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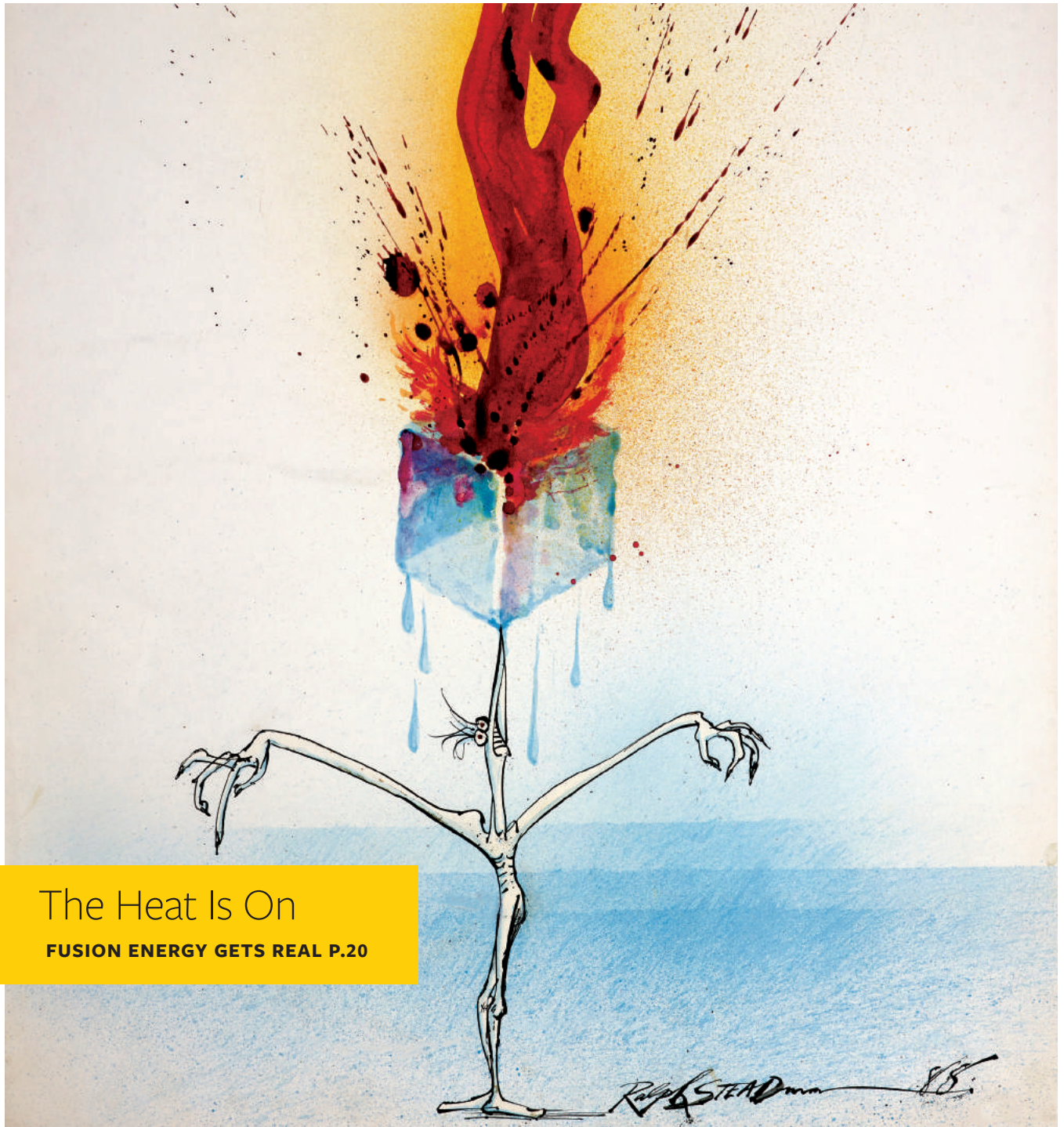
Would ET recognize our genetic code?

HOW TO READ A BRAIN MAP

Neuroscience has a problem

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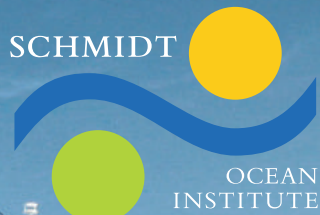
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Contents

Editor's Note

5

Visions

BY KEVIN BERGER

Readers Respond

7

Comments and letters about stories from print issue 29

Preludes

12

Why there's no such thing as a "living fossil"; the reasons behind our attraction to disgust; how brains build maps of the world; a debate about word choice in physics; and a trip to Mars.

Cover Story

CLIMATE

20

The Firestarter

On a road less traveled, this physicist is leading the world to fusion energy

BY COREY S. POWELL

The Last Word

108

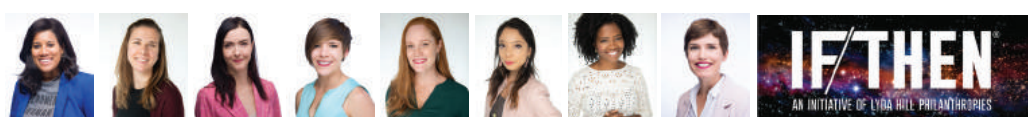
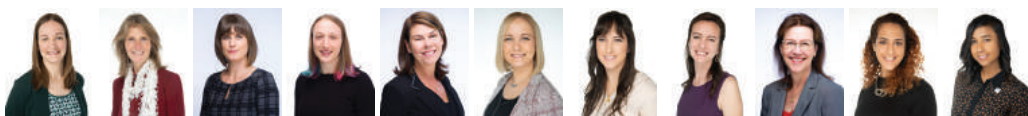
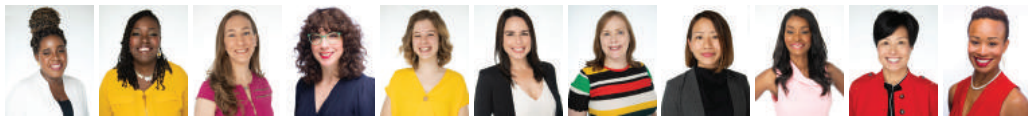
Gina Rippon

The neuroscientist on the myths about female and male brains

INTERVIEW BY CODY KOMMERS

COVER Ralph Steadman





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Features

LINGUISTICS

34 Never Say Wolf

How taboo language turned the wolf into a monster

BY DAVID ADGER

HISTORY

38 We Are All Ancient Mapmakers

*Why we still see the world like the mathematician
and poet who first mapped it*

BY CODY KOMMERS

ALIENS

44 Do We Share DNA with ET?

*If there's life beyond Earth, the genetic code
might be our common bond*

BY DANIEL OBERHAUS

NEUROSCIENCE

50 An Existential Crisis in Neuroscience

*We're mapping the brain in amazing detail—
but our brain can't understand the picture*

BY GRIGORI GUITCHOUNTS

PHILOSOPHY

60 Consciousness Isn't Self-Centered

*Think of consciousness like spacetime—
a fundamental field that's everywhere*

BY ANNAKA HARRIS

PSYCHOLOGY

68 The Cultural Distances Between Us

Mapping the world's psychological traits

BY BRIAN GALLAGHER

ASTRONOMY

78 Why Astrology Matters

*Seeing meaning in the stars is a vital part
of the scientific story*

BY MICHAEL BROOKS

PHILOSOPHY

84 We Are All Bewildered Machines

*Bewilderment is the antidote to
scientific reductionism*

BY KEVIN BERGER

TECHNOLOGY

90 The Forest Spirits of Today Are Computers

*We've made an artificially panpsychic world,
where technology and nature are one*

BY GEORGE MUSSER



NAUTILUS

EDITORIAL

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NAUTILUS *Next*

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Visions

BY KEVIN BERGER

N *INVISIBLE CITIES*, the novel by Italo Calvino, the emperor Kublai Khan strolls in his gardens of magnolias with Marco Polo, listening to the young Venetian describe the cities he's visited on his expeditions around the world.

Kublai Khan has many envoys report to him about their world travels, but he listens to Marco Polo with the most attention and curiosity. "Only in Marco Polo's accounts was Kublai Khan able to discern, through the walls and towers destined to crumble, the tracery of a pattern so subtle it could escape the termites' gnawing," Calvino writes.

That kind of detail—"the tracery of a pattern so subtle it could escape the termites' gnawing"—is what makes Calvino's writing so special. It is also what makes the theme of *Invisible Cities* so remarkable. Kublai Khan knows Marco Polo is inventing details. But he is absorbed in them because they are singular visions. Marco Polo conjures the cities to life. Calvino predates what cognitive scientists tell us about how we take in stories and construct reality. "Kublai asks Marco, 'When you return to the West, will you repeat to your people the same tales you tell me?' 'I speak and I speak,' Marco says, 'but the listener retains only the words he is expecting.'"

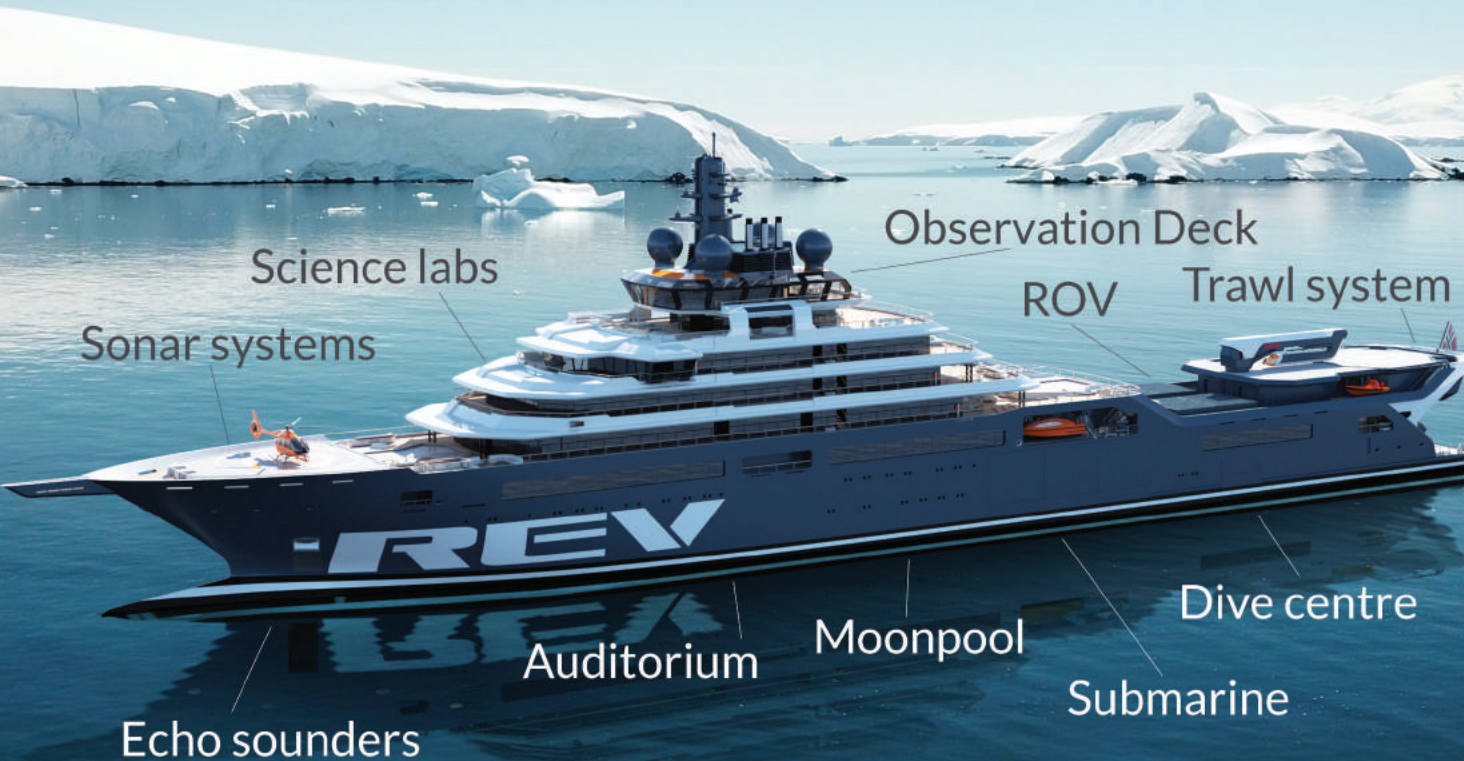
That insight is one scene in Calvino's grand canvas of how imagination magnifies the world. That theme suffuses this issue of *Nautilus*. We tend to think of science defining reality. It's the best human practice, with built-in protocols to filter out falsehoods, to capture the elements of nature. Still, the elements are represented in signs and symbols, notably language, hatched from the minds of humans. A physicist determined to repower the world with clean energy from atomic fusion is this issue's visionary hero. Whether he turns out be Prometheus, who steals fire from the gods for humanity's benefit, or Icarus, who with his wax wings flies too close to sun and crashes into the sea, remains to be seen.

Visions can be maps, one of science's best tools. Scientists map the geography of the Earth, stars in the sky, neurons in the brain, codes in artificial intelligence. Some scientists light out for unforeseen lands, like the essence of consciousness. That is Annaka Harris' quest in "Consciousness Is Not Self-Centered." Some look for the language that has molded our behavior, as David Adger does in "Never Say Wolf." Some travel back in time, where a trail of surprises await. Astrology is hokum. But in "Why Astrology Matters," physicist and science writer Michael Brooks turns back the clock to reveal that "astrology is the grit that seeded the pearl; its data-gathering, map-making, and pattern-seeking laid the cognitive foundations for modern science."

All *Nautilus* writers journey into the recesses of science to absorb every particle of information they can. They surface to make sense of what they've learned and fire up their imaginations to captivate you.

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Readers Respond

Comments and letters about stories from print issue 29.

“NEVER UNDERESTIMATE THE INTELLIGENCE OF TREES”

It seems we would need to approach this as we would evaluating an alien species. What exactly is language and intelligence? Or the converse. If aliens did visit earth would they automatically see humans as dominant as opposed to plants? Maybe not. Hell, they could possibly see dogs as our masters viewed through a certain lens, ha. Maybe we aren't as smart as we think.

—aw

Plant more trees! Trees will save the world—they eat CO₂ and excrete oxygen, essential for us animals to live. However, Dr. Simard is in la-la land to think they have any form of intelligence. They have no neural system essential for thought. Just how does an immobile “Mother Tree” look after her seedlings? It is wonderful to walk in the woods, but this research leans toward feel-good silliness.

—R. Parker

“IS THE LAW OF CONSERVATION OF ENERGY CANCELLED?”

I think we should look more closely to the history of energy conservation. It took many years to be formally defined even though the concept started shaping up earlier. What if it is just an assumption that turned into a law because no one

observed a violation? Assumptions could be wrong.

—Noel Carrascal

“I AM NOT A MACHINE. YES YOU ARE.”

Ah, well. A new version of anthropomorphism. How can there be “art” without creative self-reflection? Can one really attribute creative intent and free will to an algorithm? Novelty is one thing—meaningful personal expression is something quite different.

—George Gantz

I agree with you; however the variation I take on the position is this: Art can be about self expression, but it can also be made by other means. For example, think of marketing, and an artist communicating with the viewer, or creating a scene where an audience or viewer can experience specific conditions. The art can motivate art and thinking in specific ways. Art can be used then as a tool for learning, self-reflection, manipulation or, as hope.

—Rachel Wolfe

“WHERE IS MY MIND”

Maybe, just maybe, consciousness cannot be localized in any particular brain structure, because consciousness is a strange attractor, a high-dimensional non-linear process that involves all of the

brain's functions, built “on top of the brain,” if you will. As an emergent function it might have remarkable properties, like freewill for instance. If, of course, you are present in this moment to participate in that function.

—Allan Lindh



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

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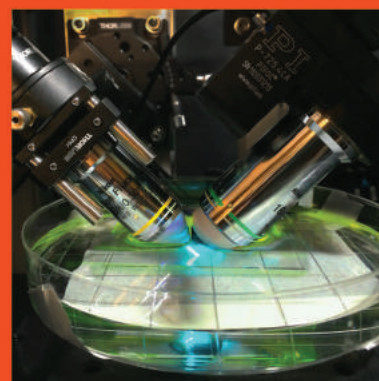
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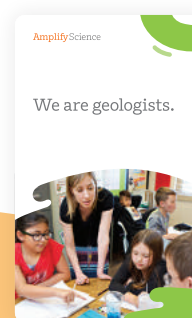
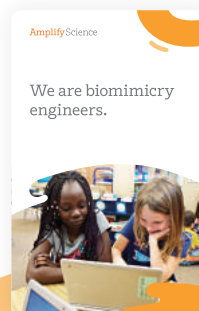
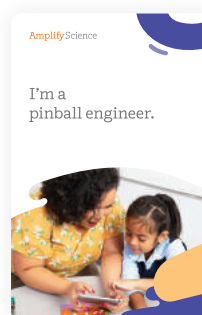
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Preludes



ENVIRONMENT

Australia's Secret Rescue of Ancient Trees

WHEN I READ THAT more than a *billion* animals had lost their lives to bushfires still raging in Australia, I froze, staring at the incomprehensible figure on my screen.

A sort of sinking feeling came. Scientists made the estimate from the numbers of animals that have died from previous land-clearing practices. It is dismaying to try to imagine all that those fires consumed. They've scorched 72,000 square miles of land and over 2,600 homes, and killed just under 30 people. The animal death toll is in the trillions when you include the invertebrates. But it lifts me up to see that, an ancient and critically endangered species, rooted in New South Wales' Wollemi National Park, survived the blaze.

In January 2020, *The Sydney Morning Herald* had the story: "Incredible, secret firefighting mission saves

Nature doesn't put evolution on pause.

'dinosaur' trees." The conifers, *Wollemia nobilis*, are uniquely wild in Australia and grow in a narrow and inaccessible gorge, the precise location of which is hidden from the public to ward off tourists and contaminants. The trees number less than 200. The effort to safeguard them from encroaching flames "was like a military-style operation," Matt Kean, New South Wales' Environment and Energy Minister, told the *Herald*. Aircraft dropped water bombs and fire retardant, and helicopters sent firefighting specialists down to irrigate the

ALEXANDER DENISENKO / SHUTTERSTOCK

forest ground, moisturizing it to slow the fire's spread. "We just had to do everything," Kean said. *Wollemia nobilis* is like a "living dinosaur."

Scientists have studied fossilized *Wollemia* dating as far back as 200 million years ago. This tree has, in a sense, outlived the dinosaurs. Encountering it can be like seeing a dinosaur-era insect encased in ancient amber brought to life. The tree's resin (the precursor to amber) is useful to paleontologists for its chemical similarity to ancient amber (fruit flies, for instance, decay rapidly in pine resin but very slowly in *Wollemia* resin).

Calling the trees, as *The New York Times* did upon *Wollemia*'s discovery, "living fossils," fails to appreciate them. They aren't relics of the past, evolved for a distant time. They've continued to evolve, an example of adaptability; in short, they are amazing survivors. In a *Nautilus* article, Ferris Jabr spoke to Alan Turner of Stony Brook University, an expert on fossil crocodylians and their ancestors. "I think the term 'living fossil' should be retired," Turner said. "It does little good because it is almost always based on oversimplifications. 'Living fossils' often are judged based on some notion of overall morphological similarity. That was the case with crocs. If you squint, these various lineages all sort of look the same, but the details are all different. It ignores how evolution works on multiple levels. I wouldn't miss it."

Charles Darwin was playing around with the phrase in *On the Origin of Species*. He made clear that "living fossil" was his "fanciful" way of highlighting the more extraordinary or strange beings he encountered—ones like the lungfish and the platypus that look like they might genetically link species disparate in space and/or time. Darwin's coinage was both "poetic and memorable," Jabr wrote, and quickly found broad acceptance. "'Living fossil' was no longer a passing phrase; it had become a powerful concept shaping scientists' attitudes toward modern species. If certain creatures were frozen in evolutionary time, the reasoning went, then they could be our windows to ancient epochs of life." But nature doesn't put evolution on pause. "It's true that the living descendants of early animal lineages can teach us about their ancestors, but the idea that any species alive today has stopped evolving is simply false," Jabr continued.

When we look at a crocodile, a "primordial dragon," Jabr wrote, "we should recognize one of evolution's greatest survivors—a compatriot of the planet every bit as modern as we are." The same goes for Australia's conifer trees. With a little help from their human friends, they can continue to show us, as Jabr put it, "There are no living fossils. Fossils cannot change; life must."

— Brian Gallagher

PSYCHOLOGY

Why We Love to Be Grossed Out

NINA STROHMINGER IS DRAWN to disgust. The psychologist has written extensively on the feeling of being grossed out, and where it comes from. The dominant idea, developed by Paul Rozin and April Fallon, is that disgust evolved adaptively from an oral revulsion to biologically harmful substances, like rotten food and bodily waste. The emotion subsequently crept into the social arena, they claimed, as we became revolted by abnormal and licentious behavior. Moral repugnance arose as a result, which retains little, if any, connection to the biological origins of disgust. It's "like a parfait," Strohminger says. "It started out as one thing and things kept getting added on as it developed."

Rozin and Fallon's theory made disgust one of the more popular human emotions to study. Strohminger finds their story intuitive, although perhaps oversimplified. In particular, she worries that the cumulative view of disgust masks a more evolutionarily complex story. Strohminger prefers to approach disgust not as a straightforward extension of the immune system's aversion to harmful substances, but as "a psychological nebula, lacking definite boundaries, discrete internal structure, or a single center of gravity."

Disgust is inherently ambivalent—it at once revolts and attracts us. This reflects, for Strohminger, the larger evolutionary ambivalence that



Disgust tends to stigmatize and dehumanize its object, including people.

disgust stems from, since we “must balance the need for nutrition against the peril of toxic comestibles, the need to socialize against the threat of communicable disease.” In short, disgust may not derive from a simple aversion to harmful substances but from a tension between the desire to explore and consume new things and the dangers of doing so.

Josh Rottman, a developmental psychologist who specializes in disgust, claims that the emotion is better understood by examining the social forces that inform it. If disgust were an adaptive behavioral mechanism for avoiding biologically harmful substances, Rottman argues, children would exhibit disgust in their most vulnerable years, when their immune system is still developing. But infants and toddlers are willing to put just about anything in their mouths, even imitation feces, and only begin to show signs of disgust around ages 5 to 7.

Rozin attributes the delayed onset of disgust to the omnivore’s dilemma, the fact that we must balance our ability to consume a wide variety of foodstuffs with the potentially steep consequences of poisoning ourselves. If disgust had a single adaptive origin, one might expect certain substances to universally elicit disgust. But universally disgusting objects don’t seem to exist.

While some Westerners are disgusted by insect larvae on a plate, Easterners are similarly revolted by the idea of lifting curdles from soured milk, adding salt, and giving the resulting product a quaint name like “cottage cheese.” The Hazda of Tanzania often consume putrid meat scavenged from lion kills. Shamans of the Koryak tribe in Siberia consume mushrooms, urinate in a pot, and pass it around for the group to sip. And the Mundari tribe in South Sudan not only showers in cow-urine but also cover their bodies with ash from dung fires to ward off infection.

Given this ethnographic variation on disgust, Rottman argues that what elicits the emotion is largely socially informed. There’s even considerable variation for disgust within a lifetime, as we can develop a taste for bloody, organ-spilling horror films as well as revulsions to odors of liquors we formerly enjoyed but once overindulged in.

Since disgust arrives in middle childhood, right around the time when social biases are formed, Rottman says, “It seems to be more of a social avoidance kind of emotion. It helps us avoid people, not only people who are sick, but also people exhibiting non-normative behaviors.” We’re not only disgusted by people who are boiled and plagued, who pose a

threat to our physical health, but also by people who seem socially ill, who pose a threat to our customs and morals.

Moral repugnance is perhaps the most complicated iteration of disgust. Daniel Kelly, a philosopher who wrote a book on the subject, considers disgust to have more cognitive than sensory signatures. “Dis-taste is sensory, a revulsion to something that tastes harmful,” he says. “But disgust isn’t merely sensory—charred human flesh might be delicious, but that’s not why we don’t eat it.” Kelly argues that the emotion shouldn’t have any authority in moral evaluation. He finds there is no “deep wisdom” in disgust, and the use of moral repugnance in decision or policy

making is irresponsible and even dangerous. “Disgust tends to stigmatize and dehumanize its object, including people,” Kelly says. “It makes it easy to treat people horribly.”

What perplexes Strohming is our attraction to aversion. “We need to account for the fact that we chase after disgust,” she said. As a matter of taste, disgust is inherently subjective. There’s no real reason why one person might crave bacon-flavored ice cream with pickles while the thought of that might make another retch. And that might be why it’s hard to explain why we chase after disgust, too. In the end, we might have just developed a taste for it.

—Marco Altamirano



ANIMALS

The Brain Cells That Guide Animals

IT MAY SEEM ABSURD to compare a tiny fruit fly’s brain to that of a majestic elephant. Yet it’s the dream of many neuroscientists to find deep rules that very different brains share. Neuroscientist Vivek Jayaraman believes that scientists are on the verge of identifying some of these deep neural rules. Jayaraman and a small number of researchers studying the brain’s GPS have, in fact, already experienced the thrill of discovering one such rule. It governs something essential—the ability of an animal to keep track

of where it’s headed. What’s more, recent experiments on flies hooked up to virtual-reality environments—one from Jayaraman’s group and another from Rachel Wilson and colleagues at Harvard—show how a fruit fly’s visual cues ensure the stability of its heading. The findings offer insight into how mammals, like us, might build maps of their world.

When you’re moving freely, certain neurons are only active when you’re facing a particular way. It doesn’t matter where you are—as long as you keep looking

The findings offer insight into how mammals, like us, might build maps of their world.

ahead, in that direction, the cell fires. These so-called head-direction cells were first identified in a region of the rat brain very close, and intimately linked to, the hippocampus, the home of place cells. There are a large number of these cells, but any one cell is only active in a certain small region of the environment. They act like a map, telling you where you are. Such a map isn't very useful without knowing where you're headed. That's why the brain also creates a mental compass, using head-direction, or compass, cells.

It is striking how closely these two systems work together. If you were to rotate the visual cues that a rat uses to define its heading, then the head-direction cells would remap themselves to this shifted world. At the same time, the place cells of the hippocampus would also rotate the mental map. These two groups of cells provide complementary information that, if correctly put together, are enough to help the rat navigate anywhere in its environment—even in the dark. Head-direction cells, in other words, don't simply respond to visual cues. They maintain their activity even when a rat can't see its surroundings (or when you cover your eyes). How does the brain set up this stable compass-like representation? More perplexingly, how does it maintain this stable heading without visual cues?

Experimental evidence in rats and mice suggests that a doughnut-like structure of head-direction cells keeps the brain's compass reliable. A 1995 paper first proposed this doughnut or "ring-attractor" picture. In it, William Skaggs and his colleagues hypothesized that the head-direction cells—which did not seem to have any visible characteristic group structure—connect together to form an imaginary ring that creates a 360-degree map of two-dimensional space.

Each cell, a point on the ring, refers to a particular heading. Nearby cells on this ring refer to adjacent and similar headings, and activate each other, while

cells that are far apart, and refer to opposing or near-opposing headings, deactivate each other. The researchers suggested a rule for how information from the brain's visual areas enters the ring of head-direction cells, contributing to their characteristic activity pattern.

They also incorporated the vestibular system of the brain, which detects head turns, to allow the ring to maintain its activity in the dark. This model of inputs allowed for only one small group of nearby head-direction cells to be active at any given time. This one "bump" of activity corresponded with the rat's heading. If the rat, or its world, turned (by, say, the rat getting flipped over) then the connections within the ring of cells and the changing visual input information would cause the bump to turn accordingly.

In a win for Skaggs and his colleagues, researchers have identified some of the cells that appear to operate according to their mathematical model. Still, it has one major hole: There is little understanding of how the brain converts visual information into a stable sense for heading. It is, at least for now, too hard to map how the millions of cells and complex connections that allow rats and mice to see connects to this ring.

This is where Jayaraman comes in. The fruit fly, it turns out, also has a region of its brain dedicated to maintaining a sense of direction. Jayaraman characterized it with his colleagues less than a decade ago. Incredibly, it is a doughnut-shaped ring exactly like the structure of the theoretical ring-attractor network. Any given cell in this ring of cells is only active when the fly is facing a particular way—exactly like head-direction cells in rodents (and, presumably, in us).

"It isn't surprising that common principles exist when the neural circuit required is under similar constraints," Fisher said. "Navigation has a number of broadly similar requirements for all animals." Given these similarities, the rules the researchers identified could inspire others to make sense of this process in mammals. General principles, like the ring-attractor model for calculating heading, provide insight into how all animals behave.

—Adithya Rajagopalan



Quantum Supremacy

PHYSICS

Should Scientists Use the Phrase “Quantum Supremacy”?

