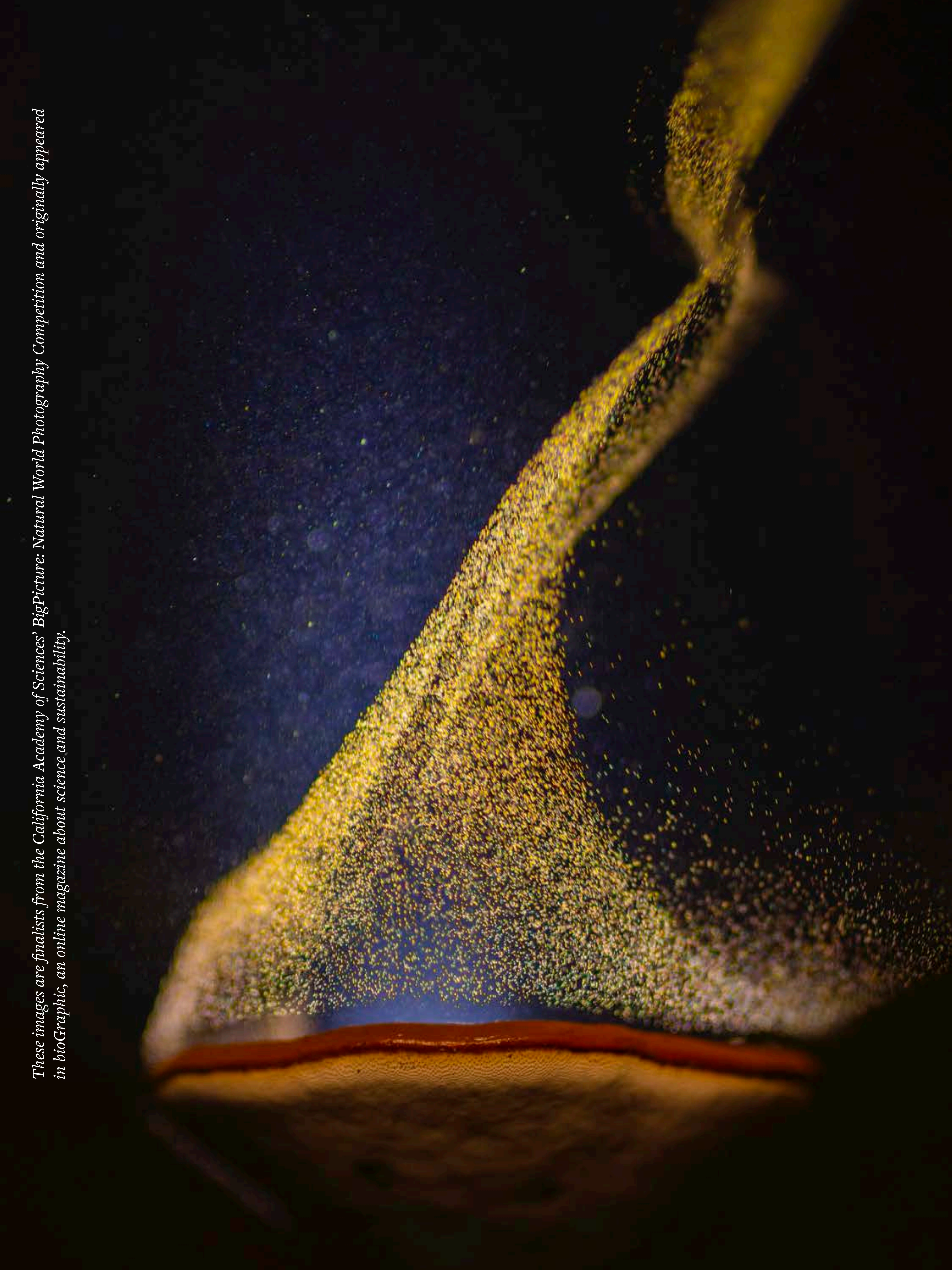
Kun Guo, a cognitive neuroscientist at the University of Lincoln, is investigating the emotional lives of dogs and how they respond to people's emotional signals. "The long history between humans and dogs may promote co-evolution of certain cognitive abilities," Guo says. He says studying dog cognition will bring multiple benefits for improving both dogs' well-being and our own.

Stephen Lea, a psychologist at the University of Exeter, says that recent longitudinal studies provide a new opportunity to investigate the effects of domestication on the evolution of cognition. Quite aside from that, he says, it's hugely important for us to see eye-to-eye with our pets so we can take better care of them: "We have a moral responsibility to ensure that the animals we choose to keep are happy."

—Gareth Willmer

Dance of Ecology

IN A NORTH CAROLINA longleaf pine forest, a Venus flytrap catches vital nutrients missing from the soil, as this hoverfly learned the hard way. (Photograph by Nick Kanakis.) Meanwhile, a plume of spores rises from the gills of a mushroom cap in India. The motes will land on soil suitable for underground filaments that spawn new mushrooms. (Photograph by Sarang Naik.)



These images are finalists from the California Academy of Sciences' BigPicture: Natural World Photography Competition and originally appeared in bioGraphic, an online magazine about science and sustainability.

The Planets with the Giant Diamonds Inside

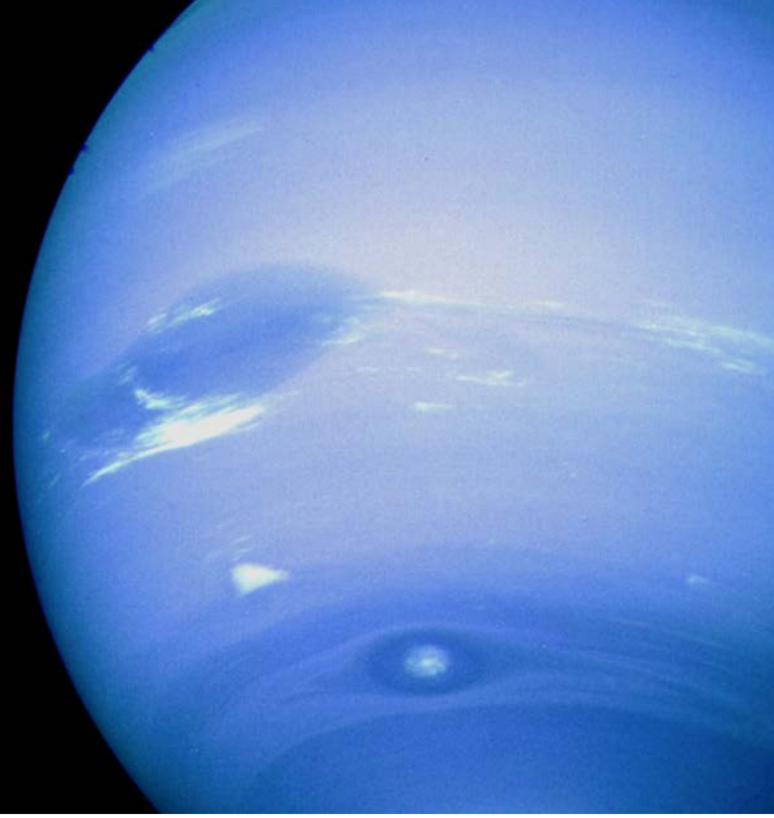
Mining the mysteries of Uranus and Neptune

BY COREY S. POWELL

ON THE DARK NIGHT of March 13, 1781, William Herschel settled down in his garden observatory in Bath, England, for a routine night of observing stars, when he noticed something out of place in the heavens. Through the eyepiece of his homemade 7-foot telescope, he spied an interloper in the constellation Gemini: "a curious, either nebulous star or perhaps a comet," as he recorded it. For weeks, he stalked the unknown object, monitoring its steady appearance and circular path around the sun until there could be no doubt about its true identity. He had discovered not a comet but a new planet, far more distant than any of the others.

Being a politically astute fellow, Herschel proposed naming the planet *Georgium Sidus*, or "George's star," in honor of King George III. The ploy worked—he promptly was named the king's astronomer and received a royal stipend—but his colleagues outside of England objected. They wanted a noble and politically neutral name like Urania, the Greek muse of astronomy. In the end, scientists settled on the even more dignified "Uranus," the ancient Greek god of the sky and ancestor of the other deities. Centuries of snickering ensued.

NASA / JPL



DARK SPOT Neptune's Great Dark Spot (middle) is an anticyclone storm (a hurricane in reverse, with a high-pressure eye) nearly as large as the entire Earth. The Spot is streaked with white clouds of methane ice and surrounded by smaller storms and dark bands circling the entire planet, all tinged a rich, deep blue by methane gas in Neptune's atmosphere.

NASA / JPL

But seriously. Uranus orbits the sun at twice the distance of Saturn, so Herschel's discovery instantly doubled the size of the known solar system. From a modern perspective, it's hard to appreciate how shocking that was. At the time, the solar system was the only charted region of space; nobody yet had a clue about how far away even the nearest stars were. In effect, Herschel had doubled the size of the entire known universe. He also brushed away the final traces of classical astronomy and astrology. Uranus is typically described as the first planet discovered since antiquity, but it's more accurate to say it was the first planet to be *discovered*, period. All the others are readily visible to the naked eye, and so were known to all. Uranus shattered the common assumption that there were no more planets beyond the six classical ones, establishing an endless-frontier ethos that resonates through science and science fiction to this day.

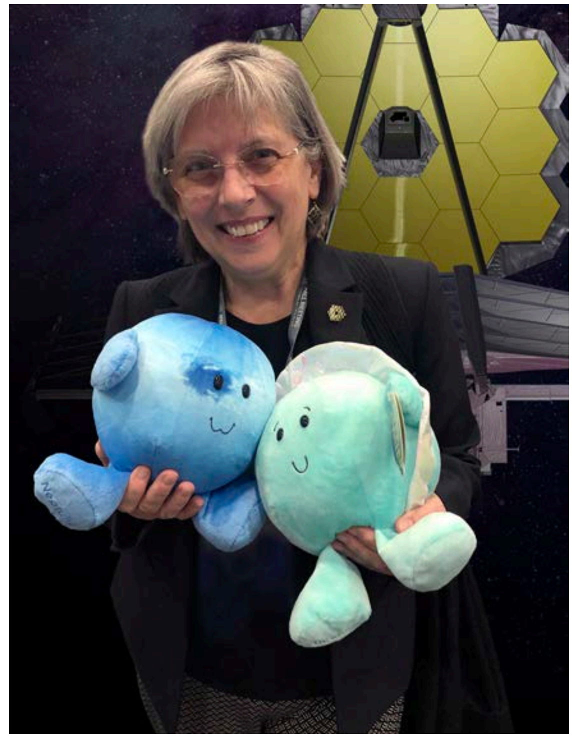
That ethos is part of daily life for Kirby Runyon, a young geomorphologist at Johns Hopkins University's Applied Physics Lab, who is developing new ways to study Uranus and its similar-but-bizarrely-different planetary sister, Neptune. Like the handful of others who study this distant duo, he is enthralled by the boundary-busting nature of the solar system's outermost planets. "What brought me into space science as a professional was the chance to, as *Star Trek* says, 'explore strange, new worlds,'" Runyon says. "If you like seat-of-your-pants, Captain Picard-style exploration, then Uranus and Neptune have to rank high in your list."

You have to admire Runyon's passion. After all, who dreams of a space voyage to Uranus or Neptune? They are not brightly ringed like Saturn, nor do they hold the prospect of life like Mars. The two planets, though, still hold a special status as worlds on the edge. They formed in chaos, at the boundary between the inner, planetary part of our solar system and the outer zone filled with far-flung comets. In this transitional zone, they also took on transitional forms, with a size and composition that places them halfway between gas giant planets like Jupiter and rocky planets like Earth. Astronomers call these in-betweeners "ice giants," and are now finding that such midsize worlds are extremely

The cloudy surfaces of Uranus and Neptune are marked with raging storms and the fastest winds recorded on any planet.

common around other stars. "Neptune and Uranus are the closest analogs in our solar system to the most populous type of planet that we know of," says Heidi Hammel, a veteran researcher of the outer planets who is now at the Association of Universities for Research in Astronomy in Washington, D.C.

Uranus and Neptune are also fascinatingly odd in themselves. Their cloudy surfaces are marked with raging storms and the fastest winds recorded on any planet, while high above they have complex systems of moons, including ones that may harbor buried oceans. All the more shame, then, that only a single spacecraft has ever visited them—and that was more than three decades ago. "They're enigmas because they are so far away," Hammel says wistfully, "but they are such intriguing enigmas."

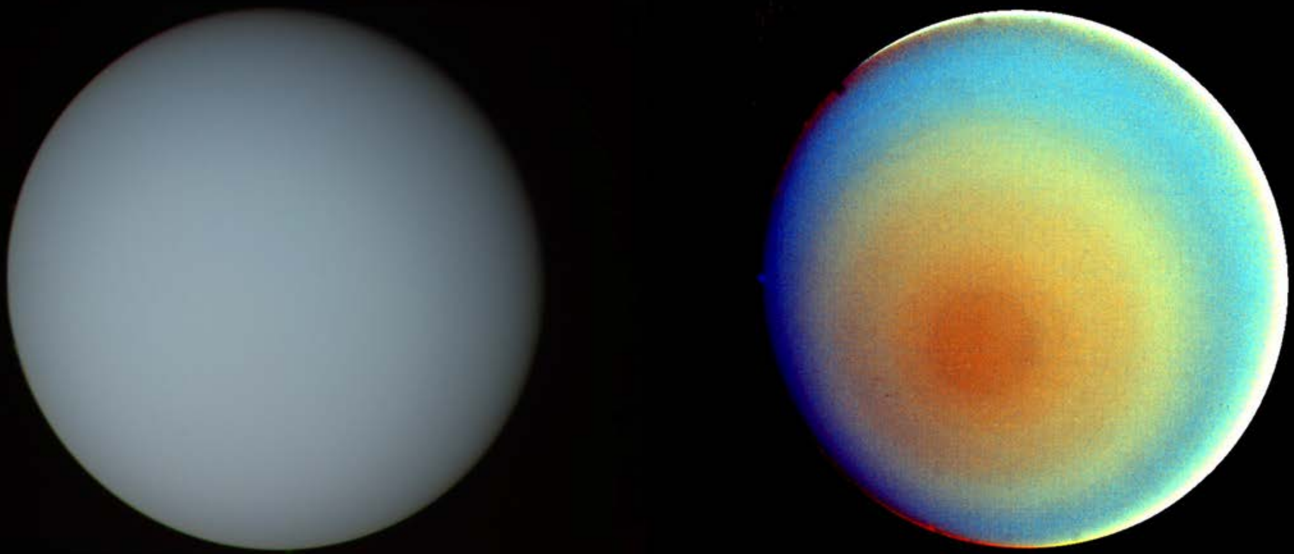


HER FAVORITE THINGS Astronomer Heidi Hammel has been leading research into Neptune and Uranus for decades. Along with the distant planets' own dynamic conditions, she says, they are compelling to astronomers "because they are the closest thing here to analogs of the most populous type of exoplanet that we know of."

NASA / AURA / SHARI LIFSON

LONG BEFORE ANYONE was poking rockets above Earth's atmosphere, Uranus was already directing astronomers on a virtual voyage through the solar system and beyond. In the decades after Herschel's discovery, observations of Uranus indicated that it was deviating from its expected orbit around the sun. By the 1820s, the discrepancy was undeniable: Either Newton's theory of gravity was wrong, or there was some object beyond Uranus that was tugging it off course. "The Newtonian theory appeared to the great majority, perhaps nearly all, astronomers to be the impregnably true system of the world," writes science historian Robert W. Smith.[1] At the same time, the discovery of Uranus had already demonstrated the possibility of more new worlds. Faith in the laws of physics dictated that there must be another, unseen planet out there.

That faith paid off on Sept. 23, 1846, when German astronomer Johann Gottfried Galle—using calculations provided by French mathematician Urbain Le Verrier, in an act of trans-national nerd comity—spotted a new planet less than one degree from its predicted location. The orbital calculations pinpointing its location took years to complete; Galle's visual search for the planet required all of one hour. Galle suggested naming it Janus, the two-faced Roman god, implying that it was facing outward toward the stars. The more optimistic Le Verrier objected. "Janus would indicate that this planet is the last of the solar system, which there is no reason to believe," he wrote.[2] Instead, he proposed Neptune, the god of the sea.



LONG NIGHT Two images of Uranus. On the left, the darker shadings correspond to the day-night boundary on the planet. Beyond lies the hidden northern hemisphere of Uranus, which remains in total darkness as it rotates. The blue-green color (enhanced) results from the absorption of red light by methane gas in Uranus' deep, cold, and remarkably clear atmosphere.

NASA / JPL

The discovery of Neptune was as transformative as that of Uranus, though in a quite different way. Uranus had already expanded the scale of the known universe. Neptune expanded the means by which we could get to know it. When Galle saw the planet exactly where Newton's equations said it should be, he demonstrated that astronomers could detect celestial bodies by gravity alone. Now they could track down objects that had never been observed, perhaps even ones so dark or distant that they fundamentally could not be observed.

Modern cosmologists use the term "dark matter" to refer to invisible mass that is thought to influence the formation and structure of galaxies across the universe; in that sense, the term traces back to a 1933 paper by the Swiss-American cosmologist Fritz Zwicky. But the concept of dark matter truly began with Neptune, the first celestial object ever discovered before it was seen. From there, things escalated quickly. German astronomer Frederick Bessell had been tracking the erratic motions of the bright stars Sirius and Procyon and deduced that they, like Uranus, were being pulled off-course by unseen objects. "The existence of numberless visible stars can prove nothing against the existence of numberless invisible ones," Bessell wrote in 1844.[3] Invisible stars sounded like an oxymoron, but the discovery of Neptune made the outlandish idea seem more plausible. The reality of those dark companions was soon confirmed; in the 1910s the objects were identified as white dwarfs, the faint, collapsed corpses of stars like the sun. Similar detective work in the 1970s led to the discovery of black holes scattered across our galaxy.

In all this excitement, Uranus and Neptune themselves largely got left behind. They languished in scientific obscurity for another century and a half, mostly because they are so damn hard to study. Uranus never comes within 1.6 billion miles of Earth, 40 times as far as Mars; Neptune is a billion miles farther still. Its apparent size in the sky is equivalent to a dime seen from a mile away. The development of deep-sky photography beginning in the late 19th century greatly boosted the study of our galaxy and led directly to the discovery of countless other galaxies beyond. For the ice giant planets, however, the new technology had an opposite effect. When astronomers stopped looking through the eyepiece and started focusing on photographic plates instead, the planets became even more obscure.

"Going back to the 1800s, early observers would look at Uranus and see bands and other features," Hammel says. Their eyes were trained to pick out the fleeting moments when the air becomes steady and fine details pop into view. Photography and early forms of digital imaging couldn't capture those split-seconds of clarity. Instead, they yielded blurry, long-exposure images that suggested the outermost planets were bland and unchanging. "The technology of the time smeared everything out, giving rise to this mythology that Uranus had no cloud features," Hammel laments. "We had a hundred years of misinterpretation."

Then at long last humans developed the technology to visit the ice giants and see them up close … and the misinterpretations just kept coming. On Jan. 24, 1986, NASA's Voyager 2 swooped over Uranus's cloud tops and sent back picture after picture of a featureless blue-green orb. By bad luck, the spacecraft had arrived at the beginning of summer in the planet's northern hemisphere, a time when the global weather turns hazy and bland. The Voyager 2 images cemented the idea of Uranus as a boring planet—a knock that still galls Hammel. "It was like, 'Let me show you a picture of what I looked like on one day in 1986.' That doesn't give you an understanding of who I am as a person," she says.

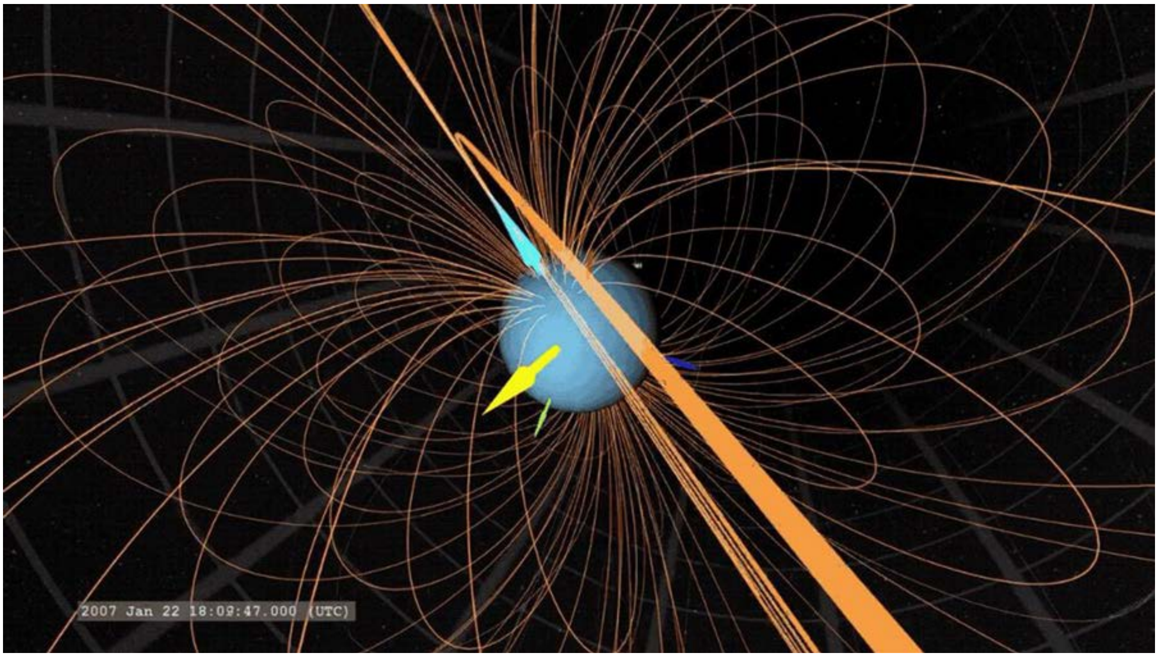
The Voyager flyby did offer hints that there's more to Uranus than meets the eye. The planet has a system of thin, dark rings, which turn out to contain large chunks—possibly the remains of a moon that was destroyed long ago. More surprising, Voyager's instruments showed that Uranus's magnetic field is tilted 60 degrees relative to its axis, as if your compass needle pointed to Houston instead of the north pole. There must be a huge, lopsided magnetic generator cranking away inside the planet, which leaves Hammel buzzing with questions: "What kind of internal structure can do *that*? Is it stable? Does it change over time?"

