NAUTILUS

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Science Is People

BY KEVIN BERGER

T**HANK YOU, SCIENCE!"** That's the first thing I thought when I got my COVID-19 vaccination. The development and distribution of a new vaccine to battle an international pandemic in a year? Wow. But on reflection, I think we should say, "Thank you, scientists!" It's the people who do the science that we are celebrating.

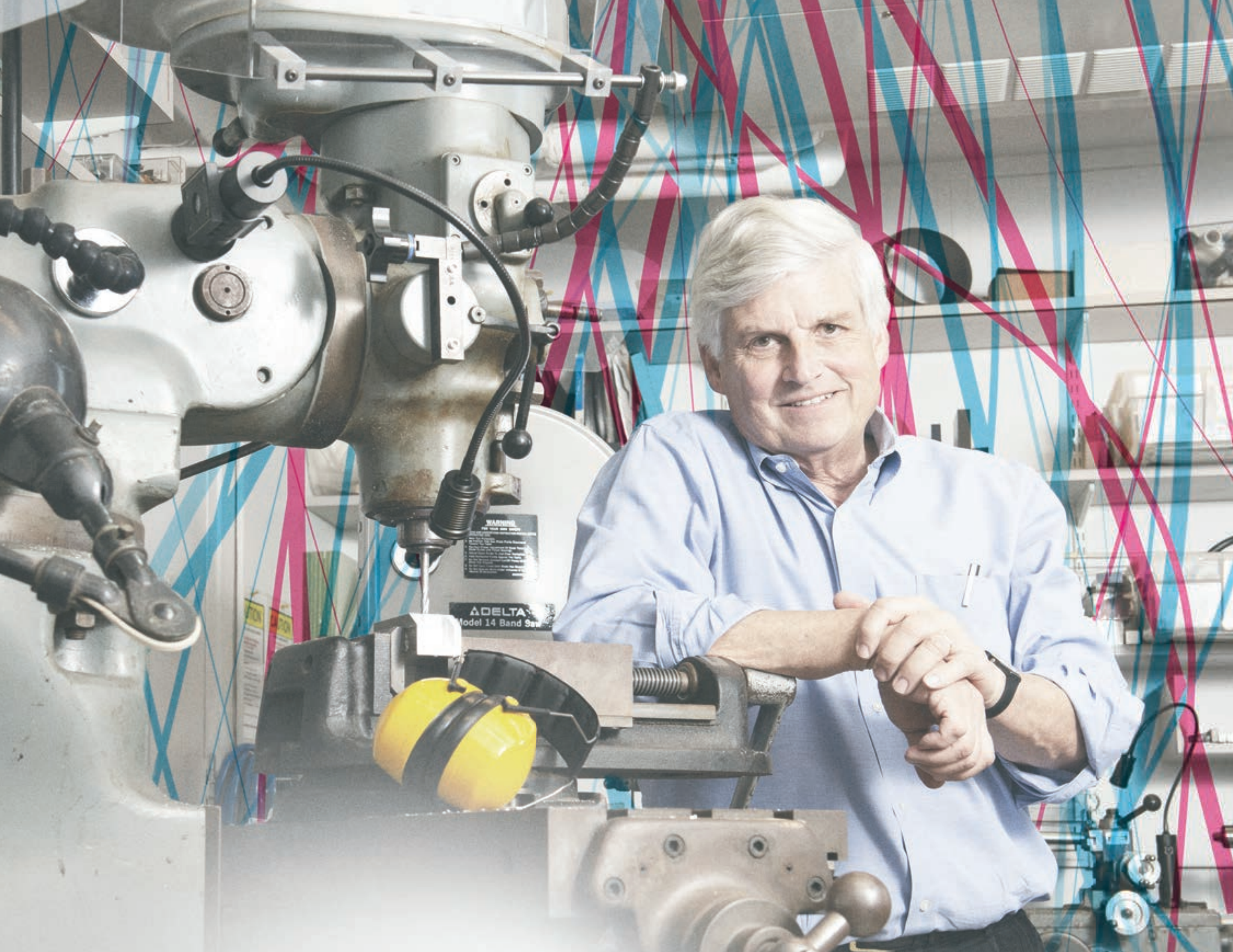
I know that's an obvious point but it often gets obscured by the personal layers of meaning we paint on the term science. Losing sight of just what doing science entails, and just what science is, informs the essay, "Gaia, the Scientist," in this issue by professor of geobiology and author Hope Jahren. "Maybe the only real way to identify a scientist is when we see the joy and frustration and late nights and failed attempts and glowing pride unspoken whenever we are offered a view of something private and beautiful," Jahren writes.

It's not the job of journalists to lionize or romanticize scientists. We want to report accurately on their work and its impacts. But at *Nautilus*, we want to take you inside the lives and minds of scientists. We want to show you the joy and frustration and late nights behind their work. We want to remind you that big ideas and technological breakthroughs, and busts, come from people.

That's one of the reasons we like to feature Q&As with scientists. Our writers encourage scientists to talk about their personal experiences so you can see the humanity behind the science. What can I say? Humans have a lot of issues. How those issues get transformed into culture-changing ideas and technologies is a story worth telling. You'll see what I mean in this issue's Q&As, in which, respectively, Nobel laureate physicist Frank Wilczek and neuropsychologist Mark Solms, a leading thinker about the nature of consciousness, talk about the powerful emotional experiences in their young lives that shaped their professional careers.

Similarly, though not in the Q&A format, David Sloan Wilson, son of Sloan Wilson, author of the classic 1950s novel, *The Man in the Gray Flannel Suit*, writes about the surprising turns in his life. It's a road that led Wilson away from his father's vocation to a career in ecology, the development of pioneering ideas in evolutionary biology, and to writing a novel himself. In what reads like a novel, but is not, Wilson's road runs through and then over the objectionable philosophy of Ayn Rand.

Ultimately, in every issue of *Nautilus*, science is a personal story.



Readers Respond

Comments and letters about stories from print issue 36.

“WHY COMPUTERS WILL NEVER WRITE GOOD NOVELS”

Many people in 1970 thought that humans would travel by flying cars or rocket ships by the year 2000. And despite all their improvements in comfort, cars in 2021 resemble the classic automobile from a century before. Here, we’re missing some key technology to advance us into flying cars and rocket ships. It’s possible that no such key technology exists and that it will never be practical to have a flying car or a family-owned rocket ship for local travel. Angus Fletcher here claims that understanding causal relationships is alien to computers. I think this problem will be easily solved through a new software technique, much as convolutional neural networks opened up the field of computer vision or how attention is advancing natural language processing.

—Chet Chamberlain

At the moment we don’t have the technology to construct an AI that encompasses all of the nuances of a neuron at the scale of an actual human brain. So for the time being, the author is right in that a current AI will never perform the same as a human brain. A far more interesting question to ponder is: What will happen when we finally can faithfully model a human brain in a computer. Will we discover that perhaps something still is missing?

—John Saunders

“DREAMING IS LIKE TAKING LSD”

If dreaming and mind wandering are like the LSD experience then why does activity in the DMN decrease (almost completely!) during an LSD trip? Wouldn’t this indicate a reduction in mind wandering? And from the first-person side, a psychedelic trip feels nothing like mind wandering or daydreaming… it feels more like their antithesis: total attention and clarity of mind.

—J. Davey

“IF ALIENS EXIST HERE’S HOW WE’LL FIND THEM”

This was certainly a fascinating read, though I do feel that some of the conjecture about the origin and therefore limits and evolution of organic life are based on the assumption that life is only possible in Earth-like conditions. I think it’s quite reasonable to suppose that we will not be able to fathom the nature of these hypothetical life forms any more than we can their intention. That may have made for a less interesting article however.

—Pavle Banovic

It is wonderful to watch two great minds let loose their creative imagination in an explosion of playful speculations. But—not to be taken too seriously! There are practical factors to be considered. It has yet to be shown that a planet-bound civilization can bootstrap itself off-planet before fully depleting the terrestrial resource base and without falling victim to the destructive capacity of the technologies required. Maybe this explains the Fermi paradox.