FORGET FOR A MOMENT that you know the meaning of “quantum supremacy,” the idea of a quantum computer outdoing its conventional counterpart. What does the phrase instantly bring to mind? Perhaps the idea that the quantum world, with its electrons, neutrons, and quarks, is, somehow, better than ours—more dazzling and awe-inspiring. Or perhaps it’s the claim that exploring quantum phenomena is more worthwhile, in a socioeconomic or in a personal, life-fulfilling sense. Or perhaps it’s the suspicion that quantum beings exist, and exert absolute control over everything we do. The point is, with “quantum supremacy,” you can imagine many ways to erect a quantum-first hierarchy. Remarkably, it’s precisely that sort of thinking, prompted by the word “supremacy,” that some scientists are wary of popularizing.

In December 2019, after Google made headlines with its announcement that it had achieved quantum supremacy, the scientific journal *Nature* received and published a letter with the headline, “Supremacy is for racists—use ‘quantum advantage.’” The authors of the letter—a quantum computing researcher, a planetary scientist, and a former *Nature* editor—argued that, in a world riven by sexism and racism, it would

be irresponsible for scientists to allow an “inherently violent” term like “supremacy” to permeate popular culture, which could risk “sustaining divisions in race, gender and class” and ward off some from pursuing computer science. This is because “supremacy” has “overtones of neocolonialism and racism through its association with ‘white supremacy,’” they wrote. “Instead, quantum computing should be an open arena and an inspiration for a new generation of scientists.”

The letter has a number of signatories, yet some found the message risible. “This sounds like something from *The Onion*,” Harvard psycholinguist Steven Pinker said on Twitter. The call to stigmatize “quantum supremacy” reminded him of a similar episode of rebranding, which saw the acronym for the Neural Information Processing Society (NIPS) change to NeurIPS. The sort of criticism “supremacy” got in the *Nature* letter instanced “a familiar linguistic phenomenon,” Pinker said, “a lexical version of Gresham’s Law: Bad meanings drive good ones out of circulation.” He wants scientists to resist banning words in this manner. “It dumbs down understanding of language: word meanings are conventions, not spells with magical powers,” he said, “and all words have multiple senses, which are distinguished in context.”

Bad meanings drive good ones out of circulation.

Julie Sedivy, a psycholinguist, struck a less dismissive tone when I asked her about “quantum supremacy.” She said the *Nature* letter authors “have a point, at least partially.” It has to do with the contingent way in which each of us relates to particular words.

“This letter points to an interesting aspect of human language: Namely, that the meanings, connotations, and associations we attach to words are heavily dependent on our own experiences with them,” she told me in an email. “Thus, imperfect convergence in our experiences with words imposes an inherent limitation to human communication. The authors argue that it’s irresponsible not to consider the experiences that other people are likely to have with the word ‘supremacy.’ In principle, it doesn’t seem unreasonable to suggest that if readers’ experiences with a word are likely to set off negative, unintended resonances, that is a sound argument for finding an alternative way to express the same idea.”

What about in practice? Sedivy said she would need answers to certain questions before deciding to do away with “quantum supremacy.” Who is the intended audience? What are the likely experiences of that audience with the term? “In this case,” she said, “the argument is weakened by the fact that the term appears in a technical scientific article. Is the term ‘quantum supremacy’ in common use among the targeted readership? If so, this will skew the representations that the audience is likely to have of the term away from the negative associations that the authors worry about.”

Theoretical computer scientist Scott Aaronson empathized with the letter’s concerns about “supremacy.” But he also couldn’t come up with another way to express the significance theoretical physicist John Preskill, who coined the term in 2012, wanted to get across. Preskill meant “quantum supremacy” to “refer to a *momentous event* that seemed likely to arrive in a matter of years,” the time when quantum computers would first outpace the fastest classical supercomputers, Aaronson wrote on his blog. “And ... ‘the historic

milestone of quantum advantage’? It just doesn’t sound right. Plus, as many others pointed out, the term ‘quantum advantage’ is already used to refer to ... well, quantum advantages, which might fall well short of supremacy.”

Sedivy underscored the difficulty. “Representations of words are essentially containers for memories of all of the uses of that word that we encounter, with more recent uses having particular weight,” she said. For someone outside quantum computing, who has encountered “supremacy” mainly in the context of political or current affairs, its meaning can’t help but be loaded. That’s a fact scientists can’t ignore.

—Brian Gallagher

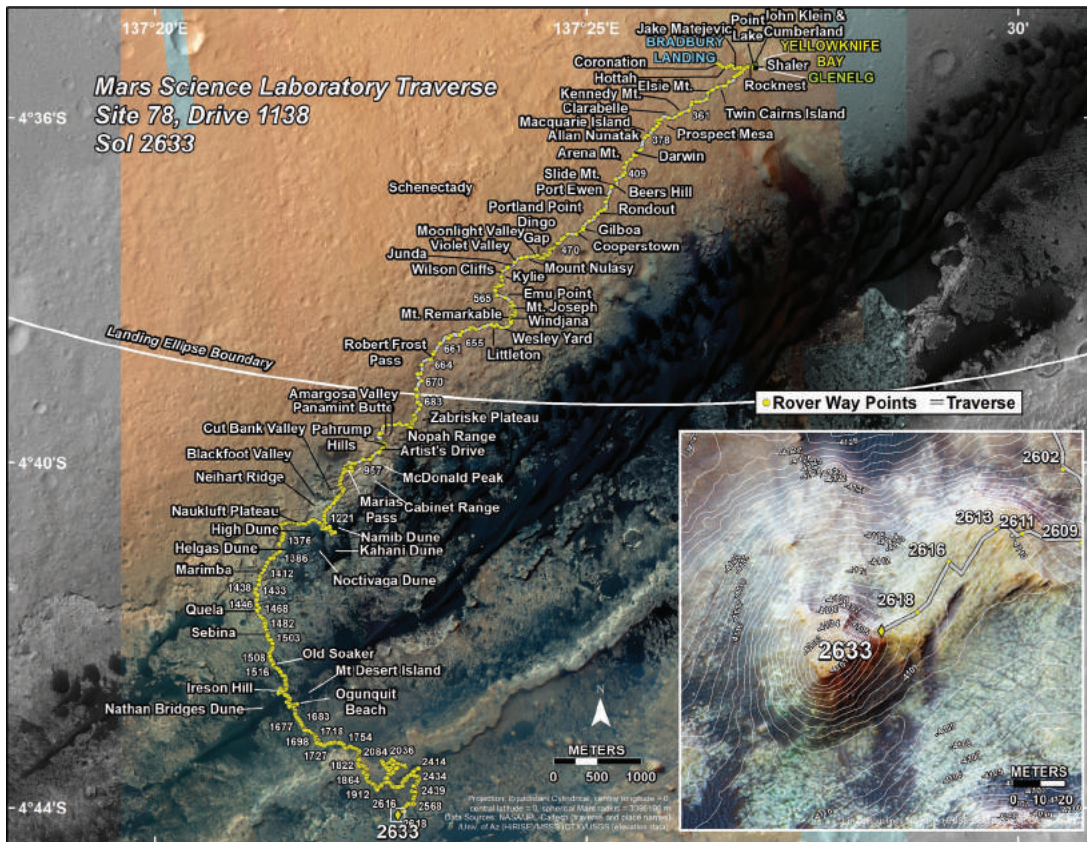
ASTRONOMY

Red Planet Ride-Along

FOR HUMAN TRAVELERS, the iconic moment of space exploration occurred a half-century ago, when Neil Armstrong planted the first human boot-print on the moon. But if you don’t mind using robots as our stand-ins, the greatest era is unfolding right now on Mars, where NASA’s Curiosity rover is rolling across the rusty, dusty surface and leaving behind tread marks that spell out the letters “J-P-L” in Morse code. JPL stands for the Jet Propulsion Laboratory, the NASA center that designed and built Curiosity along with three earlier Mars rovers. Collectively, these machines have racked up 46.4 miles of travel, tremendously expanded our understanding of the Martian environment, and energized the search for life in the universe.

Curiosity weighs in at 1,982 pounds, has an onboard nuclear generator for power, and bristles with 17 cameras, including a geology microscope and a remote-analysis telescope called ChemCam. It even shoots its own laser beams to vaporize rocks and examine their composition. Plus it’s decked out with those six JPL-imprinting wheels, each 20 inches wide.

With all that imagery flowing in, mission scientists have gone a little crazy giving names to every rock



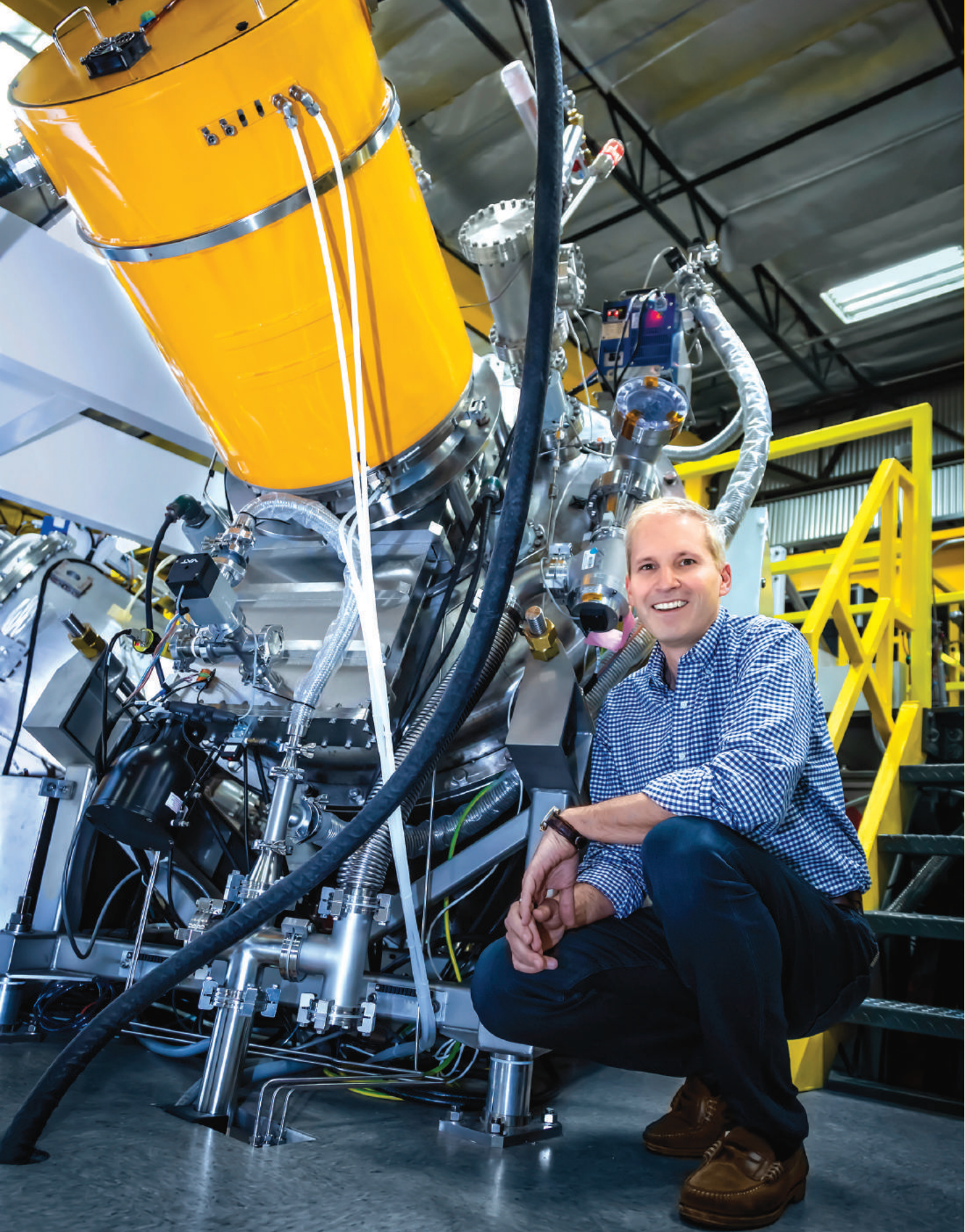
and feature that Curiosity has passed in the 13.4 miles it has traveled so far, as you can see from the map. Data gathered by the earlier missions also guided Curiosity's landing site in Gale Crater, a 3.5-billion-year-old, 96-mile-wide impact site that was subsequently filled with wet sediment and dust, then eroded away. That unusual geological setting has allowed Curiosity to examine different eras of Martian history as it drives around the crater.

As an extraterrestrial geologist, Curiosity has been an unqualified success: touring eerie Martian sand dunes, documenting bizarre rock formations and mineral salts, and demonstrating that the region near its landing site was once the mouth of a river or else a lake that intermittently flooded and dried. In the ever-optimistic NASA manner, Curiosity's project scientist, John Grotzinger, concluded that "conditions once were favorable for life" here. The rover has also discovered puzzling variations in oxygen and methane in the air, which could just maybe be signs of biological activity.

But in the search for actual life or its remains, Curiosity has left things frustratingly inconclusive.

Fortunately, NASA's next Mars rover (which was recently named Perseverance, and is scheduled to launch this summer as part of the Mars2020 mission) is intended to get down to business. It will come equipped with tools designed specifically to search for organic material: carbon-based compounds like those associated with biology. Finding organics alone would still not prove the existence of past or present life, so Mars2020 has another trick up its sleeve. It will put the most promising samples into storage tubes and hold them for a future mission to collect them and bring them back to Earth, where scientists can look for micro-fossils and perform far more sensitive chemical investigations. That final, 100-million-mile journey back home might be what it takes to finally answer the question of whether Mars is alive or dead.

—Corey S. Powell



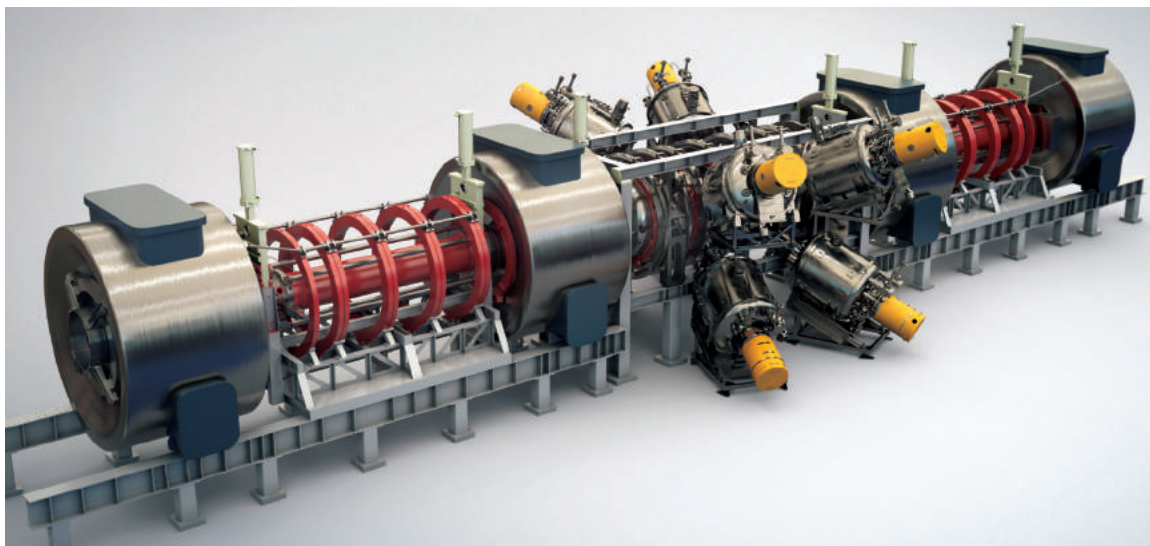
The Firestarter

On a road less traveled, this physicist is leading the world to fusion energy

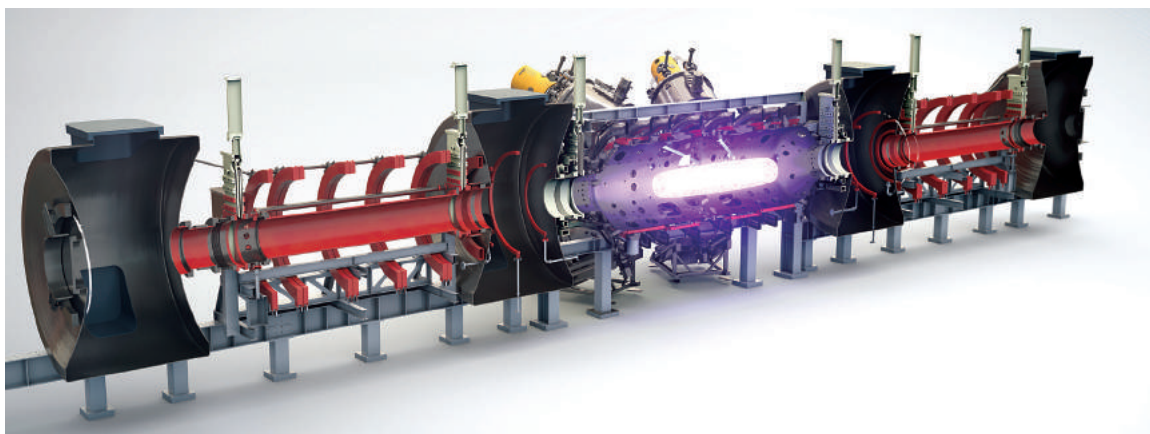
BY COREY S. POWELL

THE MODERN QUEST for Promethean fire is underway in an anonymous office park in Foothill Ranch, California, an hour southeast of Los Angeles. In the park, along a meandering drive, you will find a huge, modern warehouse building with “TAE Technologies” emblazoned on the door. Inside, you will find a 100-foot-long, \$200 million fusion-energy experiment named Norman. And in a second-floor office, upstairs from that looming machine, you will find the would-be Prometheus himself: Michl Binderbauer, TAE’s boyish-looking and relentlessly upbeat co-founder and CEO.

PROMETHEUS OR ICARUS Michl Binderbauer kneels before his neutral particle-beam injector—a technology critical to his multibillion-dollar venture to smash together protons and boron atoms, setting off a reaction that will unleash bountiful clean energy.



“NORMAN” REACTOR The latest step in Michl Binderbauer’s three-decade-long quest for fusion energy is this warehouse-filling test reactor, named after his mentor, Norman Rostoker. A cutaway (below) shows the spinning tube of superheated particles at the machine’s heart; in future versions, this is where proton-boron fusion would occur.



In keeping with the rest of the TAE headquarters, his office looks spare, functional, and slightly unfinished. The most striking object adorning the room is a large whiteboard next to his desk, its upper three-quarters jammed with equations and crude engineering sketches for upgraded fusion devices. Across the bottom, within the low reach of little hands, the business notations give way to a whimsical set of drawings created by Binderbauer’s two young children. At first he seems bemused that these silly scrawls, of all things, are what

draws my attention. Then he rolls with it and recalls a recent conversation with his 10-year-old son, who had just learned about climate change in school:

“He’s a precocious kid. He asked me, ‘Is this right? Is this really what’s happening?’ I told him, ‘I hope not. If Daddy can help, it may not happen.’ So now when people ask him what I do, he says, ‘My dad is trying to save the planet.’”

Like so much of what Binderbauer, 51, says, the story sounds too good to be true and yet utterly sincere. As

When people ask my son what I do, he says, “My dad is trying to save the planet.”

he sees it, his save-the-planet strategy is no do-gooder’s dream; it is the perfectly logical end point of a perfectly rational analysis about the state of the world. His indisputable starting proposition is that the world needs a growing supply of energy. Then he asks, how are we going to generate it? Coal, oil, and natural gas are causing disruptive and deadly climate changes, so fossil fuels cannot be the future. Nuclear power produces no direct carbon emissions, but it leaves behind radioactive waste and—fairly or not—faces bitter public resistance.

Solar and wind power are environmental darlings, but expanding them significantly will require vast new infrastructure to make their clean electricity available when and where it is needed. “Relying solely on solar and wind is a fool’s hope, I think,” Binderbauer says. Several recent studies, including a major technical analysis in the journal *Proceedings of the National Academy of Sciences*, back up his assessment: We simply do not know how to build an electric grid that can handle the inconsistent way that the sun shines and the wind blows. Even if renewables come to generate the majority of our electricity, they need to be combined with so-called dispatchable power that can be switched on at any time.

All those considerations, taken together, imply that we need something completely new in the global energy mix. Binderbauer argues that the most realistic something is fusion. Physicists know that smashing together atomic nuclei (the ultra-dense centers of atoms) and causing them to merge can release a tremendous amount of energy, far more than is possible by burning coal or natural gas, with no carbon pollution. They have dramatic proof that the process works: Fusion is what powers the sun, and it is what gives a hydrogen bomb an explosive kick. But after eight decades of research,

nobody has been able to create a machine that can make fusion happen gently, steadily, and efficiently enough to generate electricity.

Binderbauer aims to be the one to crack the code. He predicts that TAE could go from Norman to a demonstration fusion reactor within five years, and then—if everything goes right—to a prototype for a commercial fusion power plant another five years or so after that. His timetable is at least a decade faster than that of the biggest government-run fusion efforts. A handful of other private fusion startups have recently sprung up, promising their own speedy paths to fusion, but TAE has the most funding—more than \$600 million—and, laid out here in front of me, the only fully operational test reactor. The company also has the most audacious plan, pursuing a novel type of fusion reaction that would take in hydrogen and boron (common elements of water and laundry detergent) and spit out nearly limitless clean energy.

Even within the far-out world of fusion energy, Binderbauer is operating on the fringe. He acknowledges that he could end up more like Icarus than Prometheus, flying too close to the sun and falling. Still, he sees no other option. “Our generation may go down in the history books as the ones who really ruined the planet on a massive scale,” he says. “Maybe I can’t change it, but hopefully I can at least come up in the same history book paragraph that adds, ‘... but there were some who really tried.’”

RESTLESSLY REACHING FOR BETTER IDEAS seems to run in the Binderbauer family. Michl was born in Salzburg, Austria, but was constantly on the move through his childhood as his father kept relocating across Europe to explore new businesses. Eventually he took a bigger leap and settled for a year in Dallas, where American-style ambition took hold in 16-year-old Michl’s brain. That peripatetic upbringing left him with an unplaceable accent, a strange mashup that somehow resulted in something that sounds like a musical Danish lilt.

From Texas, Binderbauer embarked on his own roaming—to Southern Methodist University, the University of California at Irvine, and almost to graduate school in astrophysics at Johns Hopkins in 1990. He reversed his decision swiftly on his first visit to

It's an audacious plan—a fusion reaction that would take common elements of water and laundry detergent and spit out clean energy.

campus, when he was dismayed by a drive through nearby Baltimore neighborhoods full of homeless people and boarded-up buildings. He returned to Irvine, unsure of what to do next, when he had a transformative encounter with Norman Rostoker, his former physics professor.

Rostoker had been fascinated by the possibility of harnessing fusion energy since his early research days in the 1950s. Now he was looking for a Ph.D. student to finally help him put that idea into action. Binderbauer signed on, and got pulled into his mentor's worldview. "About a year into it, I really started to appreciate the basic idea, what fusion could do for humanity," he says. "But more important, I started to understand what wouldn't work, and why the available concepts were flawed."

Ever since then, Binderbauer's life has been guided by those twin fixations: The world needs fusion, and the world also needs a better way to make it happen.

The need for fusion was clear enough even in 1990. Scientists had already accumulated abundant evidence that carbon dioxide from fossil fuels was disrupting Earth's climate. At the same time, public sentiment in the United States had been turning sharply hostile to nuclear reactors since the Three Mile Island accident in 1979. The catastrophic explosion of the Soviet Chernobyl reactor in 1986 cemented a widespread attitude that nuclear energy is unsafe. There was also the hot-potato issue of where to put spent nuclear fuel, which remains highly radioactive. In 1987, the U.S. Congress designated Yucca Mountain in Nevada as the nation's future nuclear waste repository. Nevada residents immediately protested and the state filed a lawsuit to block the plan. Three decades later, the site still has not opened.

In sharp contrast to nuclear energy, fusion looks downright benign. "It doesn't have the nuclear footprint, it doesn't have the waste stream, and it can't have a meltdown or fallout," Binderbauer notes. The problem is that fusion is drastically harder to achieve than the fission reactions that power a nuclear reactor—which is why nuclear power is a reality today, while fusion remains a promise for tomorrow.

To get a nuclear reactor going, pretty much all you need is a stash of radioactive fuel. If you throw together a heap of purified uranium, it will start generating heat all by itself; the biggest challenge is preventing it from generating too much heat and melting down. To make fusion happen, on the other hand, you need an intense kick-start: You need to collide pairs of atomic nuclei so forcefully that they stick together, releasing some of their latent energy. The sun gets those collisions going with its enormous gravitational pressure. A hydrogen bomb does the job by whacking the nuclei with an atomic explosion.

Making fusion happen in a steady, controlled way here on Earth involves a seemingly contradictory combination of delicacy and brutality. It requires a special kind of reactor that can heat nuclei to millions of degrees while containing them so that they don't fly apart before they have a chance to collide. In other words, you need to put a lot of energy into a fusion reactor before you can get any energy out. Many experiments have now succeeded in sparking fusion reactions, but none of them has managed to get more energy out than the amount that goes in, the critical tipping point known as breakeven.

Still, fusion researchers have made a great deal of progress in figuring out how to get there. In particular, they have zeroed in on the most promising nuclear



A FUSION FACTORY Experiments at TAE require a tremendous support infrastructure of magnets, particle injectors, and sensors, along with a power-storage system that can energize the entire reactor without crashing the local electrical grid. The company hopes to spin off some of these technologies into their own money-making businesses.

reaction for achieving breakeven. The favored reaction uses two heavy versions of hydrogen, known as deuterium and tritium. The two of them both have positive charges, which normally causes them to repel each other. But if you heat them to temperatures around 100 million degrees Celsius, they will occasionally come so close together that the short-range attraction of the strong nuclear force overwhelms the long-range effects of repulsion, causing them to fuse.

Researchers zeroed in on deuterium-tritium fusion because it is one of the easiest reactions to trigger. When deuterium combines with tritium, they also release a lot of energy: One kilogram of deuterium contains the energy equivalent of 29 million kilograms of coal. Further adding to the appeal of this approach, both types of nuclei are easily obtainable. Deuterium can be extracted from ordinary water; tritium can be produced by irradiating lithium, a straightforward laboratory process.

Pretty much every major fusion experiment since the 1970s has been designed with deuterium-tritium

fusion in mind. In the south of France, an international consortium is currently constructing a \$25 billion behemoth called ITER (formerly the International Thermonuclear Experimental Reactor), which is on track to become the world's largest fusion plant when completed in 2025. It will run on deuterium-tritium. Private startups like Commonwealth Fusion Systems in Cambridge, Massachusetts, and General Fusion in Burnaby, Canada, take different technological approaches to fusion, but they, too, are planning machines that will run on deuterium and tritium. The choice of fuel is the one thing that the entire fusion world can agree on.

Well, almost. The choice of fuel lies at the heart of Binderbauer's break with the mainstream fusion community.

THE ULTIMATE GOAL of fusion projects like ITER and the Joint European Torus in Oxfordshire, England, currently the largest operational fusion plant, is to capture the tremendous energy liberated by the merger

of deuterium and tritium and put it to practical use. The plants would convert the raw fusion energy into heat, then use the heat to boil water, spin a turbine, and ultimately to generate electricity that can light your home and charge your phone. The fusion reaction is so hot that no physical object can contain it. Instead, researchers hold the fuel in place using magnetic fields—typically a donut-shaped field configuration called a tokamak. Magnets alone account for much of the tremendous bulk of a fusion plant like ITER.

But the real action in a deuterium-tritium plant, as is true for all fusion energy, takes place at the atomic scale. The nucleus of regular hydrogen is just a single proton. Deuterium is a proton bound to a neutron, the electrically neutral cousin of a proton. (Adding a neutron to an element makes it more massive but does not alter its chemical identity.) Tritium is a proton bound to two neutrons. When deuterium fuses with tritium, the end product is helium—two protons bound to two neutrons—plus a spare neutron, which goes flying off at high speed. Deuterium and tritium nuclei both carry an electric charge, which means they can be held in place with magnetic fields. Neutrons offer no such means of control. They are like cats: They do what they want.

Neutrons carry up to 80 percent of the energy in deuterium-tritium plants, so the plants will be designed to capture the neutrons and absorb their energy in a surrounding solid or liquid blanket. Some neutrons escape, though, siphoning away energy. Those strays can embed themselves into surrounding parts of the reactor, turning materials brittle and radioactive.