But the reputation of the ice giants didn't really recover until Voyager 2 reached Neptune on Aug. 25, 1989. Unlike its sibling, Neptune was a riot of activity. It seemed to be staring back at the spacecraft with its Great Dark Spot, an anticyclone storm (a hurricane in reverse, with a high-pressure eye) nearly as large as the entire Earth. The Spot was streaked with white clouds of methane ice and surrounded by smaller storms and dark bands circling the entire planet, all tinged a rich, deep blue by methane gas in Neptune's atmosphere. Beautiful, complex, and not at all boring.

The concept of dark matter actually began with Neptune, the first celestial object ever discovered before it was seen.

THE VOYAGER RESULTS REVEALED that weather operates differently on ice giants than it does here on Earth, for reasons that scientists are only starting to decipher. "Wind speeds increase as you go farther out from the sun, which is weird," says Amy Simon, a Uranus and Neptune enthusiast at NASA's Goddard Space Flight Center. On Uranus, they blow at 550 mph, as fast as a jet airplane at cruising speed. On Neptune, the winds are even fiercer, averaging 700 mph and gusting to 1,500 mph around the Great Dark Spot. They manage to pick up tremendous energy, even though Neptune receives just 1/900th as much solar heat as Earth does.

Seasons on the ice giants are also unlike anything seen on Earth or anywhere else. For one thing, the seasons are extreme, especially on Uranus: The planet is tipped sideways, so its poles spend half the time in perpetual sunshine and the other half in total darkness. For another, seasons take a long time to change, because the ice giants follow huge, lazy paths around the sun. Uranus takes 84 years to complete a single orbit, and Neptune takes 165 years. Neptune's



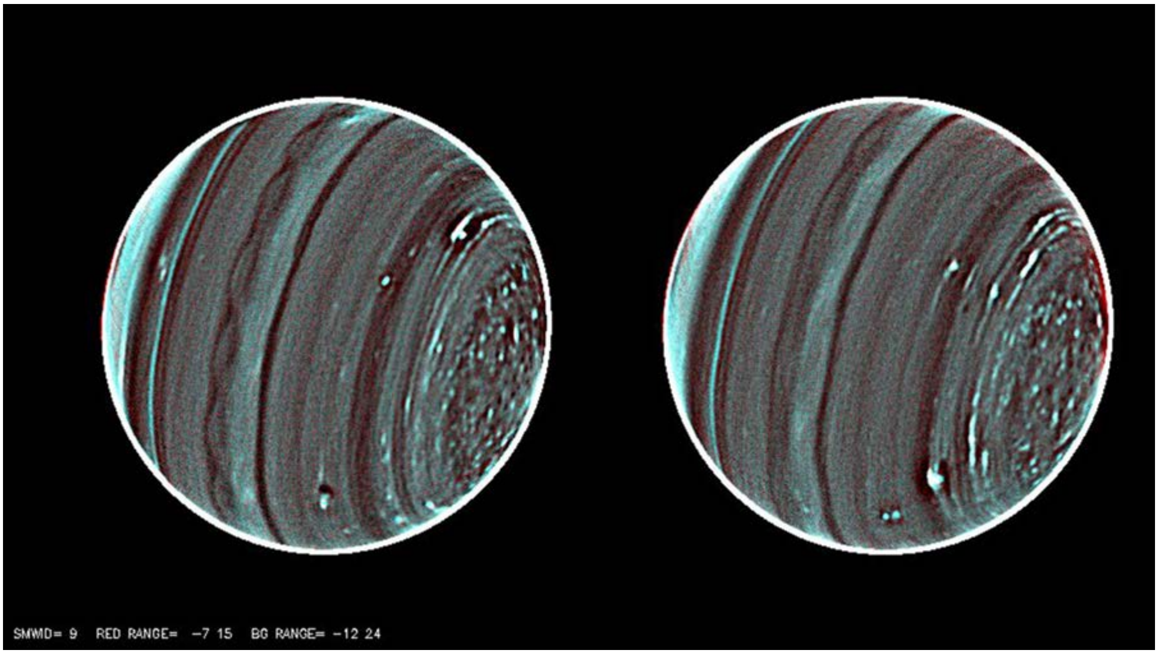
TILT NASA Voyager's instruments showed that Uranus' magnetic field is tilted 60 degrees relative to its axis, as if your compass needle pointed to Houston instead of the north pole. This image shows the magnetic field. The yellow arrow points to the sun, the light blue arrow marks Uranus' magnetic axis, and the dark blue arrow marks Uranus' rotation axis.

NASA / SCIENTIFIC VISUALIZATION STUDIO / TOM BRIDGMAN

northern hemisphere was heading into winter when Voyager flew by in 1989.[4] Springtime won't arrive until 2038. The ice giants have both the fastest and the slowest climates in the solar system, which makes them useful as extreme natural laboratories. "We run the same weather and climate codes we use on Earth, and we learn about unknown sensitivities or details that aren't quite right," Simon says. "And if someday we want to apply these codes to planets around other stars, they'd better work across our whole solar system first."

In 2014, belatedly acknowledging the mad complexity of weather on the ice giants, NASA greenlit the Outer Planet Atmospheres Legacy program, or OPAL, with Simon in charge; her glorious official title is Senior Scientist for Planetary Atmospheres Research. Once a year, OPAL takes over the Hubble Space Telescope and turns it into an outer-planet weather satellite, monitoring conditions on Uranus and Neptune (and Jupiter and Saturn, for good measure), with Simon as the interplanetary weathercaster.

For the first time, scientists have both the time and the clarity of vision to learn the long-term personalities of Uranus and Neptune. Simon's reserved demeanor



LAWRENCE SROMOVSKY, PAT FRY, HEIDI HAMMEL, IMKE DE PATER / UNIVERSITY OF WISCONSIN-MADISON

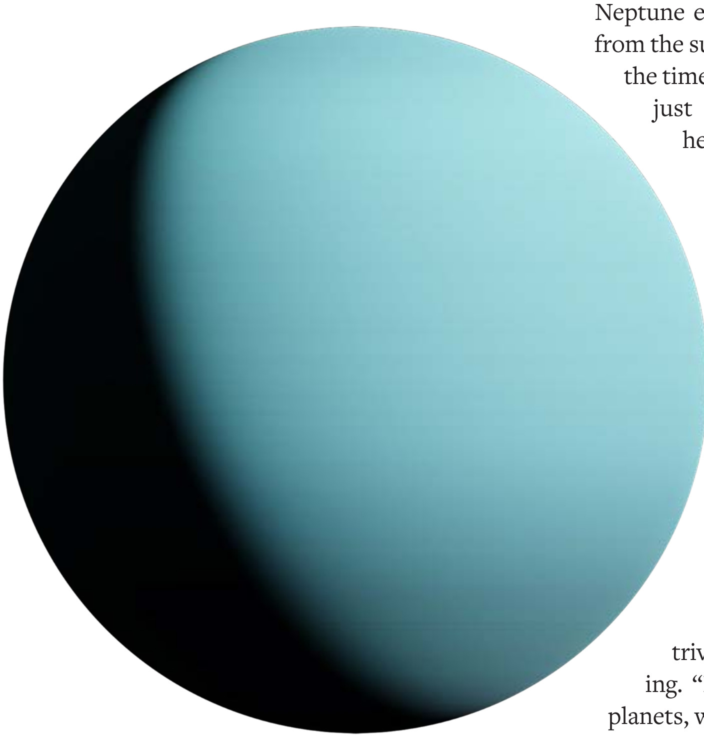
STORMY WEATHER These images of Uranus, taken by the Keck II telescope in Hawaii, are the sharpest, most detailed pictures of the planet to date, according to NASA. The north pole (to the right) is characterized by a swarm of storm-like features, and an unusual scalloped pattern of clouds encircles the planet's equator.

lights up when she describes the quirks she has been observing on her planets. As Uranus has progressed from northern summer to late autumn, its weather has transitioned from hazy to crazy. "We see a polar cap that has gotten really bright and thick. And we've seen little storms. They tend to break apart really fast, on order of an hour, because the high winds shear things apart very quickly," she says. Those changes demonstrate that even tiny variations in solar energy can transform the weather of a giant planet, nearly four times the size of Earth.

On Neptune, the most significant finding from OPAL is that the activity just never ends. "The big thing we've found has been the dark spots. In our few years of monitoring, we've seen two more of them. One was already there when we started, and it disappeared over a couple of years. The other one formed in 2019. After they form, the dark spots start to drift in latitude, just like a hurricane on Earth, until eventually they break apart," Simon says.

It's not clear what maintains all of this activity. One possible explanation, Hammel notes, is that the planets' ultra-cold air is almost frictionless, so it takes very little kick to get big storm systems going. One important

Uranus is tipped sideways, so its poles spend half the time in perpetual sunshine and the other half in total darkness.

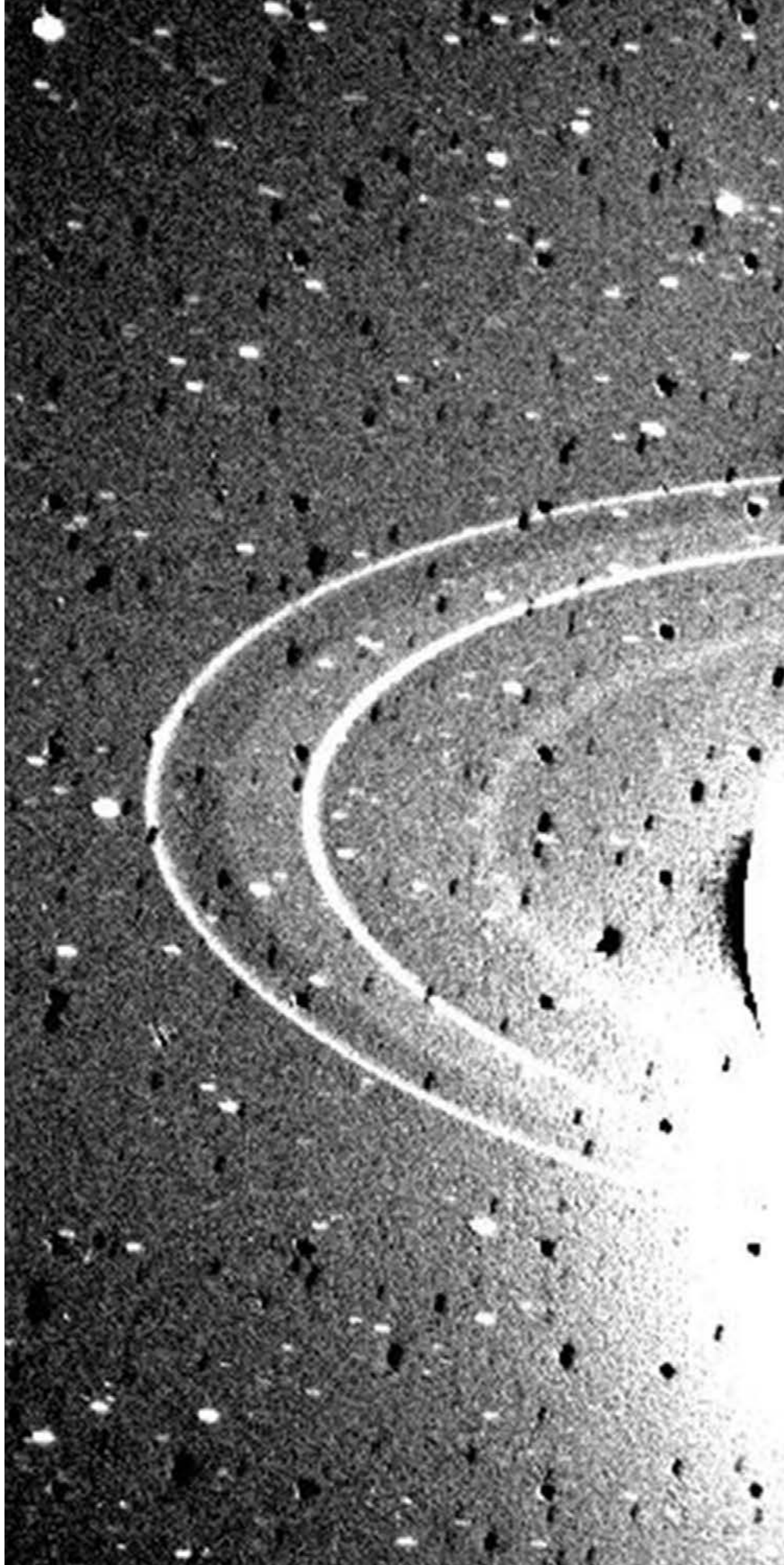


clue is that the two ice giants behave quite differently, despite being almost identical in mass, composition, and diameter. “Uranus and Neptune don’t look much alike at all. We see a lot more of the discrete storms on Neptune than on Uranus, and we don’t see much of a bright polar cap,” Simon says.

The disparity hints at stark differences deep inside the two ice giants. Voyager measurements showed that Neptune emits 2.7 times as much heat as it receives from the sun, apparently retaining a lot of energy from the time of its formation. Uranus, in contrast, sheds just a trickle of additional warmth. “Internal heat’s got to be a much bigger factor than the sunlight in driving the weather, but we’re still trying to puzzle some of that out,” says Simon. If anything, it adds another layer of mystery: Why is Neptune so much hotter under the collar than Uranus? One hypothesis is that Uranus had a near-fatal encounter with a huge protoplanet, twice as massive as Earth, some 4.5 billion years ago. The collision could have knocked it over, explaining its sideways tilt, while scrambling its interior in a way that allowed its primordial warmth to escape: one tidy explanation for two major oddities.

“It’s a nice idea, but it seems a bit contrived,” Simon says, her measured tone returning. “Every time we think we understand these planets, we realize we don’t.”

DANIEL ROBERTS / PIXABAY



NEPTUNE'S RINGS

NASA Voyager captured Neptune's rings in 1989. The long-exposure images were taken while the rings were back-lighted by the sun, which enhances the visibility of dust. The two gaps in the upper part of the outer ring (on the left) are due to blemish removal in the computer processing.

NASA/JPL

FIRST IMPRESSIONS In 1989, members of the NASA Voyager science team pore over images of Neptune's moon Triton as data from Voyager 2 stream into Jet Propulsion Laboratory. Today, young scientists like Kirby Runyon remain just as excited studying the two planets. "If you like seat-of-your-pants, Captain Picard-style exploration, then Uranus and Neptune have to rank high in your list," Runyon says.

NASA / JPL / CALTECH

ONE WAY TO LEARN MORE about the ice giants is to get under their skin, by recreating them in the lab. Based on what they can measure and infer about their overall composition, planetary scientists have deduced that both Uranus and Neptune must contain vast quantities of water, ammonia, and methane on the inside. In everyday life, we'd call that combination "Windex and natural gas." Inside the ice giants, however, these molecules mingle together into a slush that astronomers refer to generically as "ice"—hence the term ice giants. Recent experiments show that it is not like any ice you have ever seen, however.

Dominik Kraus, a physicist at the University of Rostock in Germany, leads a group of researchers who have

Inside Uranus and Neptune, diamonds could grow to the size of a person, raining down toward the core of the planet.

been shooting X-ray lasers at simulated bits of ice-giant material, heating and compressing it to match conditions in the planets' interiors. He finds that the carbon atoms spontaneously break free of their molecules and arrange themselves into diamonds. Inside Uranus and Neptune, such diamonds could grow to the size of a person, slowly raining down toward the core of the planet. The diamond rain would release energy and stir up huge currents, possibly explaining the unusual magnetic fields of Uranus and Neptune.

In parallel work, Marius Millot at Lawrence Livermore National Laboratory and his colleagues subjected water molecules to similarly extreme conditions and found that it turns into previously unseen material, "superionic ice"—a hot, black, crystalline version of water, also known as Ice XVIII. It sounds exotic, but maybe it shouldn't. Given how much water is inside the ice giants, and given how many ice giants astronomers are finding around other stars, superionic ice may actually be the most common form of water in the universe. Black ice and diamond rain could be the norm; lakes and rivers and lumps of coal may be the cosmic oddities.

Another way to know more about the ice giants is to look at the company they keep—the large systems of moons that orbit Uranus and Neptune. Like Uranus itself, its moons are tilted at a rakish, 98-degree angle. No other planet is oriented that way. Whatever knocked the planet over evidently took its moons along for the ride. "If a large impact tipped the whole planet on its side, then the gravitational excess from Uranus's equatorial bulge would have pulled its whole system of moons to be on its side as well," says Runyon.

The moons of Neptune document a whole other style of disaster, one that spared the planet but unleashed pandemonium around it. Neptune's system of moons is overwhelmingly dominated by a single large one, Triton, surrounded by 13 much smaller bodies, mostly in irregular, looping orbits. Triton orbits the planet in a clockwise direction, the opposite of every other planet and major moon, indicating that it formed separately and later got snared by Neptune. When that happened, it must have rolled through the Neptunian system like a bowling ball, as Runyon explains: "The gravitational interactions from Triton probably scattered Neptune's original system of moons. If there were

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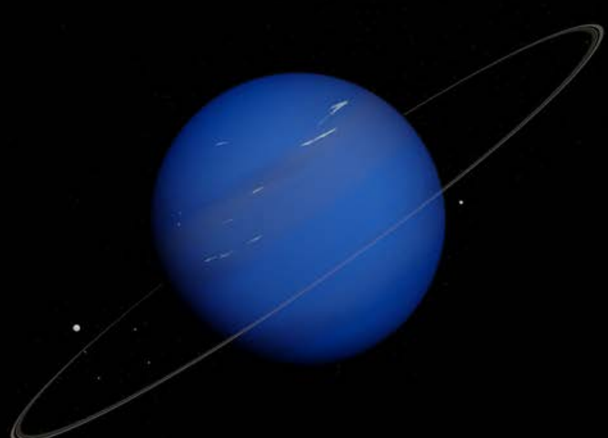

rings, it would have scattered them, too." The current moons either reassembled from the wreckage or were captured afterward. Triton also left behind a set of thin, clumpy rings that bunch together in arcs, unlike any other formation in the solar system.

The Voyager 2 flybys of the 1980s unveiled the ice-giant moons as a set of distinctive worlds. The five main moons of Uranus display ancient chasms, ripples, and hints of volcanic flows—all made of frozen water and other ices instead of rock. The two largest, Ariel and Titania, appear to have been geologically active for an extended period of time. The smallest, Miranda, is a jumble of formations that looks like a jigsaw puzzle that was put together by an inattentive child; nobody knows how it got that way. But the true marvel is Triton, a geologically youthful world that resembles a cantaloupe, its surface sculpted by "cryovolcanic" eruptions of water-ammonia lava. Triton is also dotted with active geysers, likely caused by the explosive defrosting of underground nitrogen. To the amazement of mission scientists, Voyager 2 sent back images of sooty plumes shooting 5 miles into the air and trailing for hundreds of miles.

Triton broadly resembles Pluto, but it is in many ways the wilder and more exciting of the duo (not to keep dumping on the dwarf planet, but facts are facts). It is about 15 percent larger than Pluto and, more significantly, it is more geologically active, with liquid water sloshing away underground. That's right: A moon around the coldest, most distant planet in the solar system contains a huge, underground ocean. "Triton is exchanging gravitational energy with Neptune, so it's warm and gooey on the inside," Runyon says. "On Earth, living things like warm, gooey places. If you put Earth microbes in that warm, gooey Triton ocean, they would probably survive and proliferate. Which raises the possibility, since we don't really know how things go from non-life to life, that Triton could be a habitable and inhabited world."

He's not saying aliens, mind you. He's just saying there *could* be aliens.

DESPITE ALL OF THESE INSIGHTS, we are in many ways still at the handshake stage of getting to know the ice giants. The OPAL program watches the

95C / PIXABAY

planets for less than one day a year. Voyager 2 gathered only limited information about the planet's composition and internal structure. The flybys happened so quickly that the spacecraft saw just one side of the Uranian and Neptunian moons. "There's that whole unexplored other half. We don't know what the heck is happening on the rest of Triton," Simon says.

The yearning for deeper familiarity is even more acute now that astronomers recognize Uranus and Neptune as prototypes of billions of similar worlds all across our galaxy. Right now, these exoplanets—planets around other stars—are true cyphers. Astronomers can deduce their sizes, masses, densities, and not much else. Still, that's enough to tell that many of them seem like slightly shrunken versions of Neptune, with thick, toxic atmospheres. Others, just a wee bit smaller, seem to be rocky "super-Earths." Nobody knows why this dividing line exists, or whether super-Earths could be habitable. For that matter, nobody yet knows whether ocean moons like Triton can support life. When you're dealing with ice giants, you get used to the three-word mantra: We don't know.

That mantra explains why Runyon just completed an intense round of work as project scientist on Neptune Odyssey, a proposed flagship—that is, multi-billion-dollar—NASA mission that would perform an extended survey of Neptune and Triton while dropping a probe into Neptune's atmosphere. The technology exists to mount an ambitious expedition like this. Even the sober analysts at the National Academy of Sciences have identified an ice-giant mission as a high scientific priority. Unfortunately, these kinds of projects keep getting shot down. Earlier this year, NASA came close to approving Trident, a stripped-down mission to Triton, but passed it over in favor of a pair of probes to Venus.

A big part of the problem is the waiting. It took Voyager 2 a dozen years to reach Neptune. If Trident had been approved, it wouldn't have reached its destination until 2038—and even then, it would have sent back just another snapshot. If you want to study the ice giants, you have to adapt to their pace of doing things. No one researcher is going to live long enough to witness a full cycle of seasons on Uranus, much less on Neptune. The last mission to an ice giant happened 32 years ago, and realistically the next one is not likely to arrive until the 2040s at the earliest; this is inevitably going to be a multi-generational effort. Heidi Hammel (age 0.37 Neptune years) has been at it so long that she has largely moved on to administrative work. "This is sad to say, Corey, but I kind of don't do astronomy anymore," she confesses. But she's encouraged to see people like Kirby Runyon (a spritely 0.21 Neptune years) entering the field.

Until someone invents warp drive or the like, there is no way to overcome the obstacle of time. The only path forward is embracing extreme patience as the cost—or the joy—of pressing into the unknown. After he discovered Uranus, Herschel explained it was not luck but persistence that brought the planet into view. "I examined every star of the heavens," he wrote. That night in 1783 was Uranus' "*turn* to be discovered." Perhaps now it is the ice giants' turn to be truly known, in all of their weird and wonderful glory.

COREY S. POWELL is a science editor, writer, and ice-giant lover living in Brooklyn, NY. He co-hosts the Science Rules podcast with Bill Nye.