—George Gantz

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

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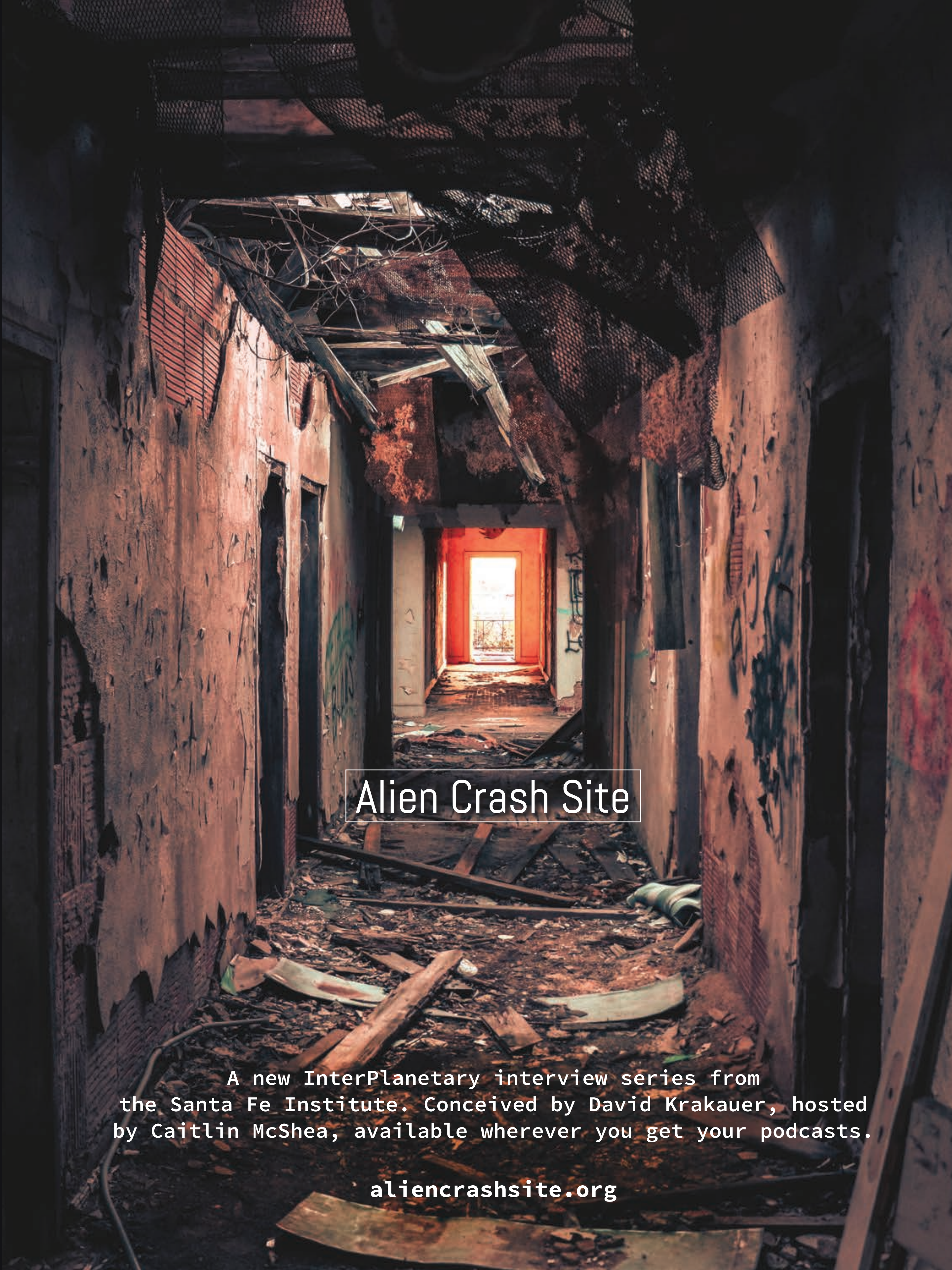
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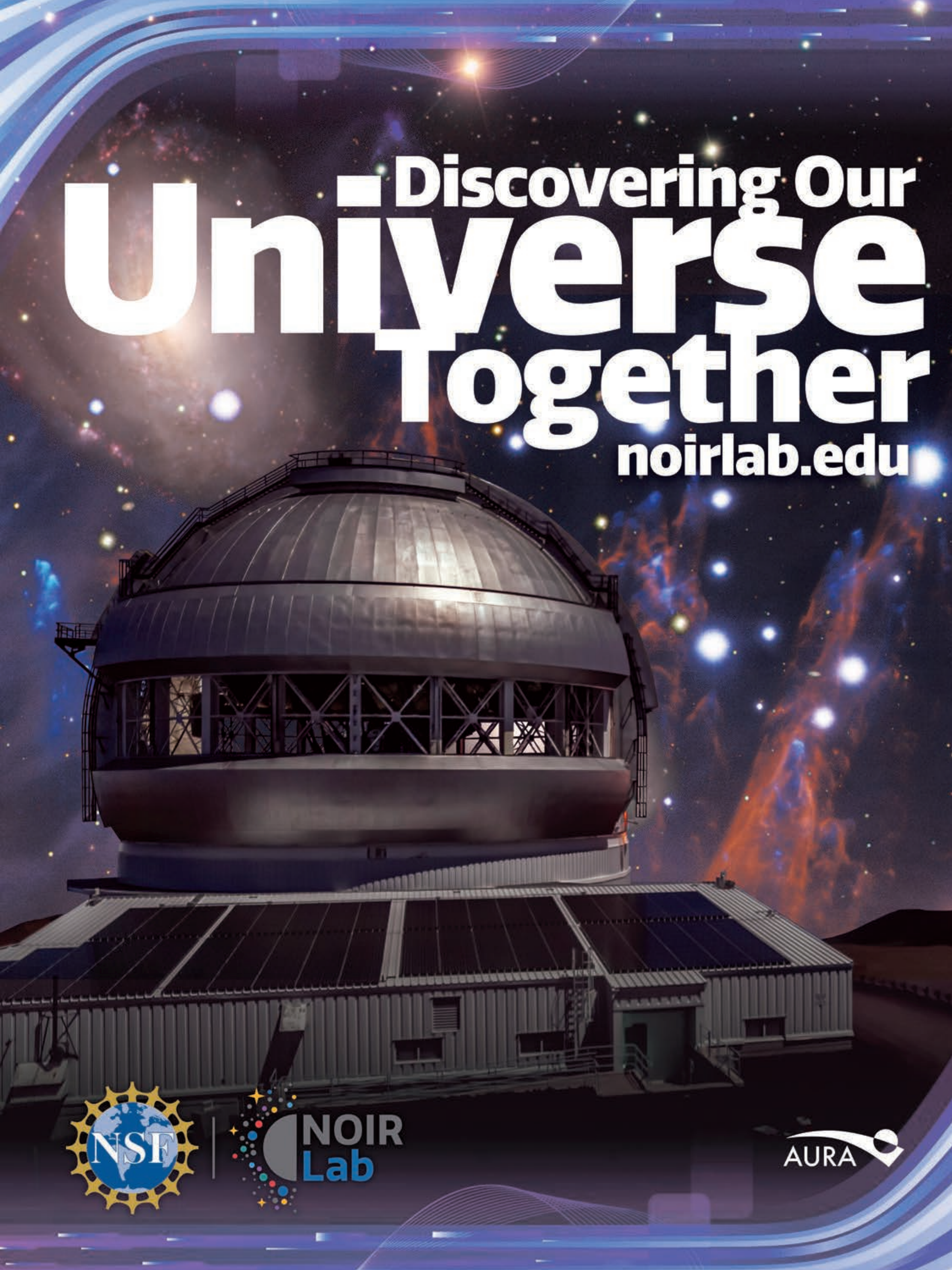
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PSYCHOLOGY

How to Quiet Your Mind

GOODSTUDIO / SHUTTERSTOCK

WE'VE ALL BEEN THERE. Stuck in our own heads, fixated on a two-minute conversation from three days ago. The voice in our heads goes from an ally to a vicious nag, just looping uselessly over the same things, again and again and again.

Ethan Kross, an experimental psychologist, neuroscientist, and author of the recent book, *Chatter: The Voice in Our Head, Why It Matters, and How to Harness It*, wants to teach us how to control the voices in our heads. Not the voices of mental illness, mind you, just the little voice we all have, cheerily (or naggingly) narrating our lives as we go about our days. Kross says our inner voices can be one of our greatest strengths—when we can control them.

What is chatter?
When we experience problems, we often turn our attention inward to make sense of them. But we often get stuck. We ruminate, we worry, we catastrophize. Chatter refers to those negative thought loops that characterize that experience of being stuck. It can involve perseverating about the past, which we call rumination, perseverating about the future, we call that worry. That's what chatter is.

How can you recognize the difference between your normal stream of consciousness and the start of a chatter spiral?
Typically it's when you find yourself rehearsing the same things over and over again. Rather than coming up with a more clear, objective solution to a problem. And you find that those negative thoughts are really beginning to prevent you from doing other things in ways that can be counter-productive. I think most of the time when people are experiencing chatter, they know it.

What are the effects of chatter?
It can make it really hard for us to think and perform well. And one principal reason for that is you only have so much ability to focus at any given moment in time. And so if all your focus is devoted toward your chatter, good luck getting anything done.