Deuterium-tritium fusion proponents see this “neutron flux” as an eminently solvable technical issue, one they’ve been aware of for decades. “We don’t have the right materials right now. They’ll need to be tested and validated, and it’s a long path, but we’re working on them,” says Tony Donné, program manager for EUROfusion, a research consortium that supports ITER. Those optimized materials should allow ITER to run for 15 years before it will require neutron-related maintenance, he expects. Bob Mumgaard, CEO of Commonwealth Fusion Systems, regards neutron flux as part of a fusion power plant’s wear-and-tear—a routine aspect of its servicing cycle, happening perhaps once or twice a year. “We can simplify the internal components,

So far no fusion reactor has managed to get more energy out than the amount that goes in.

develop maintenance scenarios,” he says. “We have such a scheme substantially in place.”

Rostoker regarded neutron flux as a potential showstopper, however. The amount of radioactivity created inside a deuterium-tritium plant would be less than what is produced by a nuclear plant, Binderbauer notes, but it could still be enough to present thorny economic, political, and regulatory issues. In an email, Mumgaard points out, “The level of radioactivity generated by neutrons is low, comparable with a medical test facility. The half-life of materials activated by neutrons is thousands of times lower than radioactive waste from a fission nuclear reactor.”

Binderbauer has another worry about deuterium-tritium fusion. Tritium is radioactive, he notes, with a half-life of just 12.3 years, meaning it needs to be handled and monitored with the same kind of caution as any other radioactive material. It is also chemically identical to the light hydrogen found in ordinary water. “If it gets in the groundwater and you drink a glass of water with tritium in it, you’ve got a 12-year time bomb ticking away inside you,” Binderbauer says. (A fact sheet from EUROfusion notes that “tritium poses a serious threat to human beings if it replaces hydrogen in our biological systems.”) Nuclear weapons facilities have developed detailed procedures for handling tritium, which is encouraging or unsettling, depending on your perspective.

“I hope this doesn’t come across too negative,” Binderbauer adds unconvincingly. Rejecting the mainstream approach to fusion was integral to his formative work with Rostoker and all that has followed from it.

STEP ONE IN ROSTOKER'S and Binderbauer's fusion quest was coming up with a substitute reaction that wouldn't involve those pesky neutrons, which sent them into the fringy field of "aneutronic fusion." The literature is full of exotic and impractical investigations in that area, such as the idea of fusing deuterium with helium-3, a lighter version of ordinary helium. It's an appealing reaction, except for the little catch that you have to go to the moon to find a supply of helium-3.

In 1994, after weighing the options and consulting with their colleague Hendrik Monkhorst at the University of Florida, the two identified a far more plausible option: a fusion reaction between a proton (a hydrogen nucleus) and the element boron. The end product of their union is three helium nuclei, with just a trace of nuclear byproducts. Proton-boron fusion eliminates more than 99 percent of the neutrons produced by deuterium and tritium (although that still leaves enough neutron flux to require careful shielding). As for the fuels themselves, they are about as harmless as you could hope for. Boron is mined as the common mineral borax, and is widely used in building materials, glass, and detergents. Hydrogen is the predominant element in every glass of water.

"I wouldn't say we fell in love, exactly, but we got convinced we could really make it work," Binderbauer says. "Now you've got almost no neutrons, and you've got a plentiful terrestrial fuel. There's no radioactive input or output in the primary reaction. The helium that comes out is completely innocuous. It was a beautiful thing."

The less beautiful thing was trying to figure out how to make proton-boron fusion actually happen. Igniting proton-boron fusion requires temperatures around 3 billion degrees Celsius, roughly 30 times hotter than deuterium-tritium fusion. Nobody had yet figured out how to get an energy gain using the easier reaction. Moving on to an even harder problem would be madness, Binderbauer understood, unless he could find a new, more effective technological approach. "We couldn't look within the box of already available concepts because they all were handicapped," he says. The tokamak is the best-studied approach to making fusion happen, but it is insufficient for the extreme demands of proton-boron fusion.

To meet those demands, Binderbauer and Rostoker developed a radically different design for a fusion reactor, one resembling a particle-physics experiment much more than a tokamak. Instead of a magnetic donut,



HOT SHOT

Test runs begin in the "formation" section, where particles are accelerated to 100 times the speed of a rifle bullet.

they would use a tube. Instead of trying to hold onto the fuel from the outside, they would spin it so that it would create its own magnetic field from the inside—a “field-reversed configuration” in the lingo of the business. And to get the process started, they would crash together beams of protons and boron nuclei, much as physicists do at huge particle-accelerator facilities like the Large Hadron Collider.

The obvious next step was to start building devices that could put these ideas to the test. “We had exhausted what we could do on the cheap. We wanted to instigate getting federal support,” Binderbauer says. So in 1997, he, Rostoker, and Monkhorst wrote a paper outlining their findings and managed to get it accepted by *Science*.

He wanted to cause a stir, and succeeded a bit too well. *Science* was inundated with critical letters. “We were naïve about thinking that people would say, ‘Well here are the shortcomings of the tokamak, here’s a smart alternative, here a machine that may be able to do a non-neutron reaction,’” Binderbauer recalls, shaking

his head at his younger self. “We didn’t anticipate the firestorm that ensued. It was overwhelming and scary.”

Judging from the letters, some of the critics either didn’t understand the paper or didn’t want to believe its conclusions. Much of the fury, Binderbauer now realizes, came from colleagues who felt like their careers were on the line, and not without justification. The *Science* paper came out just as the U.S. Department of Energy was cutting back on fusion research. The last thing people in the field wanted to see was some upstart vying for some of that scarce funding and implying that the standard approaches to fusion might be a dead end.

Binderbauer had already walked away from all of the physics and engineering work supporting deuterium-tritium fusion. Now he realized he would have to walk away from the government spending that had supported fusion research since the 1950s. “This is where we sobered up,” he says. “I told Norman, ‘Look, we’re not going to get federal dollars. Why don’t we try private?’”



CONTROL ROOM Artificial intelligence software, recently developed by TAE with help from Google, should keep the fusion fuel stable even at the 3-billion-degree temperatures needed in a commercial-scale power plant. “A year ago I was concerned about the ability to control the machine,” Binderbauer says, “but no longer.”

Relying solely on solar and wind is a fool's hope.

UP TO THAT POINT, there had been only one notable private investment in fusion energy. In the late 1970s, *Penthouse* magazine founder Bob Guccione sank \$17 million into a project to build a miniature fusion machine that snarky scientists nicknamed the Pornomak. “So we’re not the only crazy ones to try this,” Rostoker responded dryly.

With little to lose, he and Binderbauer took the plunge and incorporated—first as Colliding Beam Fusion Reactor, Inc., later as Tri-Alpha Energy, and finally as TAE. Their early efforts attracted an unusual alliance of supporters, including Nobel laureate Glenn Seaborg and actor Harry Hamlin, best known as the “sexiest man alive” actor from *L.A. Law*. After a proposed \$15 million investment from Texaco fell through at the 11th hour, they managed to scrounge up only about \$1 million, far too little to launch a fusion research lab. They drastically scaled back their ambitions and set out to build a small, proof-of-concept experiment called “the sewer pipe.” It was built from, yes, a sewer pipe, wrapped with magnets and electronics designed to create the hoped-for field-reversed configuration.

Ratty as it looks, the sewer pipe experiment produced exactly the kind of magnetic field it was supposed

to, the first tangible evidence that Binderbauer was not nuts. It is still on display at TAE. If the company succeeds, it may be remembered as the icon of proton-boron fusion.

Once TAE could demonstrate that they had a viable concept and a team that knew how to execute it, more investors began to sign on—among them the late Paul Allen, co-founder of Microsoft. That funding allowed the company to create a proper testbed for a field-reversed fusion reactor, called C-2. From there, C-2 expanded into a bigger machine called C-2U, which in turn evolved into TAE’s current monster of an experiment, C-2W.

After C-2W was completed in 2017, Binderbauer renamed it “Norman” in honor of Rostoker, who had died on Christmas Day, 2014. Norman recently completed its primary research goals, including achieving temperatures above 30 million degrees Celsius and keeping the plasma stable for 30 milliseconds—hot enough and long enough to validate that everything is working as expected. Most important, Norman validates the theory that a field-reversed reactor can be scaled up, reaching conditions beyond what is possible in a tokamak. At ultra-high temperatures, tokamaks can become leaky and difficult to maintain; a field-reversed

configuration should become more stable. TAE is betting that the theory will hold true all the way to the 3 billion degrees needed for proton-boron fusion.

Not many others in the fusion community see that as a smart wager. Donn  of EUROfusion, who has spent a career working with tokamaks, admires TAE's grand ambitions but is wary of the company's reliance on as-yet unproven physics and engineering. "You need to get orders of magnitude higher in temperature. If you go with that direction in fusion, it will add a half a century to the timescale," he predicts. Even TAE's more adventurous commercial competitors are mostly sticking with deuterium-tritium plants. Commonwealth's Mumgaard is gently biting in his assessment of proton-boron fusion. "It's a great thing to aim for, but it's going to be difficult to do," he says. "I think everyone agrees. We shouldn't hold out for perfect."

For 20 years, now, the TAE team has repeatedly braced for failure but then managed to barrel through another seemingly impassible physics barrier, says Artem Smirnov, TAE's chief technology officer—the dour yang to Binderbauer's cheery yin. Few people thought the original sewer-pipe experiment would work. Few people thought that a field-reversed reactor

We didn't anticipate the firestorm that ensued. It was overwhelming and scary.

like Norman could achieve stable, 30-million-degree heat. "But with every step we take, there's new uncertainty," Smirnov admits. "What if the scaling law fails somewhere along the way? We can't be sure until we get there."

The next step in that journey is the \$200 million Copernicus reactor, intended to reach temperatures around 100 million degrees. TAE is currently real-estate shopping in Orange County, with the goal of breaking ground this year and beginning test runs in 2023. Copernicus should be powerful enough to ignite deuterium-tritium fusion, but that is not its job; its real purpose is to scout out those unknown regions of high-temperature physics. If TAE's take on the field-reversed reactor design keeps delivering as expected,



FUSION GENERATIONS

Michl Binderbauer (right) confers with his mentor, Norman Rostoker, whose ideas guided TAE's unconventional focus on proton-boron fusion. The photo was taken at the company's Foothill Ranch, California office around 2008, while the team was developing its first large-scale experiment, the C-2 reactor.

COURTESY OF TAE TECHNOLOGIES

then Binderbauer will go all-in on his biggest bet of all: a “two-ish-billion-dollar” proton-boron fusion reactor called Da Vinci. At last, it should hit the magic 3 billion degrees, keep a proton-boron fuel stable, and produce a healthy output of fusion energy.

Da Vinci is intended to mark TAE’s transition from fusion prototypes to commercial fusion energy. It will not be powering anyone’s home, but it will be designed with electricity generation and mass production in mind. From then on, TAE will be relying heavily on companies like General Electric that have deep experience in designing and constructing power plants. “More important than the money is the industrial-scale support,” Binderbauer says. “You’re not building just one machine. You’re thinking about all the next machines, and they should be built by the industrial sector, not by TAE.”

BINDERBAUER’S ROADMAP to his kids’ energy future looks like this: The first commercial-design fusion reactor begins operation in the early 2030s. Over the next 10 to 15 years, fusion captures a few percent of the global electricity market. Companies start up production lines to crank out modular fusion reactors. Governments might provide incentives for carbon-free energy, whether in the form of taxes or subsidies, speeding the growth of the new industry. Wind and solar energy continue to expand, but fusion expands, too, balancing them out. “In the second half of the century, would fusion capture a large fraction of the market, maybe the dominant fraction? I would not be surprised,” Binderbauer says.

That would be a striking validation of Rostoker’s original vision, even if TAE does not end up being the company to bring practical fusion energy to market. Rostoker’s determination to pursue an unconventional scientific approach, followed by his decision with Binderbauer to rely on private funding, have already had a tremendous ripple effect. There are now more than a dozen startups pursuing fusion plans. “Sometimes in life, curveballs come your way and you just need to have enough intuitive sense to grasp them,” Binderbauer says. “Working with Norman was the best decision I ever made.”

He still takes inspiration, too, from one of his last interactions with Rostoker. In the fall of 2014,

Binderbauer delivered a fusion-energy presentation to a packed auditorium at a meeting of the American Physical Society—a sweet vindication after his pariah status in the late 1990s—and wanted to share the good news with his mentor. By this time, Rostoker was in the advanced stages of dementia and was unable to process the story or to recognize his friend. Even so, he could access enough memory to point to a framed photo on the wall, showing the TAE staff gathered around the C-2 reactor. Binderbauer recalls the moment vividly. “‘You know what this is?’ he asked me. And I said, ‘No, tell me Norman, what is it?’ He said, ‘This is TAE, that’s the company I started and that one of my best students runs. We’re going to go the distance. We’re going to make economically successful fusion. And it’s going to change the world.’”

Binderbauer looks at me with an opaque mix of overlapping emotions. “It’s one of the saddest stories, but also a really beautiful story. It’s the triumph of an idea.” 🌀

COREY S. POWELL enjoys exploring the outer possibilities of physics and astronomy. He writes the Out There blog and co-hosts the Science Rules podcast.

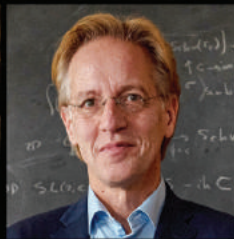
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Never Say Wolf

How taboo language turned the wolf into a monster

BY DAVID ADGER



LISTEN TO THEM, the children of the night. What music they make!”

So says Count Dracula to the hapless Jonathan Harker in Bram Stoker's novel. Dracula is talking about the wolves howling in the valley below his castle in the Carpathian mountains. This is the moment in the novel when Harker begins to feel the first twinges of fear.

The howl of the wolf, and the fear that accompanies it, sounds across millennia. Comparing the mythologies of cultures that descended from ancient European tribes, wolves loomed large in their minds. There are myths of heroes brought up by wolves, of great wolves who will devour the sun, of wolves guarding the underworld, and of warriors taken over by the spirit of wolves. Archaeological digs at Krasnosamarskoe, in the steppes north of the Black and Caspian seas, have given us clues that early peoples sacrificed, and even ate, dogs and wolves. Art and collected oral literature from across Asia and Europe hint of coming of age rituals where young men would wear wolf-skins, and live lawlessly on the land, almost becoming more terrifying than the wolves themselves.

When he used the phrase “the children of the night,” Dracula was following an ancient tradition. He was avoiding the word “wolf.” In many societies, words have power, the power to summon what they name. This idea probably emerges from rituals that took place in preparation for the hunt. It was a way of calling prey so the hunt would be successful. But if words can summon prey, they can also summon danger.

Speakers had to find ways of referring to wolves without naming them. The word for wolf becomes taboo: It shouldn't be said. Instead, the magic of summoning through a name can be tricked. By changing the sound of the word, by using another word, perhaps borrowed from another language, or by using a descriptive phrase rather than the word itself, speakers could talk of wolves, but avoid the dangerous word itself.

We can see these strategies of avoiding taboo words in English. People change the sound of words like “Hell!” or “Christ!” into “Heck!” or “Crumbs!” We

have borrowed the French word “toilet” to avoid naming the place where we defecate. When the denizens of J.K. Rowling's *Harry Potter* books use the phrase “You-Know-Who” for Voldemort, Rowling is appealing to the ancient magic of taboo.

Languages change. As people move across landscapes, their languages develop in different ways. They encounter new peoples, with different languages, and this can lead to a transformation in how people speak. But some words in languages change because the original term is avoided. Taboo, tightly tied to culture, has wrought radical changes in the original term for wolf in the languages of Europe. Like a werewolf changing its skin, the word for wolf has warped across the centuries, often in quite unexpected ways, as it traveled through the continent.

The Swedish word for wolf descends from someone outcast from society for murder.

DRACULA'S NATIVE ROMANIAN WORD for wolf is *lup*, or in the Old Church Slavonic he learned growing up in the 15th century, *vliku*. These words, Romanian *lup*, Old Church Slavonic *vliku* (which later became Russian *volk*) and English *wolf*, all descend ultimately from a word in Proto-Indo-European, the ancestor of many languages spoken across the world today. The speakers of this language probably inhabited the vast steppes between the Black Sea and the Caspian about 6,000 years ago, and had a way of life that involved farming and hunting, and, it appears, wolves.

Because languages change the sounds of words over time in very regular ways, linguists can use words in different languages to work backward to what the Proto-Indo-European words sounded like. We have developed rules which describe, often with pinpoint accuracy, how sounds change from one language to another, and these rules have been confirmed as new languages have been discovered baked into clay

Tolkien co-opted an Old English word for the evil fierce wolf-monsters ridden by the orcs.

tablets, or inked onto ancient parchment. From ancient Tocharian in the west of China, through the Sanskrit descended languages of the Indian subcontinent and the ancient Iranian and Armenian languages to the Celtic languages still spoken on the fringes of Western Europe, linguists have been able to develop rules that explain the interrelationships of hundreds of languages.

Using these rules, linguists have worked out that the original Proto-Indo-European word for wolf was pronounced something like *wlkwos*, where the *l* between the *w* and the *kw* works like a vowel (think of the *l* in *bottle*, or, for some people, in *milk*). The Romanian, Russian, and English words for wolf can all be traced back to this ancient word *wlkwos*. But that word itself was taboo, and how it changed as the Indo-Europeans spread into Europe is fascinating.

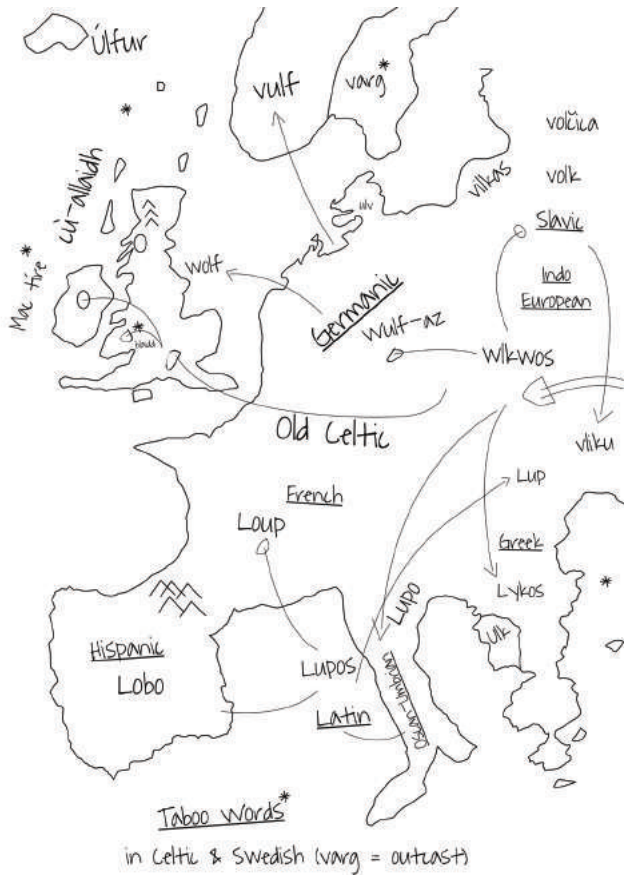
Romanian is descended from Latin, and Romanian *lup* comes from the Latin word for wolf, *lupus*. But that Latin word itself is not what linguists expect for the Proto-Indo-European *wlkwos*. Sounds change in regular ways as languages develop. Usually, Proto-Indo-European *w* becomes Latin *v*, *kw* becomes *qu*, and that vowel-like *l* becomes *ol*. *Wlkwos* should have become Latin *volquus*. The reason it didn't is almost certainly taboo. *Lupus* does make linguistic sense for some of the other languages of ancient Italy, like Oscan-Umbrian, an archaic language spoken in central Italy. In Oscan-Umbrian, Proto-Indo-European *kw* regularly changed to *p*. But linguists would still expect something like *volpus*. It seems that the ancestors of the Oscans and Umbrians also wanted to avoid the word for wolf. They did this by changing the sound of the word, tricking the summoning power of taboo by swapping round the order of *w* and *l*, and making the *w* more like a vowel.

This turned *wlkwos* into *lukwos*, which, as *kw* became *p*, transformed to something like *lupus* (we don't know the exact word). Latin speakers then avoided their word for wolf entirely by borrowing *lupus* from Oscan-Umbrian, like we borrowed *toilet* from French. As the Roman Empire expanded, that borrowed word went on to become Italian *lupo*, French *loup*, Spanish *lobo* and Romanian *lup*.

You might think it's a bit odd that Proto-Indo-European *kw* changed over time to *p*. They seem quite different sounds. But say the word *qua* out loud. You do two things when you make the first sound of this word. Your tongue connects at the back to the back of your palette, and your lips come together, pursing up in a round kiss. You can simplify this sound in two ways: remove the lip rounding, to give a *k*, or move the closure at the back of the throat to the lips, so the sound becomes *p*. Some descendants of Proto-Indo-European did the latter quite generally, like Oscan-Umbrian, but the Germanic languages usually changed *kw* to *k*. Only in a very few cases, including in the word for wolf, do we find evidence of a different route. When Proto-Indo-European *wlkwos* developed into the ancient Germanic languages, it morphed into something like *wulpaz*, once again, an unexpected change. From there it became *wulfaz*, eventually giving Icelandic *úlfr*, Danish and Norwegian *ulv*, Old English *wulf* and modern German (and English) *Wolf*.

The Swedish word for wolf, though, is *varg*. This descends from an old Norse word *vargr*, meaning someone outcast from society for underhand murder or oath-breaking, evil deeds in Viking society. This word itself comes from a Proto-Indo-European word, roughly pronounced as *hwergh*, which meant to commit a crime. *Hwergh* is found across Indo-European languages, surfacing as *vrag*, enemy, in Russian, and, in the ancient language Hittite, the related word *hurkil* signifies sin or perversion. In Old English, the word is spelled as *warg*. An Old English word for a gallows is *warg-tree*, and Tolkien co-opted the word to use for the evil fierce wolf-monsters ridden by the orcs in *The Lord of the Rings*. *Varg* is another way of avoiding the true word for wolf.

The Celtic languages take avoidance of the word for wolf to an extreme. In the older Celtic languages the Proto-Indo-European word *wlkwos* vanishes. Instead,



WOLF TRACKS Author David Adger sketched this rough etymological map of how “wolf” developed and changed sounds as it roamed across old Europe.

WHAT OF THE WORD “wolf” today? A century ago, wolves across Europe and North America had reached their nadir. Fear of the wolf, combined with hunting, poisoning, and loss of habitat, led to a plunge in wolf populations. Scientists, though, have tamped down that fear. They have shown that wolves care for their elderly and wounded, bringing them food. Wolves have hugely complex social systems, and their presence can enrich the diversity of a wild environment.

In the past quarter century wolves have begun to flourish again, as laws protecting endangered species have come into effect, and as researchers began to show that reintroducing wolves can rebalance an ecology. The reintroduction of wolves into Yellowstone National Park has seen an ecological revival of animal and plant species in the park, and across Europe wolf packs have spread to new habitats in Germany, Poland, and Spain. New conservation areas have even been put in place in Dracula’s beloved Carpathians.

Words change meaning across time. Perhaps, as we come to understand more about wolves, we will develop new ways of talking about the ever-fascinating children of the night. ☺

DAVID ADGER is a professor of linguistics at Queen Mary University of London. His most recent book is *Language Unlimited: The Science Behind Our Most Creative Power*.

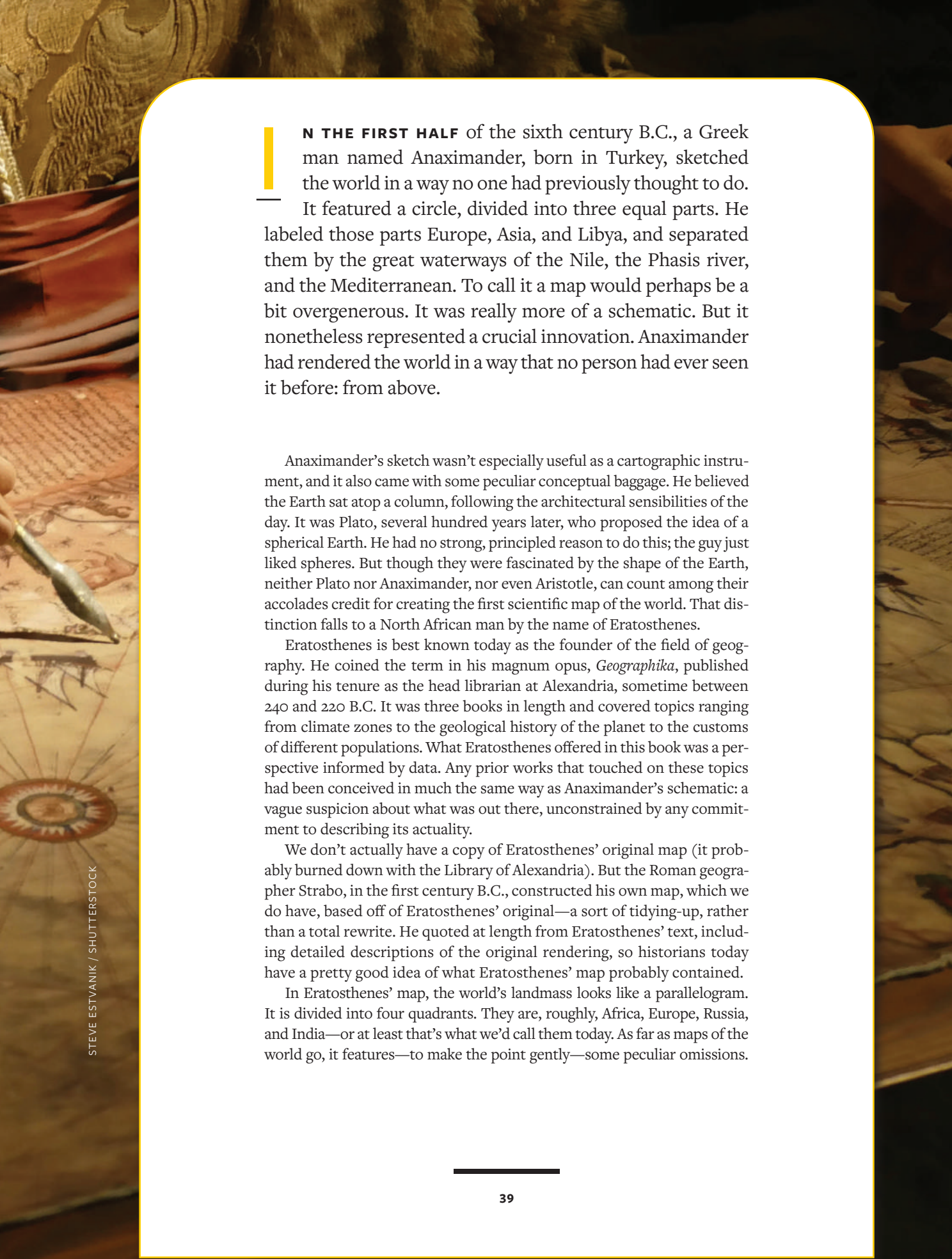
some ancient Celtic tribes co-opted a different word, derived from the Proto-Indo-European *waylos*, meaning howler. In Old Irish, a *w* at the start of a Proto-Indo-European word usually became an *f*, giving the Old Irish word for wolf, *faol*, the howling one. The Celts also used the word *cù*, which means dog, as a means of avoiding the word for wolf. Many ancient Irish heroes and kings, like Cuchulainn or Conchobar, have names apparently based on the word dog, but the meaning was likely that of wolf. In the modern Celtic languages, the taboo remains. Modern Irish uses *mac tìre*, literally, “son of the land,” since the wolf ranges freely across the countryside, while Scottish Gaelic has *cù-allaidh*, “wild dog.” In Welsh, the word is *blaidh*, which is a borrowing from a now lost ancient language of Britain, borrowed so long ago that no other word for wolf descending from Proto-Indo-European is found in the language.



We Are All Ancient Mapmakers

*Why we still see the world like the mathematician and
poet who first mapped it*

BY CODY KOMMERS



IN THE FIRST HALF of the sixth century B.C., a Greek man named Anaximander, born in Turkey, sketched the world in a way no one had previously thought to do.

It featured a circle, divided into three equal parts. He labeled those parts Europe, Asia, and Libya, and separated them by the great waterways of the Nile, the Phasis river, and the Mediterranean. To call it a map would perhaps be a bit overgenerous. It was really more of a schematic. But it nonetheless represented a crucial innovation. Anaximander had rendered the world in a way that no person had ever seen it before: from above.

Anaximander's sketch wasn't especially useful as a cartographic instrument, and it also came with some peculiar conceptual baggage. He believed the Earth sat atop a column, following the architectural sensibilities of the day. It was Plato, several hundred years later, who proposed the idea of a spherical Earth. He had no strong, principled reason to do this; the guy just liked spheres. But though they were fascinated by the shape of the Earth, neither Plato nor Anaximander, nor even Aristotle, can count among their accolades credit for creating the first scientific map of the world. That distinction falls to a North African man by the name of Eratosthenes.