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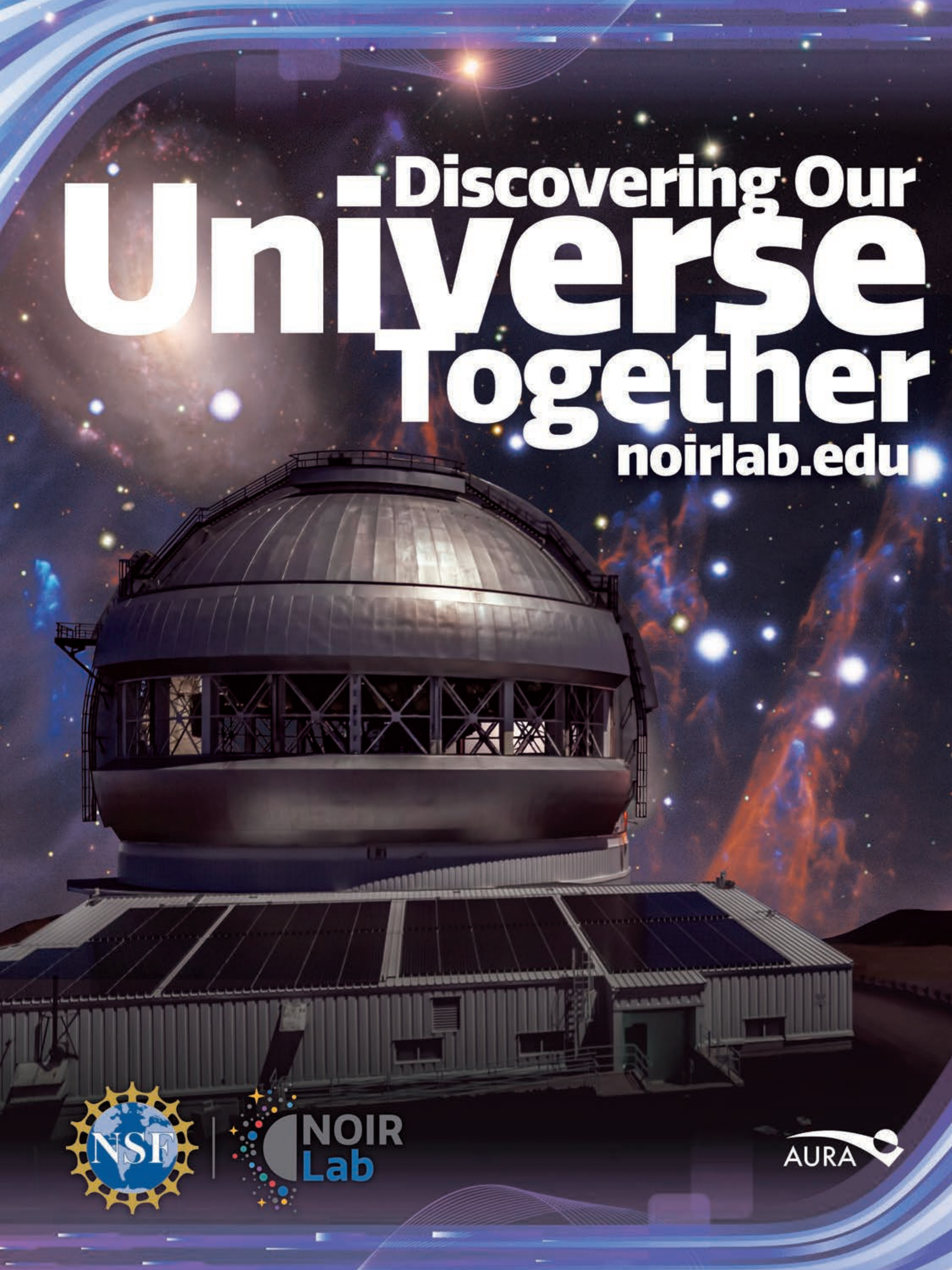
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The English Professor Who Foresaw Modern Neuroscience

Science and the humanities weren't separate cultures to this critic

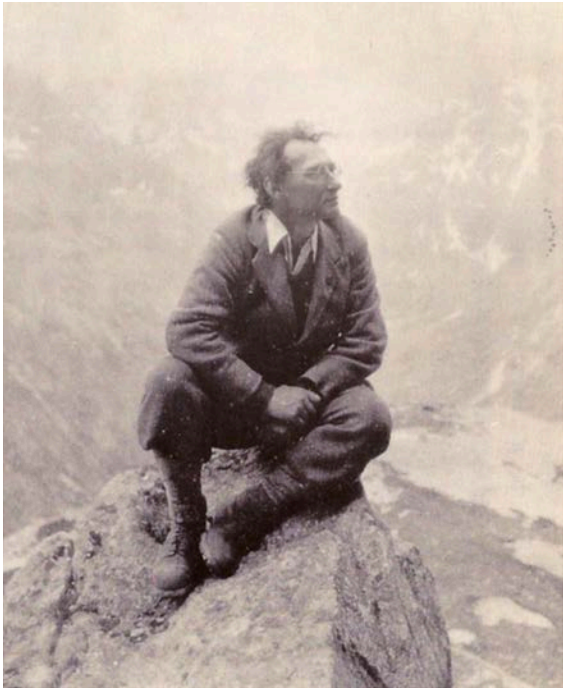
BY CHRISTOPHER COMER & ASHLEY TAGGART

IN THE 21ST CENTURY, neuroscience has been able to extend our understanding of the brain beyond brain anatomy to an increasingly functional view of cognition. Every year brings new insights on memory and imagination, and reveals often surprising areas of convergence with fields such as anthropology and philosophy. Yet it was a Cambridge professor of literature, almost a century ago in the aftermath of World War I, who pioneered a view of cognition we can recognize as strikingly modern, and who appreciated what we are only now beginning to rediscover: the great potential of interactions between the narrative arts and brain science.

At the opening of the 20th century, such interdisciplinarity was resisted. Academic culture was defined by specialists in silos. One who refused to be confined was English critic I.A. Richards. A tubercular child who missed several years of school, Richards' idea of recovery was to dedicate himself to mountaineering, spending much of his undergraduate career free-climbing the spires and turrets of his college at Cambridge. With his wife Dorothy Pilley, Richards ascended peaks in the Alps and elsewhere, such as those in Montana's Glacier National Park.

An advocate of the empirical study of literature, Richards thought of himself as an "inventor" more than a critic. In his groundbreaking *Principles of Literary Criticism*, published in 1924, Richards laid out a perspective which was deeply unsettling to his contemporaries: "A book is a machine to think with." Richards brought neurobiological perspectives to an understanding of our literary mind in an era when historical and biographical criticism was the norm, and the teaching of literature remained based on grammar and rhetoric. Indeed, he was thinking so far beyond the literary criticism and science of his day that we are still catching up.

SERGEY NIVENS / SHUTTERSTOCK



NEW HEIGHTS I.A. Richards was an adventurer in both his personal and professional lives. He was an avid mountain climber who took literary criticism to new heights. He passionately believed it was a glaring omission to ignore the workings of the brain in the process of analyzing the creative mind.

With *Principles of Literary Criticism* and its follow-up, *Practical Criticism*, Richards argued literature should be studied in its own right. Reputedly, his lectures at the School of Literature at Cambridge in the 1920s were so popular they had to be held in the streets. He advocated the "close reading" of texts, attending to sensory and emotional specificity and the play of ambiguity. This attitude became the hallmark of a new group that included Richards and his students, William Empson and F.R. Leavis, who became known as "New Critics." But science—in particular neuroscience—also became involved at this vital juncture.

This was due to an extraordinary proposal made by Richards. In *Principles of Literary Criticism*, he asserted that to establish an effective critical stance, one had to base it upon a view of the mind, identifying the mental state created by a work of art. His description of what is required of the critic was phrased in terms that would not sound out of place in a neuroscience discussion today.

Richards argued that we have a need for "a schema of the mental events which make up the experience of 'looking at' a picture or 'reading' a poem." Perhaps even more surprising, Richards delivered a highly delineated description, a compact conjectural map, of the mental steps involved in reading and interpreting a poem. Richards' thinking was broad, encompassing the physiological processes of reading as well as the psychological processes of reader response. His model emerged in a period when the school of thought dominating psychology was behaviorism, which explicitly rejected analysis of what was going on inside the organism, or the brain, in favor of the study of overt behavior. Mental imagery and imagination lay well outside the range of the behaviorists' own theoretical maps.

Richards' "hieroglyph" as he humorously dubbed it, suggested that images of words on a page are projected from the eyes to a system of repeating modular units in the brain that perform sequential operations in response to them; for example, evoking images, or emotions. While Richards stressed his sketch was not meant to be "a picture of the nervous system," it was clearly inspired by information about neural architecture. The elements within his modular units are reminiscent of nerve cells. Indeed, the whole structure is suggestive of what was then known about the functional organization of the outer layers of the cerebrum: the cortex (which has six recognized layers, even designated I-VI as in Richards' model).

Richards' model shows a line from a poem by Robert Browning, digested for meaning one word at a time. Recent research confirms this is a generally accurate depiction of how we read: A sentence is not comprehended all at once or even in a smooth stream; rather, our eyes make a series of jumps, called saccades, across the lines of text. As they alight briefly, the eyes acquire the image of a group of letters roughly equal to one word and then immediately jump farther along, pausing to sample another word or two. That such eye movements underlie comprehension has been known since the work of psychologists such as E.B. Huey in the early 1900s. Clearly, Richards was incorporating the best

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He was thinking so far beyond the literary criticism and science of his day that we are still catching up.

available experimental knowledge of the time. Even now, the complexities of eye movements continue to inform our understanding of reading dynamics, cognition, and literacy.

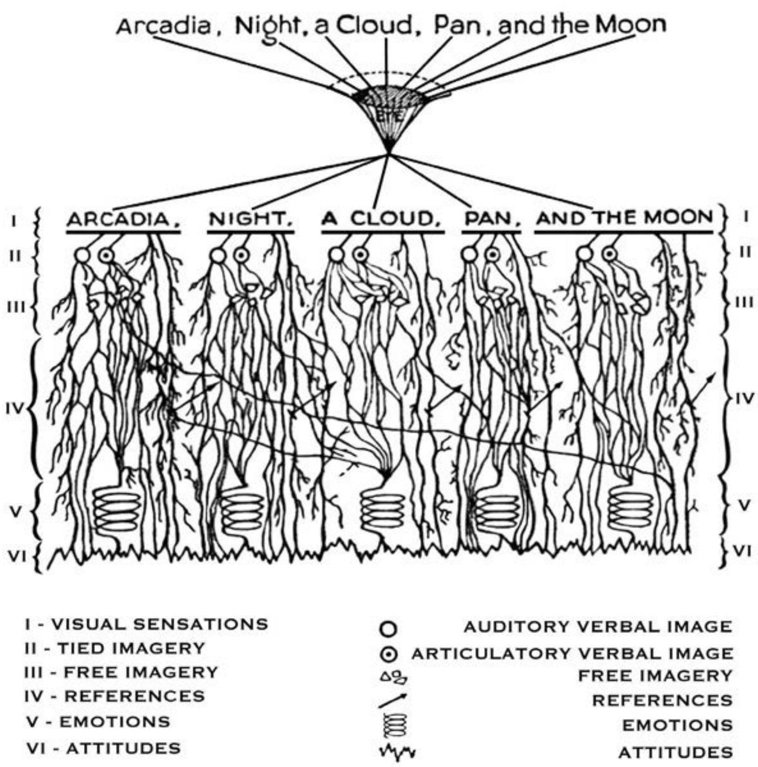
Most striking are the mental functions specified in Richards' model, really a set of steps that comprise our cognitive reactions to text. The brain first responds to the visual sensation of clusters of letters (layer I). This is followed by the elicitation of imagery in multiple modalities (II and III) and stored associations, triggered by words or phrases (IV). Layers II–IV might be best interpreted as calling up things remembered or imagined, whereas the final layers (V and VI) relate to the evocation of emotions and attitudes. Richards' conjectured dynamics, in which the serial processing of word images blends with the early involvement of memory and emotion, is consistent with current psychology and neuroscience.[1]

So where did this amazing model come from? Richards acknowledged later in life that it was inspired by the ideas of a neuroscientist: Charles Scott Sherrington. In the course of a long and illustrious career, Sherrington coined the terms "synapse" (the functional connection between neurons) and "proprioception" (the brain's sense of the state and position of the body), with publications on reflexes as fundamental sensorimotor mechanisms, and the structural organization of the primate cerebral cortex. He was awarded the Nobel Prize in 1932.

Sherrington had been a student, then a fellow, at Cambridge before 1900. His legacy was deep and well known to Richards, who arrived there in 1912. The profound imprint of Sherrington's neurophysiology is evident in the overall form of Richards' model and the language he used to describe it, outlining the competing "impulses" flowing through the system, and the resultant states of "equipoise," or balance, between them. This closely paralleled Sherrington's sense of the feedback between neural pathways when rival signals—positive (excitatory) and negative (inhibitory)—are integrated to ensure coordinated control of posture and movement. Richards' model incorporated the latest neurological thinking of his time, but went beyond to draw connections to full cognitive engagement with literature. With typical irreverence, he was later to tell his biographer that he "just translated Shelley into Sherrington."[2] It's a revelation that neuroscience was there at the birth of modern literary theory.

Richards' early foray into neurophysiology foreshadowed to a remarkable extent other recent discoveries about the processes behind reading. He emphasized the importance of memory for the critical reception of all arts because "there is no kind of mental activity in which memory does not intervene," sounding very modern indeed. Further, his work was current when Frederick Bartlett was conducting his classic studies (1932) in which he was able—from following people's ability to recall elements of stories—to show that memories are not "snapshots in time," but rather narrative constructions. Even more recently, it has been noted that Richards' ideas on cognition in 1924 were a form of "proto" connectionism in which memory was not based on fixed, archive-like properties, but instead was based on nonsymbolic and distributed forms of representation.[3]

As a critic, Richards was fascinated with the role of imagination in literary reception, suggesting profound connections between it and memory. He wrote that "imaginative construction is always at least as much determined by what is going on in the present, as by what went on in the past, pasts rather, whence it



BRAIN POETRY Richards created this chart in the 1920s. It shows a line from a poem by Robert Browning. Recent research confirms this is generally how we read: A sentence is not comprehended all at once; rather, our eyes make a series of jumps.

ADAPTED FROM *PRINCIPLES OF LITERARY CRITICISM* BY I.A. RICHARDS (1924)

springs." One of the most intriguing and productive insights of psychology and neuroscience in the early 21st century has added substance to Richards' intuition. By 2007, several neural and psychological studies showed that memory and imagination are indeed highly related processes, both occurring in multiple forms—some implicit, some explicit—and both are highly constructive. Moreover, remembering past events and imagining future ones share similar cognitive network space within the brain.[4]

Richards also had a lifelong interest in how meanings are established from words and phrases, with an early cowritten volume cheekily entitled *The Meaning of Meaning* (1923). Here again he was ahead of what the technology of the time could achieve. Recent neuroscience has confirmed his intuition that reading-derived semantic information is stored widely across the cerebral cortex and, like an atlas, word relationships appear to be clustered there by a modest number of categories of knowledge.[5]

We are now at the point where it is even possible to follow the synchronous "ticking" of several brains at once, indicating the more or less orchestrated consistency of responses to story features, and how the degree of temporal coupling between brains correlates with more effective communication. Multi-brain neuroscience offers real hope for a more empirical understanding of narratives in their natural context: as they resonate between an author and a reader, or a storyteller and an audience.[6]

Richards laid out a deeply unsettling perspective to his contemporaries: "A book is a machine to think with."

We are a storytelling species, every bit as much as a tool-using one, so it's perhaps fitting that insights from the narrative arts keep pressing their claims on neuroscience. Ingenious experiments are casting new light on what it means to hear a fictional character speak, feel their emotion, visualize an invented scene, or experience a story world. Narratives provide a rich and ever-more accessible cognitive terrain for literary creativity, virtual play, and serious analysis. Brain science is now mapping that terrain and has much to share with, and much to learn from, the humanists who got there first, especially I.A. Richards.

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Tarzan Wasn't for Her

It took an outsider to restore women to the story of human evolution

BY ERIKA LORRAINE MILAM

ELAINE MORGAN HAD SASS. In *Descent of Woman*, published in 1972, she asked her readers to take science into their own hands. "Try a bit of fieldwork," she suggested. "Go out of your front door and try to spot some live specimens of *Homo sapiens* in his natural habitat. It shouldn't be difficult because the species is protected by law and in no immediate danger of extinction." After completing observations of 20 random people, she suggested, substitute them when you are reading statements about universal human nature. The result?

> "That window cleaner is one of the most sophisticated predators the world has ever seen."
>
> "The weapon is my grocer's principal [sic] means of expression, and his only means of resolving differences."
>
> "The postman's aggressive drive has acquired a paranoid potential because his young remain dependent for a prolonged period."

Morgan added that you might imagine you were observing the wrong species and urged her readers to trust their experiences. "Remember," she wrote, "you have been living among thousands of these large carnivores all your life, on more intimate terms than those on which Jane Goodall lived among the chimpanzees."

In positing such a scenario, Morgan was engaged in serious work. All popular theories of human evolution to date, she insisted, were based on a male-centered notion of human evolution. Where were the evolutionary scenarios that began, "When the first ancestor of the human race descended from the trees, she had not yet developed the mighty brain that was to distinguish her so sharply from all the other species…"? This formed one of two major points Morgan wished to make in *Descent of Woman*.

The second was to advance a theory of aquatic adaptation that preceded life on the savannah. In semi-adaptation to a watery world, she imagined, humanity's ancestors may have lost their body hair, gained a layer of subcutaneous fat to keep them warm, learned to walk upright (keeping their heads above water while foraging for tasty snacks in the shallows), came to use stones and manufacture tools for breaking open shells, and developed the ability to control their breathing when diving beneath the surface—a precondition for true spoken language and an obvious boon to any individual trying to communicate with most of her body submerged.

In short, Morgan suggested humans acquired precisely those traits that distinguish them from the rest of the animal world while living around water, not in the arid grasslands. These activities, she noted, were associated with gathering, not hunting, an activity in which women's contributions were widely acknowledged.

Morgan's story tells us as much about the gendering of evolutionary theory during the Cold War as it does about the history of scientific debates that take place in the public eye. She submitted her manuscript to Souvenir Press with the title *The Evolution of Eve*. Just before publication, she changed it to *Descent of Woman*. "Woman," she reasoned, was a commercially appealing word in the late 1960s and she worried too that "Eve" would sound old-fashioned and Biblical to the younger, female readers she hoped to attract. Her publisher was persuaded because the title echoed Charles Darwin's *Descent of Man*, which in 1971 was enjoying a centennial moment, as it is again in 2021. Setting aside questions of feminism, Morgan's critics decried her work for its lack of concrete evidence. In this way, the popularity of evolutionary books served to amplify the political import of the theories they contained. These books also constituted a foil for professional scientists seeking to forge their own scientific standing.

DESCENT OF WOMAN fit well into a genre of colloquial science that aimed to present scientific arguments to readers with common sense but little scientific training. Such books provided scientific authors with a venue for rendering their ideas in a more conversational tone than they would be allowed in standard academic venues and provided non-scientifically trained authors, like Morgan, with opportunities to contribute to public debates over scientific ideas. By relying on arguments and evidence intelligible to nonscientific audiences, these books sold well. They were also left open to marginalization by the scientific community.

Morgan was Oxford-educated (in English), the mother of three children, lived in Wales, and had been writing screenplays and dramas for the BBC for decades. When she turned her attention to nonfiction, it was out of irritation with the evolutionary books of the time that emphasized the contributions of men. The aggressive masculinity they advanced left little room for women and, in stark opposition to these volumes, Morgan was read as a radical feminist with a sense of humor.

Morgan derided male-centered theories of human evolution as "Tarzanist."

When Robert Ardrey published his bestselling *African Genesis* in 1961, it was merely the first in a series of books depicting man as an aggressive hunter. Ardrey, an early advocate of paleoanthropologist Raymond Dart's "killer ape" theory, suggested that "even in the first long days of our beginnings we held in our hand the weapon, an instrument somewhat older than ourselves." Weapons preceded humanity, weapons fathered humanity. (Just think of the "Dawn of Man" sequence in *2001: A Space Odyssey*.) In his next nonfiction foray—*The Territorial Imperative*—it became clear that by mankind Ardrey really had meant men, and the violence with which he was preoccupied was associated with male members of a group defending their common territory against outsiders. Evolutionary pressures on groups of men, intent on hunting to support the women and children safe in camp and cooperating to defend their home from hostile incursions, drove the increased intelligence that came to characterize all humanity.

Zoologist Desmond Morris, on the other hand, was initially more preoccupied with sex than violence or male-male bonding. In the first paragraph of the introduction to *The Naked Ape*, Morris suggested that *Homo sapiens* "is proud that he has the biggest brain of all the primates, but attempts to conceal the fact that he also has the biggest penis." In contrast to Ardrey, he emphasized the development of a pair bond between adult males and females. The pair bond ensured that females remained faithful to their individual males when hunting duties called males away from camp; it reduced serious sexual rivalries between males which aided in the development of male cooperation; and the young benefited from a cohesive family unit.

Women had been ignored by the "blood-and-thunder boys."

Such a process, he was careful to add, "was never really perfected," but was a crucial component of his new ecological role as a "lethal carnivore."

Morgan had first come across the idea of an aquatic phase in humanity's deep history while reading a scant two pages that Morris devoted to the concept. She contacted the theory's originator—Sir Alistair Hardy—and asked whether he would mind if she worked on a book responding to the contemporary theories of human evolution and developing his suggestion. Like Ardrey, she may have believed that artists and writers were well-developed students of human nature, despite their lack of anthropological training. Hardy, who had conceptualized the aquatic theory 30 years earlier, initially refused to publish anything on it lest he ruin his nascent academic career. At the time, he had plenty of experience at sea and in marine biology, but lacked a permanent post. In 1960, as a recently knighted and well-established professor of zoology at Oxford, he agreed to write a brief article in *The New Scientist* proposing an aquatic past for humanity. It was to be Hardy's only publication on the topic, and he was more than happy to let Morgan run with it.

Morgan derided male-centered theories of human evolution as "Tarzanist," and her frustration with them is palpable when reading *Descent of Woman*. The scientific facts used to buttress their arguments were unassailable, she insisted, but not the interpretations of those facts. She further noted that the term "man" was ambiguous, denoting both the entire species and also the males of the species. The trick was not to confuse the two. Adding carefully that although this might sound like "a piece of feminist petulance" to some, Morgan hoped to convince her readers that

EVOLUTION'S LIB This photo of Elaine Morgan accompanied the Book of the Month Club flier for her 1972 book, *Descent of Woman*, a cultural breakthrough. A *Playboy* review stated "even the most militant male chauvinist will find it difficult to cling to all his prior convictions in the face of the evidence marshaled here."

her semantic point vitiated much of the "speculation" concerning the evolutionary origins of humanity.