What chatter does is take a stressful experience and prolong it. Stress in and of itself isn't bad. What makes stress bad is when it's prolonged over time, and that's what chatter really does.

How do we quiet chatter?
Different strategies work for different people in different situations. And it's really about combinations of strategies. When I experience chatter, I do several things. I'll do distanced self-talk. I'll do temporal distancing. I have some chatter advisors that help give me some perspective. Those aren't the people who I'm necessarily closest to, but they're people who are adept at helping me when I'm struggling with something. And I'll also take walks in nature and tidy up the office around me.

In *Chatter* you talk about how you halted a particularly bad spiral by calling yourself by name. That's

What chatter does is take a stressful experience and prolong it.

fascinating to me, the idea that what we call ourselves in the privacy of our own head has real discernible effects.
We know that it's a lot easier for people to give advice to others than it is to take that advice ourselves. And what we've learned is that language provides us with a tool for coaching ourselves through our problems like we were talking to another person. It involves using your name and other non-first person pronouns, like "you" or "he" or "she." That's distanced self-talk. It's a tool that many people stumble on without really understanding how it works. The lab work shows this tool gives you some mental space, some psychological distance from our problems, which helps you give yourself more constructive advice for how to deal with a situation.

Why do you think that is?
The idea is that when you use a name to refer to yourself, it's almost like an automatic perspective switch. It's switching your perspective because you're so used to using these parts of speech when you address others.

Why do our brains chatter?
When we experience negative emotions and try to analyze our feelings, we often zoom in narrowly on the experience to the exclusion of other ways of thinking about the event that could lead us to feel better. This leads us to get stuck in a negative cycle of thinking and feeling where we rehash what we felt and are feeling in ways that lead us to feel stuck. This psychological experience corresponds to increased levels of activity in brain networks that support self-referential and emotional processing in the brain. With respect to why this happens, it's a case of an otherwise adaptive response—engaging in self-reflection to solve a problem—that runs off track in a particular circumstance.

Can chatter be productive?
The inner voice is often amazing. It's a super power. It helps us do a lot of different things. I equate chatter with an unproductive state of the inner voice. So I think once you're in chatter, thought loops, we're not talking productivity anymore. We're talking about the opposite. But that is not to say that the goal should be to silence our inner voice or stop talking to ourselves. I think that would be a bad thing. The challenge is to figure out how to talk to yourself and use language to weigh in on your problems without getting stuck in chatter.

—Liz Greene

COGNITIVE SCIENCE

The Link Between Bioelectricity and Consciousness

LIFE SEEMS TO BE TIED to bioelectricity at every level. The late electrophysiologist and surgeon Robert Becker spent decades researching the role of the body's electric fields in development, wound healing, and limb regrowth. His 1985 book, *The Body Electric: Electromagnetism and the Foundation of Life*, was a fascinating deep dive into how the body is electric through and through—despite our inability to see or sense these fields with our unaided senses.

Biology professor Michael Levin got hooked on the subject after he read *The Body Electric*. Levin has been working on "cracking the bioelectric code," as a 2013 paper of his put it, ever since. "Evolution," Levin has said, "really did discover how good the biophysics of electricity is for computing and processing information in non-neural tissues," the many thousands of cell types that make up the body, our word for trillions of cells cooperating. "It's really hard to define what's special about neurons," he told me. "Almost all cells do the things neurons do, just more slowly."

His team at Tufts University develops new molecular-genetic and conceptual tools to probe

How do disarranged cells and organs intuit what do to?

large-scale information processing in regeneration, embryo development, and cancer suppression—all mediated by bioelectric fields in varying degrees. This work involves examining, for example, how frogs, which normally don't regenerate whole limbs (like salamanders do) can regrow limbs, repair their brains and spinal cords, or normalize tumors with the help of "electroceuticals." These are therapies that target the bioelectric circuits of tumors instead of, or together with, chemical-based therapies.

Nature seems to have figured out that electric fields, similar to the role they play in human-created machines, can power a wide array of processes essential to life. Perhaps even consciousness itself. Neuroscientists and electrophysiologists around the world are developing steadily deeper insights into the degree that electric and magnetic fields—"brainwaves" or "neural oscillations"—seem to reveal key aspects of consciousness. The prevailing view for some time now has been that the brain's bioelectric fields are an interesting side effect of the brains' activity, but not necessarily relevant to the functioning of consciousness itself.

A number of thinkers are now suggesting that these fields may be the main game in town when it comes to explaining consciousness. If they're right, it is likely that the body's bioelectric fields are also, more generally, associated in some manner with some kind of consciousness at various levels. "There are very few fundamental differences between neural networks and other tissues of bioelectrically communicating cells," Levin said in an email. "If you think that consciousness in the brain is somehow a consequence of the brain's electrical activity, then there's no principled reason to assume that non-neural electric networks won't underlie some primitive, basal (ancient) form of nonverbal consciousness."

This way of thinking recognizes that there is perhaps some intelligence (maybe even consciousness) in all of the body's bioelectric fields, which are efficient sources of information transfer and even a kind of computation. In his work, Levin pieces together how these fields can contain information that guides growth and regeneration. It may sound like a mystical notion, but it's quite physical and real, backed up by hard data.

Take frogs. "To become frogs, tadpoles have to rearrange their faces during metamorphosis," Levin said. "It used to be thought that these movements were hardcoded, but our 'Picasso' tadpoles—which have all the organs in the wrong places—showed otherwise." The apparent know-how that these bioelectric fields demonstrate, in terms of growing normal frogs in very un-normal circumstances, is uncanny. "Amazingly, they still largely became normal frogs!"

How do disarranged cells and organs intuit what do to? Levin, and philosopher and cognitive scientist Daniel Dennet, tackled this question in a rather provocatively titled article, "Cognition All the Way Down." Something like thinking, they argue, isn't just something we do in our heads that requires brains. It's a process even individual cells themselves, and not requiring any kind of brain, also take part in. To the biologists who see this as a cavalier form of anthropomorphization, Levin and Dennet say, "Chill out." It's useful to anthropomorphize many different kinds of life, to see in their parts and processes a variety of teleological experience.

A promising route for better understanding may be found, they write, in "thinking of parts of organisms as agents, detecting opportunities and trying to accomplish missions." This is "risky, but the payoff in insight can be large." For Levin, at least, bioelectric fields are key mechanisms for this kind of collective decision-making. These fields connect cells and tissues together, allowing, along with synaptic connections, for rapid

JIJOMATHAIDESIGNERS / SHUTTERSTOCK

information exchange, not only with immediate neighbors but distant ones as well.

These communication channels are involved in the emergence of cancer, which means that, according to Levin, they can potentially be useful in curing some forms of cancer. "You can [use bioelectric fields to] induce full-on metastatic melanoma—a kind of skin cancer—in perfectly normal animals with no carcinogens or nasty chemicals that break DNA," he said. You can also use these same fields "to normalize existing tumors or prevent them from forming." He's currently moving this work to human clinical models.

The importance of bioelectric fields is all about connection, information, and computation. These ingredients equal cognition for Levin and Dennett, which is, for them, a continuum of complexity that has developed over a billion years of biological evolution. It's not an all or nothing kind of thing but a spectrum—one that plays a role in development, evolution, cancer, and in the workings of consciousness itself.

—*Tam Hunt*

EVOLUTION

Life Beyond Earth Has to Play by the Rules

NOT MANY SCIENTISTS have dared to speculate on what alien life might actually, seriously, genuinely be like. One exception is Arik Kershenbaum, a zoologist at Cambridge University. Kershenbaum, a field researcher and evolutionist whose feet are firmly here on Earth, takes the novel perspective of assuming that aliens likely exist, and that if so, those of greatest interest (to him and to us) wouldn't be simple micro-organisms but, rather, complex creatures of some sort. The guiding principle of his latest book, *The Zoologist's Guide to the Galaxy*, is precisely what one would expect from a well-trained zoologist: evolution by natural selection.

What is your argument for the legitimacy of applying natural selection as a fundamental rule for life forms beyond Earth?

If we were to observe complex life in the universe, we're faced with a problem. How did that complexity arise? It's important to remember that even the original, simplest life on Earth was incredibly complex. That complexity didn't arise by chance. It couldn't have simply popped into existence, so there must be a mechanism for the accumulation of complexity. Otherwise life cannot establish itself. And certainly, it cannot achieve the kinds of complexity that we're postulating.

Then the question is, how many mechanisms are there for complexity to accumulate? It turns out that the only way, as far as we know at present, is for certain forms to persist and others to drop out, which is essentially evolution by natural selection.