Eratosthenes is best known today as the founder of the field of geography. He coined the term in his magnum opus, *Geographika*, published during his tenure as the head librarian at Alexandria, sometime between 240 and 220 B.C. It was three books in length and covered topics ranging from climate zones to the geological history of the planet to the customs of different populations. What Eratosthenes offered in this book was a perspective informed by data. Any prior works that touched on these topics had been conceived in much the same way as Anaximander's schematic: a vague suspicion about what was out there, unconstrained by any commitment to describing its actuality.

We don't actually have a copy of Eratosthenes' original map (it probably burned down with the Library of Alexandria). But the Roman geographer Strabo, in the first century B.C., constructed his own map, which we do have, based off of Eratosthenes' original—a sort of tidying-up, rather than a total rewrite. He quoted at length from Eratosthenes' text, including detailed descriptions of the original rendering, so historians today have a pretty good idea of what Eratosthenes' map probably contained.

In Eratosthenes' map, the world's landmass looks like a parallelogram. It is divided into four quadrants. They are, roughly, Africa, Europe, Russia, and India—or at least that's what we'd call them today. As far as maps of the world go, it features—to make the point gently—some peculiar omissions.



ERATOSTHENES' WORLD MAP Based in part on Alexander the Great's travel logs, and his own mathematics Eratosthenes calculated that Earth's land masses were divided into four quadrants.

The Americas, Australia, and East Asia come to mind. Even in what Eratosthenes does try to depict, he fails to grasp how expansive the Earth's landmasses really are.

From our perspective, it's clear that Eratosthenes didn't know what the world looked like. What's a little trickier to explain is it didn't really occur to Eratosthenes that his map might be off. He was confident he had pretty much nailed it. He claimed, for instance, that the only reason no one had yet sailed around the world was because of unfavorable tides, and not for more consequential reasons—like the existence of the rest of Africa, China, and Russia.

In the famous first line of his *Tractatus Logico-Philosophicus*, the philosopher Ludwig Wittgenstein presented his readers with a proposition: "The world is all that is the case." Though Wittgenstein meant this as a claim about the bounds of logic, it can also be interpreted psychologically. Our conception of the world is based on what we think is out there. In fact, that's all we think the world is—whatever's out there.

What's changed since Eratosthenes' days is technology. We now have detailed images of what the world actually looks like. What hasn't changed are the ways

our minds make sense of our surroundings. The map of Eratosthenes resembles something we all do—reconcile the terrain around us with what means the most to us. The ancient geographer didn't just produce the first map of the world. He gave us an insight into the kind of map we carry in our own heads to this day.

THE IDEA THAT an animal's brain creates a map of its environment as it runs around in it was first proposed by Edward Tolman, in his influential 1948 paper, "Cognitive maps in rats and men." Tolman's initial proposal was simply that the brain uses some sort of spatial representation to organize knowledge about the layout of the world. In his experiments, Tolman would set a rat at a random point in the maze, then measure how long it took the rat to find her way to the cheese. As expected, the rats got quicker each time Tolman put them in the maze. Tolman then compared this with a second condition. He would put a rat in the maze, but without any cheese. The rat would wander aimlessly, and whenever she got to the place where the cheese would have been, Tolman would take her out and set her back in the cage. The rats in this condition each did

five of these non-cheese trials before moving on to the normal cheese-motivated trials.

What Tolman's contemporaries would have expected to see was that the non-cheese trials didn't matter. The accepted theory of the day was that learning was motivated by reward. And without the cheese there was no reward, and therefore no learning. But that's not what Tolman found. What he discovered was that as soon as he began putting the cheese in the maze, the rats who had merely been wandering were able to solve the maze just as quickly as those who had been going after the cheese the entire time. The reason for this, Tolman explained, was that the rats were creating a cognitive map of their environment the whole time. Once they knew where in that map the cheese was, they could go straight there.

In this sense, Eratosthenes' map of the world can be thought of as a sort of cognitive map, worked out in pen and paper. Like Tolman's rats, he developed a picture of what he thought was out there. Except, unlike the rats, Eratosthenes couldn't just traipse around the world to get a feel for it. He made up for this with a particular strength of his: working out new conclusions from existing data.

Eratosthenes had little respect for disciplinary silos. He wrote quite a bit of philosophy, and his contemporaries considered his work adequate but derivative. He was a decent poet, but by no means the most renowned of his generation. The same could be said of his status as a mathematician. His friends, picking up on this pattern, took to calling him "Beta" because he was, according to them, second best in everything.

During his younger years Eratosthenes had a particular interest in prime numbers. His most celebrated mathematical invention is known today as the Sieve of Eratosthenes. The Sieve—which rhymes with "give"—is an algorithm for generating a list of all the primes up to a chosen number. To this day, it's still the most efficient way for a computer to generate all the primes up through about 100,000. The payoff for this idea would come far after Eratosthenes' own lifetime, as it is relevant in contemporary fields like number theory and cryptography.

The intellectual feat that garnered Eratosthenes the most fame in his own lifetime was his estimate of the Earth's circumference. He managed to get within

Our conception of the world is based on what we think is out there. In fact, that's all we think the world is.

about a tenth of a percent of the modern calculation using only Euclidean geometry and a few simple measurements. It was well known in the ancient world that the sun was directly over the city of Syene during the summer solstice, because of a deep well that cast no shadow. And the length of the Nile from Syene to Alexandria was also known, because it had recently been surveyed by Ptolemy II. So one day on the summer solstice, Eratosthenes measured the angle of a tall building in Alexandria. He got a reading of 7.2 degrees. Doing the math, this meant that this section of the Nile was exactly one-fiftieth of Earth's circumference (if you cut a pie into 50 equal pieces, the interior angle at the point of each slice would be 7.2 degrees). His calculation was off by about the distance between JFK airport in New York and Newark airport in New Jersey along I-95; in other words, you could walk Eratosthenes' margin of error in about nine hours. One historian calls Eratosthenes' estimate "a feat so profound yet so simple that it remains today one of the most amazing pieces of ancient scholarship, treated as such since antiquity."

There's a Greek word, *philologos*. Literally it means "lover of reason," but at its heart it meant a learned person, an academic. It was a somewhat pejorative term. An ancient Greek might use it in the same way we might say today that someone is a thinker, as opposed to a doer. Eratosthenes, allegedly, was the first to use the word to describe himself. That's sort of like someone today being declared the first "thought leader." Not necessarily by anyone else, but according to their own estimation.

Of course, he was probably correct.

IN 1976, THE PSYCHOLOGIST Stanley Milgram had just come off a decade-long research program on obedience to authority, in which he induced participants to shock one another in a dingy basement on the campus



THE TOURIST MAP This tourist map of Paris provides a kind of control study for an experiment that asked Parisians to map their city. Their results invariably looked nothing like this, the city as it's commonly pictured.

of Yale University. Milgram had recently moved to Paris, where he was keen to employ an experimental paradigm that was decidedly more benign. In particular, he was interested in what he called people's "psychological maps" of the city. "It is not," he wrote, "an examination of Paris as a geographic reality, but rather of the way that reality is mirrored in the minds of its inhabitants." How, in other words, do people's psychological maps differ from the way Paris actually looks? "The first principle," as Milgram put it, "is that reality and image are imperfectly linked."

What you might have expected Milgram to find is that his participants' maps looked like impoverished versions of a tourist map. After all, each of Milgram's participants would have seen the canonical map of Paris—featuring the Eiffel Tower, Notre Dame, the Arc de Triomphe—hundreds of times. To be sure, their hand-drawn maps wouldn't look exactly like the actual map; these people are not professional cartographers. But there is no doubt that they would have been familiar with the real thing represented as it actually is. They could also rely on their quotidian interactions with Paris, wandering its streets and traversing the cityscape as they go about their business. But that was exactly the problem.

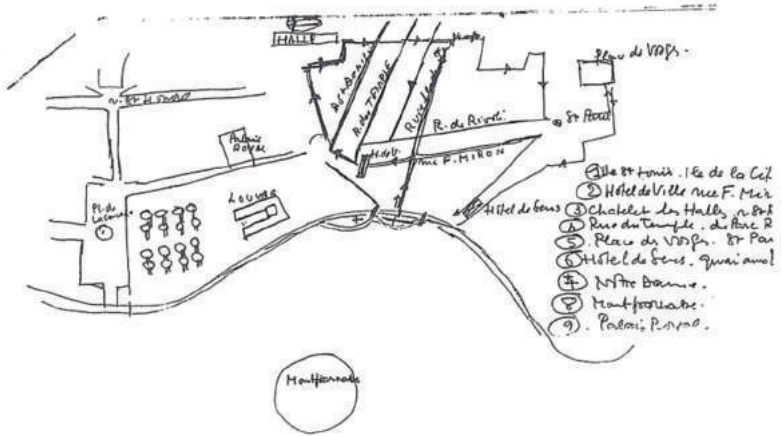
What Milgram found is that people's maps were more strongly influenced by their own idiosyncratic experiences than a general knowledge of the

The Parisians should have known how far they were off. But they confidently asserted they were right.

city's layout. One map was drawn by a 50-year-old woman who had lived for 15 years in the city's Fourth Arrondissement. She mapped that area, just north of the Seine, in scrupulous detail, down to the direction of the one-way streets. But she included almost no landmarks south of the Seine, except for Montparnasse—no Eiffel Tower, no Musée d'Orsay, no Jardin du Luxembourg.

In this respect, her map is representative of what Milgram found overall. Almost half of Milgram's participants failed to include the Eiffel Tower and other major landmarks. "She centers her map not on Paris as a whole," wrote Milgram, "but on a segment of it that has special meaning to her."

When you look a little closer, the maps of Milgram's Parisians were off in much the same way as Eratosthenes. Eratosthenes, so to speak, mapped the one-way streets around Alexandria, Athens, and the Mediterranean, where he lived most of his life. But he failed



THE LOCAL'S MAP This Paris map was drawn by a 50-year-old woman, who had lived for 15 years in the Fourth Arrondissement. Notably missing is the Eiffel Tower and other landmarks. But not the streets where she lived.

to get any details right once he set his sights on more distal terrain, like India or southern Africa. And just as with Eratosthenes, the Parisians didn't think their map was perfect, but they thought it was pretty much correct. The difference here is that, unlike Eratosthenes, they *had* seen the real thing. They should have known how far they were off. But they still confidently asserted that the reality in their head corresponded with what was out there. It didn't.

So what exactly had Eratosthenes seen that informed his map? That answer begins, as it so often does for these sort of things, with Aristotle. In his *Meteorologia*, Aristotle documented an interest in the Earth's surface. He was the first one to provide an estimate of the circumference of the Earth (it was way off). But most of his work ultimately didn't go much further than speculation. After all, how could he possibly know what the rest of the world was like when he'd never seen it?

So when Aristotle began tutoring a young pupil named Alexander around 340 B.C., there were many questions about what the Earth looked like but not many answers. Alexander, for his part, took a certain pragmatically-inclined interest in questions about the surface of the Earth. This was probably connected to the fact that he would, over the next couple decades, go on to conquer most of it.

Alexander's campaigns went throughout most of Asia minor—northeastern Africa, Macedonia and the Hellenic peninsula, the eastern Mediterranean, Arabia, and into India, just north of Bombay. These campaigns

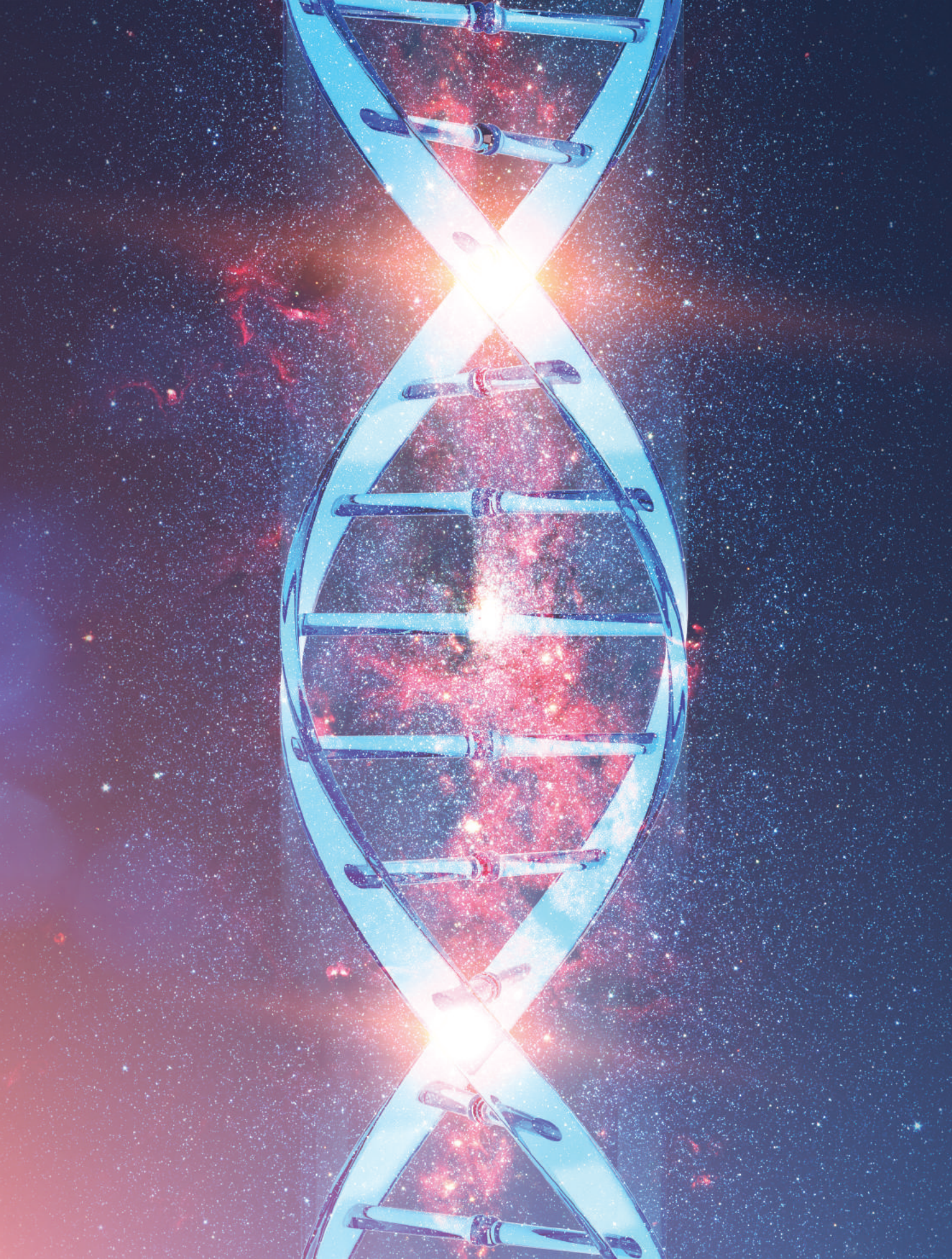
started in 336 B.C. and continued until 323 B.C., the year of Alexander's death.

By the time Eratosthenes took his station at Alexandria, all of Alexander's military personnel had returned from their travels, compared notes with one another, and had written up reports about what they had seen. And where do you think they kept those reports once they'd been filed away? The Library of Alexandria, naturally.

Eratosthenes had what Aristotle did not. He had data.

Which is what puts Eratosthenes on the same playing field as the rest of us. We can only use the data available to us to paint a picture of what's out there. Like Milgram's Parisians, and Tolman's rats, we each construct a map of reality as we go about our business in the world. And like them, we assume that what our version looks like is the real thing. The risk we run is to mistake the representation for the reality. We might think that we are exempt from the kind of mistakes Eratosthenes made, because we simply have access to so much more reliable information. But that isn't a guarantee. In the *Geographika*, Eratosthenes wrote of why he was unable to consider the possibility of another, unknown world, which might conceivably exist outside his own realm of knowledge: "For myself, however, I must speak of what is in our own." ☺

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Do We Share DNA with ET?

*If there's life beyond Earth, the genetic code
might be our common bond*

BY DANIEL OBERHAUS

THE PRIMARY DIFFICULTY of interstellar communication is finding common ground between ourselves and other intelligent entities about which we can know nothing with absolute certainty. This common ground would be the basis for a universal language that could be understood by any intelligence, whether in the Milky Way, Andromeda, or beyond the cosmic horizon. To the best of our knowledge, the laws of physics are the same throughout the universe, which suggests that the facts of science may serve as a basis for mutual understanding between humans and an extraterrestrial intelligence.

One key set of scientific facts presents an intriguing question. If aliens were to visit Earth and learn about its inhabitants, would they be surprised that such a wide variety of species all share a common genetic code? Or would this be all too familiar? There is probable cause to assume that the structure of genetic material is the same throughout the universe and that, while this is liable to give rise to life forms not found on Earth, the variety of species is fundamentally limited by the constraints built into the genetic mechanism.

On Earth we have only sequenced the genomes of a small percentage of living organisms and have only recently completed the human genome. We have successfully cloned several animals, but technical and ethical roadblocks prevent scientists from doing the same with humans. If an extraterrestrial civilization isn't burdened with ethical dilemmas about cloning, however, sending the genetic code for humans and other species may be the most effective way to teach them about our biology.

References to our genetic makeup have been a feature of interstellar messages from the very beginning. Although the first genes wouldn't be sequenced for another three years, the 1974 Arecibo message, an interstellar radio message sent from the Arecibo radio telescope in Puerto Rico, included a rudimentary bitmap of DNA's helical structure. Designed by Frank Drake, the founder of SETI, with input from Carl Sagan, the Arecibo message consisted of 1,679 binary digits arranged as a rectangular bitmap. The resulting image depicts the numbers one through 10 and the atomic numbers for the five elements that make up DNA, as well as the formulas for the sugars and bases in DNA nucleotides, a crude drawing of a human, a graphic representation of the solar system, and a picture of the Arecibo telescope.

In 1999, two interstellar radio transmissions known as Cosmic Calls included symbols for each of DNA's four nucleotides. To date, however, only a single interstellar transmission has encoded any genetic information.

To commemorate the 35th anniversary of the Arecibo message, the artist Joe Davis traveled to Puerto Rico to broadcast the genetic sequence for the large subunit of the ribulose-1,5-bisphosphate carboxylase oxygenase (RuBisCO) molecule. RuBisCO is the most abundant protein on Earth and plays a major role in converting atmospheric carbon dioxide into energy-rich molecules

Would aliens be surprised that life on Earth shared an underlying genetic code? Or would this be all too familiar?

for plants. To encode this genetic information in a signal, Davis first considered representing each of the 1,434 nucleotides with a two-bit ID (C=00, T=01, A=10, G=11) to create a 2,868-bit sequence representing the RuBisCO molecule. The problem with this, of course, is that there isn't enough information to use analysis techniques such as those described above by Elliott. Thus, any ETI that received this message would have no way to determine the coding schema used to create the message, which would essentially be an unintelligible mess of data.

For better or worse, it is unlikely that any extraterrestrials will ever receive, much less understand, Davis's message. None of the stars selected by Davis have been confirmed to host planets, and two of the target stars aren't likely able to support life even if they do. GJ 83.1 is a flare star, a type of dwarf known for periodic bursts of intense radiation and Teegarden's star is a red dwarf, a type of star that is widely believed to be too cool to support life unless the planet was so close to the star that it would become tidally locked, meaning that half of the planet would be in perpetual night.



MEET EARTH'S DNA Artist Joe Davis traveled to the Arecibo radio telescope in Puerto Rico (above) to broadcast a genetic sequence for an abundant protein on Earth. He didn't expect his interstellar message to be heard, but if it were, aliens just might recognize the code.

Even if there are intelligent inhabitants around any of the three “RuBisCO stars,” the odds that they would be able to interpret Davis’s message is quite low, given the lack of context or redundancy to correct for message corruption during transit. Davis was the first to admit that his interstellar message was meant more for his fellow passengers on spaceship Earth than extraterrestrials, but this stunt points the way to a promising future for METI (messaging extraterrestrial intelligence).

IN THE LAST FEW DECADES, biologists have sequenced the genomes for thousands of species, including humans. These are effectively the “blueprints” for the

species, but we are only just beginning to learn how to read the code. A sufficiently advanced extraterrestrial intelligence may have developed genetic engineering to the point where genomes are the equivalent to an executable computer program, which would allow them to artificially recreate a human and other terrestrial species in their own labs. This assumes that extraterrestrials are made of the same genetic “stuff” as life on Earth, but this may not be as large of an assumption as it first seems.

In some ways, it would almost be more disturbing to make contact with an intelligent extraterrestrial civilization populated by fleshy, mostly hairless hominids than a civilization of eight-eyed cephalopods, but this

possibility is not entirely out of the question. As the astrobiologist Charles Cockell has argued, empirical evidence suggests that certain features of life are deterministically driven by physical laws. Extrapolating from this, it is reasonable to believe that “at all levels of its structural hierarchy, alien life is likely to look strangely similar to the life we know on Earth.”

Cockell’s argument is analogous to the case made by pioneering cognitive scientist Marvin Minsky that extraterrestrials are likely to think like us because they are subject to the same basic physical constraints. Minsky argued that we will be able to converse with an extraterrestrial intelligence because they will think like us. If all intelligent creatures are faced with the same fundamental problems (restraints on space, time, and materials) and the methods of intelligence are determined by the nature of the problem at hand, Minsky reasoned that extraterrestrial intelligences will arrive at solutions similar to our own, namely symbolic systems for representing these problems and processes for manipulating those systems that can also be described symbolically.

It would be naïve, of course, to suggest that evolution is totally determined by the laws of physics given the significant and obvious role that chance plays in the trajectory of evolution. For example, research suggests that the probability of an asteroid impact resulting in global cooling, mass extinction, and the subsequent appearance of mammals was “quite low” 66 million years ago. It was sheer cosmic bad luck that the asteroid impacted the relatively small portion of the Earth’s surface that was rich in hydrocarbons and sulfur that ultimately choked the Earth with stratospheric soot and sulfate aerosols. In this case, the site of the asteroid impact changed the history of life on Earth in a way that could never be predicted by deterministic evolutionary laws.

The point is that although the trajectory of evolution isn’t predictable in advance, the variety of species it produces is not boundless. This contradicts the intuitive interpretation of Darwinian evolution, which suggests that natural selection results in a “tendency of species to form varieties” in infinite number.

On the contrary, Cockell argues that “evolution is just a tremendous and exciting interplay of physical principles encoded in genetic material” and “the

limited number of these principles ... means that the finale of this process is also restrained and universal.”

Consider, for example, the emergence of cellular life on Earth. Is the cellular form something that we might expect to emerge on an extraterrestrial planet, or would extraterrestrial organisms find a different mode of self-assembly?

In the 1980s, the biologist David Dreamer used carboxylic acids extracted from the famous Murchison meteorite to demonstrate that these simple molecules would spontaneously form cellular membranes when added to water. According to Cockell, this suggests that the ingredients for cellular life are “strewn throughout the Solar System in carbon-rich rocks,” which means “we might expect the molecules of cellularity to form in any primordial cloud, ready to deliver their cargo of protocell material to the surface of any planet with a waiting abundance of water.” Later experiments demonstrated that meteorites are far from the only source of molecular material that can form cellular membranes, suggesting that this mode of organization is likely common in the universe.

Similar physical laws also limit the possibilities of still more fundamental aspects of biology, such as the structure of DNA. One of the most remarkable features about DNA is that it is composed of only four nucleotides—adenine, thymine, cytosine, and guanine—that can only combine in very limited ways: adenine pairs with thymine and cytosine pairs with guanine. Is the fact that there are only four nucleotides or that they combine into two base pairs an evolutionary accident? Might an extraterrestrial intelligence have a genetic code built from six or more nucleotides, and might these nucleotides be different from the four that comprise the DNA of life on Earth? This is a possibility, of course, but there are strong reasons to believe that it is unlikely.

Adding more nucleotides to the equation increases the amount of information available to the system and means that smaller molecules can contain the same amount of information as longer molecules in genetic pools with only four nucleotides. The trade-off, of course, is that the percentage of bases that a given nucleotide can link with halves with each base pair added to the system.

For example, in a two-nucleotide system, each base can pair with half of the bases. In a four-nucleotide

Extraterrestrials are likely to think like us because they are subject to the same basic physical constraints.

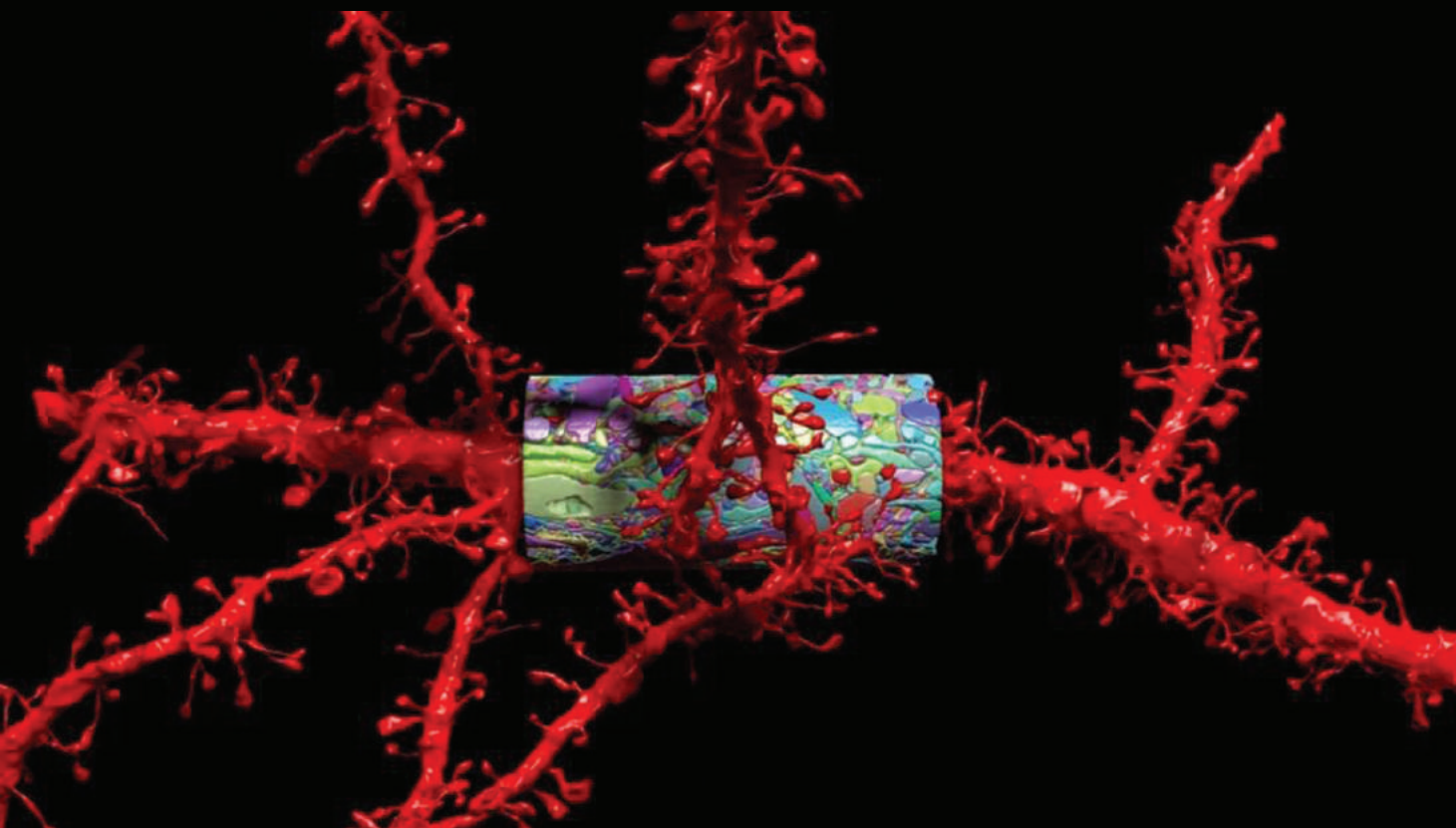
system, each base can only link with a quarter of the bases, and so on. Thus, Cockell argues, “as you add more bases, it gets more difficult to find ones that are sufficiently dissimilar to make it easy for them to be distinguished when the molecule replicates,” which results in a higher rate of errors. Indeed, computer models of RNA, the molecular interface between DNA and basic proteins, suggest that four nucleotides result in the greatest fitness.