Further, Morgan contended that based on the available evidence it was impossible to distinguish weapons from tools and impossible to know which sex invented them. "A knife is a weapon or a tool according to whether you use it for disemboweling your enemy or for chopping parsley." In fact, she reasoned, it was likely that early humans used tools for both purposes—the strict dichotomy between herbivores and carnivores in our past was never clean-cut.

Why, then, were such assumptions about the importance of men to the evolutionary progress of humanity so widespread? Morgan chalked this up to a combination of male pride and egotism. She extensively quoted Ardrey's *Territorial Imperative* in order to rebut his characterization of men as baboon-like. A male baboon, he had written, "is born a bully, a born criminal, a born candidate for the hangman's noose. He is as submissive as a truck, as inoffensive as a bulldozer, as gentle as a power-driven lawnmower. He has predator inclinations and enjoys nothing better than killing and devouring the newborn fawns of the delicate gazelle."

Morgan imagined that a male reader would naturally find this characterization appealing. She pictured him polishing his glasses, thinking: "Yeah, that's me all right. Tell me more about the bulldozer and how I ravaged that delicate gazelle." The reason such theories continued to be popular was because Ardrey's typical reader, like the author, enjoyed the idea of "all that power and passion and brutal virility ... seething within him, just below the skin, only barely held in leash by the conscious control of his intellect."

It was high time, she thought, to expose these arguments for what they really were—myths, yes, but politically useful myths. Morgan argued that man-the-hunter theories were used to "bolster up with pseudo-history and pseudo-anthropology the belief that it is 'against nature' for women to play a part in economic life." Based on evidence from modern hunter-gatherer societies, she noted that the bulk of the total diet of early humans was probably the result of gathering vegetable matter, not hunting meat. Women *were* important to the evolutionary history of humanity, but had been ignored by the "blood-and-thunder boys."

REVIEWS OF *DESCENT OF WOMAN* picked up on Morgan's none-too-subtle revisionist agenda. *Playboy* hailed it as a "stunning tour de force," speculating that, "even the most militant male chauvinist will find it difficult to cling to all his prior convictions in the face of the evidence marshaled here." Similarly, *Life* magazine described *Descent of Woman* as a lively "women's-lib prehistory." Several reviewers missed that Morgan didn't have any anthropological training, describing her as "a female anthropologist," and "a scholarly woman, educated at Oxford in the fields of paleontology, ethology, and anthropology." Yet even when people recognized her outsider status, they still acknowledged the force of her arguments against the then-standard evolutionary history of humanity. Her reviewer in *The New York Times*, for example, characterized *Descent of Woman* as "a potent commentary on the state of the social sciences in general, and anthropology in particular."

By the late 1970s, even scientists cited Morgan's *Descent of Woman* as an early critique of "man the hunter" theories of human evolution. Yet although Morgan's critique was useful, it came packaged along with her interest in Hardy's aquatic ape. Physical anthropologist Adrienne Zihlman lamented that Morgan's sensible and "substantial critique of existing evolutionary dogma did not get the attention and credibility it deserved," because it had been "contaminated by Morgan's own elaboration and support of a very dubious theory of human origins, the 'Aquatic Ape' hypothesis." Zihlman regretted the visibility of Morgan's writings because she feared readers might get the mistaken impression *Descent of Woman* was the best feminist anthropology could offer.

"Tell me more about the bulldozer and how I ravaged that delicate gazelle."

Morgan was aware that her interest in the aquatic ape might be perceived as outside the normal bounds of science. In a 1973 interview she remarked that perhaps it was easier for her to develop these ideas than for an established scientist (one can only assume she meant Hardy), because she had "nothing to lose, no high academic position to think of." She added, "if you talk about flying saucers you're branded a kook. I don't believe in flying saucers but I suppose this kind of thing looks flying-saucerish to the Establishment."

In fact, this was exactly what "Establishment" science thought. Her reviewer in *The New York Times*, for example (although he had lauded her critique of contemporary anthropology), suggested that her characterization of human ancestors as including "a breed of sea beasts" should be consumed along "with a grain or two of salt." Several years later, Zihlman, together with physician Jerold Lowenstein, wrote a brief article for *Oceans* magazine in which they compared the "Aquatic Ape Theory" to "the existence of bigfoot" and "visitors from outer space." After analyzing key aspects of the evidence, they concluded, "the Aquatic Ape Theory does not hold water, anatomically, biochemically, behaviorally or archaeologically. With a similar combination of imagination, a grab bag of unrelated 'facts' and a popular literary style, one could make an equally convincing case that our ancestors evolved in the air—as von Daniken has more or less done in his cult book *Chariots of the Gods*?"

Despite this dismissal, and with some urging from an American fan, Morgan wrote a second book, *The Aquatic Ape*, in 1982, in which she re-presented her evidence in more scientific terms. This time, she included figures illustrating her points and, notably, her prose no longer contained the feminist critique which had been so well received in her first book. Scientists remained skeptical. One reviewer noted, "Until some hard evidence is found, though, I fear we are left with several equally convincing theories floating in a sea of speculation." Lowenstein, too, remained unconvinced, remarking, "It is fun to make up evolutionary fables." Unfazed by such criticisms, Morgan published *The Scars of Evolution* in 1990 and *The Descent of the Child* five years later, each updating her evidence to reflect more recent findings. And although most scientists continued to dismiss her ideas as speculative or pseudoscientific, a small number became intrigued.

Morgan's critics used the aquatic ape theory to delegitimize feminist science.

The first sign of interest came in the form of a 1987 conference organized to debate the theory, which included both advocates and detractors. Most of the supporters, however, lacked anthropological training, including, for example, Derek Ellis, a marine ecologist from the University of Victoria in Canada, and Marc Verhaegen, a Belgian physician. Ellis argued that the aquatic ape was ecologically viable and called for scientists to test the theory, rather than dismissing it out of hand. (Anthropologists, of course, felt it *had* been evaluated.) Verhaegen, along with a handful of other scientists, began to amass new kinds of evidentiary support for an aquatic phase in human history. They argued that chimpanzees and bonobos were known to walk upright while wading in shallow water and when carrying objects in their arms, that recent paleontological evidence suggested that early hominins spent more time in swampy or coastal forests than on the savannah, and that foods high in fatty acids (like fish) could have been important to the increased brain development in our ancestors.

Anthropologists, with a few notable exceptions, have been far more reticent. The first convert was Philip Tobias, former student of Raymond Dart. Like Ellis, he came to insist that the aquatic ape needed a fair hearing. More recently, well-respected professors Richard Wrangham (biological anthropologist), Dorothy Cheney (primatologist), and Robert Seyfarth (psychologist) published a paper in which they suggested that early human ancestors used aquatic environments to forage for fallback foods, like water lilies and floodplain herbs, when their preferred foods were unavailable, and the aquatic environment in which these foods are found could have helped human ancestors become bipedal.[1]

There are several important points to note about this history of the aquatic ape. The theory itself remains controversial; all of these claims have been challenged in the scientific literature.[2] Additionally, none of the recent papers supporting an aquatic (or semi-aquatic) environment for human ancestors mention or cite Morgan or Hardy by name—to find the connection, you must look in the footnotes of the papers they do cite. Scientific theories can thus become separated from their most ardent supporters, even (perhaps especially) in cases where the equation is almost iconic.

Historians of science have spilled much ink on the demarcation question, asking how scientists and philosophers have tried to cleanly differentiate legitimate scientific inquiry from "non-science," "pseudoscience," "pathological" science, or even simply "bad" science. In considering Morgan's case, we can see that in addition to these hard demarcations, scientists in the 1970s also used feminist science as a tool of soft demarcation. By labeling Morgan's *Descent of Woman* "feminist anthropology" they sidestepped her critique and used the aquatic ape to delegitimize feminist science as a whole—precisely the reason Zihlman attacked the book as pseudoscientific. Emulating the efforts of many fringe scientists, Morgan responded by re-articulating her argument and her evidence with each new publication, in an attempt to rehabilitate her claims by presenting them in a style and language scientists would take seriously.

In order for Morgan's ideas to be considered plausible, they had to be stripped of her sharp feminist wit, dissociated from Morgan herself, and repackaged as legitimate science. In this form, her ideas are now getting the professional hearing she always wanted. In 2005, Morgan was asked whether she still felt like an "outsider" in biology. "Not nearly as much as I used to," she replied.

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This essay is adapted from "Dunking the Tarzanists: Elaine Morgan and the Aquatic Ape Theory." Reprinted with permission from *Outsider Scientists: Routes to Innovation in Biology* edited by Oren Harman and Michael R. Dietrich, published by The University of Chicago Press. Featured text by Erika Lorraine Milam. © 2013 by The University of Chicago. All rights reserved.

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Science Isn't Here for Your Mommy Shaming

When people sensationalize research, parents pay the price

BY CAILIN O'CONNOR

A **FEW YEARS AGO**, *Time* magazine published an article titled, “Cell-Phone Distracted Parenting Can Have Long Term Consequences.”[1] It reported research supposedly showing that “distracted parental attention” could hurt infant development, and especially a baby’s ability to feel pleasure later on. What exactly did this research study? Did it directly measure parental cell phone usage and test infant cognition? Did it carefully document day-to-day distractions in the lives of caregivers?

Not exactly. The article was based on the results of a single study where researchers deprived rats of nesting material.[2] These stressed rat mothers provided fragmented care to their pups, who, researchers later found, went on to develop emotional problems—as measured by their likelihood to consume sugar solution (low) and play with peers (low). Using animal models to tell us something about humans is entirely routine, and this scientific technique is an important one when it is costly, difficult, or unethical to experiment on humans directly. But it raises methodological problems. Rats aren’t humans, and insufficient bedding is not cell phone use.

Can we really draw conclusions about people using rat models? The answer is "yes," but we have to be careful in doing so. We need critical thinking about which features of a rat experiment do or do not match up with features of the human condition. In this case, a bit of critical thinking reveals that very little is shared between the experiment and its target. Clearly someone in the science-to-public process got tempted by the desire to tell a big, juicy story, rather than stick to a particularly accurate portrayal of the research. The problem is that this is all too common when it comes to popular work on parenting, and parents suffer as a result.

That was, of course, far from the first popular science article to draw questionable conclusions from scientific research. A few years ago, a set of popular articles with titles like "Drinking a Glass of Red Wine is as Healthy as an Hour at the Gym,"[3] reported research on resveratrol, a component in red wine. The study fed resveratrol to rats and found that it improved their exercise performance. But the study said almost nothing about wine, or about exercise in humans. As the lead author later pointed out, "If you're drinking red wine to get resveratrol, you would have to drink anywhere from 100 to 1,000 bottles per day."[4]

WHILE THIS SORT of misreporting is nothing new, the *Time* article reflects a wider, worrying trend—the use of scientific findings to promote unrealistic standards for modern parents. The term "mommy shaming" was added to Urban Dictionary in 2017 following a number of high-profile cases where mothers were publicly shamed for their parenting choices. In 2016, for instance, a lowland gorilla named Harambe had to be shot after a 3-year-old climbed into his enclosure. The event was followed by a massive Internet pile-on blaming the child's mother for Harambe's death.[5] She was widely criticized for failing to watch her child, and for not jumping in after to save him.

Of course, the vast majority of mommy-shaming happens in a much more mundane way. Most mothers will have stories—strangers commenting on breastfeeding choices, in-laws expressing dismay at a child's lack of discipline, the cashier who thinks junior is too old for a pacifier. I myself have never forgotten the older man who shouted at me to put a hat on my baby on a cool, cloudy day in February. Of course, fathers get these comments too, but mothers, as the public face of parenting, are the disproportionate victims of mommy-shaming.

> *Articles that make confident claims about parenting on the basis of shoddy evidence can fuel the fire—giving mommy-shamers unwarranted confidence to scold parents.*

Why do mommy-shamers feel justified in sharing un-asked-for judgments with people they may not even know? These judgments are often motivated by a desire to do right by the child. It has been pointed out that during the COVID-19 pandemic mommy-shaming has reached a fever pitch[6] as parents make new, difficult decisions about schooling, podding, and quarantining, often under enormous uncertainty. The people involved in these debates desperately want to protect the children involved.

But despite good intentions, specific instances of mommy-shaming are often harmful and unjustified. In many cases mommy-shaming involves advice that makes life harder for parents, and offers minimal, if any, benefits for the child. In other cases, like those surrounding COVID-19, the people involved simply cannot know whether their opinions are the right ones, regardless of how certain they may feel.

Popular science articles that make confident claims about parenting on the basis of shoddy evidence can fuel the fire—giving mommy-shamers unwarranted confidence to scold and cajole parents. And what's worse, too often these articles reflect social beliefs

PAGES 50-51: GOODSTUDIO / SHUTTERSTOCK

> *The problem arises when our social expectations shape the ways we interpret scientific data so that it confirms those exact social expectations.*

about what parents ought to do, rather than the other way around. While it may seem like science should lead the charge in establishing good parenting guidelines, instead norms about parenting tend to shape how the science is interpreted and communicated. This can lead to a vicious feedback cycle.

Philosophers of science argue that, when interpreting scientific results, we always, necessarily, draw on a broad web of shared belief. This has to be the case, because without some theory to help us understand the world, our observations do not mean much. In cosmology, for instance, it takes an enormous amount of background knowledge to know that certain patterns of vibrations on Earth indicate the collision of black holes 1.3 billion light-years from us. To make this jump from data to theory, we need to know about black holes, about gravitational waves, about our sensors, etc. In cases like this, it isn't bad to use our current beliefs to understand what we observe in science—it's necessary. But things can go wrong when doubtful social beliefs come into play.

Let's turn back to the rats study. Should moms be focusing on their phones and not their kids? Your gut might tell you "no." It just feels wrong. Generally, we have an idea in our society that moms should be attentive 100 percent of the time at the risk of depriving kids of the love they need to flourish. A good mother should always be thoughtful, patient, and deeply focused on her children.

Given these beliefs, we shouldn't be surprised when we see an article confirming what we already think—moms shouldn't be on their cell phones. Social beliefs, about what moms ought to be doing, come into play when we determine whether rats without bedding tell us something about moms answering work emails at the park. If we didn't already have a suspicion that the mom laughing at funny memes is shirking her duties, we might be more skeptical about the applicability of this study to humans.

This pattern repeats itself again and again. While parents are shamed for using cell phones themselves, they are also shamed over children's screen time. In 2019, it was widely reported that cell phone use was leading to the growth of "horns," especially in teenagers.[7] The central claim was that head position during cell use prompted bone spurs—relabeled as "horns" by overenthusiastic journalists—to form at the back of the neck. Critics quickly pointed out issues[8] with the original study[9]—that there was no actual measure of cell phone use, that the sample was drawn from chiropractic patients rather than the general population, and that there were contradictions in the data. But the message was already out there: Cell phones are literally reforming the bone structure of teens! In part, this is a story about poor research, but it is also a story about a public very ready to believe that cell phones harm children.

Diet is also a hot topic when it comes to social beliefs about what people, and especially mothers, ought to be doing. Take a press release this month, out of the University of California, Riverside, which proclaims, "Eating too much fat and sugar as a child can alter your microbiome for life."[10] Again, the original study was performed on mice, not humans.[11] The article implies, though, that early diet can decrease a human child's microbiome diversity after puberty, causing lasting harm from failures to provide ideal nutrition.

It makes perfect sense to find out as much as we can about how best to raise our children. The problem arises when our social expectations shape the ways we interpret scientific data so that it confirms those exact social expectations. Then science just becomes one more stick to prod parents with: A *Daily Mail* article[12] draws on research of 40-day-old hamsters to

It is incumbent on both scientists and journalists to take better care when interpreting and communicating research.

claim that teenage sex leads to mood disorders later in life; a summary of research[13] in *Science* claims that parents who don't talk enough to their babies stunt their word processing development even though the results rely on correlational data in houses high and low in socioeconomic status, rather than establishing a true causal link; a CBS article,[14] again based only on correlational data, suggests that giving children too much candy may cause violent, criminal behavior later in life. We could go on and on,[15] looking at the history of reporting on fetal alcohol syndrome, "crack babies," "refrigerator mothers," etc.

Part of the problem here stems from the way that data flows from the scientific community to the rest of society. Scientists are under pressure to yield "big-impact" findings. Results that get a lot of attention tend to get more citations, garner invitations to speak and publish, and lead to more successful scientific careers. This sometimes creates perverse incentives, where scientists benefit by presenting their research in the most exciting light, rather than with maximal accuracy. And scientists are savvy enough to understand that an article about cell phone use in parents will be much more impactful than one about bedding supplies in rats. A host of background beliefs and assumptions help determine what interpretations of evidence will be palatable, and those beliefs are not necessarily friendly to parents.

Scientists are not the only ones seeking to drive readership. Journalists, likewise, are under enormous pressure to produce pieces that capture attention. And, likewise, they understand that an article about the dangers of teen sex is much more likely to go viral than an article about the dangers of sex in hamsters. Across the pieces discussed in this article, in some cases the scientists involved promoted irresponsible interpretations of their work, in other cases journalists took liberties in communicating otherwise responsible science. It is incumbent on both scientists and journalists to take better care when interpreting and communicating research.

So, if you read something that sounds suspiciously mommy shame-y, or otherwise conveniently flatters self-serving beliefs you already hold, take a few minutes to dig deeper. Do the results really support the claims being made? Or are the writers using science to simply reinforce our strong feelings about what moms ought to be doing? In the case of red wine and exercise, based on my correspondence with the lead author on the study, it seems that a journalist simply invented the "one glass of red wine = one hour of exercise" claim, and others followed suit in a bizarre game of science-communication telephone.

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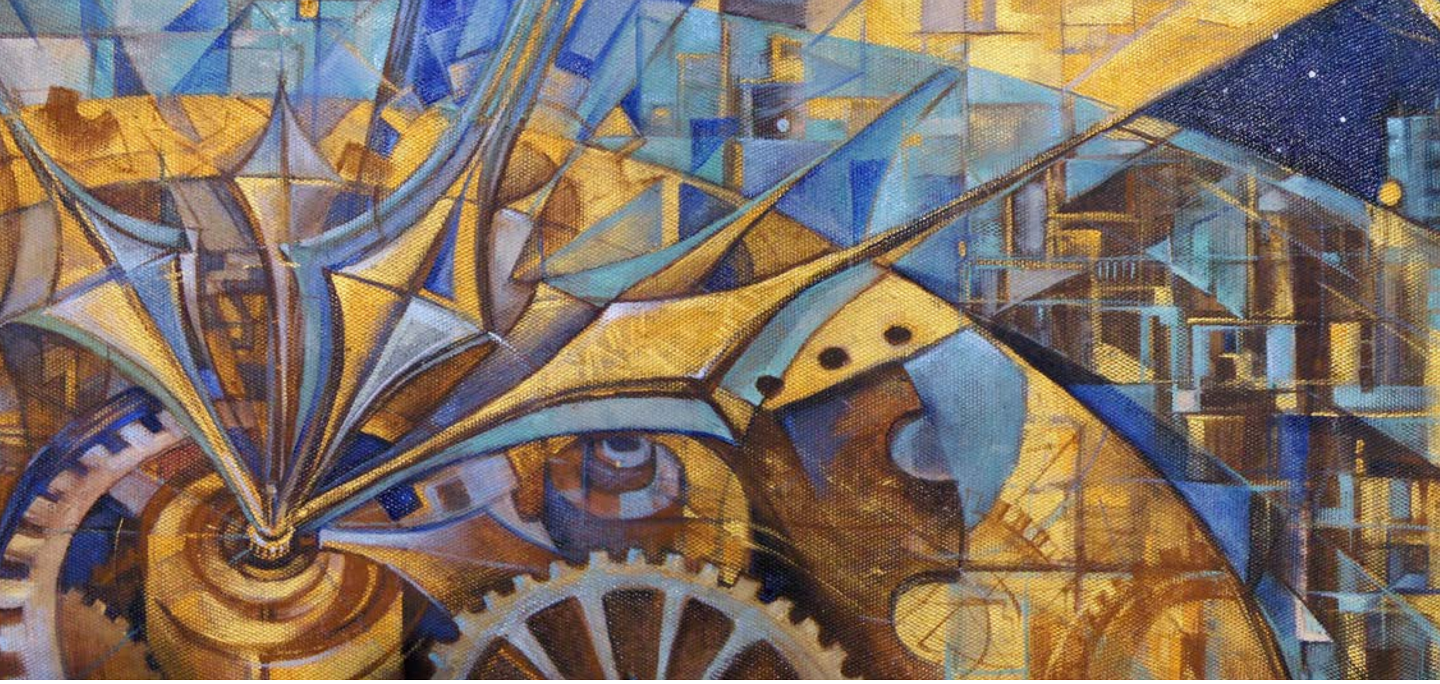

Is the Universe Open-Ended?

An intriguing proposal about what makes reality tick under the surface

BY CALEB SCHARF

ONE OF MY FAVORITE albeit heavily paraphrased quotes from Albert Einstein is his assertion that the most incomprehensible thing about the universe is that it is comprehensible. (What he actually said, in his 1936 work "Physics and Reality," is more longwinded, and includes a digression into Immanuel Kant and the meaning of "comprehensibility," but he does write "... the eternal mystery of the world is its comprehensibility.") In truth, this statement holds back a little. The greater mystery is that the universe is actually capable of self-comprehension.

NINA EZHIK / SHUTTERSTOCK

From a time nearly 14 billion years ago when all matter and energy existed in an exquisitely uniform and boring state, the cosmos has evolved to contain complex structures that—in at least one tiny spot in our solar system—have gained mysterious things like agency and consciousness that compel them to try to decode reality. In doing so they (meaning we) also produce interpreted versions of reality that they place in a "dataome."

By dataome, I mean all of the data (and the information it contains) that we generate, utilize, and propagate but which is not encoded in our DNA. The dataome encompasses cave paintings to books, flash drives to cloud servers, and all the structures built in service of those things. We exist in an uneasy symbiosis with this dataome, whose interests may not always align with ours even though the information it carries for us is critical for our evolutionary success. That includes the information we create describing our experience of reality itself.

Every equation of physics or every computer simulation of how planets, stars, and galaxies orbit and evolve is a bizarre imprint of an interpretation of the universe by the universe, built into the universe by the rearrangement of its atoms into a dataome. But there's an even deeper perspective: Was all of this really inevitable? Did we ever have a choice in creating a dataome or doing any of the things we do, and does any self-aware entity in the universe have a choice either?