You write, "We have enough diversity of adaptations here on Earth to give us at least potential mechanisms that seem appropriate solutions, even on worlds almost unimaginably different from ours." Want to elaborate?

It reflects something that people don't often think about, which is that the number of solutions to the problems that animals face is actually quite limited. So by various rules, either physical or mathematical laws, life can't do just anything. It's highly constrained.

One example is flight. We know there aren't that many different ways you can fly. There's ballistic flight. You can jump like a cricket. Not particularly useful. You

ANDREA IZZOTTI / SHUTTERSTOCK

can use aerodynamic flight, with wings that generate lift through the flow of a fluid over an airfoil. These are things well understood by physicists and not specific to Earth. Or you can have buoyant flight, like a hot air balloon or a zeppelin. There are a few others, like jet propulsion, but the point is that these solutions are used over and over again. Buoyant flight is used by millions of species. All fish fly buoyantly. We often think of flight as going through air, but air is also a kind of fluid.

Other planets may have atmospheres of density and viscosity more similar to water than to air. So when you're thinking of other worlds, you've got to change the parameters a little bit. But you're still constrained by this restricted number of flight modalities. So to say that alien animals will have wings is not a radical suggestion. It's just saying that somewhere, it is almost inevitable that creatures are making use of an airfoil to generate lift.

> There may be intelligent life all across the universe.

What might we expect from an evolutionary perspective as to the intelligence of ETs?
Intelligence is a tough one. But one thing I think we can say is that any alien planet with complex life will have a range of different intelligences, according to the demands of their niche. We have some good ideas, but don't really know a great deal about why even humanlike intelligence evolved. It likely has a lot to do with navigating social relationships, remembering for reciprocity, and things like that. But in any case, it took 3.5 billion years to evolve technological intelligence, so it's clearly not something that pops up every day, and we don't know whether it might be more common or less on other planets.

But even then, would we expect a technological alien civilization to have arrived at its intelligence via the same route that it did in humans?
Laurance Doyle, a friend of mine at the SETI Institute, told me "There are two types of organisms in the universe: folks and critters." Folks is anyone who can build a radio telescope, and critters is everyone else.

Apart from being a dig at people who aren't physicists or engineers, there's actually something a bit more subtle here, which is that there may be intelligent life all across the universe. But we're not going to know about it unless it's broadcasting radio waves to us, unless it reaches a particular kind of technological development.

Think of non-technological intelligences on Earth. And there are plenty. We can agree that dolphins are extremely intelligent. They probably have internal mental lives that are complex, rather like ours. But they don't have technology and they never will. They don't have a need for it, and it gives them no adaptive advantage. So alien planets may be swarming with dolphins and other extremely intelligent creatures. But we'd never know, because they're not enough like us to build a radio telescope, to send signals that we would pick up. In some ways we're condemned to find life that's like us.

—David P. Barash

PSYCHOLOGY

How to Reduce Cognitive Bias

WOULD YOU LIKE to be more rational? Of course. Who doesn't want to behave and think more reasonably? Good news: New research, from psychologist Ellen Langer, suggests mindfulness, or at least an aspect of it, can help. By "mindfulness"—a feature of Buddhism for thousands of years, and a subject of scientific investigation for a few decades—most people mean a mental state you can be in. Let's try.

Pay attention to your current sensations—the feeling of your back against a chair, or the weight of your phone in your hand. Pay attention to the thoughts and feelings flitting in your mind. Don't "judge" them. Merely notice that they're there. If you find yourself bringing past or possible future events into your imagination, let those drift off, and attend again to your present sensations, thoughts, and feelings. Not too difficult, right? Being mindful for a few seconds is easy. Being mindful for an hour is very difficult.

The people in the mindful group also became more rational, in terms of bias.

One way to encourage people to be more mindful is to ask them to try to notice more things, and one way to measure mindfulness is to measure their ability to do so. Langer and her colleague Philip Maymin used this aspect of mindfulness to try to reduce that familiar enemy of rationality—cognitive biases.

Maymin and Langer randomly divided 109 people into a "mindless" control group, a "low-mindful" group, and a "mindful" group. The low-mindful group chose their favorite of two random-dot patterns with subtle triangles. The mindful group looked at two slightly less random images, and spotted hard-to-find differences between them. Then they looked at two nearly identical images of a fruit pile at once, and tried to spot which fruit, from one of the piles, was missing. Maymin and Langer measured people's mindfulness using a 14-item measure that focuses on flexibility of thinking and noticing new things (an admittedly Western conception of mindfulness).

The results confirmed that the mindful group, as a result of the attention they paid to their task, was actually mindful, and the mindless and low mindful groups were not.

The people in the mindful group also became more rational, in terms of bias. Maymin and Langer quizzed them with questions measuring 22 cognitive biases. These included the conjunction fallacy (thinking that the amount of something specific is greater than the general category, like Republican bankers are more common than bankers), and the gambler's fallacy (thinking that, after flipping a coin and getting "heads" a few times, "tails" will be more probable than 50 percent on the next roll). They found that the mindful group showed improvement on 19 out of the 22 biases.

It appears that mindfulness reduces cognitive bias, but these results need to be interpreted carefully. For one thing, although it purports to be about mindfulness in general, it is not clear the study's intervention

YULIANAS / SHUTTERSTOCK

and mindfulness measure get at what people often take mindfulness to mean. Neither the intervention nor the scale addresses thinking about the future, judgment of thoughts, focus, or mindfulness meditation (the practice of doing nothing but sitting, or sometimes walking, and paying attention to the here and now). So, this study does not show evidence that your rationality is improved by being mindful in the sense of how you go about dealing with your own thoughts.

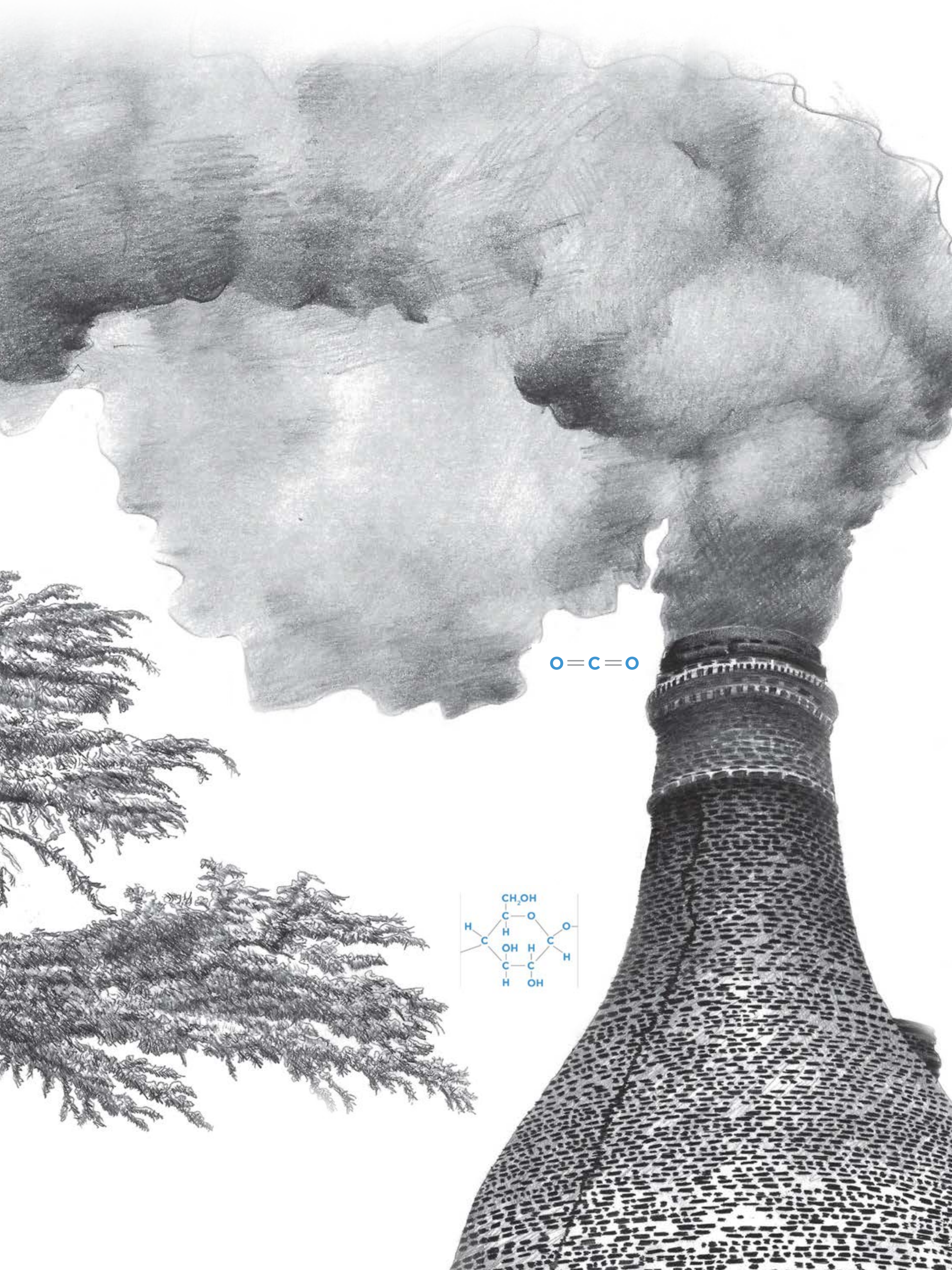
It might be better to interpret these findings as showing that cognitive bias can be reduced by encouraging people to pay closer perceptual attention to their environment—an important aspect of mindfulness, which many people often think of as a stress reducer that, practiced regularly and enough, can lead to a happier life.