As for the types of base pairs, research using synthetic nucleotides to expand the number of base pairs in the genetic code has demonstrated that swapping these synthetic base pairs out of the normal code or adding them usually produces unstable results. However, organisms such as bacteria that have synthetic nucleotides added into an expanded genetic alphabet have been shown to be stable under stringent laboratory conditions. The results of ongoing experiments with the many possible base pairs suggest that the four base pairs we see in RNA and DNA are optimized to meet the conditions that allow for its replication, but also the preservation of its structure.

If the brain and its cognitive structures are in fact optimized for the embodied experience of the organism, this suggests that the thesis that extraterrestrials will think similarly to us is not so far-fetched after all. 🌀

DANIEL OBERHAUS is a staff writer at *Wired*, where he covers space exploration and the future of energy. He is the author of *Extraterrestrial Languages*.

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An Existential Crisis in Neuroscience

*We're mapping the brain in amazing detail—but our brain
can't understand the picture*

BY GRIGORI GUITCHOUNTS

COURTESY OF LIGHTMAN LAB AT HARVARD UNIVERSITY



ON A CHILLY EVENING last fall, I stared into nothingness out of the floor-to-ceiling windows in my office on the outskirts of Harvard's campus. As a purplish-red sun set, I sat brooding over my dataset on rat brains. I thought of the cold windowless rooms in downtown Boston, home to Harvard's high-performance computing center, where computer servers were holding on to a precious 48 terabytes of my data. I have recorded the 13 trillion numbers in this dataset as part of my Ph.D. experiments, asking how the visual parts of the rat brain respond to movement.

Printed on paper, the dataset would fill 116 billion pages, double-spaced. When I recently finished writing the story of my data, the magnum opus fit on fewer than two dozen printed pages. Performing the experiments turned out to be the easy part. I had spent the last year agonizing over the data, observing and asking questions. The answers left out large chunks that did not pertain to the questions, like a map leaves out irrelevant details of a territory.

But, as massive as my dataset sounds, it represents just a tiny chunk of a dataset taken from the whole brain. And the questions it asks—Do neurons in the visual cortex do anything when an animal can't see? What happens when inputs to the visual cortex from other brain regions are shut off?—are small compared to the ultimate question in neuroscience: How does the brain work?

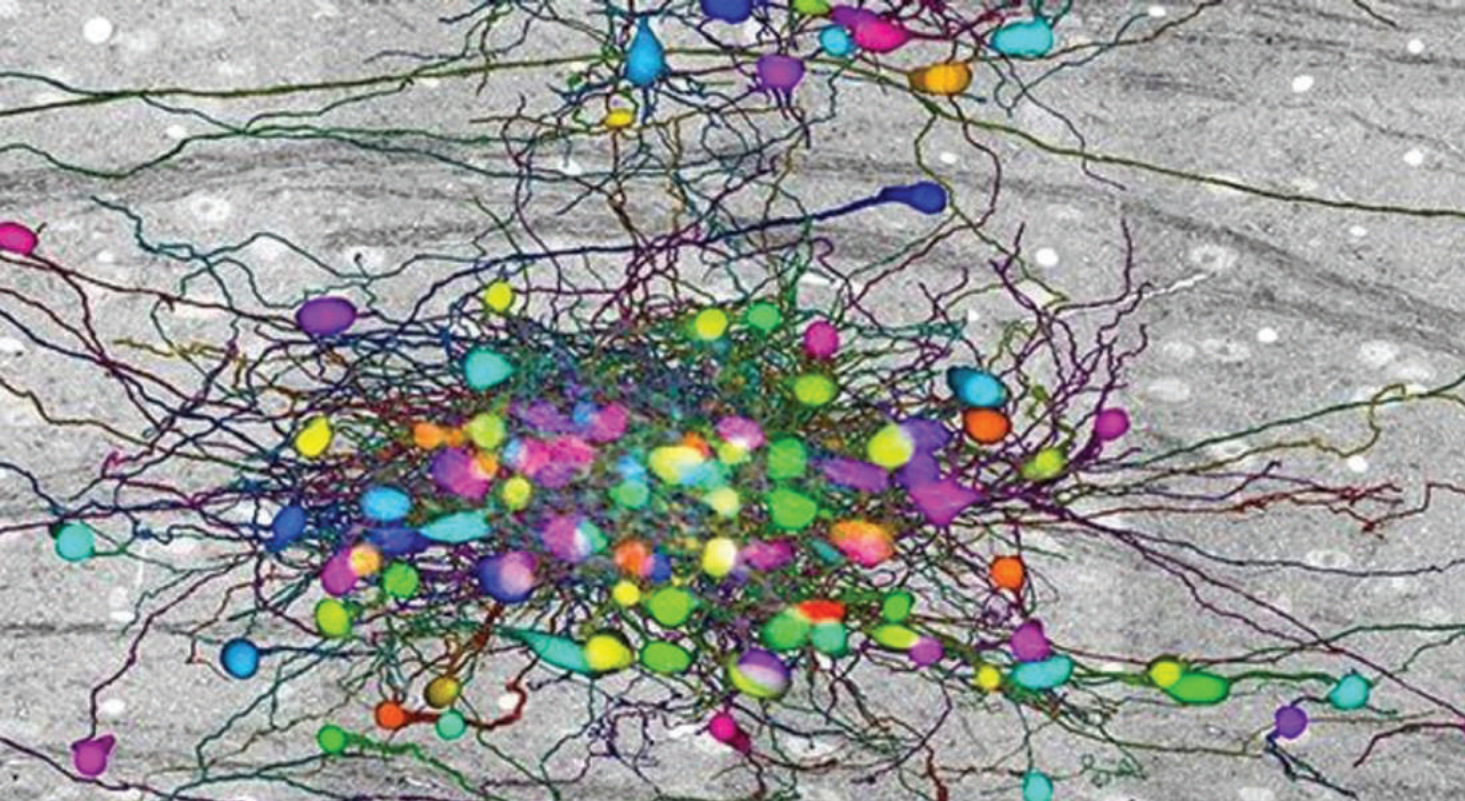
The nature of the scientific process is such that researchers have to pick small, pointed questions. Scientists are like diners at a restaurant: We'd love to try everything on the menu, but choices have to be made. And so we pick our field, and subfield, read up on the

hundreds of previous experiments done on the subject, design and perform our own experiments, and hope the answers advance our understanding. But if we have to ask small questions, then how do we begin to understand the whole?

Neuroscientists have made considerable progress toward understanding brain architecture and aspects of brain function. We can identify brain regions that respond to the environment, activate our senses, generate movements and emotions. But we don't know how different parts of the brain interact with and depend on each other. We don't understand how their interactions contribute to behavior, perception, or memory. Technology has made it easy for us to gather behemoth datasets, but I'm not sure understanding the brain has kept pace with the size of the datasets.

Some serious efforts, however, are now underway to map brains in full. One approach, called connectomics, strives to chart the entirety of the connections among neurons in a brain. In principle, a complete connectome would contain all the information necessary to provide a solid base on which to build a holistic understanding

(Left) A rendering of dendrites (red)—a neuron's branching processes—and protruding spines that receive synaptic information, along with a saturated reconstruction (multicolored cylinder) from a mouse cortex.



LIVING COLOR This electron microscopy image of a slice of mouse cortex, which shows different neurons labeled by color, is just the beginning. “We’re working on a cortical slab of a human brain, where every synapse and every connection of every nerve cell is identifiable,” says Harvard’s Jeff Lichtman. “It’s amazing.”

of the brain. We could see what each brain part is, how it supports the whole, and how it ought to interact with the other parts and the environment. We’d be able to place our brain in any hypothetical situation and have a good sense of how it would react.

The question of how we might begin to grasp the entirety of the organ that generates our minds has been pressing me for a while. Like most neuroscientists, I’ve had to cultivate two clashing ideas: striving to understand the brain and knowing that’s likely an impossible task. I was curious how others tolerate this doublethink, so I sought out Jeff Lichtman, a leader in the field of connectomics and a professor of molecular and cellular biology at Harvard.

Lichtman’s lab happens to be down the hall from mine, so on a recent afternoon, I meandered over to his office to ask him about the nascent field of connectomics and whether he thinks we’ll ever have a holistic

understanding of the brain. His answer—“No”—was not reassuring, but our conversation was a revelation, and shed light on the questions that had been haunting me. How do I make sense of gargantuan volumes of data? Where does science end and personal interpretation begin? Were humans even capable of weaving today’s reams of information into a holistic picture? I was now on a dark path, questioning the limits of human understanding, unsettled by a future filled with big data and small comprehension.

LICHTMAN LIKES TO SHOOT FIRST, ask questions later. The 68-year-old neuroscientist’s weapon of choice is a 61-beam electron microscope, which Lichtman’s team uses to visualize the tiniest of details in brain tissue. The way neurons are packed in a brain would make canned sardines look like they have a highly evolved sense of personal space. To make any sense of these

COURTESY OF LICHTMAN LAB AT HARVARD UNIVERSITY

images, and in turn, what the brain is doing, the parts of neurons have to be annotated in three dimensions, the result of which is a wiring diagram. Done at the scale of an entire brain, the effort constitutes a complete wiring diagram, or the connectome.

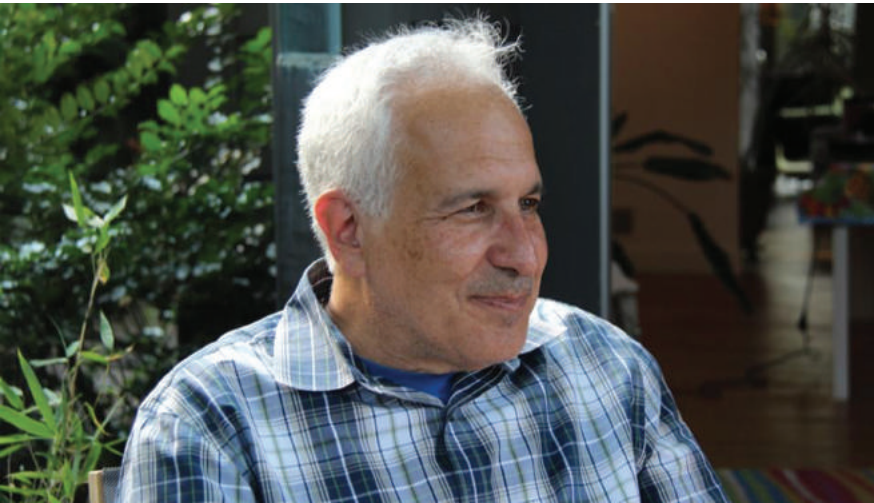
To capture that diagram, Lichtman employs a machine that can only be described as a fancy deli slicer. The machine cuts pieces of brain tissue into 30-nanometer-thick sections, which it then pastes onto a tape conveyor belt. The tape goes on silicon wafers, and into Lichtman's electron microscope, where billions of electrons blast the brain slices, generating images that reveal nanometer-scale features of neurons, their axons, dendrites, and the synapses through which they exchange information. The Technicolor images are a beautiful sight that evokes a fantastic thought: The mysteries of how brains create memories, thoughts, perceptions, feelings—consciousness itself—must be hidden in this labyrinth of neural connections.

A complete human connectome will be a monumental technical achievement. A complete wiring diagram for a mouse brain alone would take up two exabytes. That's 2 billion gigabytes; by comparison, estimates of the data footprint of all books ever written come out to less than 100 terabytes, or 0.005 percent of a mouse brain. But Lichtman is not daunted. He is determined to map whole brains, exorbitant exabyte-scale storage be damned.

Lichtman's office is a spacious place with floor-to-ceiling windows overlooking a tree-lined walkway and an old circular building that, in the days before neuroscience even existed as a field, used to house a cyclotron. He was wearing a deeply black sweater, which contrasted with his silver hair and olive skin. When I asked if a completed connectome would give us a full understanding of the brain, he didn't pause in his answer. I got the feeling he had thought a great deal about this question on his own.

"I think the word 'understanding' has to undergo an evolution," Lichtman said, as we sat around his desk. "Most of us know what we mean when we say 'I understand something.' It makes sense to us. We can hold the idea in our heads. We can explain it with language. But if I asked, 'Do you understand New York City?' you would probably respond, 'What do you mean?' There's all this complexity. If you can't understand New York

*I was now on a dark path,
unsettled by a future filled
with big data and small
comprehension.*



THE MAPMAKER Jeff Lichtman (above), a leader in brain mapping, says the word “understanding” has to undergo a revolution in reference to the human brain. “There’s no point when you can suddenly say, ‘I now understand the brain,’ just as you wouldn’t say, ‘I now get New York City.’”

City, it’s not because you can’t get access to the data. It’s just there’s so much going on at the same time. That’s what a human brain is. It’s millions of things happening simultaneously among different types of cells, neuromodulators, genetic components, things from the outside. There’s no point when you can suddenly say, ‘I now understand the brain,’ just as you wouldn’t say, ‘I now get New York City.’”

“But we understand specific aspects of the brain,” I said. “Couldn’t we put those aspects together and get a more holistic understanding?”

“I guess I would retreat to another beachhead, which is, ‘Can we describe the brain?’” Lichtman said. “There are all sorts of fundamental questions about the physical nature of the brain we don’t know. But we can learn to describe them. A lot of people think ‘description’ is a pejorative in science. But that’s what the Hubble telescope does. That’s what genomics does. They describe what’s actually there. Then from that you can generate your hypotheses.”

“Why is description an unsexy concept for neuroscientists?”

“Biologists are often seduced by ideas that resonate with them,” Lichtman said. That is, they try to bend the world to their idea rather than the other way around. “It’s much better—easier, actually—to start with what the world is, and then make your idea conform to it,” he said. Instead of a hypothesis-testing approach, we might be better served by following a descriptive, or hypothesis-generating methodology. Otherwise we end up chasing our own tails. “In this age, the wealth of information is an enemy to the simple idea of understanding,” Lichtman said.

“How so?” I asked.

“Let me put it this way,” Lichtman said. “Language itself is a fundamentally linear process, where one idea leads to the next. But if the thing you’re trying to describe has a million things happening

simultaneously, language is not the right tool. It’s like understanding the stock market. The best way to make money on the stock market is probably not by understanding the fundamental concepts of economy. It’s by understanding how to utilize this data to know what to buy and when to buy it. That may have nothing to do with economics but with data and how data is used.”

“Maybe human brains aren’t equipped to understand themselves,” I offered.

“And maybe there’s something fundamental about that idea: that no machine can have an output more sophisticated than itself,” Lichtman said. “What a car does is trivial compared to its engineering. What a human brain does is trivial compared to its engineering. Which is the great irony here. We have this false belief there’s nothing in the universe that humans can’t understand because we have infinite intelligence. But if I asked you if your dog can understand something you’d say, ‘Well, my dog’s brain is small.’ Well, your brain is only a little bigger,” he continued, chuckling. “Why, suddenly, are you able to understand everything?”

We have this false belief there's nothing that humans can't understand.

Was Lichtman daunted by what a connectome might achieve? Did he see his efforts as Sisyphean?

"It's just the opposite," he said. "I thought at this point we would be less far along. Right now, we're working on a cortical slab of a human brain, where every synapse is identified automatically, every connection of every nerve cell is identifiable. It's amazing. To say I understand it would be ridiculous. But it's an extraordinary piece of data. And it's beautiful. From a technical standpoint, you really can see how the cells are connected together. I didn't think that was possible."

Lichtman stressed his work was about more than a comprehensive picture of the brain. "If you want to know the relationship between neurons and behavior, you gotta have the wiring diagram," he said. "The same is true for pathology. There are many incurable diseases, such as schizophrenia, that don't have a biomarker related to the brain. They're probably related to brain wiring but we don't know what's wrong. We don't

have a medical model of them. We have no pathology. So in addition to fundamental questions about how the brain works and consciousness, we can answer questions like, Where did mental disorders come from? What's wrong with these people? Why are their brains working so differently? Those are perhaps the most important questions to human beings."

LATE ONE NIGHT, after a long day of trying to make sense of my data, I came across a short story by Jorge Louis Borges that seemed to capture the essence of the brain mapping problem. In the story, "On Exactitude in Science," a man named Suarez Miranda wrote of an ancient empire that, through the use of science, had perfected the art of map-making. While early maps were nothing but crude caricatures of the territories they aimed to represent, new maps grew larger and larger, filling in ever more details with each edition. Over time, Borges wrote, "the Art of

Cartography attained such Perfection that the map of a single Province occupied the entirety of a City, and the map of the Empire, the entirety of a Province.” Still, the people craved more detail. “In time, those Unconscionable Maps no longer satisfied, and the Cartographers Guilds struck a Map of the Empire whose size was that of the Empire, and which coincided point for point with it.”

The Borges story reminded me of Lichtman’s view that the brain may be too complex to be understood by humans in the colloquial sense, and that describing it may be a better goal. Still, the idea made me uncomfortable. Much like storytelling, or even information processing in the brain, descriptions must leave some details out. For a description to convey relevant information, the describer has to know which details are important and which are not. Knowing which details are irrelevant requires having some understanding about the thing you’re describing. Will my brain, as intricate as it may be, ever be able to make sense of the two exabytes in a mouse brain?

Humans have a critical weapon in this fight. Machine learning has been a boon to brain mapping, and the self-reinforcing relationship promises to transform the whole endeavor. Deep learning algorithms (also known as deep neural networks, or DNNs) have in the past decade allowed machines to perform cognitive tasks once thought impossible for computers—not only object recognition, but text transcription and translation, or playing games like Go or chess. DNNs are mathematical models that string together chains of simple functions that approximate real neurons. These algorithms were inspired directly by the physiology and anatomy of the mammalian cortex, but are crude approximations of real brains, based on data gathered in the 1960s. Yet they have surpassed expectations of what machines can do.

The secret to Lichtman’s progress with mapping the human brain is machine intelligence. Lichtman’s team, in collaboration with Google, is using deep networks to annotate the millions of images their microscopes collect from brain slices. Each scan from an electron microscope is just a set of pixels. Human eyes easily recognize the boundaries of each blob in the image (a neuron’s soma, axon, or dendrite, in addition to everything else in the brain), and with

some effort can tell where a particular bit from one slice appears on the next slice. This kind of labeling and reconstruction is necessary to make sense of the vast datasets in connectomics, and have traditionally required armies of undergraduate students or citizen scientists to manually annotate all the chunks. DNNs trained on image recognition are now doing the heavy lifting automatically, turning a job that took months or years into one that’s complete in a matter of hours or days. Recently, Google identified each neuron, axon, dendrite, and dendritic spike—and every synapse—in slices of the human cerebral cortex. “It’s unbelievable,” Lichtman said.

Scientists still need to understand the relationship between those minute anatomical features and dynamical activity profiles of neurons—the patterns of electrical activity they generate—something the connectome data lacks. This is a point on which connectomics has received considerable criticism, mainly by way of example from the worm: Neuroscientists have had the complete wiring diagram of the worm *C. elegans* for a few decades now, but arguably do not understand the 300-neuron creature in its entirety; how its brain connections relate to its behaviors is still an active area of research.

Still, structure and function go hand-in-hand in biology, so it’s reasonable to expect one day neuroscientists will know how specific neuronal morphologies contribute to activity profiles. It wouldn’t be a stretch to imagine a mapped brain could be kickstarted into action on a massive server somewhere, creating a simulation of something resembling a human mind. The next leap constitutes the dystopias in which we achieve immortality by preserving our minds digitally, or machines use our brain wiring to make super-intelligent machines that wipe humanity out. Lichtman didn’t entertain the far-out ideas in science fiction, but acknowledged that a network that would have the same wiring diagram as a human brain would be scary. “We wouldn’t understand how it was working any more than we understand how deep learning works,” he said. “Now, suddenly, we have machines that don’t need us anymore.”

YET A MASTERLY deep neural network still doesn’t grant us a holistic understanding of the human brain. That point was driven home to me last year at a



The brain may be
too complex to be
understood by humans.

A network with the same diagram as the human brain would be scary. We'd have machines that don't need us anymore.

Computational and Systems Neuroscience conference, a meeting of the who's-who in neuroscience, which took place outside Lisbon, Portugal. In a hotel ballroom, I listened to a talk by Arash Afraz, a 40-something neuroscientist at the National Institute of Mental Health in Bethesda, Maryland. The model neurons in DNNs are to real neurons what stick figures are to people, and the way they're connected is equally as sketchy, he suggested.

Afraz is short, with a dark horseshoe mustache and balding dome covered partially by a thin ponytail, reminiscent of Matthew McConaughey in *True Detective*. As sturdy Atlantic waves crashed into the docks below, Afraz asked the audience if we remembered René Magritte's "*Ceci n'est pas une pipe*" painting, which depicts a pipe with the title written out below it. Afraz pointed out that the model neurons in DNNs are not real neurons, and the connections among them are not real either. He displayed a classic diagram of interconnections among brain areas found through experimental work in monkeys—a jumble of boxes with names like V1, V2, LIP, MT, HC, each a different color, and black lines connecting the boxes seemingly at random and in more combinations than seems possible. In contrast to the dizzying heap of connections in real brains, DNNs typically connect different brain areas in a simple chain, from one "layer" to the next. Try explaining that to a rigorous anatomist, Afraz said,

as he flashed a meme of a shocked baby orangutan cum anatomist. "I've tried, believe me," he said.

I, too, have been curious why DNNs are so simple compared to real brains. Couldn't we improve their performance simply by making them more faithful to the architecture of a real brain? To get a better sense for this, I called Andrew Saxe, a computational neuroscientist at Oxford University. Saxe agreed that it might be informative to make our models truer to reality. "This is always the challenge in the brain sciences: We just don't know what the important level of detail is," he told me over Skype.

How do we make these decisions? "These judgments are often based on intuition, and our intuitions can vary wildly," Saxe said. "A strong intuition among many neuroscientists is that individual neurons are exquisitely complicated: They have all of these back-propagating action potentials, they have dendritic compartments that are independent, they have all these different channels there. And so a single neuron might even itself be a network. To caricature that as a rectified linear unit"—the simple mathematical model of a neuron in DNNs—"is clearly missing out on so much."

As 2020 has arrived, I have thought a lot about what I have learned from Lichtman, Afraz, and Saxe and the holy grail of neuroscience: understanding the brain. I have found myself revisiting my undergrad days, when I held science up as the only method of knowing that was

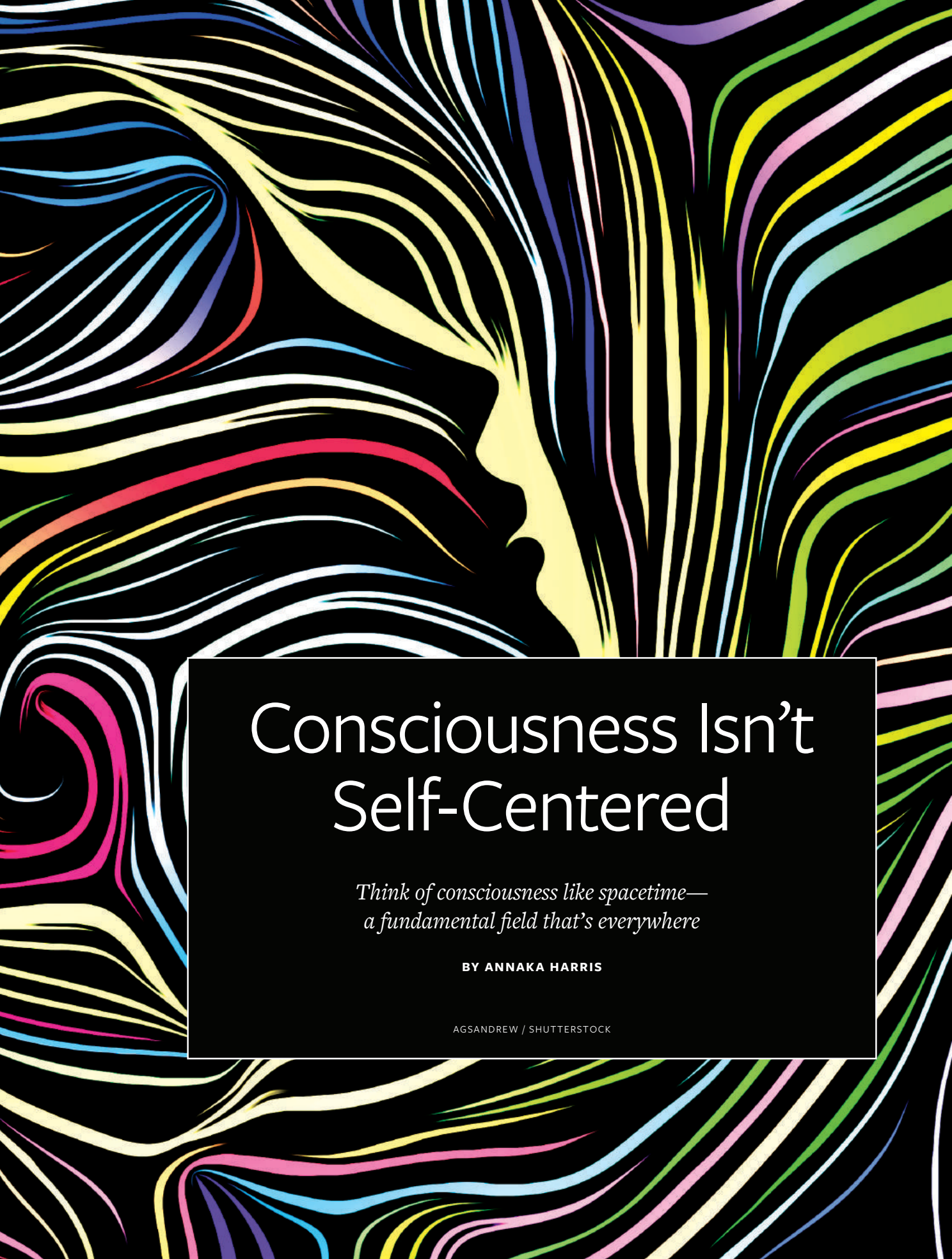
truly objective (I also used to think scientists would be hyper-rational, fair beings paramountly interested in the truth—so perhaps this just shows how naïve I was).

It's clear to me now that while science deals with facts, a crucial part of this noble endeavor is making sense of the facts. The truth is screened through an interpretive lens even before experiments start. Humans, with all our quirks and biases, choose what experiment to conduct in the first place, and how to do it. And the interpretation continues after data are collected, when scientists have to figure out what the data mean. So, yes, science gathers facts about the world, but it is humans who describe it and try to understand it. All these processes require filtering the raw data through a personal sieve, sculpted by the language and culture of our times.

It seems likely that Lichtman's two exabytes of brain slices, and even my 48 terabytes of rat brain data, will not fit through any individual human mind. Or at least no human mind is going to orchestrate all this data into a panoramic picture of how the human brain works. As I sat at my office desk, watching the setting sun tint the cloudless sky a light crimson, my mind reached a chromatic, if mechanical, future. The machines we have built—the ones architected after cortical anatomy—fall short of capturing the nature of the human brain. But they have no trouble finding patterns in large datasets. Maybe one day, as they grow stronger building on more cortical anatomy, they will be able to explain those patterns back to us, solving the puzzle of the brain's interconnections, creating a picture we understand. Out my window, the sparrows were chirping excitedly, not ready to call it a day. 😊

GRIGORI GUITCHOUNTS is about to defend his Ph.D. in neuroscience. You can read a bit about his 48 terabytes of rat brain data on [bioRxiv](#).



The background of the entire page is a vibrant, abstract pattern of thick, flowing lines in various colors including yellow, blue, green, pink, and white, set against a black background. These lines create a sense of movement and depth, resembling a stylized representation of spacetime or a complex neural network. In the center of the image, there is a black silhouette of a person's head in profile, facing right. The entire composition is framed by a thin white border.

Consciousness Isn't Self-Centered

*Think of consciousness like spacetime—
a fundamental field that's everywhere*

BY ANNAKA HARRIS

AGSANDREW / SHUTTERSTOCK

THE GREAT MYSTERY OF CONSCIOUSNESS is why matter lights up with felt experience. After all, we are composed of particles indistinguishable from those swirling around in the sun; the atoms that compose your body were once the ingredients of countless stars in our universe's past. They traveled for billions of years to land here—in this particular configuration that is you—and are now reading these words. Imagine following the life of those atoms from their first appearance in spacetime to the very moment they became arranged in such a way as to start *experiencing* something.

Many assume there is probably no felt experience associated with the microscopic collection of cells that make up a human blastocyst. But over time these cells multiply and slowly become a human baby, able to detect changes in light and recognize its mother's voice, even while in the womb. And, unlike a computer, which can also detect light and recognize voices, this processing is accompanied by an *experience* of light and sound. First, as far as consciousness is concerned there is nothing, and then suddenly, magically ... *something*. The mystery lies in the transition. However minimal that initial something is, experience apparently ignites in the inanimate world, materializing out of the darkness.