In a wonderfully lively, and extraordinarily ideas-dense, near 70-page long 2013 essay titled "The Ghost in the Quantum Turing Machine," the theoretical computer scientist Scott Aaronson goes deep in search of arguments for and against such free will. It's such fun that I want to spend some time with it here. He points out that many of us conflate the idea of random unpredictability with free will. For example, I can feel like I'm exerting free will if I, well, I don't know, spontaneously write the word "sponge" here. It certainly seems entirely random.

That, Aaronson argues, is probably not right because what we call randomness actually follows well-defined statistical rules of probability, and in that sense is never "free." Its unpredictability is predictable. By contrast there is a class of unpredictable phenomena that can't be measured by random probabilities; they have a different form of unpredictability. This is described by a property called *Knightian uncertainty* after one Frank Knight, an economist working on these ideas in the 1920s. In modern vernacular this is very much like the "black swan event" idea popularized skillfully by the writer and mathematical thinker Nassim Taleb. A black swan event is extremely rare, impacts the world greatly, and has explanations invented for it after the fact. But if that event or behavior can't ever be objectively quantified by probabilities it's likely in the category of Knightian uncertainty.

Here's an example based off of Aaronson's explanation: Imagine that a computer program generates random numbers as part of its operation. Perhaps it's picking random color mixtures for its screen-saver. But if it picks the number 669988 there is a bug in its code that will cause it to crash. The original programmer knew this, but since 669988 is merely one choice out of a million possibilities for this six-digit number, they decided those were acceptable odds.

However, what if the code instead asks a human to provide a random six-digit number? The programmer cannot possibly know how likely it is for 669988 to be input. It could be a person's lucky number, there could be some weird human predisposition to these digits. Instead of being predictably unpredictable it is simply unpredictable, and cannot be described by straightforward mathematical probabilities. Instead it reflects the free will of a human being.

But if you are a physicist (or a proper philosopher) you might pick a fight with this. That's because, you'd say, what a human does at any moment is ultimately a consequence of a very long, very complex, chain of events. Each of those events can be broken down to individual interactions and occurrences of atoms and electrons, photons, and laws that—even if probabilistic—do still describe all options at all times; they're all predictably unpredictable. And that includes things like quantum uncertainty. Surely we can always explain a human action, or anything else, by simply going far enough down this chain of random things. In this case there is no genuine free will; no real Knightian uncertainty in the base pieces of reality.

There is no neat and tidy probabilistic solution. It will never be known why the chicken crossed the road.

Aaronson argues that if the very earliest (quantum) state of the universe has Knightian uncertainty then things are more interesting. The precise state of the new universe need not be determined by the statistical rules of randomness. It could be just as weirdly unpredictable as the previous example of someone perversely guessing the code-crashing number. In this case the information that describes that state—and subsequently all states that the universe will take on, including all of its atoms, us, and any aliens—can be considered (in Aaronson's terminology) as being made of "freebits." And freebits are kind of like the last word in cosmic choice.

These freebits also have to be quantum in nature. That means they are also "qubits"—the version of plain old 1 and 0 bits that applies to objects and systems exhibiting quantum behavior. They are fuzzy, undetermined things until called upon and snapped into focus. That's a complication that I'm going to avoid really dealing with, because it will really make our heads hurt. Luckily, to get a sense of where freebits lead us doesn't require knowing all of those details.

The story to pay attention to is simply that these freebits could stick around throughout the history of the universe. Or, to turn this the other way: Suppose you want to track back the chain of events that led to a specific incident—something interesting in a physics experiment, or a chicken crossing the road. For some incidents there will be a chain that goes *all the way back* to the original freebits. And because those freebits obey Knightian uncertainty it means that there is no ultimate answer for why you saw what you saw, no neat and tidy final, probabilistic solution. It will never, ever be known why the chicken crossed the road.

That could, perhaps, also apply to structures like the human brain and its thoughts. If we could disentangle the untold quadrillions of molecular and atomic interactions and chained events in a brain, and the ever-so-subtle nudges of quantum uncertainty here and there, we might find that it all leads back to the original freebits, thereby restoring some kind of free will to ourselves. I'm not suggesting any sort of daft mystical quantum-brain connection; this is all just physics (well, all physics-at-the-boundary-with-philosophy). But it could well be that your spontaneous decision to place an unsuspecting chicken at the roadside is truly Knightian, with a lineage going all the way back to the Big Bang.

Yet, this also implies that there are only so many ways that anything can happen in the cosmos, only so many ways that history could unfurl. It's rather like taking a cross-country road trip from one continental coastline to another: You only have so many places you can start from, and each will influence where you end up. Is the universe truly open-ended in its capacity to generate informational novelty? Perhaps not entirely.

You might, if you've survived reading this far, be wondering how many freebits we're talking about. After all, the knowable universe is big but decidedly finite. We can only ever observe the realm of the cosmos from which light has had time to reach us since the Big Bang some 13.8 billion years ago. This is tricky, but we can actually estimate the maximum number of any kind of bits (not just freebits) in the observable universe as approximately ten-to-the-power-of-122 (or 10^{122}). The implication is that this is the limit of the number of interesting things that can *ever happen* in the universe. No do-overs, no extras, this is it.

TO BE FREE If we could disentangle the quadrillions of molecular and atomic interactions in a brain, and the ever-so-subtle nudges of quantum uncertainty, we might restore some kind of free will to ourselves.

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But this also means that freebits, and bits, are getting "used up" over time. Indeed, they must be for events to occur. And this brings us full-circle back to the classical physics ideas of the laws of thermodynamics and entropy, and the Landauer limit on energy needed to erase bits. Storing and accessing information means using energy. But if you use energy you have to maintain or increase the entropy of the cosmos (generally speaking). If there are a finite number of bits in all of reality, even if a huge number like 10^{122}, then eventually the universe runs out of ways to change its entropy, and its bits.

Randomness follows well-defined statistical rules of probability, and in that sense is never "free."

At this point the story connects to the far, far, far cosmic future in which everything is in thermal equilibrium: Space is at the same temperature, everywhere. There are no hot and cold spots, no ways for energy to flow from warm things to chilly things. No more bits to flip and the universe ends up as a tepid bath, full of nothing but regrets. (Although regrets imply information, and there would be no way to access that at this late stage.)

Is any of this a valid description of the world that has been and is to come? We don't really know, although our best bet is that the ever-expanding universe is indeed heading to eventual boredom in thermal uniformity. Concepts like freebits are, for now, merely intriguing proposals about what makes reality tick under the surface.

The essential point to all of this is that information shows itself to be more than one might expect. It isn't just a way to probe the fundamentals of nature; it may be part of the fundamentals. Consequently, the fact that the human dataome is becoming increasingly entwined with the fabric of the universe—as pieces of manipulated matter and energy—means that we (as living things) are fully committed to the universal drive toward that future ocean of unchanging, equilibrated spacetime. It is as if we popped out of the vacuum as a temporary fluctuation of energy, and we've been clawing our way back ever since.

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My 3 Greatest Revelations

The author on writing his new book, The Ascent of Information

BY CALEB SCHARF

TOLD TO KEVIN BERGER

1

THE "DATAOME" IS HUGE

The dataome is shorthand to describe all of the externalized information we generate in symbolic representations: drawings, music, books, computing, data storage. It's all of the information we utilize and propagate, along with ourselves, through time and space. It's not encoded in our genes but it's clearly heritable. I can read a copy of a text from 1,000 years ago and it has stayed intact all that time. Money, too, now circulates through corporations and institutions that deal with information as their primary resource. The dataome is the correlation and dissemination of information or misinformation that has swamped us. It can feel like its own species.

If you take an elevated perspective, you can see this extraordinary continuum of weird stuff we call information has been emerging and propagating itself for billions of years on Earth. For me, the big revelation was: Wait a minute. There is no real difference between the dataome—our externalized world of books and computers and machines and robots and cloud servers—and us. That means the dataome is a genuine alternative living system here on the planet. It's dependent on us, but we're dependent on it too. And for me that was nerve-wracking. You get to the point of looking at it and going, Wow, the alien world is here, and it's right under our nose, and we're interacting with it constantly.

2

WE CO-EXIST WITH AN ALTERNATE LIVING SYSTEM

When you buy into the dataome, you look at our species differently. We aren't what we thought we were. We already know and accept that we have the microbiome. We carry around more genes in our microbes than we do our own genes. Humans have roughly 30,000 identified genes. Some estimates place the microbial gene count at 200 million. In a sense, we're already aware we co-exist with other informational stuff, it just happens to be biological.

If we accept the dataome is another alternate living system, and it's clearly in an intimate symbiotic relationship with us, we realize we can't exist fully without it. Pretty much everything we do as a species, good and bad, comes down to the propagation of information, the exchange of information. We are not isolated creatures, we're highly social creatures. We are constantly exchanging information that enables us to build a library for survival on this planet. It's proven an incredibly successful approach to survival. If I can remember what happened 1,000 years ago, that may inform me for success today.

What does it do for us if we see the world this way? It gives us a new handle on what is best for us, as a species and as individuals, and it gives us clues to how to optimize things. If you're not aware that you're in this deep symbiosis, you'll do crazy stuff that's not good for the overall equilibrium.

Every day we generate more data than is represented by every word spoken by every human being who ever lived.

The dataome started growing when we were able to mass produce books. Today, with electronic data, it's undergoing a massive exponential growth.

Right now, we generate something like 2,000 exabytes of data a year. That means that every day we generate more data than is represented by every word spoken by every human being who ever lived. If you take every conversation of every human that ever lived across all of their lifetimes, across almost 200,000 years, we make more than that amount of data every day. And it's accelerating. And it requires energy. If things carry on at the rate they're occurring at the moment, in terms of energy use, we're on course to, in 20 to 40 years, require as much energy just to support the dataome as we generate in totality for all of our civilization today. From the Darwinian point of view of the dataome, this is fantastic, because it gets to grow. It's occupying more niches too. It doesn't care if the data is cat videos or pictures of your sandwich. But from our point of view, this is undoubtedly detrimental to the physical environment.

From my perspective, we have been asking the wrong questions. We've been asking, "Why is this all happening? How do we solve this?" But we need to step back and ask, "What are we, really? What kind of species are we?" We've been focused on our biological form. What I'm saying is we aren't what we thought we were. We're this biological form plus data in a symbiotic relationship. You can't disentangle the two. We're going to keep making the same mistakes and coming up with the wrong kind of therapy until we recognize that.

3

THE REAL SINGULARITY HAPPENED 200,000 YEARS AGO

People now talk about the accelerating growth of technology, the emergence of machine learning and artificial intelligence. They talk about transcendence, the potential for us to upload ourselves into some new form, perhaps into a computerized form. They also talk about the technological singularity, the idea that there could come a point of such extraordinary growth in the sophistication of technology that there's a transformation. It's like this switch goes off and suddenly the machines take over. Technology accelerates to an extent that's unimaginable to us. It actually leaves us behind.

But these ideas of transcendent singularity in the future undersell the extraordinary transition and transformation that happened over the last 200,000 years when *Homo sapiens* emerged as a distinct species. It's a nice fantasy to think about future singularity. But that's just part of a continuum. It really began when biology started to implement information external to itself in the way humans did it. Transcendence moved life to a different kind of instantiation 200,000 years ago. Humans distinguished themselves by enabling knowledge, by enabling information, to be carried through time in a far more explicit way than any other species had done. Termites build and leave behind a nest, and it's an extraordinary structure. Birds too. But there's no evidence that any other species leaves information that is so meaningful for subsequent generations as us. The real singularity was that point at which specific information about the world, about experiences, about ideas, about inventions and creations, began to live alongside us.

EUREKA MOMENT
Inspiration for his new book, says astrobiologist Caleb Scharf, came when preparing to give a talk on the search for intelligent life in the universe. "Then I started thinking, 'Well, what does intelligent life mean on Earth?' The first thing that came to mind was the information we generate."

NERISSA ESCANLAR

Shakespeare is a great example to illustrate the persistence of information. Here's one individual, one human, who was particularly capable and productive, but could create all this externalized information. His children couldn't inherit it genetically. But the rest of us could inherit it. It has propagated through time and changed form. It's been transformed from books into movies. And information represents not just the physical world but ideas about the world. A beautiful picture, whether it's a piece of abstract expressionism or Renaissance masterpiece, invokes more than just, "Oh, well there's a horse or a castle that someone built." It invokes ideas and experiences, and allows you to inhabit another part of the human experience, or to explore your own inner experience.

The ability to transfer a sense of experience or emotional state is something we're able to do through art and literature. I would rank that form of data as important as any other. It helps us understand ourselves better as individuals. As a scientist, you step back and say, The Darwinian view of the world is important for survival. I'm sure our individual capacity to understand ourselves, to moderate our emotions, to make ourselves not despair or be manic, to avoid habits that feel detrimental, fits into some grand accounting scheme in the end. Having a better sense of ourselves and our connection to the dataome will allow us to pass along our genes and contribute to the propagation of our species.

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KEVIN BERGER is the editor of *Nautilus*.

What Made Early Humans Smart

Walking upright made our ancestors easy prey. It also made them get smart.

BY KEVIN BERGER

T**ALKING TO JEREMY DESILVA** about human evolution was so fun. As was reading his recent book, *First Steps: How Upright Walking Made Us Human*. I learned something new and fascinating on every page. Do you picture our hominin ancestors as hunters? I did. Not so much. "They were the hunted," DeSilva writes. Let's take another look, as modern paleoanthropologists have, at the Taung child's skull, one of paleontology's most famous fossils, the remains of a child from the species *Australopithecus africanus*, discovered in 1924. A reanalysis of the Taung child, DeSilva tells us, showed talon marks in its eye sockets. "A bird of prey, probably a crowned eagle, must have plucked the Taung child from the ground and carried it off to be eaten." See, I told you. Fun!

I might summarize DeSilva's book and our interview as, "Everything I thought I knew about why humans walk upright is wrong." And DeSilva, a paleoanthropologist at Dartmouth College, is an insightful and genial guide. I told him I was moved by his admission in *First Steps* that "for the first few minutes of every visit with a new fossil, my calipers, camera, and scanner remain idle. I just sit, alone, with the remains of my ancestors." He smiled. "I love fossils," he said. "When I first sit with a batch of fossils, I think of them as individuals. I think, 'Hey, a million years from now, if I'm lucky enough to be a fossil, and there's some paleontologist standing over me, I hope they take a moment to think about me as an individual, and apply everything that they can possibly think of scientifically to squeeze information out of my bones, to retell the story of what my life was like.' That's what we do as paleoanthropologists."

I began our interview by asking about the misperception that lingers to this day in his field and specialty.

RONI SETIAWAN / SHUTTERSTOCK

OSTRICH POWER Human feet are a nightmare for bipedal locomotion; too many fragile moving parts, says Jeremy DeSilva, holding an ostrich foot. Unlike Johnny-come-lately *Homo sapiens*, "The ostrich had a quarter of a billion years to master bipedal locomotion. What you get is a foot that an engineer would argue is a much more optimal form for locomotion."

What are the most popular wrong scientific explanations for why humans walk upright?
As new evidence is discovered, we always can change our minds, right? But one wrong idea that's still with us—the basis of *2001: A Space Odyssey*—is we were a violent species from the get-go and evolved bipedalism to free our hands for weaponry. It was based on a misinterpretation of fossils discovered at a site called Makapansgat in South Africa. The bones were supposedly butchered at the hands of *Australopithecus*. But it turns out they were remains that had been consumed by hyenas. There's another popular idea that we evolved bipedalism to see over tall grass. But honestly, if you're looking over tall grass and see a predator, the worst thing you could do is run away on two legs. We're too slow. It would make sense that you run away on all fours, when you could gallop at twice the speed of a typical human, or not even a typical human, an exceptional human.

So even Usain Bolt would be toast?
Yes, he would. Even the fastest human being that we can possibly imagine, probably the fastest human who's ever lived, is pathetically slow compared to your typical quadrupedal animal on an African savanna. Usain Bolt tops out at about 28 miles an hour. That's half the speed of a galloping zebra or antelope or leopard or lion.

To me, the greatest revelation of your research is we didn't evolve from hominins that walked on all fours. We evolved from ones who already walked upright.
This is a really hot topic in our field right now, and the field is divided on this, and I might be completely wrong; we'll see as we find more fossils. But my interpretation from the key time periods when bipedalism was emerging, is that apes are not moving on their knuckles. They're not adapted for life on the ground. Instead, they're up in the trees, moving with hand-assisted bipedalism, much like an orangutan, gibbon,

The image of a chimpanzee turning into a human that we see on T-shirts may not be how this all unfolded.

and siamang do now. We call them "lesser apes," and they moved bipedally a lot. What's interesting is the knuckle-walkers, gorillas and chimpanzees, don't move bipedally very frequently.

We have fossils, mostly from Southern Europe, where apes appear to have a body posture that's a little more upright. What's fun is the possibility that knuckle-walking might actually be the more recently evolved locomotion. The image of a chimpanzee slowly turning into a human that we see on T-shirts and coffee cups and bumper stickers may not be how this all unfolded. It could very well be that the common ancestor was more upright, and that chimpanzees and gorillas evolved knuckle-walking independently.

That famous image is called "March of Progress." Tell us about it.

"March of Progress" was an illustration done by a Russian artist, Rudolph Zallinger, in a 1965 *Time-Life* book called *Early Man*. It's this beautiful foldout that shows ancient apes down on all fours, and it has them slowly rising up to modern humans. At the time, with the fossils we had, you could create a narrative like that. But in the last half century we've made so many amazing discoveries that show the human family tree is much more diverse. The pace of evolutionary change is quite different and it turns out that upright walking is the earliest of these evolutionary changes. The earliest bipeds on the ground were evolving from things that were upright to begin with in trees. Really all that happened was an ecological change. These hominins were living in environments that had fewer and fewer trees. To continue to get from point A to point B to get your fruit and other food resources, you already are pre-adapted for an upright posture and moving on two legs. In that case, bipedalism wouldn't be a new locomotion, it'd be an old locomotion. It was just in a new setting on the ground, rather than in trees.

If bipedalism makes us slow, easy prey, why didn't our ancestors go extinct? Why are we here?

It's a great question. What are the advantages in freeing the hands? We could carry objects—food and babies. There are also thermo-regulatory adaptations. By being on two legs rather than four, you can disperse heat better. Maybe those things became factors that allowed us to survive.

What's the most beneficially adaptive trait for early hominins to walk upright?

I don't know. I would disagree with any characterization that said there was one reason. If there was one reason, we'd know it. It'd be obvious. In fact, bipedalism could have evolved independently in different hominins in Africa. With the fossils we have, there's the tantalizing possibility that it didn't just happen once. If we've learned anything about evolutionary trends, it's that good ideas evolve over and over again. For instance, the evolution of feathers and dinosaurs independently evolved three times. You could get the independent evolution of bipedalism multiple times.

It's a misnomer, isn't it, to think only one hominin existed at a time?

It is. One of the things we're learning from new fossil discoveries is there appears to be these different species of early human, or hominin, coexisting on the landscape with different anatomies or adaptations in their feet and legs. They would've walked very differently. A classic example is Lucy's species, *Australopithecus afarensis*, who lived about 3.5 million years ago, spanning from Ethiopia to Tanzania.

A few years ago, a colleague of mine, Yohannes Haile-Selassie, discovered a partial foot skeleton in Ethiopia, in sediments dated to the same age as Lucy. The expectation was it's a foot from Lucy's species. But Lucy's species didn't have a grasping big toe, and this one does. It has other parts of the bony anatomy that are consistent with pushing off the ground on two legs. So here we have something walking on two legs, but walking on two legs very differently from the way Lucy and her kind did.

I tell my students all the time about how much fun it would be to jump in a time machine and go back to Africa 3 or 4 million years ago. You'd see all these different kinds of hominins coexisting on a landscape, eating slightly different things, moving in slightly different ways.

You write that Lucy's life would have been hard. How so?
Imagine you're just about the slowest animal in your environment. You're small. Lucy was about three and a half feet tall, a full grown adult *Australopithecus*. She wouldn't have gotten any bigger. Her growth plates are fused, her wisdom teeth had erupted. And she's sharing the landscape with a Homotherium, a large saber tooth cat. They were ancestors of hyenas and were enormous. Some were ancestors of leopards and lions. All of these things would have gladly eaten an *Australopithecus*. In fact, we have some fossils with puncture marks in the back of the head. We know they got eaten.

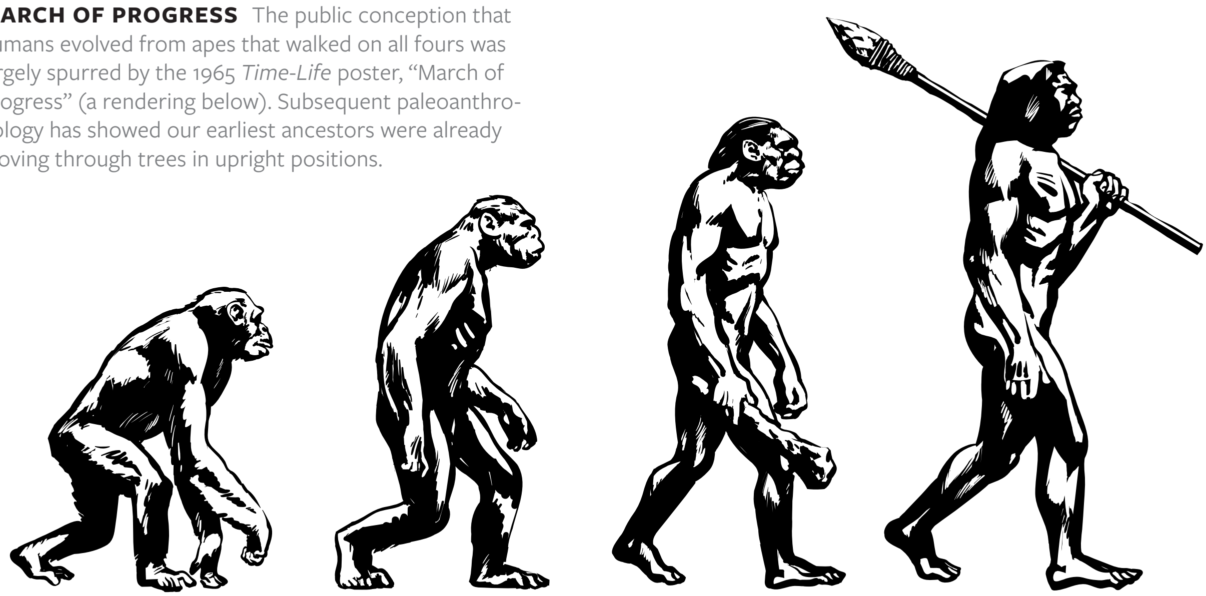
Lucy would have woken up in a tree. That's how you stay away from getting eaten at night. She would have had to have hang tight as large cats were finishing up their meals from that night. And she would have been hungry. To eat, her group would have to come down out of the trees. But if you're a biped, you can't just put a baby on your back. The baby's going to slide right off.