Is it better to be mindful? There is some evidence that, in general, people are happier if they are thinking about what they're doing, even if that thing isn't any fun, like washing the dishes. However, there is also evidence that thinking about happy things from your past (nostalgia) increases pain tolerance, positive mood, empathy, and creativity, and reduces anxiety, boredom, and stress. So, though mindfulness is generally good, it's perhaps not something to strive for at *every* moment. But, it is encouraging to know that merely paying attention to the details of your environment can make you a little more rational.

—Jim Davies

Carbon in Black and White

CARBON IS A BUILDING block of life. Because of its strong atomic bonds, it yields the complexity of life around us. These illustrations by John Barnett picture two sides of the ubiquitous element, its beauty and danger.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What Makes Music Universal

Music brings us together to show us how different we are

BY KEVIN BERGER

MY FRIEND ROBERT BURTON, a neurologist and author, wanted to share a song with me last year, and sent me a link to an NPR Tiny Desk Concert. "It's wonderful to see truly new and inspiring music," he wrote. I clicked open the link to a band who appeared to have journeyed from their mountain village in Russia to busk for tourists in the city square. Three women wore long white wedding dresses, thick strands of bead necklaces, and Cossack hats that towered from their heads like minarets of black wool. They played, respectively, a cello, djembe drum, and floor tom drum. They were joined by an accordion player who could pass for a bearded hipster from Brooklyn.

The accordionist was the first to sing. A bray of syllables erupted from him like an exorcism. A steady drumbeat followed and then the women commanded the singing. Their vocals ranged from yodels to yips, whoops to whispers. At first turbulence reigned, as if the women were singing different songs at each other. But soon their voices blended into a melody that curled like a river. Their harmonies resonated, as if emanating from a deep hollow, and the melody rushed on. The song ended in a crescendo of wild abandon.

The song was called "Sho Z-Pod Dupa" by the band DakhaBrakha, which means give/take in their native Ukraine. Bob Boilen, who created the Tiny Desk Concerts, wrote DakhaBrakha "sounds like nothing I've ever heard, with strands of everything I've ever heard." That's a nice line, and I agree. I didn't understand a single word of "Sho Z-Pod Dupa," the vocal styles were otherworldly, and I related to every note. The other two songs in the Tiny Desk Concert were just as thrilling. The comments I sampled on YouTube, where the video has been viewed more than 2.5 million times, expressed a similar enthusiasm. "This is gold," wrote one commenter. "Music is the universal language of all cultures."

ILLUSTRATION BY **JORGE COLOMBO**

The debate over universality has raged like a battle of the bands among scientists.

DakhaBrakha is the perfect band to make the view ring true that people around the world speak the same musical language. It steeps its songs in traditional Ukrainian folk music but spices them with ingredients from around the world, such as raga drones from India, metrical drumming from Japan, and languid blues from America. DakhaBrakha call its music "ethno-chaos" but what makes it captivating is not the chaos but the way the global sounds amplify the Ukrainian ones. The quartet has released six albums and played concerts across the globe since 2007. Everywhere DakhaBrakha has played, fans have rhapsodized about the joy and pathos in their music. Humans have bodies that want to dance, sorrows that want company. It was a wonderful coincidence to learn about DakhaBrakha while I was immersed in the scientific debate about the universality of music.

I admit it's not a new debate. More than 100 years ago, savvy musicologists were already singing a different tune about the widespread claim that all music could be reduced to pitches and intervals established by universal principles of math—integer ratios, to be exact—laid down by Pythagoras. The maverick thinkers showed that musicologists who boosted the theory that musical scales hewed to the ancient Greek's math were tone deaf to music and instruments, like a Javanese gamelan, heard outside the concert halls of Europe.[1] Mozart wasn't the lodestar of the musical universe.

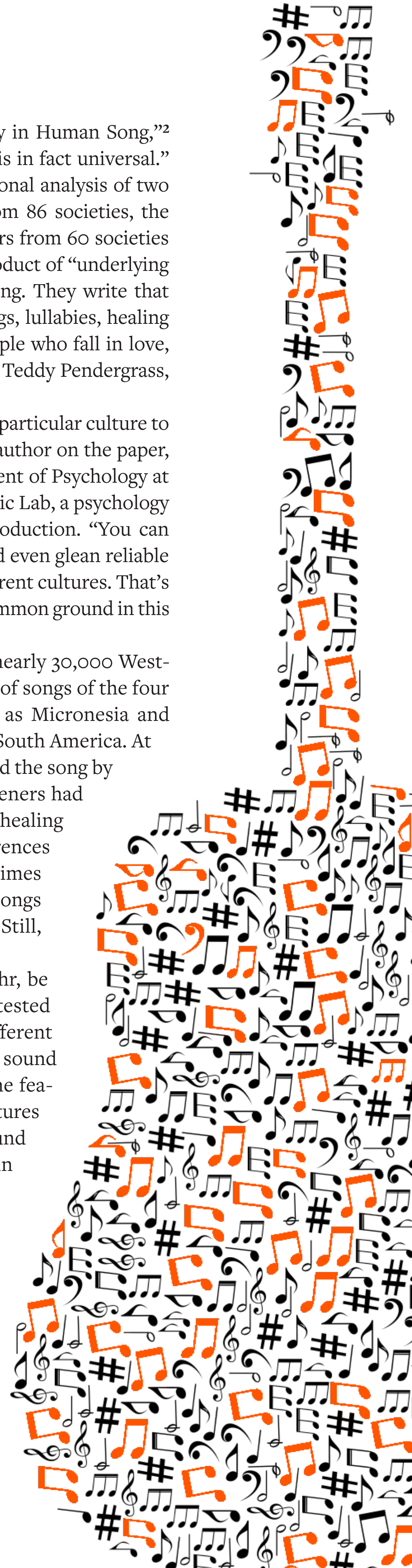
In the past two years, the debate over whether music is universal, or even whether that debate has merit, has raged like a battle of the bands among scientists. The stage has expanded from musicology to evolutionary biology to cultural anthropology. This summer, in the journal *Behavioral and Brain Sciences*, more than 100 scholars sound off on evolution and universality of music. I love the din. The academic discord gives way to a symphony of insights into the meaning of music in our lives. It may be a cliché to say music is the sound of our shared humanity. But it feels transcendent to be in tune with a person from another culture. There's something alchemical about knowing we share the same biology. Originate from the same place. Share the same desires. But there's more to the story. My recent adventures in the fields of music research have instilled in me, deeper than ever before, the feeling that music is what makes us human. I also have a new appreciation of what universality in music really means.

A 2019 PAPER in *Science*, "Universality and Diversity in Human Song,"[2] got me thinking anew. The paper concludes, "Music is in fact universal." The conclusion is based on an impressive computational analysis of two cross-cultural datasets, one of recordings drawn from 86 societies, the other of ethnographers' notes about musical behaviors from 60 societies around the world. The authors assert music is the product of "underlying psychological faculties" sparked by the basics of living. They write that four song types are heard in every society—love songs, lullabies, healing songs, dance songs. All cultures are animated by people who fall in love, have babies, seek spiritual health, and, if I may quote Teddy Pendergrass, get up, get down, get funky.

"We've shown you don't need to be familiar with a particular culture to understand and enjoy its music," Samuel Mehr, lead author on the paper, told me. Mehr is a research associate in the Department of Psychology at Harvard, where he is principal investigator at the Music Lab, a psychology laboratory studying music perception and music production. "You can find music meaningful and artistically interesting, and even glean reliable information, objective facts, from music made in different cultures. That's really interesting socially because it shows there's a common ground in this artistic product across cultures."