People often use the word "consciousness" to refer to higher-order functions, like self-awareness or thought. But I'm addressing consciousness in the most fundamental sense—as experience, regardless of the content. As I write in my recent book, *Conscious*,

Thomas Nagel once described consciousness in his famous essay "What Is It Like to Be a Bat?" in terms of whether or not it *feels like something* to be an organism. In other words, consciousness is what we're referring to when we talk about experience in its most basic form. Is it *like something* to be you in this moment? Presumably your answer is yes. Is it *like something* to be the chair you're sitting on? Your answer will (most likely) be an equally definitive no. It's this simple difference we can all use as a reference point for what I mean by the word "consciousness." Is it *like something* to be a grain of sand, a bacterium, an oak tree, an ant, a mouse, a dog? At some point along the spectrum the answer is yes, and the great mystery lies in why the lights turn on for some collections of matter in the universe.

How does felt experience arise out of non-sentient matter? The Australian philosopher David Chalmers famously termed this the hard problem of consciousness.¹ Unlike the "easy problems" of explaining

behavior or understanding which processes in the brain give rise to various functions, the hard problem lies in understanding why some of these physical processes have an experience associated with them at all. And the fact that the hard problem has persisted for so many decades, despite the advances in neuroscience, has caused some scientists to wonder if we've been thinking about the problem backward. Rather than consciousness arising when non-conscious matter behaves a particular way, is it possible that consciousness is an intrinsic property of matter—that it was there all along?

This notion sounds crazy, but the question has been seriously posed. It falls under the category of theories referred to as panpsychism, which entertains the possibility that *all* matter is imbued with consciousness in some sense. If the various behaviors of animals can be accompanied by consciousness, the thinking goes, why not the reaction of plants to light—or the spin of electrons, for that matter? Panpsychism postulates that consciousness is embedded in matter itself, as a fundamental property of the universe. And while the term has been attached to a wide range of ideas throughout history, contemporary panpsychism describes reality very differently than the earlier versions, and it is unencumbered by any religious beliefs. Modern panpsychism is informed by the sciences and fully aligned with physicalism and scientific reasoning.

We have a deeply ingrained intuition that systems that act like us are conscious and those that don't are not. We strongly believe, as a result, that consciousness arises out of complex processing in brains. But are these useful assumptions? When our intuitions don't match the mounting evidence, the goal of science is to push past them—e.g., the Earth is a sphere, disease is caused by germs, gravity warps spacetime. The idea that consciousness emerges out of non-conscious material, in fact, represents a kind of failure of the typical goal of scientific exploration: to arrive at as simple an explanation as possible. The celebrated biologist J.B.S. Haldane, for example, argued that the notion of the “strong emergence” of consciousness is “radically opposed to the spirit of science, which has always attempted to explain the complex in terms of the simple ... If the scientific point of view is correct, we shall ultimately find them [signs of consciousness

in inert matter], at least in rudimentary form, all through the universe.”²

My own sense of the correct resolution to the mystery of consciousness, whether or not we can ever achieve a true understanding, is split between a brain-based explanation and a panpsychic one. So while I'm not convinced that panpsychism offers the correct answer, I *am* convinced that it is a valid category of possible solutions that cannot be easily dismissed.

When considering panpsychic views it's important to first distinguish between consciousness and thought. We should be careful not to reflexively rail against the idea that rocks and spoons are conscious, which is obviously false when put this way. If consciousness is fundamental, all matter must entail consciousness by definition, but that doesn't mean it makes sense to specify such things as “moon consciousness” or “tree consciousness.” We would expect that the region of spacetime occupied by a rock, say, entails consciousness because matter is present there. We can't imagine what that region of particles feels like (or that it has a unified perspective at all, which seems unlikely). What we can be fairly sure of, however, is that it doesn't contain a humanlike experience or even a single “point of view.” Just as we wouldn't expect (the collection of atoms that make up) a rock to get up and walk or sing—that's not what atoms configured in such a way *do*—we also wouldn't expect it to feel a single, unified point of view. And we certainly wouldn't expect it to have anything like human thoughts or intentions.

If some version of panpsychism is correct, we would still assume that information in a complex and integrated form is required to produce experiences like ours. We shouldn't feel compelled to wonder if there is a specific “rock consciousness” any more than we're compelled to wonder if there is a “rock-plus-the-five-blades-of-grass-the-rock-is-touching consciousness.” That description of consciousness is based on an anthropomorphic view, projecting separateness in isolated packages: me, you, rock, spoon. But perhaps there is a felt experience present—in a form we can't imagine—across the matter in any given area of spacetime.

THE QUESTION ARISES: If the most basic constituents of matter do indeed have some level of conscious experience, how is it that when they form a

Is it possible that consciousness is
an intrinsic property of matter—
that it was there all along?



more complex system—such as a brain—those small points of consciousness combine to create a new conscious subject? For instance, if the individual atoms and cells in my brain are conscious, how do those separate spheres of consciousness merge to form the consciousness “I’m” experiencing? What’s more, do all of the smaller, individual points of consciousness cease to exist after giving birth to an entirely new point of view? This is referred to as “the combination problem,” and according to the *Stanford Encyclopedia of Philosophy*, it’s “the hardest problem facing panpsychism.” It has kept many scientists and philosophers otherwise willing to entertain the idea that consciousness is a fundamental property from fully endorsing panpsychism. However, it seems to me that the obstacle one faces here isn’t a combination problem but the confusion of *consciousness* with the concept of a *self*.

There are different ways of using the word “self.” There’s the autobiographical self, which is the story of who I am: *My name is Annaka, I have two daughters, I’m a good swimmer*. And if I wake up tomorrow with amnesia and don’t remember my name or anything else about who I am, I’ve lost my sense of being the “self” called Annaka, and I now feel like a very different person. But the sense of self I’m referring to goes deeper than the autobiographical self and isn’t necessarily bound up with a specific identity. The deeper sense of self would still be present if I lost my autobiographical self. It’s the “I” that amnesiacs refer to when they say, “I don’t know who I am! I don’t remember my name or where I live!” The deeper sense of self is the experience of being a single, concrete entity that has a precise center or location and is doing the experiencing. And this concept of the self is an illusion. While it’s admittedly a tough illusion to relinquish, we know it does not offer us an accurate representation of the underlying reality.

When discussing the combination problem, philosophers and scientists tend to speak in terms of a “subject” of consciousness, which is just another way of pointing to the experience of self in its most basic form. Therefore, rather than speak in these terms, it may be more accurate to instead talk about the content and quality of conscious experience at any given location in spacetime, determined by the matter present there.

THE COMBINATION PROBLEM MAY, in fact, be a reason to favor a version of panpsychism in which consciousness is fundamental in the form of a continuous, pervasive field, analogous to spacetime. Just as spacetime and gravity have an interactive relationship, consciousness can be thought of as a fundamental “field” that interacts with, and is integral to, matter. We typically don’t think of spacetime as bits and pieces that build on each other (it’s simply *everywhere*), and I don’t think we should be tempted to think of consciousness, if it is indeed a pervasive field, as divisible into building blocks either. Rather, it makes more sense to talk about a field that contains a range of *content*—the content depending on the other forces or fields it’s interacting with. In the same way that gravity is a two-way street—matter warps spacetime and the shape of spacetime determines how matter moves—a consciousness field would imbue matter with another property, giving rise to the range of content experienced. Under this view, content is divisible, but consciousness isn’t. Therefore, consciousness is also not interacting *with itself*, as it would be in the act of “combining.” Considering consciousness to be fundamental allows for matter to have a specific internal character everywhere, in all of its various forms.

If consciousness is fundamental, then the questions that prompt the combination problem are potentially the same as all the other questions we might ask about spacetime in which we *don’t* anticipate this problem. All matter would entail consciousness, and complex systems, such as human brains, would give rise to certain types of content in those locations in spacetime. Even if each individual atom has its own experience, *consciousness itself* is not necessarily isolated. The matter might be isolated, and therefore the *content* associated with the consciousness at that location is isolated. But consciousness itself would not be said to be isolated. Again, we can think of consciousness as analogous to spacetime: How it’s affected by matter depends on the matter in question (its mass, in the case of spacetime). Similarly, a consciousness field might be “shaped” by matter in terms of experiential quality or content. And this line of thinking yields interesting questions. How does the content that appears in an area of consciousness depend on the configuration of matter present in that location in spacetime? Are there experiences of overlapping or merging content?

Experience apparently ignites in the inanimate world, materializing out of the darkness.

In a related conversation I had with the neuroscientist Christof Koch, we discussed what might result from a hypothetical experiment in which two brains were connected together as successfully as the two hemispheres of a single brain are connected. Since various experiments with split-brain patients—people whose right and left hemispheres have been surgically disconnected—have shown that the contents of consciousness can be separated, would two brains wired together produce a new, integrated mind? If Christof and I had our brains wired together, for instance, would it create a new Christof-Annaka consciousness—a new single point of view? Would a new mind be produced, with access to all of the content that had previously been experienced separately by our brains—all of our thoughts, memories, fears, abilities, etc.—constituting a new “person”?

Even if the answer is yes, I don’t think we encounter a combination problem in this thought experiment. We run into problems only if we see the conscious experiences of myself and Christof as “selves” or “subjects”—permanent structures of consciousness with fixed boundaries. In the instance of connecting two brains, we might simply have an example of consciousness changing its content or character. In the same way the content of your consciousness changes when you close and open your eyes: The trees and sky are available to your field of view and then they’re not. When you dream, you experience environments quite different from your actual surroundings, maybe even feeling yourself to be a different person altogether. During both of my pregnancies, I found myself experiencing drastic variations in the contents of my consciousness—sensations in my uterus I had never before known were on the menu of experience, an obsession with tomatoes and tomato sauces in every form, feelings of panic and

other more amorphous emotions, physical pain, insomnia. I didn’t feel like “myself,” and I expect I wouldn’t feel like myself during a mind meld with a 62-year-old male neuroscientist either. But it doesn’t necessarily point to a *combination problem* for consciousness.

We run into a combination problem only when we drag the concept of a “self” or a “subject” into the equation. The solution to the combination problem is that there is really no “combining” going on at all with respect to *consciousness itself*. Consciousness could persist as is, while the character and content changes depending on the arrangement of the specific matter in question. Maybe content is sometimes shared across large, intricately connected regions and sometimes confined to very small ones, perhaps even overlapping. If two human brains were connected to each other, both people might feel as if the content of their consciousness had simply expanded, with each person feeling a continuous transformation from the content of one person’s consciousness to the whole of the two, until the connection was more or less complete. It’s only when you insert the concepts of “him,” “her,” “you,” and “me” as discrete entities that the expanding or merging of content becomes a combination problem.

It reminds me of the classic device of characters switching places in a story or film. But when we look closely at what this actually entails, it becomes obvious that there’s no “self” to transport from one person to another. Being someone else would be no different than what it’s already like to be that person. It seems paradoxical, but we end up simply stating the obvious: “That’s what it’s like to be over there as that configuration of atoms, and this is what it is to be over here as this configuration of atoms.” It’s analogous to saying, “The configuration of atoms that compose a leaf result in all of its expected leaf properties, but if you take all of those atoms and reassemble them into a collection of H₂O molecules, they will take on the expected properties of water. That’s what molecules *do* in that configuration and this is what they *do* in this configuration. Likewise, that’s what molecules *feel like* in that configuration, and this is what they *feel like* in this configuration.” We are again led back to consciousness and content—where matter (and therefore content) is combining, but consciousness isn’t.

If two human brains were connected, both people might feel as if their consciousness had expanded.

If consciousness itself doesn't combine, then we no longer face a combination problem. The experience of consciousness need not be continuous or maintained as an individual self or subject. Nor is it necessarily extinguished when the smaller constituents of matter combine to make more complex systems, like brains. The human sense of being a self, along with an experience of continuity over time through memory, may in fact be a very rare form of content. Is it possible that alongside the conscious experience of "me," there is a much dimmer experience of each individual neuron, or of different collections of neurons and cells in my body and beyond? Could the universe literally be teeming with consciousness—with content flickering in and out, overlapping, combining, separating, flowing, in ways we can't quite imagine—ruled by physical laws we don't yet understand?

Imagine you're floating in empty space or in a vast body of water without perceptions—without the ability to hear, see, or feel anything. Now imagine your senses are gradually being turned on, one at a time. First, vision. You can see light of varying brightness, coming in and out—then brighter light, dimmer light, pulsating light. Next, imagine light that takes on shapes: a circular light, a beam of light, light that extends far into the distance. Adding color perhaps: a reddish light that transforms to orange, yellow, blue. Slowly bring in sounds, tastes, smells—each arriving one at a time, in as pure a form as possible. You're simply experiencing what arrives in your awareness, without concepts, or words to describe the experience. Finally, imagine the

sense of touch coming online in the form of pressure or heat—spanning broad areas and in small, pinpoint locations in space.

It's difficult to maintain this type of imagery for long, but we can get enough of a sense of this state to acknowledge that, at the very least, something like it is *possible*. Might it in fact resemble the experience of someone coming out of a coma? Or of an infant? Or of a much simpler life form, such as a honeybee or a worm? And maybe it's worth going one step further to consider whether plants, or even particles, have some minimal conscious experience?

Perhaps the term panpsychism, because of its history and associations, will continue to pose obstacles to progress in consciousness studies. We might need a new label for the work in which scientists and philosophers theorize about the possibility that consciousness is fundamental. However, we're so far from having a working theory that it seems premature to label it with an "ism," and perhaps it's more helpful to simply give a name to this category of theories, such as "intrinsic nature theory" or "intrinsic field theory." At the very least, it seems clear that the current incomplete picture gives us good reason to keep thinking creatively about consciousness—and specifically to continue entertaining the idea that it perhaps goes deeper than our intuitions have led us to believe. ☺

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The Cultural Distances Between Us

Mapping the world's psychological traits

BY BRIAN GALLAGHER

I F YOU ASK SIRI to show you the weirdest people in the world, what images might you see? In fact, none. Siri showed me different links to the same scientific paper, published a decade ago, with the questioning title, “The weirdest people in the world?”

By some stroke of luck, or a divine favor from the science-communication gods, “weird” turns out to be an acronym for capturing the weirdness of people raised in Western, educated, industrialized, rich, and democratic societies. WEIRD people, like myself and many of you reading this, are, unfortunately, part of a problem that still faces psychology, a discipline largely dedicated to parsing what all humans share in common: The field’s research subjects are too damn weird. For too long, psychologists have focused their research on “one particular culture,” Michael Muthukrishna, an assistant professor of economic psychology at the London School of Economics, told me. “To be honest, it’s worse than that, because scientists were actually looking at a subset of that population, undergraduates, who aren’t representative of less educated populations within the country.”

In February 2020, a story in *The Atlantic* described how “The weirdest people in the world?” has made waves in the years since Joseph Henrich, now at Harvard University, wrote the paper with his colleagues. The WEIRD people problem is well documented—psychological findings based on Western populations don’t replicate in non-WEIRD populations—yet psychologists have yet to rectify this limitation. Muthukrishna, who did his doctoral dissertation under Henrich, said cross-cultural psychologists often still rely on online “convenience sampling” from around the world, yet participants are superficially diverse. *The Atlantic* called this “The Problem That Psychology Can’t Shake.”

To Muthukrishna, the problem isn’t so implacable. He’s the lead author of a paper in *Psychological Science*, co-authored with Henrich and others, titled, “Beyond WEIRD







Psychology: Measuring and Mapping Scales of Cultural and Psychological Distance.” The researchers have come up with a way to quantify how close and far, culturally, societies are from one another. In particular, the paper illustrates how culturally distant countries are from the United States and China—two societies distinguished by their wealth of psychological data and their relatively strong cultural separation. This helped him make the point that “cultural psychology is not the difference between China and the U.S.—it’s the difference between societies all over the world,” Muthukrishna said. Measuring those differences, though, can seem like an “impossible task if you’re not doing it theoretically and systemically.”

In a conversation by Skype, Muthukrishna walked me through his findings, using his maps and figures, both from the paper and from his website, culturaldistance.com.

CULTURAL IQ “Humanity is much smarter than any of us,” says Michael Muthukrishna. “Because of cultural evolutionary forces, over time we are acquiring social norms and institutions and beliefs, and things that work.”

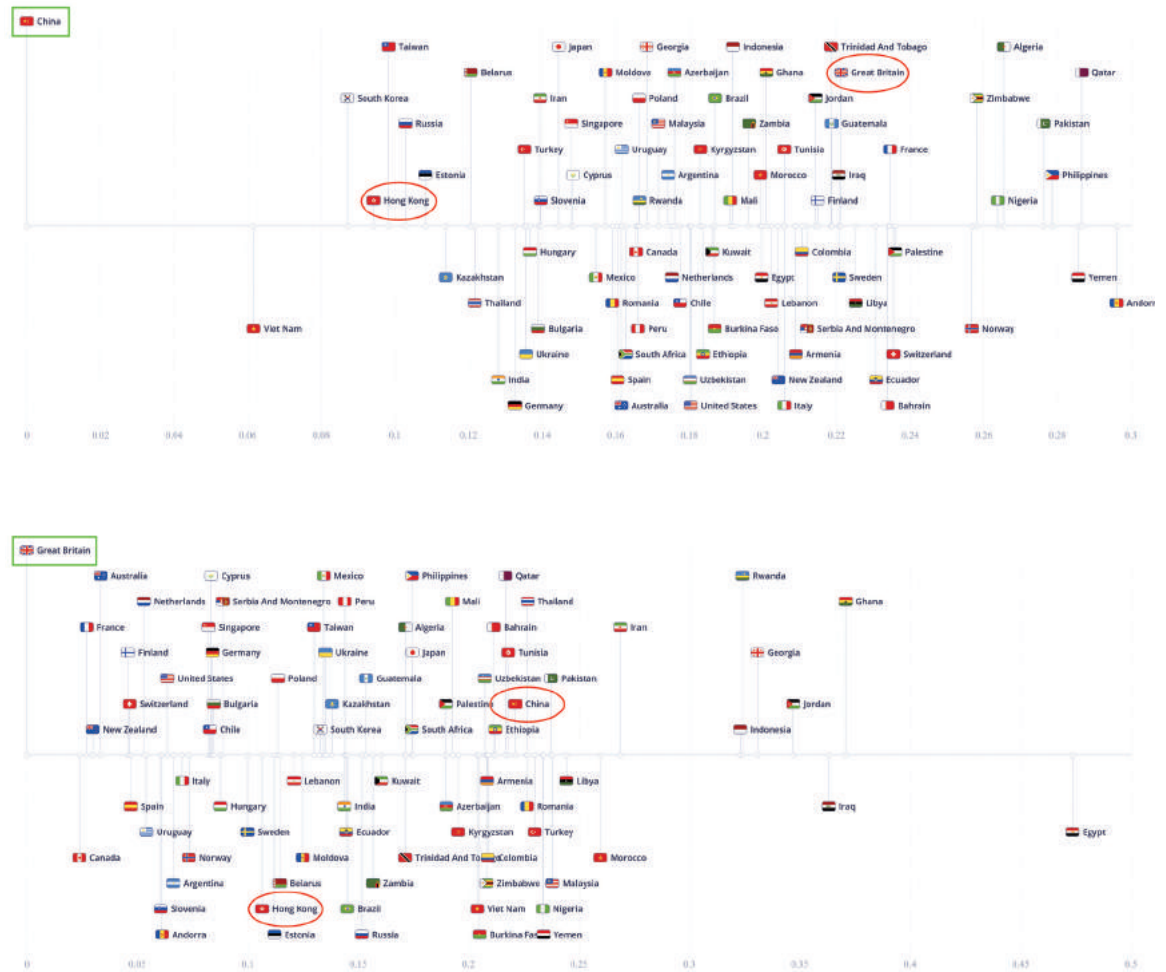
How do you explain cultural evolution?

What makes us a new kind of animal, and so different and successful as a species, is we rely heavily on social learning, to the point where socially acquired information is effectively a second line of inheritance, the first being our genes. Imagine something like a cyclical drought. You may have never experienced one, so you have no idea how to survive in one, and maybe even your parents haven’t, but say Grandma remembers that when she was a child, a drought came and everyone went to the mountain, past the forest, and they discovered water. So, she guides them to safety. These kinds of stories exist in the anthropological record.

That gets you to social learning, but dual-inheritance theory goes a little further and says, actually, that inheritance is itself an evolutionary system. It has variation. When people socially learn from each other, they often learn without understanding why what they’re copying—the beliefs and behaviors and technologies and know-how—works. People tend to home in on who seems to be the smartest or most successful person around, as well as what everybody seems to be doing—the majority of people have something worth learning. When you repeat this process over time, you can get, around the world, cultural packages—beliefs or behaviors or technology or other solutions—that are adapted to the local conditions. People have different psychologies, effectively. We almost speciated around cultural lines.

How do your cultural distance maps offer insight into the political situation going on between China and Hong Kong?

Hong Kong is fairly close to China, where you’ve got Vietnam and South Korea. But the distance from China to Hong Kong is something like the distance from the United States to Brazil, or the United States to Switzerland. It’s quite a distance.



Here's what's interesting: Hong Kong is also quite close to Great Britain. The distance between Great Britain and Hong Kong is not that different to the distance between China and Hong Kong. Hong Kong shares cultural features with China, but it also shares features with Great Britain, unsurprisingly given the 100-year history. There are naturally going to be cultural clashes between how you think Hong Kong should run. The people are Chinese, but they're also British in some sense.

To what practical use could this cultural-distance map be put?

There's military implications, corporate implications. Where do coalitions work out and where do they break down? I could see if cultural distance predicts past trade successes or failures. Some aspects of culture—pride, honesty, degree of liberal attitudes, value placed on authority—can impede trade communications or trade relationships. It's under-explored. It's something we're looking at right now in my lab.

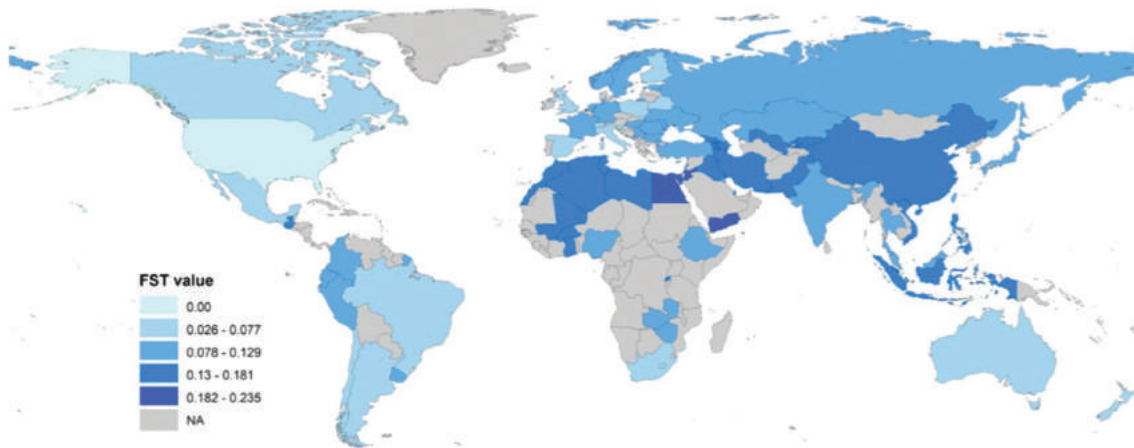
How do you measure cultural differences?

We apply a statistical technique used in genetics, called (*FST*), or the fixation index, not to a genome, but a

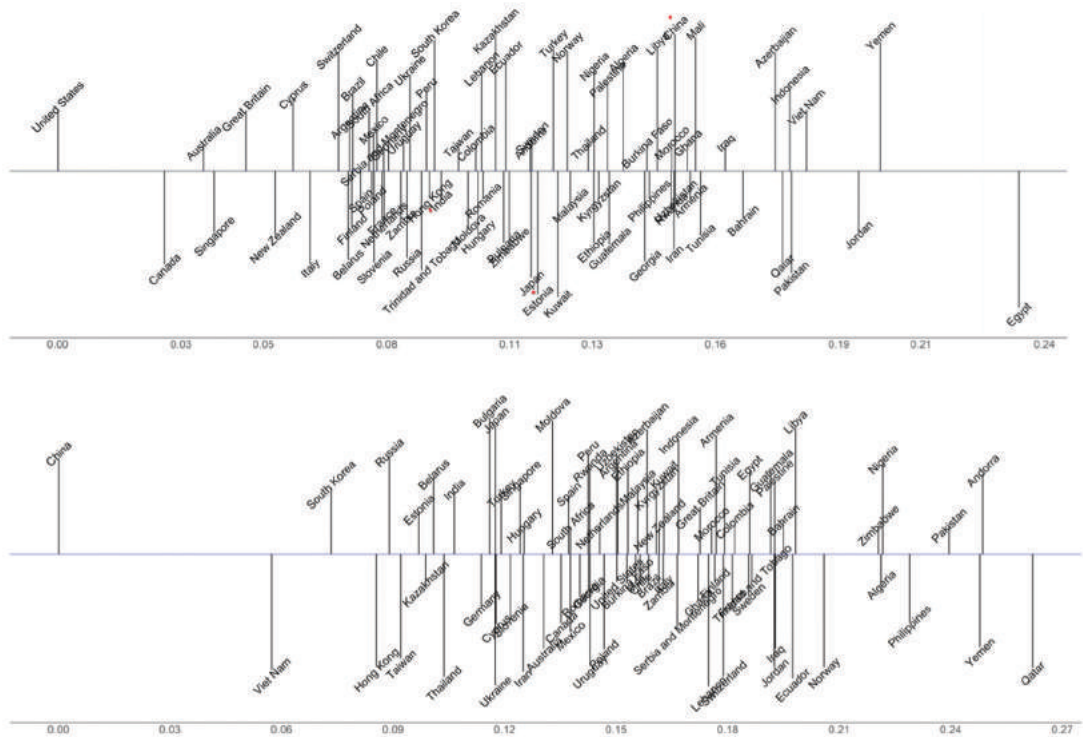
culturome, or surveys of cultural beliefs and behaviors—in this case, the World Value Survey. So, in the genetics case, say you're looking at the allele frequencies for eye color. If you have one population that's entirely blue eyes and another population that's entirely brown eyes, all of the variation between those populations is between groups. The between-group variation is equivalent to the total variation. When you divide the two, you're going to get 1. That's the maximum (*FST*), as different as any of the population can be. You could do this sort of analysis across all of the loci in a genome to figure out how genetically distant, for example, two fish populations are that live in two different ponds that, occasionally, becomes a single pond. We use the same math to look at a culturome. Instead of loci for eye color or hair type, we treat questions on the survey as loci.

What sort of traits are covered in the World Values Survey?

There's politics, like attitudes toward democracy; social relationships, like how to raise children; religious norms and traditions; and attitudes toward sex, finances, law, environment, science and innovation, arts and creativity, sports and recreation, the media, and consumerism.



AMERICAN LIKENESS This chart uses varying shades of blue to show how culturally close other countries are to the United States.



SCALES, COMPARED Just because a country may be culturally far from the U.S. doesn't mean it is therefore close to China—Yemen is culturally distant from both, as these charts demonstrate.

What do you get after applying that statistical technique to the culturome?

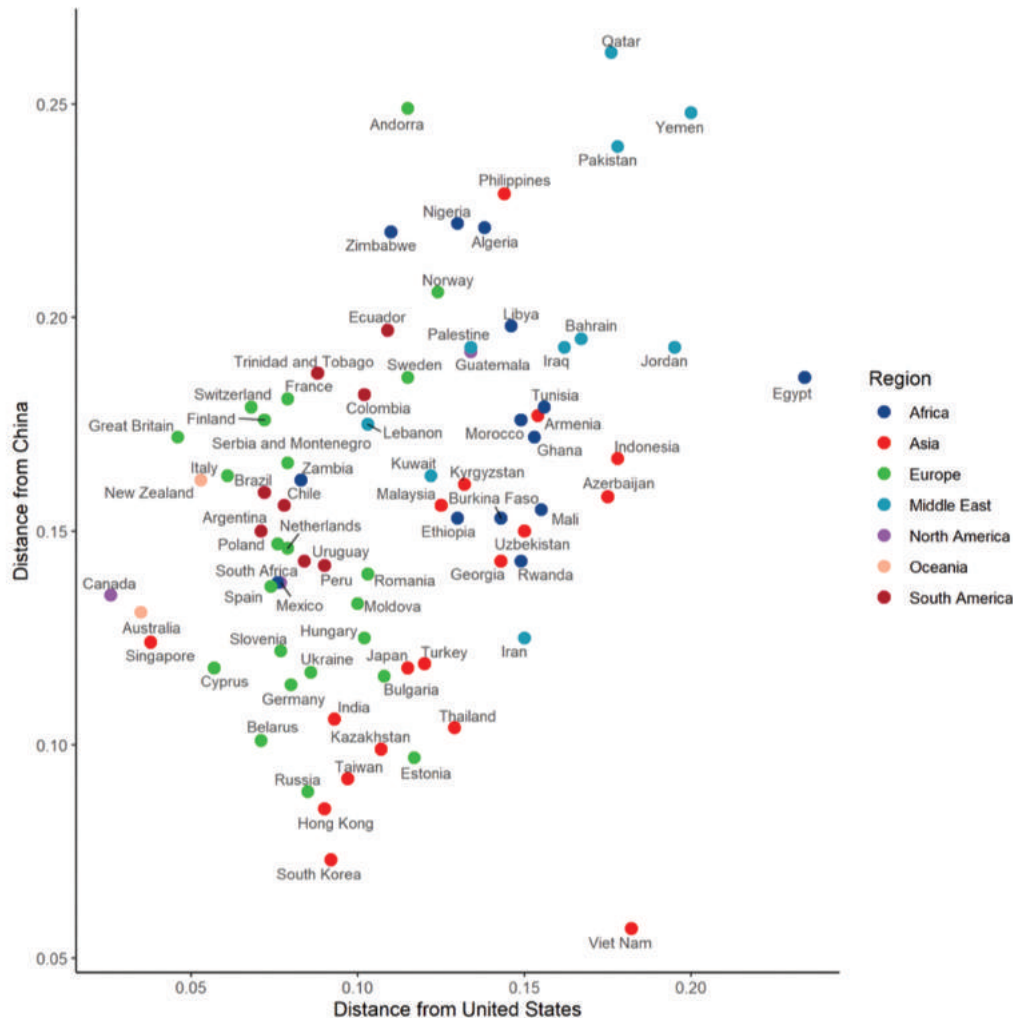
What you end up getting is this n -dimensional space of different loci. In other words, when societies differ from one another, they can differ along many different dimensions. Take this map [on page 72], which depicts the American scale. It shows how culturally close you are to the U.S.