Baby chimpanzees and baboons cling to the fronts or wide backs of their mothers. Being upright means we have to physically carry our kids. So now Lucy is physically carrying her kid. Now, in her arms, she's got this little fleshy meal for any carnivore, and she needs to go find food for herself in an environment littered with predators. And yet she survived! What an amazing testament to the resilience of our ancestors. Their survival is why we're here.

What were key traits of Lucy's survival?
If you're living in a cooperative group, as I think early hominins were, you're sharing food. You give it to relatives, your own children, and to others in the group, who then reciprocate. That builds trust and a cooperative culture that is essential for survival. To me, the only way that hominins could've survived through these millions of years of living in an environment that is full of predators is if they looked after each other and were hyper cooperative with one another.

How do paleoanthropologists know early hominins were cooperative?
One of the best pieces of evidence we have is a fossil of an individual who's broken a leg bone, a femur. This is long before hospitals, doctors, casts, anything like that. The beauty of the fossil is you can see a healed fracture. Imagine 2 million years ago, you break your leg. There's no way you should survive. But a hominin did. The key word is healed. He survived that trauma. I don't think he could have done that alone.

MARCH OF PROGRESS The public conception that humans evolved from apes that walked on all fours was largely spurred by the 1965 *Time-Life* poster, "March of Progress" (a rendering below). Subsequent paleoanthropology has showed our earliest ancestors were already moving through trees in upright positions.



Did bipedalism lead to cooperation?

I think so. We think about humans having evolved from something very chimpanzee-like, and chimpanzees can be incredibly aggressive and violent. But we are equally related to bonobos, who are not aggressive or violent. They're female-dominated and don't exhibit the same territorial behaviors that chimpanzees do. Now, we didn't evolve from either of those. They're our cousins. We share a common ancestor with them. But they provide an interesting mirror through which we think about ourselves and what that common ancestor was like.

We all know how awful humans can be to each other. That's well-established. But we overlook the fact that humans are extraordinarily cooperative with one another, tolerant of each other, kind, helpful, and empathetic. To me, what allowed an ape to survive for millions of years on a difficult landscape without weaponry, was that we looked after each other, we took care of each other. We had each other's backs. If someone was injured, we helped them to a tree.

Maybe it's better to say cooperation is a byproduct of being a vulnerable biped.

That's exactly right. An ape that's bipedal and isn't nimble in trees is a recipe for extinction. But here we are. Something allowed us to pass through those rigors of natural selection. And it's cooperation. One of the prime examples is childbirth. In non-human apes, childbirth is relatively easy. The baby is usually facing forward, toward the mother's belly, when it's born. But in humans, because of the changes to the pelvis associated with walking on two legs, a baby has to corkscrew through the birth canal and it ends up being born facing backward most of the time, and that requires assistance. One of the cultural universals in humans is to have assistance during birth, usually in the form of an experienced midwife. If you're trusting someone, another member of your group, during childbirth, then you're going to trust them at other times.

How did bipedalism lead to brain development?

This one's more speculative. We're not entirely sure. Darwin hypothesized that bipedalism and tool use and canine reduction and brain size evolve in concert. You can see Darwin's ideas in the "March of Progress"

Usain Bolt tops out at about 28 miles an hour. That's half the speed of a leopard or lion.

illustration. As bipedalism is getting more refined, brains are getting bigger. But that's not consistent with the evidence. Instead, we find bipedalism goes back to the origins of the lineage. Brain size doesn't inflate until much later. About 2 million years ago, we start seeing a real increase in brain size. The brains of *Australopithecus* get a little bit bigger than their predecessors, but nothing like what we see in genus *Homo*. That leap in growth is about getting enough energy to sustain this energetically costly organ, the brain.

Energy is a zero-sum game, right? There's only so much energy available and the body allocates it to the most demanding organs?

That's right. One of the hypotheses about brain growth is derived from what's called the "expensive tissue hypothesis." Energy is allocated to the brain, but where are you getting that energy from? The argument is the digestive system. Essentially the intestines reduce in volume, and by reducing that expensive tissue, you're able to allocate more energy to a larger brain. But if you do that, you're not able to digest plants as well anymore, unless you cook them. So there seems to be this relationship between the diversification of our diet, eating more meat and marrow, scavenging, and hunting. And fire plays a role too, because now you can cook. All those things are fueling brain growth.

UNCLE LEO / SHUTTERSTOCK

I LOVE LUCY "I love fossils," says Jeremy DeSilva. The paleoanthropologist loves the stories they tell, particularly the story of Lucy (a museum replica shown here), an *Australopithecus afarensis*, whose life would have been incredibly hard. "And yet she survived!"

GREGGRABOWSKI / SHUTTERSTOCK

Where does bipedalism enter the picture?
Coinciding with this, we see an increase in leg length. We start to see a more human-like arch to the foot. It's almost as if these final tweaks made bipedalism even more efficient, and allowed us to travel greater distances, expand our home range. By expanding our home range, we're now able to extract more resources from our environment. We can eat animals and the plants from a larger radius.

Did bipedalism contribute to humans being omnivores?
I think it did. We can tell from isotope signatures in the teeth of our earliest ancestors that they were eating stuff in a forested environment. They were eating fruits and leaves, typically what an ape would eat. But when you get to *Australopithecus*, Lucy's time, you get a huge shift in the profile of the isotopes. They show that Lucy started eating lots of different things in different environments. That's consistent with a biped spending more time on the ground than in trees to get their food.

Remember, Lucy's life was hard. She can't afford to be a picky eater. She's not going to search and search for that one thing she's craving. There are predators all over the place. She'll get eaten and her kid will get eaten. She needed to eat anything. She needed to eat grasses and leaves and fruit. Maybe there's a carcass with a little bit of meat left on it, and she could munch on that. She could dig for underground tubers and munch on those. Insects, termites, birds, eggs, lizards, snails—you name it, she was eating it. And humans do that today.

I guess that shoots down the trendy diets that say we should eat one particular type of food because our early ancestors did.
[Laughs]. Whenever someone asks me about the Paleo diet, I'll say, "Which population are you talking about? Are you talking about the humans who were living in Northern Asia, the humans who were living in Europe, the humans who were living in Africa on a grassland environment, the humans who were living in a forested region, the humans who were living on coasts?" During the Paleolithic, you're going to have very different diets depending on the human population we're talking about. It's because humans are unbelievably, dietarily flexible. We can eat anything. In those varied habitats, we did eat everything. There's no one-size-fits-all diet for humans.

Whenever someone asks me about the Paleo diet, I'll say, "Which human population are you talking about?"

Here we are in 2021, living in an entirely different world, of course, than our hominin ancestors did. How is bipedalism not adapted to contemporary life?
I threw out my back a couple of weeks ago and couldn't walk. Our lower back is a mess. Most mammals move on all fours and their spine is horizontal, it operates like a suspension bridge. By being bipedal, we've turned that spine vertical, a bad idea. And to make sure that the torso is oriented over the hips, and that all of our joints are aligned and balanced, there's a curve that's introduced into the spine. A colleague of mine, Bruce Latimer at Case Western Reserve University, refers to this as a series of cups and saucers. That's how unstable the spine is. Slip discs are very common. We're one of the few mammals that develop scoliosis.

Then there's the real nightmare: the foot. If you were going to challenge an engineer to design a structure that has to be compliant enough to absorb forces from the ground, but then rigid enough to push off the ground, and maybe even elastic enough that it can absorb some energy to push off the ground, the last thing they would do is make it out of 26 parts. And your foot has 26 individual bones. Between your two feet, you've got 52 bones, which is a quarter of your skeleton. A quarter of the human skeleton is made up of foot bones. Why? It's because we're modified apes, and apes need all those foot bones to grab onto trees; they use their feet in much the same way we use our hands. By evolving bipedalism, natural selection can only work with pre-existing forms. It tinkered with this ape foot. I think of it as using duct tape and paper clips to patch together and stiffen up this foot. And it's good enough, right? We're here and we can move from point A to point B. But evolution doesn't care about comfort, and so we've got a lot of problems.

Is there a larger message about evolutionary biology in our anatomical problems?
Yes, and it comes back to what we were talking about before. Humans buffer themselves with culture. Is natural selection still operating on humans? Absolutely. It has for the last 6 million years. Our foot anatomy may be suboptimal and lead to problems. But we solve our problems culturally and socially. Thankfully, we're not twiddling our thumbs and waiting for natural selection to solve them for us.

KEVIN BERGER is the editor of *Nautilus*.

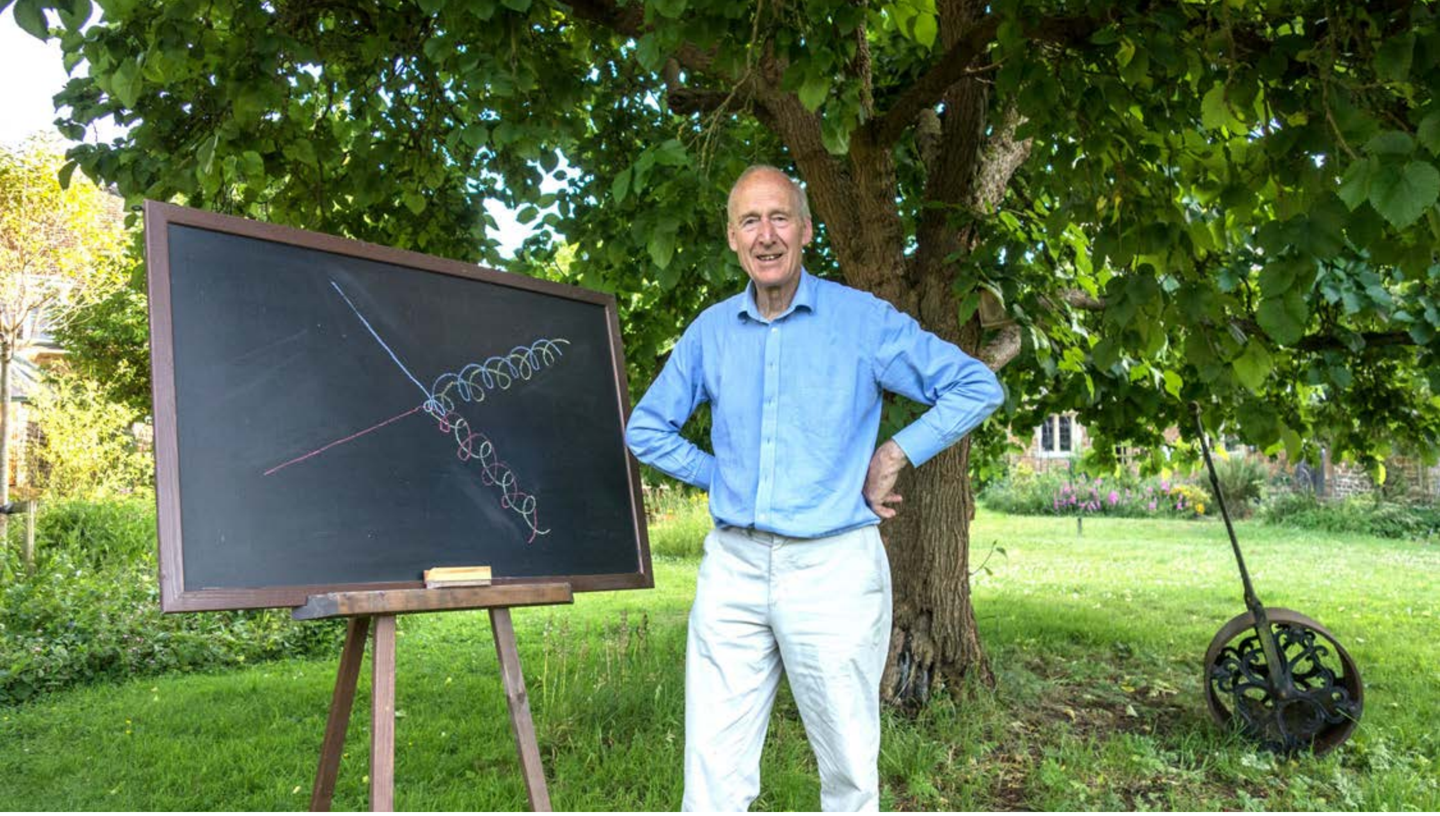
The Country Gentleman of Physics

Julian Barbour's ideas about time and the universe have always roamed free of academia

BY MICHAEL BROOKS

PHOTOS BY KAROL JALOCHOWSKI

JULIAN BARBOUR'S OBSESSION with time began on Oct. 18, 1963. The 26-year-old Cambridge graduate in mathematics was on a train to the Bavarian alps, where he and a friend planned to climb the Watzmann, Germany's third highest peak. The newspaper in his hand contained a summary of a *Scientific American* article by British physicist Paul Dirac. "He questioned whether four-dimensional symmetries are a fundamental feature of the physical world," Barbour recalled. Dirac was pulling apart Einstein's conception of the three dimensions of space and one of time, looking for deeper truths. The next day, Barbour woke with a headache and told his friend he was in no state to climb. "I said, 'You'll have to go up the mountain on your own.'" Left alone with his thoughts, Barbour sat and asked himself "What is time?"



DANCES OF TIME According to Julian Barbour, time is not necessarily an arrow that flows in one direction, from past to future. He set up a blackboard in his garden and explained to photographer Karol Jalochowski: "It's much more natural to define the direction of time by how structure and order form."

Barbour assumed the question came from Dirac's writing, but he later re-read the article, and the question wasn't in there. "There's not a word about Dirac asking what time is. I must have invented that to give myself the confidence to challenge this thing," he said. "I suppose I thought that, if Dirac had said it, it must be worth taking on!"

The question of the nature of time, so big he couldn't quite claim it for himself, would dominate Barbour's life. In 1999, he published his initial conclusion, *The End of Time*, which declared time to be an illusion that has no place in the fundamental description of how the universe works. The book was variously described as "provocative" and "fascinating." In *The New York Times*, Simon Saunders, a philosopher of physics, hailed it as "a masterpiece." But the most gratifying reaction was surely that of John Archibald Wheeler, the stellar (in every sense) physicist who coined the term "black hole." Wheeler said, "Plato and Aristotle, if they had read this book, would still be discussing it."

This April, as he sat in the kitchen of his 360-year-old house in Oxfordshire, England, Barbour, 84, was still discussing the concept of time with the excitement of a 26-year-old. In December, 2020, he published *The Janus Point*, his first book since *The End of Time*. It's named after the two-headed Roman god who simultaneously looks forward and backward. Barbour's thesis is that the Big Bang, which he calls the Janus Point, seeded the flow of time in two directions. Time "no longer has one direction, from past to future, but instead has two: from a common past at the Janus point to two futures in the two directions away from it," Barbour writes.

Lee Smolin, a faculty member at the Perimeter Institute of Theoretical Physics, called *The Janus Point* "simply the most important book I have read on cosmology in several years ... both a work of literature and a masterpiece of scientific thought."

I'm not as well-placed to judge as Smolin, but the book does feel refreshing and different: a closely argued, substantive take on one of the biggest unsolved

"Plato and Aristotle, if they had read this book, would still be discussing it," John Archibald Wheeler said.

mysteries of physics, written by someone who has wrestled with not only the physics, but also the history and philosophy relevant to his subject. What's more, Barbour's approach, unlike many in the popular science game, is to publish only when he thinks he has something worth saying. That alone is enough to make him worth listening to. Not that it's easy to get to grips with his central thesis, as Barbour anticipated. That's why his book contains extra white spaces between paragraphs in places: Here, Barbour writes, readers can pause "for a tea or coffee break." But rather than have tea by myself at home, I decided I would learn more by having tea with the author himself. Barbour was very happy to oblige.

When he greeted me at his front door, Barbour embodied the quintessential English country gentleman at leisure. He was wearing a fleece gilet zipped over his russet sweater. His slate corduroy trousers were slightly short in the leg—he is a tall, slim man. His feet were covered by thick light gray socks shoved into Birkenstock sandals. He was quick to smile and laugh. He had the air of someone who used to captain the school cricket team.

Before he made waves in the physics world, Barbour was not an academic superstar. At Cambridge he earned what he called "a rather ordinary second-class degree," and then opted to take a year off to go and live in Munich to improve his German (at a school run by the man who had been Hitler's chief interpreter, it turned out). There he met Peter Mittelstaedt, a young academic who had been Werner Heisenberg's student. "He invited me to do a Ph.D. with him," Barbour said. Barbour wanted to research Ernst Mach's ideas about the nature of time, but Mittelstaedt said, "No, that's much too risky—you probably won't get anywhere, and you'll never get a job." Instead, Barbour wrote his Ph.D. on general relativity. "Frankly, my thesis was a very modest affair," he said.

Despite ditching Mach, he remained convinced that he would never hold down an academic job. When he had to make a decision about it, he asked an acquaintance what would be expected of him if he took a research post. The answer—to publish one or two good papers a year—horrified Barbour. "I said there's no way I'm going to be able to do that."

Giving up on the idea of academia, Barbour came back to England. Having learned Russian while in Germany, Barbour began to earn a living translating classic Russian physics papers for Plenum Publishing in New York and the American Institute of Physics. "It was very boring work but a steady income," he said. "And it left about a third of my time free to develop my ideas." To further satisfy his intellectual cravings, Barbour became a hanger-on at physics conferences, feeding on the ideas and digesting them in his spare time. "I liken myself to a bee going to get nectar from academia," he said.

Barbour writes at a custom-made semi-circular desk in his house, College Farm, which he bought from Oxford University's New College in November 1963. He can see his childhood home from College Farm's first floor windows. Both buildings, like most of the village, are constructed from a golden stone that seems to have been designed to capture and re-radiate late afternoon sunshine; the setting is, a real-estate agent would say, idyllic. As if to confirm this, there is a sign mounted on the side of Barbour's house. It points toward the back, and proclaims that somewhere down there lies Arcadia, the mythical idyll of the ancient Greeks. Next door to College Farm, the other side of the path to Arcadia, is the church of St. Peter ad Vincula, built in the 12th century. It's not hard to imagine a young Hugh Grant rushing through the churchyard in a morning suit and mumbling apologies for being late again. This is the England of *Four Weddings and a Funeral*, of John Betjeman, of stopped clocks. Which is appropriate for a man who has spent most of his life battling time.

Barbour suggests that art might provide a better guide to the true nature of the universe than science.

In many senses, declaring time to be illusory was the low-hanging fruit. Our deepest theories suggest that time is not fundamental to the universe: It doesn't really figure, except as a marker of change, in quantum physics. In relativity it is malleable, its moments undefinable across the universe. The big question left open is what causes our experience of time's arrow—the one-way flow of moments. Barbour has explained what he thinks is the answer in *The Janus Point*. That answer, he said, has lain in plain sight, waiting to be discovered since the late 18th century.

In 1772, the French mathematician Joseph-Louis Lagrange made an extraordinary discovery. Approximately, it's this: Imagine there are three particles moving around and interacting only via Newton's law of gravity. Lagrange showed that the size of this total system—the diameter of an imaginary circle that encloses all three particles—will vary in a very odd way. The diameter will shrink to a minimum at some moment in time, then grow again—forever. The whole three-particle system never returns to that minimum size.

Amazingly, Lagrange's result works for any number of particles. And when Barbour read about it, he thought it might work for an entire universe; after all, what is a universe but a load of particles swirling about? If true, this would mean that the universe hit a minimum size at some point, and then grew ever afterward. And that minimum is what we think of as the moment of the Big Bang. In Barbour's Janus-headed universe, time runs in two directions, away from that point of minimum size. Lagrange's proof of a minimum size, he said, gives us a cause for the arrow of time. Why do we experience time only running forward? Because we're moving away from Lagrange's minimum, and a mathematical law says we can never return there.

"I've been interested in the arrow of time for almost as long as I can remember, and nobody has ever come up with a suggestion that a law of the universe says there must be one," Barbour said. "It's extraordinary that it has been sitting there for four centuries."

While Barbour is bullish about what he has pulled together from his studies of the history of science, it's not clear to other physicists that the Janus Point idea solves the problem of time's arrow. For a start, it is a purely classical idea that makes little sense in terms of a more fundamental approach such as quantum field theory. What's more, Barbour's model ought to, but can't explain the origin of the initial fluctuations in the stuff of the universe, which are essential to explain the large-scale structure that astronomers have observed with exquisite precision. And so, while the arguments can sound convincing to some, cosmology insiders are generally wary of giving the Janus Point too much credit.

Such critiques won't deter Barbour from pursuing his ideas. Even now, with two masterpieces under his belt, he is not done. He is physically fit, and walks for more than an hour every day. Some things are slowing down, he admits—he has to re-read the previous day's work before he can continue to write, for instance—but he is undaunted by age. "I think the things that really count, the conceptual ideas, are fine," he said. And so, like time, he is always moving forward. "There's two more books I'd like to put out," he said. One is a history of thermodynamics that he has already half-written. The other is a new, typically ambitious, idea for uniting Einstein's relativity with quantum physics to create a single "quantum gravity" framework for describing the cosmos. "It came to me literally as I was writing the final chapter [of *The Janus Point*]," he said.

A ROOM OF HIS OWN Julian Barbour writes at a custom-made semi-circular desk in his house, College Farm, which he bought from Oxford University's New College in November 1963. He can see his childhood home from College Farm's first floor windows.

The root of this new idea owes a debt to his original inspiration: the Austrian physicist Ernst Mach. Deep study of Mach's work has led Barbour down the road of formalizing a theory with his various collaborators. He summarizes the essence of it as asking, "What sort of initial data do you need to predict what the future will be?" The key, Barbour said, is to make sure you consider the expansion of the universe. "That brings all the interesting structure, formation and everything," he said. He is excited by the possibility that developing this idea will solve the measurement problem of quantum mechanics as well as uniting quantum theory with relativity. He also thinks, even more controversially, that it could identify meaning in the universe. "If this new idea about time and quantum gravity is correct, I think that is possible."