The authors conducted an experiment in which nearly 30,000 Westerners listened on a website to a random generation of songs of the four types. The songs originated from places as varied as Micronesia and Western Africa, Southeastern Europe and Southern South America. At a rate better than chance, listeners correctly identified the song by type. Distinct musical features tipped them off. Listeners had little trouble telling dance songs from lullabies or healing songs, given their tempos and beats. But some differences were subtler. Love songs and lullabies, which sometimes may not be easy to tell apart, differed because love songs demonstrated a larger range of accents and pitches. Still, listeners sensed the distinctions.

Could elements of a Brahms lullaby, I asked Mehr, be heard in a Western African lullaby? "We haven't tested Brahms directly," he said. "But key features across different world regions reliably predict what makes a lullaby sound like a lullaby. So it wouldn't be surprising if the same features that make a Brahms lullaby soothing are the features that make a lullaby from rural India, or Siberia, sound soothing." In the paper, Mehr and coauthors explain that listeners' abilities to identify unfamiliar songs by type suggests "that universal features of human psychology bias people to produce and enjoy songs with certain kinds of rhythmic or melodic patterning that naturally go with certain moods, desires, and themes."



GLOBAL VILLAGE Ukraine's DakhaBrakha (l-r): Nina Garenetska, Olena Tsybulska, Marko Halanevych, and Iryna Kovalenko. "It is interesting for us to explore the musical culture of the world, absorb it and rethink it," Halanevych said. "It is interesting how Ukrainian songs sound in uncharacteristic circumstances."

ANDRIY PETRYNA

Some world music scholars viewed the paper with, well, horror. On social media, and in commentaries solicited by Mehr, they proclaimed the paper struck many sour notes, and the sourest of all is the term "universal." "The idea that there is such a thing as musical universals (let alone that it should be studied) is deeply ethnocentric and Eurocentric," wrote one scholar. "I prefer not to approach music in a universal way," wrote another. "Every culture perceives facts and music in a different way depending on their cultural background." At the inception of the study, one national grant reviewer told Mehr that his study was "carrying on the tradition of the Nazi party." "He assumed we were going to be doing totally biased work and making grand claims about the superiority of one culture over another," Mehr said. "Which is just ludicrous."

Patricia Shehan Campbell, chair of music education at the University of Washington, put the controversy into perspective for me. Campbell is an ethnomusicologist who has studied indigenous music in communities around the world. She is co-editor of the recent book, *Global Music Cultures*. Campbell excitedly told me about her favorite recent discovery, music made by the Wagogo people in a village in central Tanzania. "I was in disbelief when I first heard a recording of it," she said. "It was so beautiful." She has traveled to Tanzania seven times in the past decade to hear and learn about it in person. The intoxicating music, played on percussion, two-string fiddle, thumb piano, and sometimes a zither, is accompanied by harmonious singing and dancing. "To be in that village and be a part of the singing and the dancing, which is so rhythmic and so clear, is an experience that can't completely be rendered into words," Campbell said.

Ethnomusicologists often have such powerful personal experiences. They live among the musicians, absorb their ways of life, and become immersed in music with its own cultural traditions. "Ethnomusicology is the development of human understanding through music in field settings, not labs," Campbell said. "A healing relationship develops when you're working with a family in a small community. You come to know these people and want to protect the nuances of their music, make sure it continues." Putting a universal label on music obscures those nuances.

"The idea of music as a universal human activity is accepted," Campbell continued. "But when we get down to detailing it, we find so much variety in its sonic elements, its social and individual uses." Campbell agreed Mehr's four song types could be heard in global cultures. But given the song types were derived from sound files and ethnographic notes, rather than being heard and studied in person, their value to musicologists was debatable, "at least from the perspective of those working humanistically rather than statistically," she said.

Mehr was familiar with the criticism. "All I can say is there are tradeoffs," he said. "We're going to lose some of the rich detail by doing quantitative analysis of culture. We'll never be able to match the level of detail that you get when you do rich narrative ethnography. But at the same time, we can make generalizations to all societies in a rigorous fashion that corrects for bias in a way that rich narrative is never going to be able to do."

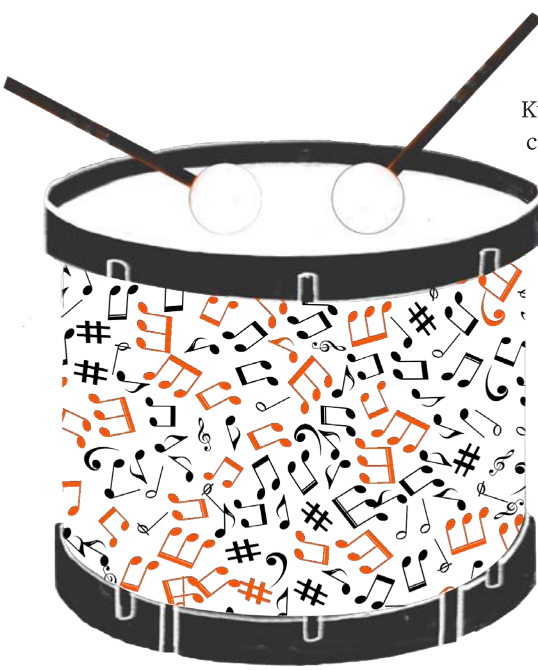
The four song types, though, did seem to shrink the canvas of world music. Songs, after all, arose from more social and emotional conditions than loving, dancing, healing, and raising kids. And musical elements that defined one song type could be heard in another type. Also, a healing song might serve as a dance song. Mehr explained the four song types didn't arise from a computational analysis of the datasets. Rather, he chose the four types based on "ideas in the psychology and evolutionary biology of music," and looked for them in the datasets. "We didn't have enough resources to study more than four kinds of music, and those were four kinds that were easy to find worldwide," Mehr said.

I WAS INTRIGUED by the four types, and wanted to ask ethnomusicologists, experts in a specific region, if the types defined the songs in their part of the world. I had just the experts in mind.

After being enchanted by DakhaBrakha's music, I read about its history and members. It made perfect sense, given the ethnic signature of their songs, that the three women in the band are trained ethnomusicologists; they studied at the University of Kiev. Nina Garenetska, the cellist, and one of the singers, told me she has traveled across Ukraine "to find the bearers of ancient, outdated 'club' folklore and record the material." That material, also collected by other members of the band, in some cases from their relatives, constitute most of DakhaBrakha's songs. Garenetska focused her studies on wedding music heard in a culturally distinct area of southwestern Ukraine.

"I went to a certain village many times, talked to the residents, was at a traditional wedding, studied the dialect, manner of performance, clothes, the wedding ceremony completely," she said. "This is a big job that takes a lot of time to immerse in that space to study the tradition." I should say my interview with Garenetska and Marko Halanevych of DakhaBrakha was done over email. I sent my questions in English and the band had them translated into Ukrainian so they could answer, and translated back into English for me.

I asked Garenetska if lullabies, love songs, dance songs, and healing songs, were major features of Ukrainian music. "Yes, of course, humanity has invented certain rituals that are associated with the seasons, so in all cultures, there are some similar genres," she said. "Everyone gets married (wedding songs), everyone is born (lullabies), everyone dies (cries) and has ritual church songs. Our favorite category is the songs of the calendar cycle, namely *vesnyanky* (about spring), Kupala songs, mermaid songs, harvest songs, carols, Christmas carols, and of course wedding songs. They have the necessary rhythmic pulsation, which combines well with the rhythm of the drums, so it is easier to work with them."



I told the band members that even though I didn't understand the lyrics to "Sho Z-Pod Dupa," the song was a joy. What was it actually about? "In one magical place, a spring flows from under the root of an oak tree, and there Ivan feeds his horse, and for some reason, the horse does not drink water," Halanevych said. "So Ivan starts beating him. And the horse answers him, 'Don't beat me, I am still being useful to you.' "

Putting a universal label on music obscures its nuances.

I had to smile. When you added the lyrics, "Sho Z-Pod Dupa" was not exactly the universal language of all cultures. Did Garenetska think there was a universal quality in Ukrainian music? "It so happened that mostly all Ukrainian songs have a sad character," she said. "These are lyrical, everyday songs about love and hard fate. People liked to sit and to get sad."

I WAS BEGINNING TO QUESTION whether the conviction that music is universal was valuable. What seemed universal was not that music draws out a shared humanity, but that humans project their own meanings on it. We all share a happy delusion about oneness.

In a recent interview, Sona Jobarteh, a musician and composer from Gamba in West Africa, a virtuoso on the Kora, a multi-stringed lute with a gourd body, explained her music did not mean the same to all listeners. To the Mande people of Western Africa, she said, her music evoked "that sense of belonging, pride, identity, all that swell in you that just makes you feel so proud of where you come from when you hear it. That's different to other people who listen to it and just feel, 'It's amazing. It touched me. It made me cry,' you know, whatever it is."