The deeper the blue, the more culturally distant you are. If you look at Canada and parts of South America, they're not all that culturally distant. If you look at Europe, many places are quite culturally similar to the U.S. Whereas you look at, let's say, North Africa and the Middle East—quite culturally different, and somewhere

in between you have East Asia. But just because, on this map, Taiwan and Colombia are, culturally, similarly distant from the U.S., it doesn't mean that they are culturally similar to one another.

The map is a visual representation of another figure [above], in which we're cutting a line through that n -dimensional space and collapsing it down.

If you look at the U.S., Canada is culturally similar, as is Australia. If you look at China, Vietnam and South Korea are quite culturally similar. The point, though, is that the world, culturally, doesn't go linearly from the U.S. to whatever the endpoint is—Egypt, in this case. Those countries in between the U.S. and Egypt are not similar to each other because they fall in between



CULTURE PLOTTING This chart shows another way to visualize cultural distance from both the U.S. and China.

them. To see this, look at this chart [above], in which I draw distance from China and distance from the U.S. You can see that some countries are not close to either China or the U.S.

Being far culturally from the U.S. doesn't mean being close to China.

Exactly. And if you look at a place like Qatar, Yemen, or Pakistan, it is not close to China, not close to the U.S.

Tell us what the numbers mean. On the map, the U.S. is zero, and the next blue shade is 0.02 to 0.077.

The one nice thing about (*FST*), or the fixation index, is that it meaningfully goes from zero to 1, in the same way that a correlation is meaningful from -1 to 1. The fact that the maximum score from the U.S. is no more than 0.25 means that you're not in that situation I described earlier, where it's all blue eyes and all brown eyes. In other words, most humans around

A lot of our beliefs are signaling our membership.

the world have more in common with one another than they have differences. If they had more differences than they had in common, you would have scores above 0.5. The fact that our scores are basically bounded between zero and 0.3 tells you that the cultural distance between countries can be quite large, but not enormous to the point where we're totally different.

It would be pretty insane, then, for another country to exist that was at around 0.7 cultural distance from the U.S.?

Yes, that would be like a cultural Galapagos. It would be a culture that didn't love their children and, I don't know, primarily had sex with animals. They'd spend all their time in the water, swimming. They would believe that children rule the society and not adults. It would be one of those fantasy worlds.

How do you end up with a cultural distance number between zero and 0.3 for particular countries?

We take the last two waves of the World Value Survey, from 2005 to 2015 and, within that scale, we look at all of the traits that, theory and some evidence suggests, should be culturally transmissible. Then we take the aggregate across all of the traits. You don't have to capture everything—just a wide array of traits—because cultural evolutionary theory says that cultural traits should cluster within a society, meaning the things that I measure will be correlated with other aspects of the culture. As long as you do that, you're going to have a fairly reliable scale. It is astonishing how robust this is. You can randomly toss out 60 percent of the questions, and the scale won't deviate all that much.

What's an example of cultural traits clustering?

One of my favorite examples of this is vaccinations and homeopathy. Homeopathy is basically about taking a

little bit of something poisonous to make you better and stronger. Logically, that sounds a lot like a vaccination to me, a little bit of something bad makes you well, but even though there might be this tenuous logical connection, if you believe in homeopathy, you probably are also anti-vaccine.

Why do certain traits tend to cluster around each other?

That falls right out of cultural evolutionary theory. The reason that they cluster within a population is because of common sources of information. If you say, "I believe in evolution," or, "I don't believe in evolution," it doesn't really affect your life. I mean hell, if you say the Earth is flat, that doesn't really affect your life. A lot of our beliefs are signaling our membership. They were acquired from who we consider to be successful or prestigious models, or copied by the majority of people within our social groups. So you can get this artificial clustering simply because the prestigious models are pushing idiosyncratic things.

How does this genetics-inspired method of culture measurement compare to others psychologists use?

Some people will take mean differences on dimensions that they think matter—individualism and collectivism, for example. And then they'll say, for instance, "Ukraine is more individualistic than is China." But what that really does is reduce a population to a point estimate. In reality, populations aren't like that—they're distributions. In the United States, there's got to be people who are very collectivist, very family-oriented and people who are very individualist. Same in China.

How do you think about cultures that foster or facilitate anti-democratic tendencies like corruption?

People often think, "Why are some countries corrupt?" To me, that's not the puzzle. The puzzle is: Why are some countries able to suppress corruption? The reason I frame it that way is because, from a cultural

Most humans around the world have more in common with one another than they have differences.

evolutionary perspective, corruption is what is natural to us. We cooperate with friends who we regularly interact with through direct reciprocity. You scratch my back, I scratch yours, I help you, you help me, screw me over, I screw you over. We rely on reputation, and so on. Corruption, I argue, is one scale of cooperation—a lower, more natural, more stable scale—undermining another. A president gives a contract to his daughter, and we say that’s nepotism. But really that’s inclusive fitness, undermining institutional punishment. If you give a job to a friend because they are your friend, that’s cronyism. But that’s also just direct or indirect reciprocity, undermining our meritocracy. So, if you’re a democracy, you need to be on the same page so that you’re only arguing at the margins. But if you are very regionally diverse to the point where people can coordinate as groups, then those groups will undermine the higher-order cooperation, like a democracy.

Has political culture in the U.S., to your eye, undergone any significant change?

Institutions rest on invisible cultural pillars. For example, it doesn’t matter what the Constitution says if you ignore it. If you don’t have a belief in the rule of law, then it doesn’t matter how good your legal systems are. They won’t get applied, which is what’s at stake in the recent political happenings in the U.S. It’s not just the institutions that are being challenged—it’s the norms. That, to me, is the real threat. Because lower-order scales of cooperation, like family and friends, are more stable, society is always at risk of slipping backward, not emphasizing higher-order scales of cooperation, like merit and rule of law and other institutions. To love your family, and to be there for your friends, is a very natural instinct. But you have to put limits on that. Every generation has to relearn those limits. Our Western institutions co-evolved with norms

that supported them. That's why they're so difficult for economists to transport. If it were true that it was just institutions, Liberia would be one of the most successful countries on Earth, because it took a bunch of U.S. institutions. But it's not, because the norms behind them are missing.

Is most of the world individualist or collectivist?

I think most of the world is collectivist. Places that are more collectivist are also more nepotistic. Those two things go hand-in-hand. Places filled with disease or lacking in material security, where governments failed to provide for their citizens, tend to be places where citizens have no choice but to rely on friends and family. You really need to be xenophobic, to keep outsiders away who can bring in disease. Doing things your own way is generally a recipe for harming your group. Individualism is on the rise, but it's interesting to people because they realize that when they travel. They're like, "Wow, you really care a lot about your family. Your family makes a lot of decisions for you." It's an obvious cross-cultural difference.

How did individualism arise in a mostly collectivist world?

Jonathan Schultz has a paper in *Science* where he argues that, in Europe, the banning of cousin marriage may have increased individualism. He tries to show a causal relationship. The Catholic Church decided that cousins were no longer allowed to marry each other in the way that they do pretty much everywhere in the world. That resulted in a breakdown of kin relations. If you marry people, normally you get more and more distant from one another, unless you start marrying your cousin. Then your uncle is also related to you. Most of the world operates that way. But you can breed more individualists when you don't have these tight family connections as a result of that ban, which leads to other things, like being more mobile. You move into cities, you freely choose the occupation you want to take up. It's a fairly recent phenomenon, but it's probably spreading wide, especially with urbanization. In places higher in material security, you can afford to be a bit more individualistic. You need to suppress the incentives to be there for your family, to be there for your friends and to ignore the meritocracy.

This reminds me of *The Irishman*. The movie depicts how Mafia connections to the government, or connections among family and friends to the government, can play out badly.

Absolutely. You'll start to see it everywhere. Once you have this perspective, it makes a lot of sense. When groups can coordinate with one another, they become powerful and can sometimes take down less coordinated groups. 😊

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Why Astrology Matters

Seeing meaning in the stars is a vital part of the scientific story

BY MICHAEL BROOKS

A FEW YEARS AGO, I went to an astrologer as research for a radio show exploring strange beliefs. Vishal knew only my name, and date and place of birth, and didn't tell me anything terribly profound until I asked him about the car I had just bought. He tapped something into his laptop. I waited.

"I see two cars in your future," he said.

I laughed. "Does that mean I've bought a dud?"

"I can't tell you that," he said.

A fortnight later, a mechanic phoned while working on my new car. He informed me I had indeed bought a dud, and suggested I return the car, get my money back, and buy another one.

I bought a second car. Two cars. It's just a coincidence, isn't it?

The basic premise of astrology is the stars and the planets exert an influence over events on Earth. The stars' and planets' exact influence depends on their motions and relative positions, such as when they appear close together in the sky. If we had all the data about how the sky looked when you were born, say, we could use it to say something about your future, your personality,

and maybe your best course of action over the next few weeks, months, or years.

To the informed scientific mind—a relatively new phenomenon—astrology can't possibly work. That's because these heavenly bodies are nothing more than agglomerations of rock, dust, or gas. There are distant influences from the stars and planets, but they're called the gravitational and electromagnetic forces. The gravitational force creates an attraction between masses. Electromagnetic forces transmit light, heat, magnetic attraction, and repulsion. There is a pull on Earth due to these bodies' masses, and we see the light (and, in the sun's case, feel the heat) they emit. That's it. They certainly have nothing to say about the purchase of motor vehicles by science writers with a Ph.D. in quantum physics but no ability to spot a dodgy used car. Why would they?

PAVEL MALITSKYI / SHUTTERSTOCK

Newton bought a book on astrology but couldn't make sense of it. So he began to study Euclid.

Some might walk away at this point, seeing no value in discussing astrology. However, astrology is a vital part of our human, and scientific, story. We have been making astrological connections—mapping the heavens and trying to discern their influence on the Earth—for much longer than we have been doing science. And with very positive results: Astrology had a huge influence on the development of science, sometimes directly. In 1663, Isaac Newton bought a book on astrology at the Sturbridge Summer Fair. It was an act of curiosity, but Newton found that he couldn't make sense of it because he didn't know enough geometry. And so he began to study Euclid. This is how Newton got hooked on mathematics.

Most of the influence has been more subtle. Astronomy, for example, arose as an attempt to do better astrology. The 16th-century astrologer and mathematician Jerome Cardano even taught the public to read the skies for themselves, publishing a primer on astronomy within his 1538 astrological guide. “One who wishes to attain knowledge of the stars must begin with knowledge of the planets,” Cardano explains. And so he lays out the movements of the known planets, and instructs the reader on how to find each of them in the sky. He was, according to the Princeton scholar Anthony Grafton, “a 16th-century counterpart to Patrick Moore or Carl Sagan.”

CARDANO IS THE FIRST ASTROLOGER mentioned in *A Scheme of Heaven*, a fascinating new book by Alexander Boxer, a data scientist with a Ph.D. in physics. In the book, Boxer explores the difficult relationship between science and astrology. He honors the latter as “the ancient world’s most ambitious applied mathematics problem, a grand data-analysis enterprise.” It involved gathering thousands of years of observations of heavenly motion, and the concomitant earthly events—whether they be births, deaths, kingdoms lost, or riches gained—into enormous datasets. Throughout its history, Boxer writes, astrology has aimed high, looking to

produce “nothing short of a systematic account linking the nature of the heavens to our own human nature.” Like ancient AI, it was the job of astrologers to identify patterns in the gathered data and extract meaning from the correlations they found. Who can blame them if they sometimes saw patterns and meaning where there were none?

It’s not even as if they were blind to this possibility. An underappreciated fact about astrology is that many of its practitioners never fully believed in it. Cardano, for one, wrote a great deal about the inaccuracies of the astrological art (as well as the possibility that it was all a great delusion). And he was far from alone. The great astronomer Tycho Brahe produced astrological interpretations of supernovae and comets and horoscopes for his patrons, but also wrote criticisms of astrology. The same is true of Johannes Kepler. All of these great minds saw the failed predictions, the problematic ambiguities, and the claims based on insufficient data.

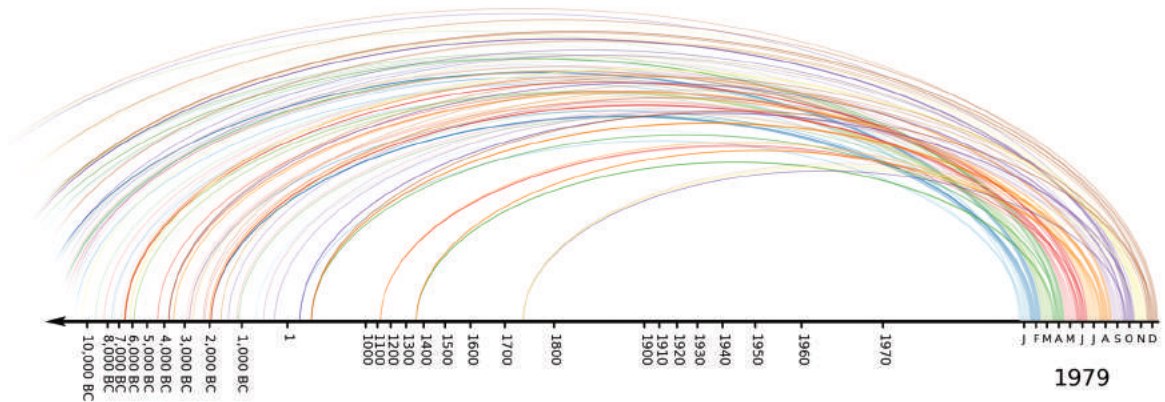
But while many astrologers were conflicted about the claims they were making for astrology, few had the economic resources to ditch it entirely. Boxer details a conversation between the poet and scholar Francesco Petrarca and his astrologer friend Maino Maineri. At the time they are both working for the Visconti family who ruled Milan, but Petrarca relentlessly ribs Maineri about the inadequacies of his astrological service. You can’t even use the stars to predict next week’s weather, he says, how can you possibly advise our boss about business and military strategies? Maineri’s reply is almost heartbreaking: “My opinion about this is no different from yours, my friend, but this is how one must live here.”

Petrarca would appreciate the modern experimental confirmations of his suspicions, such as the one published in *Nature* in 1985. Called “A double-blind test of astrology,” it compared astrologically inferred personality against personality assessments made by psychologists. The astrologers were given a natal chart and three psychological assessments, one of which came

Table 6.2: Zodiac Ancestors for some Famous 1979'ers

Name	Claim To Fame	Birthday (1979)	Z-Code	Birthday Of Their Nearest Zodiac Ancestor
DREW BREES	Quarterback, New Orleans Saints	January 15	5499894	December 27, 212
LEO VARADKAR	Prime Minister of Ireland	January 18	5499895	March 1, 7614 BC
ADAM LEVINE	Singer, Maroon 5	March 18	53BBA07	April 30, 6583 BC
NORAH JONES	Singer, songwriter	March 30	53B0BB1	March 27, 1362
HEATH LEDGER	Actor, <i>The Dark Knight</i>	April 4	53B0BB3	March 31, 1362
KATE HUDSON	Actress, <i>Almost Famous</i>	April 19	5300B09	March 27, 390
JAMES MCAVOY	Actor, <i>X-Men</i> franchise	April 21	5401B0A	July 12, 9143 BC
LANCE BASS	Singer, NSYNC	May 4	5401004	Before 10,000 BC
MARKUS PERSSON	Creator, <i>Minecraft</i>	June 1	5412124	June 9, 1934 BC
CHRIS PRATT	Actor, <i>Guardians of the Galaxy</i>	June 21	5412231	July 31, 6523 BC
JASON MOMOA	Actor, <i>Game of Thrones</i>	August 1	5424447	July 28, 1362
PINK	Singer, songwriter	September 8	5435550	August 27, 228
JOHN KRASINSKI	Actor, <i>The Office</i> (U.S.)	October 20	5546776	Before 10,000 BC
MICHAEL OWEN	English footballer	December 14	5558986	January 1, 2230 BC

ZODIAC ANCESTORS Data analyst Alexander Boxer calculates there's been 30,180,228 "Z-codes" or "distinct astrological moments" from 10,000 B.C. to 2020. To illustrate the rarity of these moments, he created these charts. The chart on the left lists famous people born in 1979, shows their Z-code, and links them to their nearest Zodiac ancestor. The other one on the bottom links every day in 1979 to its nearest Zodiac ancestor. Does the fun data give astrology some credibility? It does not.



ALEXANDER BOXER

An underappreciated fact about astrology is many of its practitioners never fully believed in it.

from the person whose natal chart was under scrutiny. Astrologers correctly matched the natal chart with the psychological assessment only 34 percent of the time. In statistical terms, they did no better than pure random chance.

Boxer has expanded the available data again by examining four datasets in two experiments. One test involved comparing the timings of road traffic fatalities against astrological suggestions regarding the best moment to travel. The second stacked Renaissance investment advice against data from the Dow Jones Industrial Average. In neither case was there any indication that astrologers, for all their thousands of years of data mining, have stumbled across useful patterns.

Boxer has tried his best to help astrology out by mining the most complex datasets he could find. One frequent criticism, for instance, is that two individuals can have wildly different life experiences despite being born with identical, or near-identical, astrological identities. But perhaps, Boxer says, the astrological identity is just not well-enough defined.

Boxer's contribution here is the "Zodiac code," a string of seven alphanumeric characters, based on the eight contributors to an individual's horoscope drawn up by second-century Hellenistic astrologer Vettius Valens. The Zodiac Code, or Z-code, is a shorthand description of the positions of the heavenly bodies at the time of a person's birth. There are 44,789,760 different Z-codes, Boxer says. It sounds like a lot, but each Z-code can be shared by upward of 30,000 people on Earth. It is hard, then, to claim that astrology can offer predictions or advice that are unique to the individual. But, Boxer suggests, perhaps its power lies in making certain moments unique, or at least rare.

To test this, Boxer created a data-dump of historical Z-codes. From 10,000 B.C. to today, Boxer calculates, there has been a total of 30,180, 228 "distinct astrological moments." It is surprising how rarely they repeat. For instance, the last time someone with the actor Heath Ledger's Z-code appeared on Earth was in the year 1362 (they were born on March 31). Boxer's own Z-code last appeared on May 20, 2669 B.C., when

Imhotep was building Egypt's first pyramid. An unfortunate who was thrown to the lions, as documented in Vettius Valens' second-century A.D. *Anthologies*, has shared a Z-code with no one since: The next person with that code will be born on March 30, 3328.

Is it enough to give astrology some credibility? No. A horoscope can only serve as "a cosmic reminder" of how unique each moment is. "It's awe-inspiring and humbling to consider that the configuration of the heavens on our birthday, or any given day, will almost certainly never repeat in our lifetime," Boxer says. "Even the sum of human history has played out against a backdrop of just a small fraction of astrological possibilities." But the bottom line is that there is no discovered pattern that backs up the suggestion that these possibilities have affected human lives in any way. The data gives astrology nothing.

In the end, Boxer, like me, doesn't think there is any reason to believe in astrology—but we are both Tauruses, so what can you expect?

IN FACT, THROUGHOUT HISTORY, philosophers and scientists have always charted the world with the available data of the time—and they have always got things wrong.

"Men will from time to time revert to darkness out of boredom with light," said the 17th-century philosopher and mathematician Gottfried Leibniz in an essay he wrote at the beginning of the 18th century. "Ours is such a time," he went on, "with great opportunities to learn the right things being spurned, and a wealth of the most lucid truths being disregarded in favor of obscure trivialities." Leibniz was a champion of sober thought, a mathematician clever enough to invent calculus at the same time as Isaac Newton. His essay was called "Against Barbaric Physics" and railed against a resurgence in magical thinking. Physics stripped of all mysticism is "too clear and simple for these people," Leibniz complained. "How can any reasonable person today subscribe to a belief in fantastic qualities that is tantamount to a betrayal of all natural principles?"

It might sound like Leibniz is talking about a resurgent interest in astrology, but he's not. He's talking about forces—in particular, Newton's argument that forces can act at a distance. The idea that the planets are

"gravitating and striving toward each other," and that "matter is supposedly able to perceive and covet even things which are remote" is "fanciful," Leibniz says.

Leibniz thought as little of Newton's gravitational force as he did of astrology, which he dismissed as "pure nonsense." That said, he was a great believer in the power of Biblical prophecy. "The prophets of the Old Testament have amazingly foreseen the detail of the new," he once wrote to Sophia, Electress of Hanover. He firmly believed that the Jesuits embodied the locusts who rise out of the Abyss in the Book of Revelation. "This is something that should not be doubted unless one is a disciple of the Antichrist," Leibniz says.

We find it easy to forgive Leibniz his biblical follies because of his valuable contributions to mathematics and science. We do the same for Newton, whose follies were arguably greater. And we should extend the same courtesy toward ancient astrologers.

I'm not ashamed to say that I have a soft spot for astrology. Historically, astrology is the grit that seeded the pearl; its data-gathering, map-making, and pattern-seeking laid the cognitive foundations for modern science. Rather than rudely dismiss it as an embarrassing product of ignorant times, we should acknowledge its contribution.

And astrology remains useful today. It provides a useful illustration of the vexatious fallibility of human intellectual achievement—including, and perhaps particularly, the sometimes illusory certainties of science. It's certainly something to keep in mind as we make our modern maps of particles, forces, and strange cosmological energies. Who knows? Perhaps future generations will lump 21st-century interpretations of data together with those of the astrologers—a laudable but clumsy attempt to find meaning in the meaningless—and wonder why we learned nothing from the failings of the earliest attempts to understand the universe. ☺

MICHAEL BROOKS holds a Ph.D. in physics, and is the author of *The Quantum Astrologer's Handbook*.

We Are All Bewildered Machines

Bewilderment is the antidote to scientific reductionism

BY KEVIN BERGER

WHEN DID YOU REALIZE you were a machine? A fancy machine, for sure. But one whose parts and operations can be described like the components of a computer. I remember a day in 2012 when this thought pierced me to the bone. I was in the lab of John Donoghue at Brown University. Donoghue is a professor of neuroscience and a pioneer in the development of brain-computer interfaces. With easygoing authority, Donoghue was detailing for me the ways he and his colleagues taught Cathy Hutchinson, a 58-year-old woman who had lost control of her limbs in a stroke, to control a robotic arm with her thoughts and sip coffee from a bottle. It was a matter of basic math and biology, Donoghue said, with, yes, some sophisticated technology.

MARGARITA STESHNIKOVA / SHUTTERSTOCK



Surgeons implanted a micro-electrode array with 100 sensors in Hutchinson's motor cortex, the brain's control center for movement. Donoghue then had Hutchinson watch a cursor moving across a computer screen and imagine she was moving the cursor with a mouse. As she pictured moving the cursor left and right, forward and backward, the micro-electrodes picked up electrical "spikes" in her neurons. Donoghue's team recorded the pattern of spikes associated with each direction, then programmed the robotic arm to recognize them.

When it was coffee time, Hutchinson wore an electronic device on her head that looked like a tiny top hat. It registered the spikes from her implanted array and relayed them to the robotic arm. The woman, who had not been able to feed herself for 14 years, directed, with her thoughts alone, the robotic arm to pick up the bottle and bring it to her lips. Donoghue showed me a video of the historic drink. When Hutchinson finished her coffee and had the robotic arm remove the straw from her mouth, a smile glowed across her face.

I was startled. Human movement, and by extension, human feelings, can be charted (with a little help from a probability theorem) right down to the binary activity of specific neurons? Donoghue smiled. He was standing beside the metallic blue robotic arm that Hutchinson had used. "Well, the brain is a machine," he said. "It's just a biological machine, right?" Yes, but didn't that formulation seem a bit, well, reductive, lacking humanity?

"Humanity" was no doubt the wrong term for my opprobrium. Donoghue had been patient with me all afternoon. His explanations were often personal. As a child, Donoghue suffered from Leggs-Calvé-Perthes disease, which prevented him from walking for two years. In his first job after college, he worked at the Walter E. Fernald State School, an institution for the mentally handicapped. "I was looking at brains in the lab and then looking out the window at people who had brain diseases that completely took away their humanity, their ability to interact," Donoghue offered. "I've been trying to understand what the brain is doing because to me the brain is the organ of our humanity. It gives us our mental life, and that makes us what we are."

Studying science up close has caused me more than once to face an image of myself as an electrochemical robot, built on nature's assembly line.

After I left the lab, I walked down the sloping green lawns of the Brown University campus, through the red brick colonial halls, reflecting on the notion that our brain is a machine. It's technically true, I guess, but coming from Donoghue, it felt kind and wise. He and his colleagues had shown science at its best, restoring humanity to a person who had lost it. But as I continued to walk toward downtown Providence, picturing my thoughts as bursts of little numbers, I felt unsettled. It's taken me a good while to figure out why.

I'VE SPENT THE PAST DECADE and more engaged in science, but I came of age in the humanities. Growing up, I schooled myself in literature and music. I lived for the transcendent—the infinite metaphor, the ageless melody—that struck me without calculation. My favorite arts were adventures to places I could never imagine, but when I got there, felt at home. Reading fiction was a continuous discovery of myself. I always felt like a bigger person after finishing a novel I loved. My passion for the arts launched my career in journalism. I began covering music and ranged to the environment, politics, crime, sports, and, now that I think of it, most every dance in the human parade.

I leaped into science journalism because I wanted to continue my journey to new places. I had always read popular science but was now deep into the minute details of academic journals, spending hours in the field with scientists. But studying science up close has caused me more than once to face an image of myself as an electrochemical robot, built on nature's assembly line. Neurotransmitters explain this behavior, hormones that. Goodness, you think, I have no free will, I'm just a bunch of parts off nature's shelf. It can be an abject feeling.

But I began to find my way out. I'm sure this sounds naïve to real scientists, but I've learned in the layers of research, answers are on the surface, mysteries in the



A TREE GROWS IN FICTION Richard Powers in the Smoky Mountains, not far from his home, where he wrote his 12th novel, *The Overstory*.

depths. When I was unnerved by the mechanics of science, it was because I felt the weight of a final definition pressing on me. But there is none. The investigation of nature has no end, and neither does the complexity of its interrelationships. A machine with 1,000 trillion connections, as our brain has, has an infinity no less than a magnificent poem. Science opens up the world rather than closes it down. Fittingly, an artist helped me arrive at this conclusion.

Unlike any novelist I've read, Richard Powers brings the natural world to life through science. Every exceptional artist peels away clichés and reveals the world anew. But how often does an artist magnify the complexities of nature, and our relationship to them, through a command of science? In dramatic plots that invariably turn on humans' oversized control over nature, Powers has ushered readers into the labs of genetics, pediatric medicine, artificial intelligence, neurobiology, and this year, in his 12th novel, *The Overstory*,

dendrology, the study of trees, and in particular their remarkable biotic communication.

Powers set the stage for his philosophy of science in one of his early novels, *The Gold Bug Variations*, released in 1991, which portrays the life of a research scientist who helps crack the genetic code. The "purpose of all science, like living, which amounts to the same thing, was not the accumulation of gnostic power, fixing of formulas for the names of God, stockpiling brutal efficiency, accomplishing the sadistic myth of progress," Powers wrote. "The purpose of science was to revive and cultivate a perpetual state of wonder. For nothing deserved wonder so much as our capacity to feel it."