Finding the meaning of the universe is not something that most scientists would consider to be within their remit. The convention is that artists, writers, and philosophers are the ones to bring us meaning. But Barbour seems happy to swap the roles of science and the arts. He even suggests that art might provide a better guide to the true nature of the universe than science. In *The Janus Point*, he writes that human moments of deep creativity "might be subliminal inspirations from the whole universe," and that a performance of a great operatic aria can capture something of the cosmos as neatly as any mathematical equation. He sees humans as actors in the universe's drama, describing himself as "a participant in whatever the universe does."

Whether academic colleagues see him as a scientist, a thinker, a writer, or a provocateur, Barbour is a much-appreciated participant in the scientific universe. He is an optimist and an idealist: His character is not that of the hard-nosed, always-skeptical ivory-towered researcher. He is a glass-half-full guy; he admits to being a Platonist who believes in the existence of ideals—an Arcadia hiding somewhere down a sun-dappled lane—that we can't quite see. The pursuit of this elusive idyll seems to be what makes him tick.

This may be why the 17th-century German physicist and philosopher Gottfried Leibniz kept coming up in our conversation. It's not so much Leibniz's thoughts on time that seem to interest Barbour; it's much more about Leibniz's view of the universe. Leibniz suggested that pursuit of perfection is the ultimate underlying purpose of the universe's unfolding. Voltaire mocked Leibniz for suggesting that we live in the best of all possible worlds, but Barbour shares Leibniz's view. In many ways, Barbour's life's work is a continuance of Leibniz's effort to justify idealism despite our experience of life. "I'm inclined to think, with Leibniz, that there is more good than bad in the world," he told me.

During our conversation, Barbour couldn't find the right word to summarize Leibniz's philosophy. The next morning at 7:35 he sent me an email. "The word I was looking for is theodicy," he said. It means justifying God, the attempt to show that there is no inherent reason why the existence of evil rules out the existence of a good, omnipotent deity. There does seem to be a theodicy at the heart of Barbour's work: with the universe moving away from its minimum, all things can and must happen; you have to tolerate evil if you want good to exist. As Barbour puts it in the book, "There is no light without the dark."

And, at 84, perhaps he is in a good position to judge. Through experiences that range from mountain-climbing to being in the room when a young theoretical physicist first presented the idea we now call Hawking Radiation, to dealing with his wife's suffering with Alzheimer's disease, he has learned that making the most of time is what matters. His kitchen is peppered with pictures of his grandchildren, and he uses Zoom to talk to at least one of his children, who live, respectively, in France, Argentina, and South Africa, almost every day. Family means more to him than ever; Barbour recently lost his wife and, even more recently, a daughter (they are memorialized together in the dedication of *The Janus Point*).

"Nobody has ever come up with a suggestion that a law of the universe says there must be an arrow of time."

At the end of our conversation, I raised the physicist Carl Sagan's suggestion about meaning: that our lives, however insignificant or painful they seem, have a cosmic significance because humans are the means by which the universe achieves knowledge of itself. "I've never read Carl Sagan," Barbour said.

It's easy to feel daunted, perhaps a little unschooled, in Barbour's presence. His knowledge of the history of physics has a vast scope, much broader than almost anyone working in the field. His gift is that he knows what has been thought, and what has been said, and he finds ways to synthesize those insights and draw new ideas out from within their implications. But Barbour is open to new ideas too. "I think Sagan's was a good hunch," he said.

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OLGA POPOVA / SHUTTERSTOCK

The Botanist Who Defied Stalin

His dream of feeding the world died in prison.
His dream of a seed bank lives on.

BY LEE ALAN DUGATKIN

IN 1913, 26-YEAR-OLD RUSSIAN BIOLOGIST Nikolai Vavilov went to the John Innes Horticultural Institute to study at the feet of legendary geneticist William Bateson. While there, Vavilov attended lectures at nearby Cambridge University, and could often be seen bicycling around the city in his trademark suit and tie. He and Bateson became lifelong friends, and the Mendelian genetics that Bateson and his team championed—and that remains the core of the field of genetics to this day—was burned into Vavilov's scientific soul.

The visit to England was cut short as a result of World War I and Vavilov returned home, where he began doctoral work on plant disease resistance, in part to alleviate the constant shortages of food in Russia. As he did, he began a one-man crusade to scour the planet collecting crop varieties that were disease resistant and might also shed light on the evolution of domesticated plants. For the next 25 years Vavilov's travels and adventures, recounted in detail in his massive work *Five Continents*, would make Indiana Jones look like a Boy Scout. He collected hundreds of thousands of seed samples from 60 countries, beginning with Iran and the Pamir region in 1916, Afghanistan in 1924, Algiers, Morocco, Tunisia, Lebanon, Syria, Mesopotamia (Iraq), Palestine, Jordon, Ethiopia (Abyssinia), Greece, Cyprus, Crete, Italy, and Spain in 1926. And he was only just getting started. Other collecting missions took him to China, Japan, Taiwan, and Korea, as well as Mexico, the United States, Canada, Germany, France, England, the Netherlands, Colombia, Peru, Bolivia, Chile, Argentina, Uruguay, Brazil, Trinidad, Puerto Rico, and Cuba.

THE INDIANA JONES OF SEEDS Nikolai Vavilov collected hundreds of thousands of seed samples from 60 countries in his attempt to build a repository of all the world's seeds. He hoped his research would save the world, and his homeland in particular, from hunger.

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Reputed to sleep only four hours a night, Vavilov used the extra time to master more than a dozen languages, so he could converse with local farmers to learn what they knew about the plants he was studying, and to write more than 350 papers and books.

On his first trip in 1916, he was arrested at the Iran-Russia border and accused of being a spy, because he had a few German textbooks with him. In the Pamir mountain region of central Asia, Vavilov traversed death-defying mountain passages, an experience, he wrote, "which afterwards this traveler remembers best. Such moments steel one for the rest of one's life: they prepare a scientist for all difficulties, all adversities and everything unexpected." He'd need that steel—over and over. On his trip to Afghanistan, he fell as he was stepping between two train cars, and was left dangling by his elbows as the train roared along. On his trip to Syria he contracted malaria *and* typhus, but carried on.

As he collected and studied domesticated plants and their ancestors all over the planet, Vavilov began to develop radical new ideas about domestication per se and evolution writ large. At a June 1920 meeting of the All-Russian Congress on Breeding and Seed Production, he introduced his "law of homologous variation." The idea was to take the idea of homology—similarity due to shared evolutionary history—and build a predictive model of plant variation. Because evolutionarily-related plant species have similar sets of genes, Vavilov argued that if he knew the traits present in one species—for example, flower color, number of inflorescences, seed shape, stalk length, pollination time, and so on—he could predict the parallel traits in closely related species. And the law could be applied at the genus or family level as well. When Vavilov introduced the idea at the meeting, people rose up and cheered, "biology has found its Mendeleev," for creating a sort of periodic table of plant variation. In time, Vavilov found evidence for his law in wheat, rye, millet, oats, cotton, grasses, potatoes, and other domesticated plants. Rumors spread that Nevsky Avenue in Petrograd (soon to be renamed Leningrad, and eventually St. Petersburg) was going to be renamed the Avenue of Homologous Lines.

Vavilov's travels provided him with a unique global perspective, which led him to identify "centers of plant domestication." He introduced the centers idea in 1924, and over the subsequent decades tweaked the

number—between five and eight—based on new data, most often including southwestern Asia, southeastern Asia, coastal areas of the Mediterranean, Abyssinia, the Mexican-Peruvian region, the Chiloé archipelago (near Chile), the border between Brazil and Paraguay, and one island center, near Indonesia. Above and beyond the scientific importance of his ideas on homologous variations and centers of origin, Vavilov believed they had practical merit and might "serve as the foundation for all breeding and genetic work of the next and later Five-Year Plans."

Recognition and then honors soon followed. In his home country, Vavilov was one of the first scientists to receive the Lenin Prize, was elected a member of the Academy of Sciences of the USSR, and was eventually made a foreign member of the Linnaean Society, the American Association for the Advancement of Science, and many other academies around the world.

Much more important to Vavilov than the accolades was his small empire of institutes and field stations devoted to the study of the biogeography, genetics, and evolution of domesticated crops. This empire was part of the labyrinth that was Soviet bureaucracy, but was born in 1920-21 when Vavilov took the helm at the Department of Applied Botany in Petrograd and culminated in his leading the All-Union Institute of Plant Industry (known by the Russian acronym VIR), and the Lenin All Union Academy of Agricultural Sciences (VASKhNIL). Each of these organizations employed scores of scientists, technicians, and workers and had associated branch field stations: When Vavilov was president of VASKhNIL, it alone was comprised of 111 research institutes, 206 specialized "zonal stations," 26 agricultural research stations, and 36 breeding stations.

As early as 1921 Vavilov had dreams of amassing a world seed bank that would serve science and act as a repository of crops that could be used to feed the planet. As he traveled and collected he constantly sent back seed samples, hundreds of thousands of them in total, to the institutes and field stations under his bailiwick.

Vavilov dreamed of amassing a world seed bank that would act as a repository of crops that could be used to feed the planet.

BY THE MID-1930S the problem for Vavilov, and so many other Russian biologists, was that it had become a very dangerous time to be a Mendelian geneticist in the Soviet Union.

The trouble started when, in the mid-1920s, the Communist Party elevated a number of uneducated men from the proletariat into positions of authority in the scientific community, to glorify the "average man." Trofim Lysenko fit the bill. He had been raised by poor farmers in the Ukraine, hadn't learned to read until he was 13, and had no university degree, having only studied at the Vocational School for Gardeners in Uman, Ukraine in 1917. The only training he had in crop breeding was a brief course in cultivating sugar beets at the Kiev Agricultural Institute.

Lysenko had a mid-level job sowing peas at the Gandzha Plant Breeding Laboratory in Azerbaijan when he convinced a *Pravda* reporter, who was writing a puff piece about the wonders of peasant scientists, that the yield from his pea crop was far above average, and that his technique could help feed his starving country. The Oct. 8, 1929 *Pravda* article claimed "the barefoot professor Lysenko has followers . . . and the luminaries of agronomy visit . . . and gratefully shake his hand." The article was fiction, but brought Lysenko to national attention, including the attention of Josef Stalin.

A bag of seeds could make the difference between life and death for a Leningrader.

Lysenko soon claimed to have conducted experiments in which wheat and barley produced higher yields during stretches of cold weather after their seeds were frozen in water before planting. Using this method of "vernalization," he said he could double crop yield in the Soviet Union in just a few years, in part by transforming spring grain crops into winter grain crops. Next he claimed that not only would plants that went through the process of vernalization produce higher yields, but that their *offspring* would also produce higher yields. Much evidence from laboratories around the world had already shown that this form of inheritance—called the inheritance of acquired characteristics or Lamarckian inheritance—simply did not work, and there were no controlled studies showing it in operation. But Lysenko argued that the inheritance of acquired characteristics was more philosophically akin to Marxist philosophy than was the Mendelian genetics championed by Europeans and Americans, as well as the vast majority of Soviet geneticists. Stalin, who was promoting the idea that if the economy was transformed, everything would change for all and the generations to come, was enamored with Lysenko's idea that manipulating the conditions of the environment changed not only the genetics of the organisms in that environment, but their descendants as well.

Lysenko never undertook any controlled experiments on increased crop yield or the inheritance of acquired characteristics. Virtually all of the data he claimed to have collected was either slipshod, or, more often yet, downright fabricated. But with Stalin as his ally, Lysenko launched a crusade to discredit work in what he called "Western genetics," by which he meant Mendelian genetics. At an agricultural conference held at the Kremlin in 1935, when Lysenko finished a fire-spitting speech in which he called Western geneticists "saboteurs," Stalin rose to his feet and yelled, "Bravo, Comrade Lysenko, bravo."

VAVILOV HAD ACTUALLY BEFRIENDED a young Lysenko in the 1920s, when Lysenko was receiving national acclaim for his ideas about increasing crop yields, a topic that was always near and dear to Vavilov. Initially hoodwinked by Lysenko, over time, as he looked into Lysenko's claims, Vavilov became suspicious, and he asked a student of his to see if Lysenko's results could be replicated. They could not, and Vavilov became Lysenko's outspoken opponent. In retaliation, in late 1933 Stalin's Central Committee forbade Vavilov from any more travels abroad and Lysenko warned Vavilov and his student that "when (their) erroneous data were swept away . . . those who failed to understand the implications" would also be "swept away."

This was no idle threat. Lysenko's powerbase was well known: "The whole country knows of the debate taking place between Vavilov and Lysenko," one his cronies stood up and announced at a meeting. "Vavilov will have to change his ways, because Stalin said that things must not work the way Vavilov says but as Lysenko says." Within a few years, working with Stalin and others, Lysenko was well on the way to purging Mendelian geneticists from the ranks of Soviet science, having them fired or thrown into prison if they did not swear allegiance to Lysenko's views. He had also, for all intents and purposes, removed all mention of Mendelian genetics from biology textbooks at every level from grade school on through university.

Vavilov was undeterred and kept up his fight against Lysenko. He was not a polemicist by nature, and in public his responses were usually centered on the data he and others had collected on Mendelian genetics and the lack of evidence from Lysenko, but in 1939 at a meeting of the All-Union Institute of Plant Breeding, he gave a talk in which he declared, "We shall go into the pyre, we shall burn, but we shall not retreat from our convictions." Shortly after that, when he was in Moscow, Vavilov and Lysenko got into a heated argument. One of those present told a friend, "now he is going to be arrested...because he said such a terrible thing to Lysenko. He said 'thanks to you our country has been overtaken by other countries.' "

Lysenko, who by this time had usurped the presidency at VASKhNIL, and was Stalin's right-hand man in science, had enough of this thorn in his side. On Aug. 6,

NO EVIDENCE? NO PROBLEM "Average man" Trofim Lysenko had no university education or relevant qualifications, but was promoted to a position of power in the Soviet government anyway, from which he attempted to squash those with opposing views—like Mendelian geneticists.

WIKIPEDIA

SAVING SEEDS During World War II, heroic scientists safeguarded the immense store of seeds at the VIR in what is now St. Petersburg. It was later renamed the N.I. Vavilov All-Russian Scientific Research Institute of Plant Industry, and remains a major seed repository today.

1940, while traveling in the Ukraine, Vavilov was picked up by four men wearing dark suits, taken to Moscow by the NKVD (the predecessor to the KGB), and put in the dreaded Lubyanka prison, where, for the next 11 months, he was interrogated, primarily by lieutenant Alexander Khvat, on 400 separate occasions, for a total of 1,700 hours.

Khvat, of course, had no trouble gathering phony evidence that Vavilov had "damaged the landing grounds in the Leningrad Military Region by sowing the airports with seeds containing weeds." The results from an "expert commission" that Khvat had assembled, told him of the "high concentration of socially hostile elements" at Vavilov's institutes, and of "twenty-one employees of noblesse origin, eight from the priesthood, twelve honorary citizens [code for tsarists], and ten from the merchant class."

Eleven months later, at Vavilov's "trial," conducted by a panel of three generals (not judges), he was formally accused of acting as one of "the leaders of an anti-Soviet organization … (being) an active participant in an anti-Soviet organization of right-wingers operating within the Commissariat for Agriculture and several scientific institutions in the USSR. . . . (and) in the interests of these anti-Soviet organizations carrying on widespread wrecking activity aimed at disrupting and destroying the collective farm system and the collapse and decline of socialist agriculture in the USSR."

The verdict was a foregone conclusion, and Vavilov's subsequent appeal was denied. The original death sentence was eventually commuted to 20 years in prison. On Oct. 16, 1941 he was packed on a train, with hundreds of others, and sent to Saratov Prison

DIMITRIY GURYANOV / WIKIMEDIA

Number 1. When Vavilov's sentence began, the VIR institute at 44 Herzen Street in Leningrad, the largest of his research institutes—and one that Lysenko had yet to get his hands on—housed about a quarter of a million different seed samples from around the world, including some 35,000 wheat, 10,000 corn, 26,000 legume, and 1,200 fruit samples, collected largely, though not entirely, by Vavilov himself.

On June 22, 1941, almost four months before Vavilov began rotting in Saratov Prison Number 1 for being a Mendelian geneticist, Hitler invaded the Soviet Union. On Sept. 8, 1941, the siege of Leningrad began: By the time it ended almost two and half years later, at least 800,000 Leningraders (and perhaps significantly more, scholars debate the exact figure) were dead, the vast majority as the result of starvation and malnutrition.

During the winter of 1941-42, the worst period of the Nazi siege, Vavilov's team at the VIR in Leningrad knew that their leader had been abducted, but beyond that, little information was available. For the moment what mattered most to them was that the single largest part of Vavilov's collection was under their guardianship in the heart of Leningrad. Many of the men at the VIR had been sent to the front to fight, and others like E.V. Wolf, a botanist and expert in plants that produce volatile oils, and E. Gleiber, the archivist at the VIR, of whom Vavilov had once said "for the sake of the cause he will give away the shirt off his back," were killed in the almost daily bomb raids. But a small team of women and men remained at the VIR with the seeds. They knew everything about what they studied and guarded. They also knew that the collection was in grave danger. The Nazi SS *Sammelkommandos* (collecting commandos) not only wanted the seeds at the field stations that Vavilov had set up all over the Soviet Union, they wanted the seeds at the VIR, in their pursuit of food to provide for the new *Lebensraum* (living space) they thought the war would bring. The VIR seeds were of particular importance as a treasure trove of genetic varieties of crop plants that the *Sammelkommandos* craved so desperately.

The Nazis were just one problem that the seeds and their scientist guardians faced. Lysenko and Stalin continued to imprison people for promoting Mendelian genetics, a cornerstone principle at VIR, and that meant the researchers there were potential targets. But that was not an immediate threat to the VIR team, which, during the siege of Leningrad, meant it was not a threat at all.

Exceptional cold, with temperatures plummeting to -35 degrees Celsius, was an immediate threat to the collections, and escape from it seemed almost impossible, with frost penetrating even the deepest basements. Firewood was almost as scarce as food, but somehow, burning whatever would burn, they kept the stoves lit and the seeds, for the most part, survived.

The most heartrending threat to the seeds was the citizens of Leningrad themselves. In the winter of 1941-42, the daily food ration was down to a morose 250 grams. People were eating pet food and pets. They were ripping down wallpaper and scraping off the glue, which, when mixed with water, had the texture of a watery porridge. They boiled anything that could be eaten. For many that was not enough, as the makeshift diary of 12-year-old Leningrad resident Tanya Savicheva made painfully clear: “28 December 1941 - Zhenya died. 25 January 1942 - Granny died. 17 March - Lyoka died. 13 April - Uncle Vasya died. 10 May - Uncle Lyosha died. 13 May at 7:30am - Mama died. The Savichevas are dead, everyone is dead. Only Tanya is left.” Little Tanya’s diary was not discovered until long after the war, but a frozen corpse in a Kafkaesque pose on the streets of Leningrad during the siege, cigarette dangling from its lips, and a bloodless finger pointing to the location of one of the recent mass graves that dotted the city landscape, told the same story.

Vavilov could only have dreamed of the technology required to build and maintain a seed vault inside a mountain that sits in permafrost.

That’s what it had come to. A bag of seeds could make the difference between life and death for a Leningrader. The VIR scientists understood that all too well, but they had to do what they had to do to guard the treasure for this and future generations. Some samples, for which there were replicates, were sent to other institutes and field stations: For everything else they triple-locked every entrance, sealed up the windows with iron bars, and kept three or more people on duty at the VIR 24 hours a day. It worked—losses to the citizens of Leningrad were incidental, in part because of security, and in part because there were very few attempts to appropriate the seeds.

If Stalin, Lysenko, the Nazis, and the people of Leningrad were not enough of a threat, there were the rats. Mad with hunger and armed with razor-sharp teeth and bodies that contorted like shape shifters capable of entering the smallest of spaces, the rats that hadn’t starved to death themselves were everywhere. But the VIR staff was smarter still and devised a way to hang the canisters with the seed treasure between the shelving units. That slowed the rats down. They also divided up each type of seed into replicate packets so that if some of the treasure was lost in rat guts, some of it would still survive.

Like virtually everyone in Leningrad, the 16 scientists remaining at the VIR were slowly starving to death during the siege, the difference being that in arms reach they had an abundance of rice and other forage that could save them. But, they understood that these samples, the genetic diversity they captured, and all that they had taught science, were priceless. What’s more,

the seeds had come to stand for Vavilov himself and his Herculean efforts. And so they never ate any of them.

Over that winter Alexander Stchukin, an expert on groundnuts, starved to death at his desk at the VIR, as did Dmitry Ivanov, a specialist on rice, Georgi Kriyer, an expert on medicinal herbs and Liliya Rodina, whose expertise lay in grain crops. Others on the VIR team—including A. Korzun, G. Kovalevsky, N. Leontjevsky, A. Malygina, and M. Steheglov—succumbed to starvation as well that winter. Fortunately, some of those who survived, like Vavilov's friend, Vladmir Lekhnovich, an expert on potatoes, lived to document it all for future generations.

VAVILOV WOULD HAVE BEEN PROUD had he known (he didn't) what his colleagues had sacrificed to guard the treasure. The following winter, on Jan. 24, 1943, as the siege went on, Vavilov complained of chest pains, shortness of breath, and diarrhea, and was admitted to the hospital at Saratov Prison Number 1. He looked like a ghost. The doctors recorded "maceration, pale skin, and swelling in the feet," and diagnosed him with "dystrophy from prolonged malnutrition." Two days later he was dead. The man who had collected more plant samples than any person in history, had cheated death repeatedly, and had worked to solve the puzzle of famine in his homeland, had been slowly and methodically starved to death.

It would be another decade before the Soviet government would admit that Vavilov's trial had been a sham, and then only in the coarsest, most bureaucratic manner possible, noting "gross breaches" of the law had been committed, and that the investigation had been "tendentious and unobjective." But in time the rehabilitation was complete. The VIR in what is now St. Petersburg was eventually renamed the N.I. Vavilov All-Russian Scientific Research Institute of Plant Industry, and remains not only a major seed repository, but a leading research center on plant domestication.

Vavilov, and those who starved at the VIR, could only have dreamed of the technology required to build and maintain a seed vault inside a mountain that sits in the permafrost of Spitsbergen, a remote Norwegian island 1,300 kilometers north of the Arctic circle. But the Svalbard Global Seed Vault is the futuristic version of what Vavilov had begun in 1921. Dubbed the Doomsday Vault, with a proclaimed mission to serve as "a global seed vault to serve as a backup storage facility ... to store duplicates (backups) of seed samples from the world's crop collections," it opened in 2008, as a repository that would ultimately contain *all* the world's crop plant genetic diversity. That vault is capable of storing 4.5 million different varieties of plants within its temperature controlled, -18 degrees Celsius facilities: With an average of 500 seeds per sample, that's 2.5 billion seeds. Precisely the sort of place that Vavilov had dreamed of.