Interestingly, the Jobarteh interview, in *Greater Good Magazine*, was sent to me by Patrick Savage, an ethnomusicologist, who is a leading scholar in what makes music universal. I had interviewed him earlier and we'd struck up a casual email exchange. But Jobarteh's insight that listeners' responses vary across cultures didn't contradict his scholarship.

"I don't like absolutists saying music is all universal or it's all culturally relative," Savage said. "I think about it as a continuum. It's perfectly fine to recognize that, say, 70 percent of the things that we see in music of a given culture are shared with most other musics around the world, and another 30 percent is distinct to that culture. The fact that people like me spend years or lifetimes getting to understand a specific style of music and its nuances doesn't mean we can't use music to connect with people from other cultures, other places, even if we don't understand everything about it. I see music as a tool for good, for connecting people, even if it's not 100 percent universal."

Savage has studied Japanese folk music, notably the style known as minyo. He is a proficient musician and sang a minyo song for me during our interview. Traditionally the song was sung by farmers as they led their cows across fields. If I didn't know Savage was a Westerner, born in Wisconsin, I would have thought the singer behind the quavering vocals was Japanese. It was freaky cool. In his professional life, Savage is an associate professor in the Faculty of Environment and Information Studies at Keio University in Japan, where he runs the CompMusic Lab, applying computer science to musicology.

Music, which comes naturally to us, is not something we share with other primates.

In a 2015 paper in the *Proceedings of the National Academy of Sciences*, Savage and colleagues analyzed a dataset of 304 global music recordings and isolated 32 specific musical features.[3] (The dataset was not the same one that Mehr used for his 2019 paper.) The recordings included Western and non-Western music in manifold styles from nine global regions. Savage computed the musical features from various domains: pitch, rhythm, phrasing, instrumentation, performance, style, social context. He ranked the features by how consistently they appeared in music of all nine regions. Eighteen of the features were shared relatively widely.

I asked Savage to listen to "Sho Z-Pod Dupa" by DakhaBrakha to see where it fell on his universal scale. He said it contained 15 of the most universal features, such as "two-beat subdivisions," which was the number one most common feature, "chest voice," "discrete pitches," "motivic patterns," and "group performance." Savage was intrigued by the song's "yodel-like leaps," which he said were rare in most other musics. "Another strikingly non-universal feature," he said, "is the rare use of dissonant homophony—harmonizing in narrowing intervals—which is historically something that Western classical composers avoid, but here and in other regional styles, such as the Balkans and Papua New Guinea, is common. It's one of the things that makes this recording sound so haunting and beautiful."

Savage said the DakhaBrakha song exemplified a sentence in his 2015 paper and a key theme in his ongoing research. Music evolved, he wrote, to promote "group coordination and cohesion, as exemplified by the universal tendency to sing, play percussion instruments, and dance to simple, repetitive music in groups." The idea that music has played a role in social bonding is a passage to the subculture of music research in evolutionary biology that lies beneath the world of notes. If music is truly universal, its

VITALIY VOROBYOV

SOUND OF UKRAINE While DakhaBrakha spices its music with global sounds, the heart of its music is its native land: "In our humble opinion, the Ukrainian song is unique in polyphony and expansive melody. It is quite normal for a Ukrainian song to have three or four voices," explained Nina Garenetska (far right).

creation and effects must be written somewhere in our biology. Music must have bestowed some adaptive trait on our ancestors in the competition of the jungle. Or not.

CURRENTLY, THE SONG that music may sing in human evolution is featured in *Behavioral and Brain Sciences*. Savage and Mehr are center stage. They each, with their respective colleagues, penned separate articles that have attracted 60 responses from a cast of scientists who study music.

Savage wrote that music is for social bonding like vision is for seeing.[4] Performing music is a natural act that calls out to be shared. Singing, drumming, and dancing in harmony with others generates "positive feelings" and "mutual accomplishment." As evolutionary biologists have long shown, language draws people together too. As does grooming. But music does it better. It can bind more people across wider areas. Social bonding, gained through music, yields evolutionary dividends that include "a larger group of potential allies, increased child rearing success, increased mating success, and better-functioning coalitions," Savage wrote.

Drawing on a library of research in music and science, Savage took his thesis directly to the brain. Music, with its combinations of rhythms and pitches, activates mechanisms in the brain's motor system, the neural

Music underscores how different people can be and still feel connected.

directors of walking, talking, and, more to the point, dancing! Music sets up mental expectations of the next note and then meets or upends those expectations to deliver an emotional rush. As our brains groove along the continuum of anticipation and surprise, they stir chemicals that spark rewarding feelings of sociality, the same chemicals behind love. “There’s a world of evidence that when people move in synchrony, they are more willing to help each other to cooperate,” Savage said to me.

Having assimilated a lot of the same research, Mehr doesn’t buy the theory that music evolved for social bonding.[5] “Evolution doesn’t really care how bonded you are with your partners,” he told me. “Evolution cares about reproductive success. And you can have reproductive success in the absence of social bonding. We tested that in the texts of anthropologists and ethnomusicologists writing about musical behavior. Do keywords associated with social bonding and group cohesion turn up reliably with music? And the answer was, not so much.”

In his *Behavioral and Brain Sciences* paper, Mehr stated music evolved as a “credible signal” in at least two contexts: territorial calls and infant care. “In mammals, loud auditory signals are frequently antagonistic, and territorial advertisements are a prime example,” Mehr wrote. Territorial calls signal an area is occupied. Music, notably loud singing and drumming, was “a means for groups to credibly show off their qualities to other groups.” Music also served parents well. “Human parents increase their offspring’s fitness by attending to them and protecting them from harm,” Mehr wrote.

But parents are busy and attention is a limited resource. So to signal their care and attention, particularly when they had more than one child and had to focus on the youngest, our ancestral parents sang to their kids. The features of music, consistent with credible signaling, Mehr concluded, "give rise to a universal human psychology of music."

Scholars' responses to Savage's and Mehr's theses varied, some in support, some not. For instance, Steven Pinker, a professor of psychology at Harvard, author of *How the Mind Works* and other popular books about cognitive science, wasn't sold on either thesis. But he's not sold that music meets any of the criteria of a Darwinian adaptation, like language or stereo vision. He has called music "auditory cheesecake," a satisfying dessert, but not a nutritious meal needed for survival. He praised Mehr for "performing masterful necropsies on the bond-the-group and woo-the-ladies hypotheses," but stopped short of endorsing his "signal" thesis. "If territorial and infant signaling were the most robust explanations for the evolution of music, we should see signs that those two functions are particularly robust, universal, archetypal, pervasive, and salient in the panoply of musical experience," Pinker wrote. "But that is exactly what was *not* found in Mehr *et al.*'s (2019) mammoth cross-cultural survey." Pinker in fact was one of the paper's *et al.*'s. The four types of songs spotlighted in the paper, Pinker added, "were pretty much equally robust, distinctive, and universal."

Reading the many responses to Savage's and Mehr's papers is an education in how scientists fill in the blanks of one another's research to produce an amazing, comprehensive body of work—without arriving at a conclusion. The universality of music is wired into our biology. How could we deny it? But why? And, genetically, where?

Language draws people together too. As does grooming. But music does it better.

Aniruddh Patel, a professor of psychology at Tufts University, author of the 2008 book, *Music, Language and the Brain*, and numerous papers on the evolution of music, is a respected scholar in the field. Both Savage and Mehr reference his work in their studies. Patel told me he has favored the social bonding theory for music in his past work, but wasn't ready to stake his claim on it. When you surveyed the fields of science for how and why music evolved, he said, "I don't think there's overwhelming evidence for any single hypothesis, and I don't think that many of them are mutually exclusive."

What excites Patel, and guides his current research, is that music, which comes naturally to humans, is not something we share with other primates. That fact, he said, "is a clue that something has changed in our brains relative to other primates." He added, "The most interesting thing about us as species is that we literally mixed biology and culture in our brain. We have an innate predisposition for music, there's no question about that. But learning plays a huge role. If there has been a gene-culture coevolution for musicality, the larger message for the sciences is that the interplay of biology and culture has shaped important aspects of the human mind. If you want to wax philosophical, the idea that we have evolved to be musical suggests that the arts are baked into human nature."

GLOBAL VOICES Composer Osvaldo Golijov (third from left) with (l-r) Wu Tong, Nora Fischer, and Biella da Costa, vocalists on Golijov's recent album, *Falling Out of Time*. "I want to write the music that I feel I came to the world to write," Golijov said. "The music that I and no one else will write."