Because Powers has succeeded so wonderfully in mixing science into moving stories, I was anxious to talk him about the kind of experience I had with Donoghue. Today Powers lives in a split-level wooden house tucked into the Tennessee foothills of the Smoky Mountains. I went to see him there in April 2018.

POWERS SPEAKS SOFTLY but carries a big intellect. We sat at a kitchen table where every window in the room looked out on trees. I told him about my old dread of seeing into the gears of nature. He knew the theme well. “Grasping the underlying material principles of life has profoundly changed our self-conception,” Powers said. “But I’m pushing back against this notion that a mechanistic view reduces our humanity. It doesn’t. There’s a beautiful Lewis Thomas essay, ‘On Matters of Doubt,’ in which he says the common denominator between science and art is bewilderment. I’m sure you know it.”

I do indeed. Thomas, a physician, who died in 1993, is my exemplary science writer. He was an accomplished scientist who wrote from experience and late-night reflection. His lucid essays, laced with wit and humility, may be the closest that science writing has come to prose poetry. In “On Matters of Doubt,” from the early ’80s, Thomas wrote, “We would be better off if we had never invented the terms ‘science’ and ‘humanities’ and then set them up as if they represented two different kinds of intellectual enterprise.” Despite the fact we did, he wrote, there was a “common earth beneath the feet of all the humanists and all the scientists, a single underlying view,” and that view “is called bewilderment.” “Most things in the world are unsettling and bewildering, and it is a mistake to try to explain them away; they are there for marveling at and wondering at, and we should be doing more of this.”

Powers loved Thomas’ idea that bewilderment was the common ground between science and art. “The word ‘bewilderment’ has such a great etymology,” he said. “It means to partake in the state of being wild. It’s lovely to think that amazement is a recognition the wild is part of us. There’s amazement and there’s awe. It’s largely a function of literacy that someone, because of their natural capacities, but more often because of their environmental encouragement or discouragements along the way, believes the world is properly apprehended through one of those kinds of awes—the humanities or science—and not the other. Then the other kind of awe is going to seem like an incursion, it’s going to seem like a reduction, it’s going to seem a diminishment, right?”

I suggested to Powers that divide arises from a fear that science—biology in particular—robbed the

romance from human life. That was my fear when I was with Donoghue in Providence. “The fear that deep biologism creates in a lot of people may be related in a way to the fear of the naïve music listener to hearing that they’re being jerked around by a deceptive cadence,” Powers said. “The fear is that mechanism will replace mystery. It doesn’t. It multiplies mystery many orders of magnitude. I mean, which is a more amazing story: That some omnipotent force, who by coincidence looks just like us, whipped up everything *ex nihilo*, created us like Geppetto created Pinocchio, then set us loose to ponder his magnificence, or that a few simple forces, through countless trillions of steps in an unsponsored process produced people capable of understanding the nature and function of genes? The second story feels many orders of magnitude more mysterious and overwhelming than any supernatural explanation.”

I know that overwhelming feeling well. In the pages of cosmology and evolution and neurology, I’ve been left wondering more than once over questions like how did consciousness arise and why. Powers has stitched the messy colors of human emotion into the big questions and pursuits of science. You feel the importance of science in the byways of his narratives and sense the deeper you travel into the systems of the natural world, the wider your capacity for appreciation of it grows.

Again, Powers said, consider music. “The reality is analyzing music with specific names like major tonics and minor keys, which seem counter to the mere surrender to music, are incredible intensifiers to those who know what they mean, and who understand the decisions on the part of the composer to produce certain affective responses. The people who are in a position to be analytical about that affect, I would argue, have a more intensely affective response to it. And there’s nothing you can’t bring into that equation which won’t further intensify your depth and understanding of the way that beauty is made.”

The music analogy hit home for me. Over a lifetime of listening to and loving music, studying its history and structures, often through interviews with musicians and composers themselves, I have felt my musical emotions grow. Knowledge pries open feelings you never knew you had. How remarkable to realize science does the same. Being exposed to the neurons that make our limbs move, or learning the modal scales

“So long as science has a program of being in charge, it will be at war with art.”

that distinguish Miles Davis’ *Kind of Blue*, are not ends in themselves. They are journeys into the depths of beauty and humanity—a powerful lesson for which I have writers like Powers and Thomas to thank. They remind me that artists and scientists share the same drive for exploration and revelation, that scientists and artists elevate one another. “That’s our superpower, that’s humankind’s superpower—to be an artist and a scientist and to find ways in which each one of those capacities enhances and gives depth to the other,” Powers said.

During the course of our conversation, Powers returned to his latest novel, *The Overstory*, to spotlight the bridge between science and art. The novel revolves around a gang of disparate activists who battle timber companies to protect the remaining old-growth forests in the Pacific Northwest. Understanding the nature of trees and their role in ecosystems, which include us, was critical to preserving their habitats and ours, the novel offers. Success didn’t stem from textbook knowledge about trees, it grew from realizing we shared the world with trees in mutual interdependence. “We are

mere components in complicated interdependent and reciprocal processes,” Powers said. In other words, we are not in charge. “So long as science has a program of being in charge, it will be at war with art. Because the best thing that art does, the thing that’s really in the corner of the artist, is that sense of surrender to things larger than yourself.”

Powers and I took our talk to the mountains. We hiked up a winding trail, past the uniform trees in a second-growth forest to the big, unruly ones in an ancient grove. Under a dark canopy of trees, surrounded by patches of wildflowers and carpets of moss, I was delighted, courtesy of Powers, to learn the names of the trees and the ecological processes by which they had prospered. As he spoke, I thought to myself how science can re-enchant nature when our hope for it ran dry. Best of all, though, were the moments when I stopped thinking about definitions altogether, and simply let go into nature. ☺

KEVIN BERGER is the editor of *Nautilus*.



The Forest Spirits of Today Are Computers

*We've made an artificially panpsychic world,
where technology and nature are one*

BY GEORGE MUSSER

YEARS BEFORE SMART HOMES became a thing, I replaced all the switches in our house with computerized switches. At first, it was just a way to add wall switches without pulling new wire. Over time, I got more ambitious. The system runs a timer routine when it detects no one is home, turns on the basement light when you open the door, and lights up rooms in succession on well-worn paths such as bedroom to kitchen. Other members of the family are less enthusiastic. A light might fail to turn on or might go out for lack of motion, or maybe for lack of any discernible reason. The house seems to have a mind of its own.

Under the rubric of “ubiquitous computing,” “smart dust,” and the “Internet of Things,” computers are melting into the fabric of everyday life. Light bulbs, toasters, even toothbrushes are being chipped. You can summon Alexa almost anywhere. And as life becomes computerized, computers become lifelike. Modern hardware and software have gotten so complicated that they resemble the organic: messy, unpredictable, inscrutable. In machine learning, engineers forswear any detailed understanding of what goes on inside. The machine learns rather like a dog: by trial and error, with ample treats. Some systems even have features we commonly associate with consciousness, such as creating models of their environment in which they themselves are actors—a kind of self-awareness.

Gradually, we are turning an old philosophical doctrine into a reality. We are creating a panpsychic world.

Panpsychism—the proposition that consciousness is fundamental and ubiquitous—is one of humanity’s oldest ideas. It has cycled in and out of fashion in Western philosophy and has been enjoying a resurgence of late. For many neuroscientists and philosophers, panpsychism will be an essential feature of a theory of consciousness: Whatever mechanism creates the human mind need not be limited to humans.

But I’m talking about a different kind of panpsychism—artificial panpsychism. All the computers with which we surround ourselves are starting to be endowed with a rudimentary sentience. We are placing minds everywhere and instilling seemingly inanimate objects with mental experience. To my knowledge only one thinker—the computer scientist and science-fiction author Rudy Rucker—has described panpsychism as a phenomena we might create, although even he doesn’t think it very plausible. I would go further and say, not only is it plausible, it is happening. By dispersing intelligent artifacts, humanity is awakening the material world.

TRADITIONAL PHILOSOPHICAL PANPSYCHISM

comes in multiple varieties, but all have one intuition in common: that subjective experience can’t be reduced to mechanistic physics. Proponents make three main arguments. The first is that there doesn’t seem to be any principled way to draw the line between conscious and non-conscious. If we are conscious, why not a dog?

We are placing minds everywhere and instilling inanimate objects with mental experience.

A paramecium? A protein molecule? A proton? These systems lie on a continuum with no obvious break.

Second, panpsychism would solve the hard problem of consciousness. The objective methods of science seem inherently incapable of explaining subjective experience. The scent of a rose or awfulness of scratching a blackboard is not decomposable into smaller pieces, not mathematically describable, and not experimentally accessible. It seems to require a new feature of reality as deep as anything in physics, or perhaps even deeper. Complex minds are composed of simpler ones—“mind dust,” as William James put it. If so, everything in the universe is conscious to some degree.

Panpsychism might also solve a complementary problem: the hard problem of matter. Philosophers such as Hedda Mørch and Philip Goff argue that physics describes what material objects do, but not what they are—their intrinsic nature. Subjective experience might plug that gap, because it is intrinsic. There is something about scents and screeches that is impossible to grasp by reference to anything else; it must be experienced directly. By this argument, everything in the world has phenomenal as well as material qualities.

Third, several of today’s leading theories of consciousness imply panpsychism. One of the most popular, Integrated Information Theory, takes our psychological unity as its starting point. Our sensations form a seamless whole, and brain activity reflects this coherence. When people are awake or dreaming, their neurons fire in a coordinated way; when in deep sleep or a coma, neural activity is fragmented. The theory surmises that an information processing system is conscious to the extent that its parts act in harmony. Anything with parts—which is to say, anything beyond a



HOW ROMANTIC Few people experience nature red in tooth and claw, or would want to. We romanticize nature, just as we do our advanced technology. So what's the difference?

structureless elementary particle—has the potential to be conscious by this theory. Another line of thinking, based on the free-energy principle put forward by neuroscientist Karl Friston, observes that any self-sustaining structure has to maintain its boundary against external insults, which requires an internal model of the world. That is a core feature of mind.

Whether or not you buy these arguments, and many don't, you can foresee two types of artificial panpsychism. If it's true that mind cannot emerge from mindless atoms and must be a new fundamental ingredient of nature, you can imagine mind engineering: assembling components not to perform some function, but to achieve some type of experience. And if not—if we can make minds out of mindless atoms after all—then artificial panpsychism is a straightforward extension of present technology.

Neuroscientists have some evidence for the latter. Consciousness seems to be a specific cognitive function performed by identifiable brain mechanisms that not all species possess. There was an evolutionary rationale for it to develop; it needn't have been built in from the start. When experimental subjects become consciously aware of something, certain brain areas change in activity; people who exhibit conscious awareness are able to reason across gaps in time, follow complicated directions, and imagine things that have never existed. When they perform tasks without conscious awareness, as if on autopilot, they are limited to reacting to what is in front of them. Consciousness also

helps us socially. We are always trying to fathom other people's thoughts and motivations, and self-awareness may emerge as we turn this ability on ourselves. Other mammals possess these same brain areas and show analogous behavior.

So, consciousness helps us navigate a complex world. And if consciousness helps us, it could help robots and computers, too, giving engineers a practical reason to design it into their systems. Out of philosophical caution, we might still question whether these systems are conscious. That is perhaps unknowable. But if they act as if they are, people will treat them as such. Thus we have both elements of panpsychism. Engineers have achieved the “pan”—they have embedded computers everywhere—and are working on the “psychic.” Mind dust, meet smart dust.

When debating panpsychism, the question is not whether, but when. Either the world already is panpsychic or it will be.

RUCKER HAS IMAGINED such a transformation. In a short story for *Nature* in 2006, he speculated that brain-to-brain interfaces might be applied to non-human objects. The protagonist mind-melds with a rock.

In a 2008 physics paper, Rucker addressed an objection to panpsychism raised by Karl Popper and others. A mind needs memory. Without it, organisms could only be reactive; they could have no inner life. Yet basic physics is memoryless. How the universe evolves depends only on its current state; it doesn't matter how

it reached that state. Memory is a higher-level feature requiring large assemblies of atoms. Simple structures lack it. How, then, could they be conscious? Rucker speculated that exotic new physics, such as the dynamics of higher dimensions of spacetime, could endow even the simplest system with memory. The cosmologist Bernard Carr has explored similar ideas.

Rucker incorporated these musings into his novels *Postsingular* and *Hylozoic*. In *Postsingular*, the world is infested with nanobots that network together into a hive mind. In *Hylozoic*, the material world itself springs to life as a result of higher-dimensional physics and ejects the nanobots. Rucker depicts two steps toward artificial panpsychism, technological at first, then anti-technological.

The books paint a fascinating picture of a fully sentient world. People can telepathically communicate not just with friends and family, but with atoms, burbling brooks, and the planet as a whole. If your friends come over for dinner, the group forms a temporary collective mind that you can commune with. Every act becomes a negotiation: You had better apologize to the brook for urinating on its bank and talk nice to your hand tools. Say the right words to the right atoms and you can heal wounds or fly like Superman. On the downside, villains can brainwash atoms, unraveling the fabric of reality.

In the world Rucker portrays, you can see the emotional appeal of panpsychism, how it enchants people who find the world of physics cold and impersonal, and how it would imbue all things with moral status. Environmentalists, in particular, are drawn to that. People maybe wouldn't pollute streams that could talk back. Artists, too, often speak of their work as a negotiation with their materials. "Art is really a cooperative endeavor, a work of cocreation," wrote philosopher David Abram in *The Spell of the Sensuous*, one of the most eloquent evocations of this romantic view of panpsychism.

FOR RUCKER, THE SECOND STAGE in the panpsychic transformation is essential. The world of nanobots doesn't qualify as panpsychic to him. A philosopher might agree. True panpsychism embeds mind within basic physics; it's not enough to scatter smart chips like seed corn. On his website, Rucker publishes an extensive series of notes about the backstory to his novels. He writes: "Already my car talks to me, so does my

If we could hear machines converse, they would sound like the squeaking and squawking of a rainforest.

phone, my computer, and my refrigerator, so I guess we could live with talking rocks, chairs, logs, sandwiches. But they'd have 'soul,' not like chirping electronic appliances, which is really kind of different."

But is it? If your house is filled with picture frames, vacuum cleaners, and smart speakers that dim the lights, answer your questions, dodge around your feet, and watch over you, it may well be the suburban equivalent of living among forest spirits. It will not matter where the minds come from as long as they are there.

Any sufficiently advanced technology is indistinguishable from nature. Agriculture de-wilded the meadows and the forests, so that even a seemingly pristine landscape can be a heavily processed environment. Manufactured products have become thoroughly mixed in with natural structures. Now, our machines are becoming so lifelike we can't tell the difference. Each stage of technological development adds layers of abstraction between us and the physical world. Few people experience nature red in tooth and claw, or would want to. So, although the world of basic physics may always remain mindless, we do not live in that world. We live in the world of those abstractions.

For now, we can just about maintain the distinction between technology and biology. But what seems like high technology to us now might seem like a law of nature to future generations. Having forgotten the origin of the computers that permeate their world, people might take them to be an innate feature of the universe. Their philosophers might well assume that mind is fundamental. (You might also wonder whether alien civilizations, which could be billions of years ahead of

Imagine being a conscious electron. You have some kind of inner life, but no senses, no mouth, no opposable thumb.

us, are invisible to us because they are so deeply woven in the fabric of our reality.)

Digital panpsychism is rather more plausible than higher-dimensional physics, anyway. Rucker magics away the problem of communicating with other minds by making a hand-wavy appeal to quantum effects. But in an artificially panpsychic world, it's just a matter of wiring. Brain-to-brain interfaces are already under development. Neuroscientists have linked the brains of rats and of monkeys using implanted electrodes and of humans using scalp electrodes and external magnets. Last year, a team of scientists and visionaries speculated about using nanotechnology. As a proof of principle, some conjoined twins share neural circuits: one feels, tastes, and sees what the other does. It is not outlandish to imagine that brain interfaces could be extended to artificial brains.

A brain could also be linked to an artificial-intelligence system by adapting the “chip test” proposed by Susan Schneider. Scientists would swap parts of your brain for functionally equivalent electronic components to see whether it affects your conscious experience. If not, this would demonstrate that consciousness can be implemented in any substrate and is not specific to brain tissue. But it might also be a way to share subjective experiences with our electronic creations.

FOR ABRAM, MUCH OF THE APPEAL of panpsychism is that it makes us engage with the non-human; it takes us out of ourselves. Artificial panpsychism is starting to do that. Right now, technology is closely tied to specific human needs. But as machines proliferate, they will have their own needs, which other machines will satisfy. If we could hear them converse, it would sound like the squeaking and squawking of a rainforest. An ecosystem is emerging with its own logic that, for better or worse, is not human logic.

You might well wonder whether that is desirable. My family, driven mad by our smart house, certainly would.

But if artificial panpsychism has troubling aspects, so does the natural variety. In all the debates over panpsychism, skeptics concede its romantic aspects. Nobody asks whether they would really want to live in such a world.

A panpsychic world is not a warmly embracing community. Unless telepathy really is possible, most minds would be locked in, forming a vast crowd of atomized individuals. Imagine being a conscious electron. You have some kind of inner life, but no senses, no mouth, no opposable thumb. You feel utterly alone. You will have to endure forever; death can bring you no relief. It sounds like the very definition of hell. Admittedly, the electron's experience is unimaginable in human terms, and we shouldn't project our own values onto it. But isn't that what writers and thinkers do when they romanticize mentality?

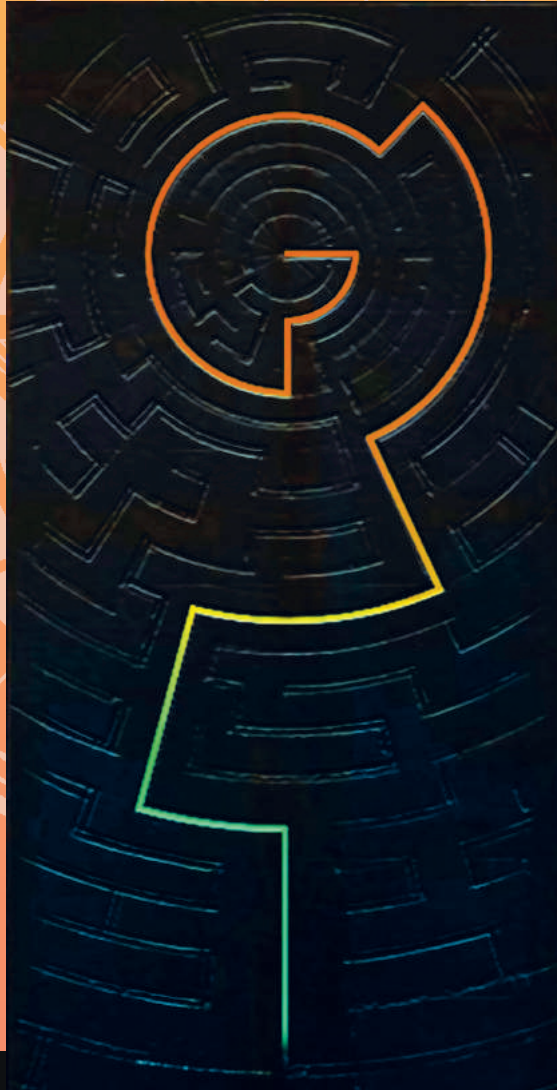
And there are other issues. Forget about privacy. You couldn't so much as take a shower in solitude. Moral considerations could backfire. It's impossible to reduce our environmental footprint to zero, and depending on what kind of mind you think things possess, your every breath might cause suffering. Vegetarians might find that eating tofu is as morally fraught as carving a steak. And as soon as you tell an artist they have to do something—in this case, respect their materials—they want to try the opposite. They might long for the freedom of an insensate world.

The good thing about artificial panpsychism is that it is our choice. If we don't want to live in a world surrounded by minds, we don't need to go there. ☺

GEORGE MUSSER is an award-winning science writer and the author of *Spooky Action at a Distance* and *The Complete Idiot's Guide to String Theory*. Follow him at @gmusser

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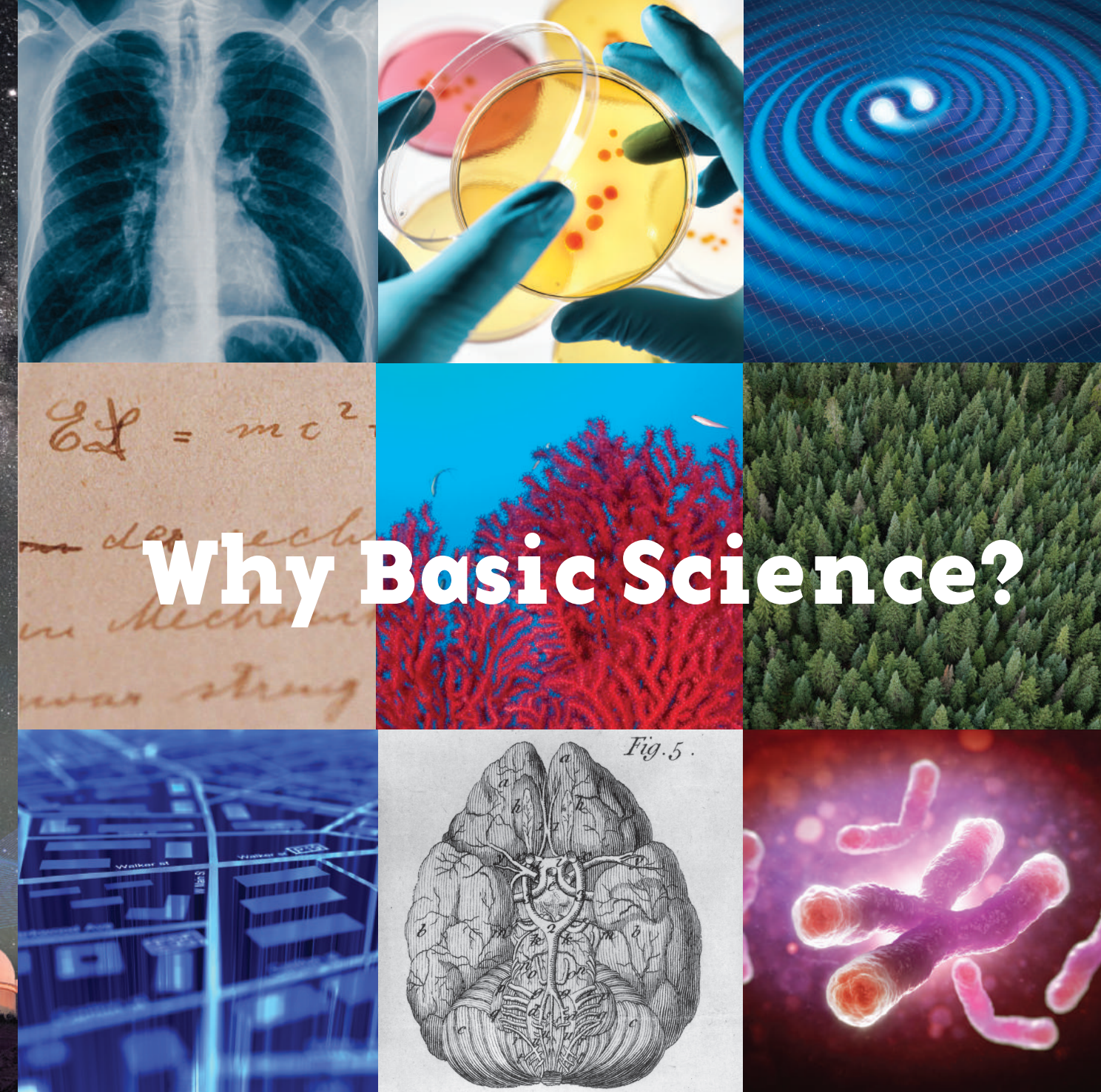
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Issue Index



30

2020
80 ALIENS
81 MAPS
82 PANPSYCHISM



29

2020
77 UNDERWORLDS
78 ATMOSPHERES
79 CATALYSTS



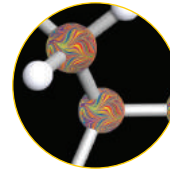
28

2019
75 STORY
76 LANGUAGE



27

2019
72 QUANDARY
73 PLAY
74 NETWORKS



26

2019
68 CONTEXT
69 PATTERNS
70 VARIABLES
71 FLOW



25

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



24

2018
56 PERSPECTIVE
57 COMMUNITIES
58 SELF



23

NOV/DEC 2017
54 THE UNSPOKEN
55 TRUST



22

SEPT/OCT 2017
52 THE HIVE
53 MONSTERS



21

JULY/AUG 2017
50 EMERGENCE
51 LIMITS



20

MAY/JUNE 2017
48 CHAOS
49 THE ABSURD



19

MAR/APR 2017
46 BALANCE
47 CONSCIOUSNESS

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18

JAN/FEB 2017

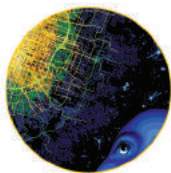
44 LUCK
45 POWER



17

NOV/DEC 2016

42 FAKES
43 HEROES



16

SEP/OCT 2016

40 LEARNING
41 SELECTION



15

JULY/AUG 2016

38 NOISE
39 SPORT



14

MAY/JUNE 2016

36 AGING
37 CURRENTS



13

MAR/APR 2016

34 ADAPTATION
35 BOUNDARIES



12

JAN/FEB 2016

32 SPACE
33 ATTRACTION



11

NOV/DEC 2015

30 IDENTITY
31 STRESS



10

SEP/OCT 2015

28 2050
29 SCALING



09

JULY/AUG 2015

25 WATER
26 COLOR
27 DARK MATTER



08

MAY/JUNE 2015

22 SLOW
23 DOMINOES
24 ERROR



07

MAR/APR 2015

19 ILLUSIONS
20 CREATIVITY
21 INFORMATION



06

WINTER 2015

16 NOTHINGNESS
17 BIG BANGS
18 GENIUS



05

FALL 2014

13 SYMMETRY
14 MUTATION
15 TURBULENCE



04

SUMMER 2014

10 MERGERS &
ACQUISITIONS
11 LIGHT
12 FEEDBACK



03

SPRING 2014

07 WASTE
08 HOME
09 TIME



02

WINTER 2014

04 THE UNLIKELY
05 FAME
06 SECRET CODES



01

FALL 2013

01 HUMAN UNIQUE
02 UNCERTAINTY
03 IN TRANSIT

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Gina Rippon

The neuroscientist on the myths about female and male brains

INTERVIEW BY CODY KOMMERS

NO DISTINGUISHING CHARACTERISTIC

We have yet to discover any kind of reliable structural difference which will reliably distinguish the brains of men from the brains of women. I think that's an important point to make, and it takes people by surprise. There are lots of research papers that say "I found a sex difference in the amygdala" or whatever structure. But the replication of those studies doesn't hold up. It's important to remember that right now, we do not have any kind of clearly distinguishing characteristic which reliably distinguishes the brain of a man from the brain of a woman.

GENDERED BY THE WORLD

We are much more aware as neuroscientists of how what's going on outside the brain—the environment, the culture, your experiences—will interact with the brain and change its structure and function. So if you are in a culture where there is a major emphasis on differences between males and females, then those cultural expectations and attitudes and the experiences they afford will also have brain-changing implications. There's a big emphasis on the fact that males and females are different. And our brains are tuned to respond to differences, so our brains are being gendered by our world.

THE STEREOTYPE EFFECT

If we know that people have a social brain and one of the things they seek is the feeling of belonging, the fact that how they perform will be recognized, rewarded, celebrated, whatever, you don't have to look very far within science to show that that is not equally the case for males and females. And

therefore what looks like a paradox is not a paradox. Because actually you have these very bright girls who have a whole range of different skills, and they don't have to look very far into science to think "Actually, I'm not sure that's where I'd like to spend my talents." Stereotypes have a very powerful effect—it's almost like it's a self-fulfilling prophecy.

CELEBRATE STRENGTH

Celebrating people as individuals, rather than as representative of some stereotypical group, would be great. Focusing more on people's strengths—what they're good at; what they like doing—rather than whether they're a member of one gender or the other, or one sex or the other, or whatever, would be good. Stereotypes, of course, are amazing shortcuts, and our brains use shortcuts all the time. There's a nice list attached to a group label, which makes life easier for our brain as it's driving us through the world. So it's quite a hard force to undermine. But just noticing that people are different, and not saying "all my male colleagues are like this" or "my female colleagues are like that." When you actually look at the

male and female colleagues, you realize there's a huge amount of difference within the groups, as opposed to between the groups. So maybe that would be the big thing: Notice how you stereotype people, and then see how big the differences are between the people to whom you've attached a single label. 😊



JAMES WALLER

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