As of today, 1,074,537 samples from around the globe sit in the Svalbard Global Seed Vault. Among those samples are 60 boxes from depositor 1739365, the N.I. Vavilov All-Russian Scientific Research Institute of Plant Industry. In those boxes lay samples from 148 species and 41 genera of domesticated plants collected from 109 countries. Many are the descendants of the seeds Vavilov himself collected.

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Our Little Life Is Rounded with Possibility

Science expressed only in terms of what happens is getting in the way of progress

BY CHIARA MARLETTO

IF YOU COULD SOAR high in the sky, as red kites often do in search of prey, and look down at the domain of all things known and yet to be known, you would see something very curious: a vast class of things that science has so far almost entirely neglected. These things are central to our understanding of physical reality, both at the everyday level and at the level of the most fundamental phenomena in physics—yet they have traditionally been regarded as impossible to incorporate into fundamental scientific explanations. They are facts not about what is—"the actual"—but about what could or could not be. In order to distinguish them from the actual, they are called counterfactuals.

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We cannot bring about transformations that laws of physics declare to be impossible.

Suppose that some future space mission visited a remote planet in another solar system, and that they left a stainless-steel box there, containing among other things the critical edition of, say, William Blake's poems. That the poetry book is subsequently sitting somewhere on that planet is a factual property of it. That the words in it could be read is a counterfactual property, which is true regardless of whether those words will ever be read by anyone. The box may be never found; and yet that those words could be read would still be true—and laden with significance. It would signify, for instance, that a civilization visited the planet, and much about its degree of sophistication.

To further grasp the importance of counterfactual properties, and their difference from actual properties, imagine a computer programmed to produce on its display a string of zeroes. That is a factual property of the computer, to do with its actual state—with what is. The fact that it could be reprogrammed to output other strings is a counterfactual property of the computer. The computer may never be so programmed; but the fact that it could is an essential fact about it, without which it would not qualify as a computer.

The counterfactuals that matter to science and physics, and that have so far been neglected, are facts about what could or could not be made to happen to physical systems; about what is possible or impossible. They are fundamental because they express essential features of the laws of physics—the rules that govern every system in the universe. For instance, a counterfactual property imposed by the laws of physics is that it is impossible to build a perpetual motion machine. A perpetual motion machine is not simply an object that moves forever once set into motion: It must also generate some useful sort of motion. If this device could exist, it would produce energy out of no energy. It could be harnessed to make your car run forever without using fuel of any sort. Any sequence of transformations turning something without energy into something with energy, without depleting any energy supply, is impossible in our universe: It could not be made to happen, because of a fundamental law that physicists call the principle of conservation of energy.

Another significant counterfactual property of physical systems, central to thermodynamics, is that a steam engine is possible. A steam engine is a device that transforms energy of one sort into energy of a different sort, and it can perform useful tasks, such as moving a piston, without ever violating that principle of conservation of energy. Actual steam engines (those that have been built so far) are factual properties of our universe. The possibility of building a steam engine, which existed long before the first one was actually built, is a counterfactual.

So the fundamental types of counterfactuals that occur in physics are of two kinds: One is the impossibility of performing a transformation (e.g., building a perpetual motion machine); the other is the possibility of performing a transformation (e.g., building a steam engine). Both are cardinal properties of the laws of physics; and, among other things, they have crucial implications for our endeavors: No matter how hard we try, or how ingeniously we think, we cannot bring about transformations that the laws of physics declare to be impossible. But by thinking hard enough, we can come up with more and better ways of performing a possible transformation—for instance, that of constructing a steam engine—which can then improve over time.

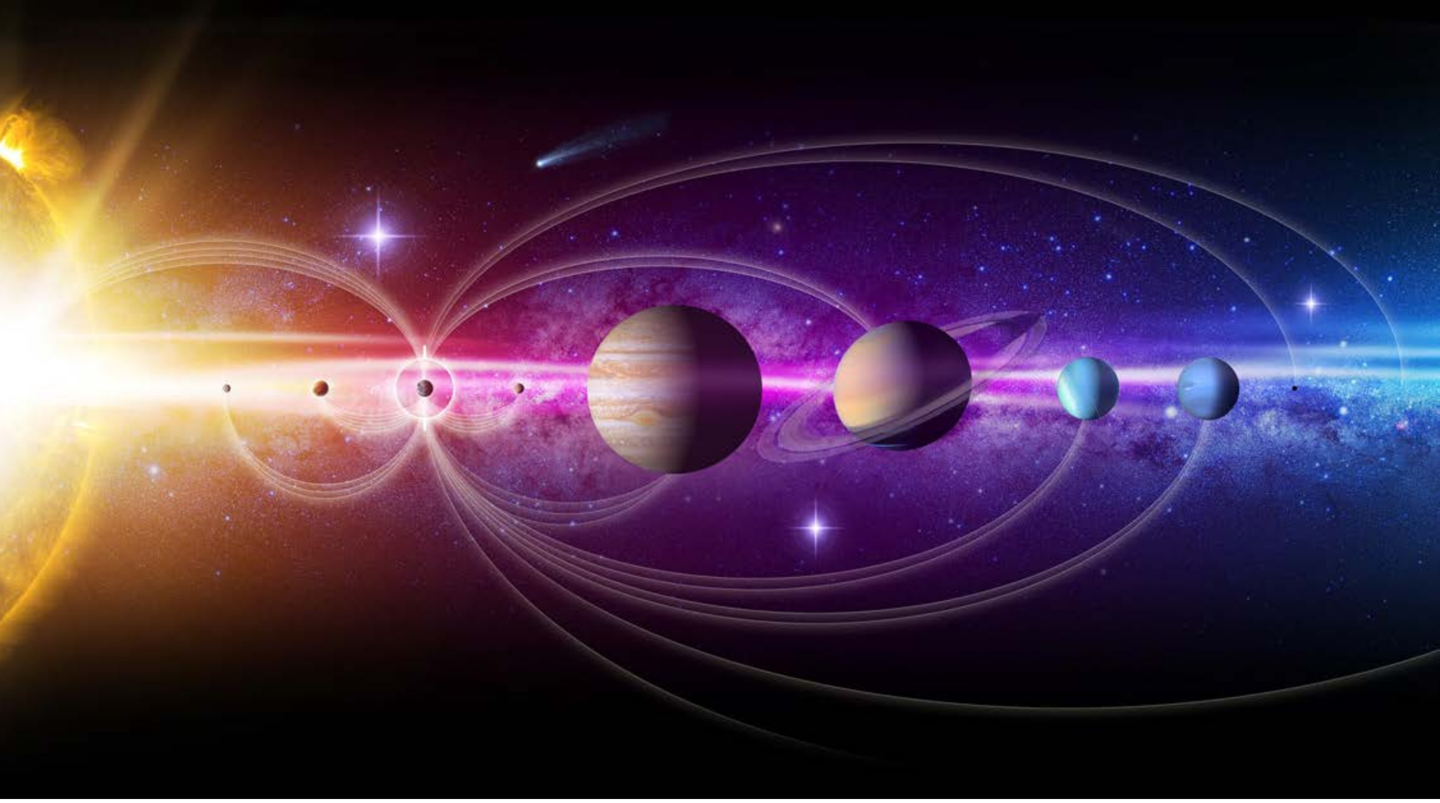
In the prevailing scientific worldview, counterfactual properties of physical systems are unfairly regarded as second-class citizens, or even excluded altogether. Why? It is because of a deep misconception, which, paradoxically, originated within my own field, theoretical physics. The misconception is that once you have specified everything that exists in the physical world and what happens to it—all the actual stuff—then you have explained everything that can be explained. Does that sound indisputable? It may well. It is easy to get drawn into this way of thinking without ever realizing that one has swallowed a number of substantive assumptions that are unwarranted. You can't explain what a computer is solely by specifying the computation it is performing at a given time; you need to explain what the possible computations it could perform are, if it were programmed in possible ways. More generally, you can't explain the presence of a lifeboat aboard a pirate ship only in terms of an actual shipwreck. Everyone knows that the lifeboat is there because of a shipwreck that could happen (a counterfactual explanation). And that would still be the reason even if the ship never did sink!

Despite regarding counterfactuals as not fundamental, science has been making rapid, relentless progress; for example, by developing new powerful theories of fundamental physics, such as quantum theory and Einstein's general relativity; and novel explanations in biology—with genetics and molecular biology—and in neuroscience. But in certain areas, it is no longer the case. The assumption that all fundamental explanations in science must be expressed only in terms of what happens, with little or no reference to counterfactuals, is now getting in the way of progress.

LET'S CONSIDER one of the most rare and important properties in our universe: resilience. Most things in our universe are impermanent. Rocks are inexorably abraded away; the pages of books tear and turn yellow; living things—from bacteria, to elephants, to humans—age and die. Notable exceptions are the elementary constituents of matter—such as electrons, quarks, and other fundamental particles. While the systems they constitute do change, those elementary constituents stay unchanged. Entirely responsible for both the permanence and the impermanence are the laws of physics. They put formidable constraints on everything in our universe: on all that has occurred so far and all that will occur in the future.

The laws of physics decree how planets move in their orbits; they govern the expansion of the universe, the electric currents in our brains and in our computers; they also control the inner workings of a bacterium or a virus; the clouds in the sky; the waves in the ocean; the fluid, molten rock in the glowing interior of our planet. Their dominion extends even beyond what actually happens in the universe to encompass what can, and cannot, be made to happen. Whatever the laws of physics forbid cannot be brought about—no matter how hard one tries to realize it. No machine can be built that would cause a particle to go faster than the speed of light.

The laws of physics are the primary explanation for that natural tendency for things to be impermanent. The reason for impermanence is that the laws of physics are not especially suited for preserving things other than elementary components. They apply to the primitive constituents of matter, without being specially crafted, or designed, to preserve certain special



LAW & ORDER The laws of physics decree how planets move in their orbits. They govern the electric currents in our brains and the inner workings of a virus. Whatever the laws of physics forbid cannot be brought about. Their dominion, though, extends to what can be made to happen.

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aggregates of them. Electrons and protons attract each other—it is a fundamental interaction; this simple fact is the foundation of the complex chemistry of our body, but no trace of that complexity is to be found in the laws of physics. Laws of physics, such as those of our universe, that are not specially designed, or tailored, to preserve anything in particular, aside from that elementary stuff, I shall call no-design laws. Under no-design laws, complex aggregates of atoms, such as rocks, are constantly modified by their interactions with their surroundings, causing continuous small changes in their structure.

From the point of view of preserving the structure, most of these interactions introduce errors, in the form of small glitches, causing any complex structure to be corrupted over time. Unless something intervenes to prevent and correct those errors, the structure will eventually fade away or collapse. The more complex and different from elementary stuff a system is, the harder it is to counteract errors and keep it in existence. Think of the ancient practice of preserving manuscripts by hand-copying them. The longer and more complex the manuscript, the higher the chance that some error may be performed while copying, and the harder it is for the scribe to counteract errors—for instance, by double-checking each word after having written it.

Given that the laws of physics are no-design, the capacity of a system to maintain itself in existence (in an otherwise changing environment) is a rare, noteworthy property in our universe. That's what I call resilience. That resilience is so hard to come by has long been considered a cruel fact of nature, about which many poets and writers have expressed their resigned disappointment. Here is a magisterial example from a speech by Prospero in Shakespeare's *The Tempest*:

> Our revels now are ended. These our actors
> (As I foretold you) were all spirits, and
> Are melted into air, into thin air,
> And like the baseless fabric of this vision,
> The cloud-capp'd tow'rs, the gorgeous palaces,
> The solemn temples, the great globe itself,
> Yea, all which it inherit, shall dissolve,
> And, like this insubstantial pageant faded
> Leave not a rack behind. We are such stuff
> As dreams are made on; and our little life
> Is rounded with a sleep.

Now, those lines have such a delightful form and rhythm that, on first reading, something important may go unnoticed. They present only a narrow, one-sided view of reality, which neglects fundamental facts about it. If we take these other facts into consideration, we see that Prospero's pessimistic tone and conclusion are misplaced. But those facts are not immediately evident. In order to see them, we need to contemplate something more than what spontaneously happens in our universe (such as impermanence, occasional resilience, planets, and the cloud-capped towers of our cities). We have to consider what can, and cannot, be made to happen: the counterfactuals—which, too, are ultimately decided by the laws of physics.

The misconception is that once you have specified everything in the physical world, you have explained everything.

THE MOST IMPORTANT ELEMENT that Prospero's speech neglects is that even under no-design laws, resilience can be achieved. There is no guarantee that it shall be achieved, since the laws are not designed for that; but it can be achieved because the laws of physics do not forbid that. An immediate way to see this is to look around a bit more carefully than was possible in Shakespeare's time. There are indeed entities that are resilient to some degree; even more importantly, some are more resilient than others. Some of them very much more. These are not, contrary to what proverbs and conventional wisdom might suggest, rocks and stones, but living entities.

Living things in general stand out as having a much greater aptitude to resilience than things like rocks. An animal that is injured can often repair itself, whereas a rock cannot; an individual animal will ultimately die, but its species may survive for much longer than a rock can.

The laws of physics, expressed as counterfactuals, offer a chance for improvement.

Consider bacteria. They have remained almost unchanged on Earth for more than 3 billion years (while also evolving!). More precisely, what has remained almost unchanged are some of the particular sequences of instructions that code for how to generate a bacterium out of elementary components, which are present in every bacterial cell: a recipe. That recipe is embodied in a DNA molecule, which is the core part of any cell. It is a string of chemicals, of four different kinds. The string works exactly like a long sequence of words composed of an alphabet of four letters: Each word corresponds roughly to an instruction in the recipe. Groups of these elementary instructions are called genes by biologists.

It is the particular structure, or pattern, of bacterial DNA that has remained almost the same over such a long time. In contrast, during the same period, the arrangement and structure of rocks on Earth have profoundly changed; entire continents have been rearranged by inner movements taking place underneath the Earth's crust. Suppose some aliens had landed on Earth early in prehistory, collected DNA from certain organisms (say, bluegreen algae), and had also taken a picture of our planet from space; and that they were to come back now to do the same. In the pictures of the planet, everything would have changed. The very arrangement of continents and oceans would be utterly different. But the structure of the DNA from those organisms would be almost unchanged. So, after all, certain things in our universe, like recipes encoded in DNA, can achieve a rather remarkable degree of resilience.

The other element that Prospero's speech disregards is that living entities can operate on the environment, transform it, and (crucially) preserve the ability to do so again and again, thus leaving behind much more than "a rack." The Earth still bears the signs of bacterial activity from a billion years ago (for instance, in the form of fossil carbon). Plants have caused a dramatic change in the composition of the atmosphere by releasing gaseous oxygen as a side effect of converting the sun's light into chemical energy via photosynthesis. Humans, too, are capable of transforming the environment in a wide set of conditions. Contrary to Prospero's view, palaces, temples, and cloud-capped towers can achieve resilience—because they are products of civilization. Humans can restore them by following a blueprint—or rather, again, a recipe—of how they were initially built, guaranteeing that they will endure much longer than their constituent materials. In principle, a 3-D printer provided with such a recipe could reconstruct from scratch any ancient palace that happened to be completely destroyed.

The human life span may be still constrained, but technology has already extended it well beyond that of our ancestors. By changing the naturally occurring environment, human civilization is tentatively improving and growing. We now have the knowledge to produce warm (or cooled) houses, powerful medications, efficient transport on Earth and even into space, and tools to save ourselves labor, to lengthen our lives and make them more enjoyable. We have majestic works of art and literature, music, and science. Those very words in Prospero's speech are an example of our literary heritage, and they have survived—together with countless other wondrous outputs of human intellectual activity. So, rather than fading away, this pageant we have set up, which sustains us, has been under way for centuries. The rest of life's show on Earth has endured even longer, for billions of years.

Of course, the resilience of our civilization is constantly threatened by severe problems, which crop up as we try to move forward. Some of them, such as global warming and fast-spreading pandemics, are in fact a byproduct of the very progress I have described. These problems present considerable challenges and could easily wipe out several aspects of the progress we have made.

But it is possible to take steps to solve those issues, no matter how serious they appear; and the laws of physics do not forbid still greater improvement. They do not guarantee improvement or resolution, but nor do they forbid it: Resilience and further progress, by addressing problems such as the climate crisis, are both possible. The laws of physics, expressed as counterfactuals, offer a chance for improvement. By contemplating what is possible in the universe, in addition to what happens, we have a much more complete picture of the physical world. Prospero's gloomy conclusion is partial and profoundly misguided. It was nothing more than an unreal nightmare.

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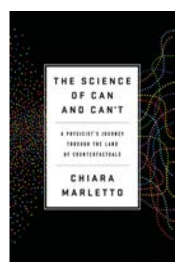

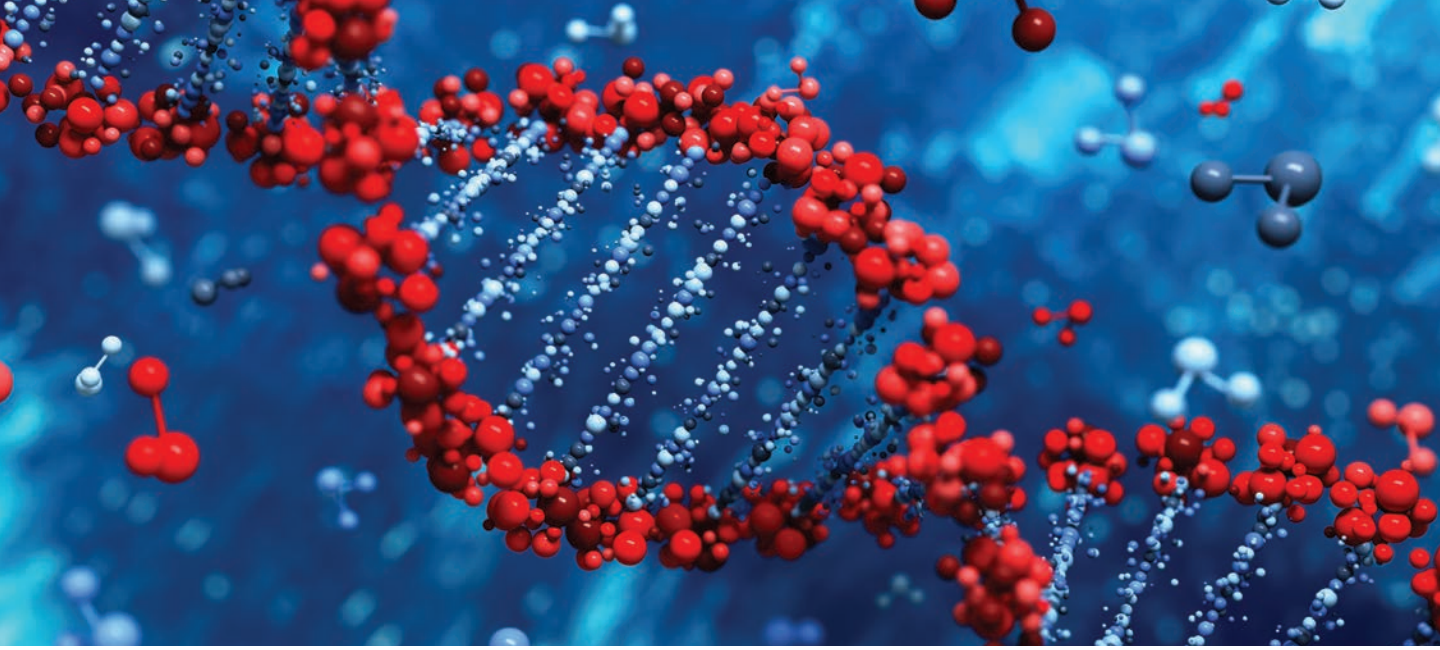

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Please share your projects, your stories and your inspiration during this difficult time

Cultural Programs of the National Academy of Sciences has created a questionnaire to collect information about creative responses to the coronavirus pandemic. Collaboration and integrative ideas are critical now more than ever. Please help us collect information as we generate a time capsule of creative responses. Share your creative projects or add projects that have inspired you.

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Sabine Hossenfelder

The theoretical physicist and popular YouTuber on how she communicates science

INTERVIEW BY BRIAN GALLAGHER

PUBLIC OUTREACH

I feel like it's part of my profession as a scientist to pass on knowledge. Public outreach comes more naturally to me than teaching. I enjoy it more. To some extent, outreach is not generally acknowledged as being part of my profession. If I were teaching, I could collect credits, and I could put this interview on my CV, and it might help me get a job. But with a YouTube channel it's more like, OK, she has this weird hobby—I think physics and other things might be interesting to other people. That's certainly the feedback I get. As abstract as it is, physics enriches your life.

A BETTER AUDIENCE

I started writing a blog in 2006. I was working mostly on particle physics and quantum gravity, and most of the audience was interested in reading about them. But over the years my interests shifted. I drifted more toward philosophy, the foundations of physics. I'm now doing more astrophysics, dark matter. The problem with blogs is it becomes hard to find a new audience. Every time I write about something that doesn't fit the previous niche, no one would read it because they'd be, "Oh, what's this? This is not what I signed up for." YouTube doesn't entirely solve the problem. Its algorithm tries to classify your channel and look for an audience. But it's more tied to the individual thing that you produce, and tries to find an audience for it. My YouTube audience is more aligned with what I'm interested in—How do we use science? How does it work?—instead of this very narrow particle physics stuff.

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BEYOND MATH

In physics, all our theories are math. If you don't understand math, you don't really understand physics because you can't follow the logical conclusions. But if you're fine to be told that if I make the following assumptions, then this follows, then you can get some understanding of the logic. A problem is analogies—comparing the real thing with something else. I struggled with that a lot when I was a teenager trying to understand special relativity. Books on it talk about space shuttles and rockets and lasers bouncing on mirrors. If you take some of these ideas and try to generalize them, it doesn't work. You run into contradictions because you didn't understand or weren't even shown the underlying principles. These are fancy ways to explain math. But if you only use these descriptions and try to apply them for something else it will almost certainly go wrong.

RIGHT BALANCE

It's important to get rid of the terminology. It's not that people don't understand it. If you explain a concept to them, what it means, they will understand. But the more of these words you carry around with you, the larger the cognitive load. If I'm listening to or reading something in a discipline which is not my own, by the time you have three, four, five, six new words that you have to keep in mind, the more likely it becomes completely incomprehensible. There's always some balance to find between simplification and oversimplification. I hope that most of the time I do it correctly.

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