DAVID O'CONNOR

INTUITIVELY, IT SURE SEEMS music is inherent in our nature. But my research brought me an insight that felt like a revelation. Patel spoke about "musicality." Savage also used the term in his *Behavioral and Brain Sciences* paper: "musicality encompasses the underlying biological capacities that allow us to perceive and produce music." Music itself is what blossoms out of our biology into 1,000 sounds, shaped and colored by the world's individual cultures. The debate over the universality of music can get too focused on what people have in common. Music around the world may share psychological and structural elements. But those commonalities are overtures to how diverse music can be. Our underlying musicality, you might say, allows us to appreciate music's individuality. Ultimately the most human thing about music is it underscores how different people can be and still feel connected. Maybe that's why art is baked into our nature. I wanted to ask the artist.

One of the most remarkable musicians who bridges cultures is Argentinian composer Osvaldo Golijov. Nearly all of his acclaimed works are steeped in the tango of his native land. But that's just a starting point for music that expresses the world in countries of notes. In his album, *Ayre*, a song cycle; *Le Pasion segun San Marcos*, an opera; *Yiddishbbuk*, a chamber-music work; and most recently, *Falling Out of Time*, a song cycle based on a poetic novel by David Grossman about the death of his son; you hear the distinct sounds of Morocco, Mali, Israel, and America. They blend into musical figures like Picasso paintings.

Like the members of DakhaBrakha, Golijov told me how satisfying it was to experience concert audiences around the world being swept into his music. Rhythm was the thing. "Before music is emotion it's motion," he said. "I think all universal musics have rhythm. The attempt to negate rhythm just doesn't resonate with our biology. Our blood circulates. We have two legs and we walk. We breathe in and out. We have a heartbeat."

Golijov asked me about my research. I told him about the four basic song types that had come out of Mehr's study. Oh, yes, of course, he said, love and healing and dance very much shaped his music. He was particularly intrigued by the fourth type, lullabies. He thought about it for a moment and then said that composing was like the first lullaby.

"A lullaby didn't start as notes," Golijov said. "It didn't start from a mother saying, 'OK, I'm going to go, 'Do re mi.' The mother starts humming and at some point that becomes a tune. The impulse to calm or love her baby becomes a note, a line, and evolves into whatever she repeats. We like repetition. We like to hear the same story every night. My music is the same. What do I want to say? Do I want to calm a baby? OK, I will start there. And, yes, at some point, I will arrive at precision—the precision of gesture, of speech, of rhythm, of color. So that original gesture that didn't even have notes at the beginning becomes pure music. The origin doesn't matter anymore."

KEVIN BERGER is the editor of *Nautilus*.

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REFLECTIVES
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ASPIRING
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That Is Not How Your Brain Works

Forget these scientific myths to better understand your brain and yourself

BY LISA FELDMAN BARRETT

THE 21ST CENTURY is a time of great scientific discovery. Cars are driving themselves. Vaccines against deadly new viruses are created in less than a year. The latest Mars Rover is hunting for signs of alien life. But we're also surrounded with scientific myths: outdated beliefs that make their way regularly into news stories.

Being wrong is a normal and inevitable part of the scientific process. We scientists do our best with the tools we have, until new tools extend our senses and let us probe more deeply, broadly, or precisely. Over time, new discoveries lead us to major course corrections in our understanding of how the world works, such as natural selection and quantum physics. Failure, therefore, is an opportunity to discover and learn.[1]

But sometimes, old scientific beliefs persist, and are even vigorously defended, long after we have sufficient evidence to abandon them. As a neuroscientist, I see scientific myths about the brain repeated regularly in the media and corners of academic research. Three of them, in particular, stand out for correction. After all, each of us has a brain, so it's critical to understand how that three-pound blob between your ears works.

HAND DRAW / SHUTTERSTOCK

MYTH NUMBER ONE is that *specific parts of the human brain have specific psychological jobs*. According to this myth, the brain is like a collection of puzzle pieces, each with a dedicated mental function. One puzzle piece is for vision, another is for memory, a third is for emotions, and so on. This view of the brain became popular in the 19th century, when it was called phrenology. Its practitioners believed they could discern your personality by measuring bumps on your skull. Phrenology was discredited by better data, but the general idea was never fully abandoned.[2]

Today, we know the brain isn't divided into puzzle pieces with dedicated psychological functions. Instead, the human brain is a massive network of neurons.[3] Most neurons have multiple jobs, not a single psychological purpose.[4] For example, neurons in a brain region called the anterior cingulate cortex are regularly involved in memory, emotion, decision-making, pain, moral judgments, imagination, attention, and empathy.

I'm not saying that every neuron can do everything, but most neurons do more than one thing. For example, a brain region that's intimately tied to the ability to see, called primary visual cortex, also carries information about hearing, touch, and movement.[5] In fact, if you blindfold people with typical vision for a few days and teach them to read Braille, neurons in their visual cortex become more devoted to the sense of touch.[6] (The effect disappears in a day or so without the blindfold.)

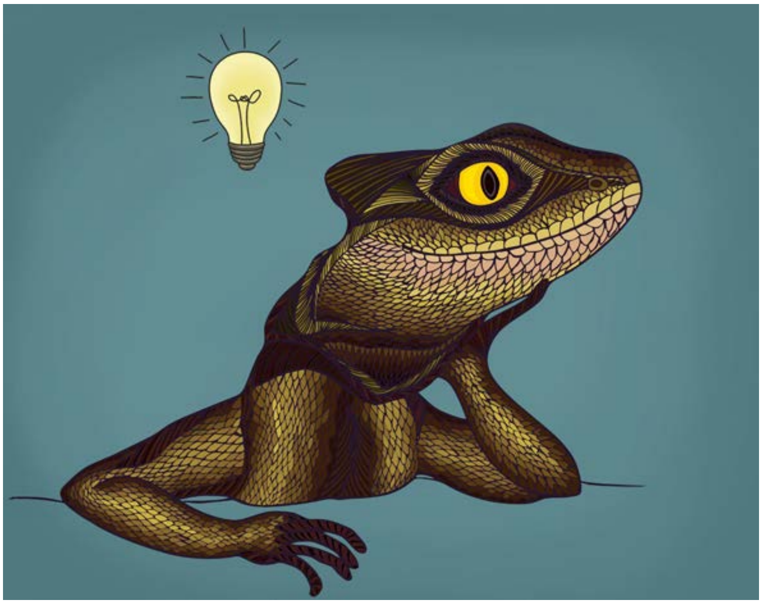
In addition, the primary visual cortex is not necessary for all aspects of vision. Scientists have believed for a long time that severe damage to the visual cortex in the left side of your brain will leave you unable to see out of your right eye, assuming that the ability to see out of one eye is largely due to the visual cortex on the opposite side. Yet more than 50 years ago, studies on cats with cortical blindness on one side showed that it is possible to restore some of the lost sight by *cutting* a connection deep in the cat's midbrain. A bit more damage allowed the cats to orient toward and approach moving objects.

Perhaps the most famous example of puzzle-piece thinking is the "triune brain": the idea that the human brain evolved in three layers. The deepest layer, known as the lizard brain and allegedly inherited from reptile ancestors, is said to house our instincts. The middle layer, called the limbic system, allegedly contains emotions inherited from ancient mammals. And the topmost layer, called the neocortex, is said to be uniquely human—like icing on an already baked cake—and supposedly lets us regulate our brutish emotions and instincts.

Brains don't work by stimulus and response. All your neurons are firing at various rates all the time.

This compelling tale of brain evolution arose in the mid 20th century, when the most powerful tool for inspecting brains was an ordinary microscope. Modern research in molecular genetics, however, has revealed that the triune brain idea is a myth. Brains don't evolve in layers, and all mammal brains (and most likely, all vertebrate brains as well) are built from a single manufacturing plan using the same kinds of neurons.

Nevertheless, the triune brain idea has tremendous staying power because it provides an appealing explanation of human nature. If bad behavior stems from our inner beasts, then we're less responsible for some of our actions. And if a uniquely human and rational neocortex controls those beasts, then we have the most highly evolved brain in the animal kingdom. Yay for humans, right? But it's all a myth. In reality, each species has brains that are uniquely and effectively adapted to their environments, and no animal brain is "more evolved" than any other.



LIZARD BRAIN Why does the tale linger that our instincts stem from a part of our brain inherited from reptilian ancestors? Because if bad behavior stems from our inner beasts, then we're less responsible for some of our actions.

GALINA GALA / SHUTTERSTOCK

Myth number one is that specific parts of the human brain have specific psychological jobs.

So why does the myth of a compartmentalized brain persist? One reason is that brain-scanning studies are expensive. As a compromise, typical studies include only enough scanning to show the strongest, most robust brain activity. These underpowered studies produce pretty pictures that appear to show little islands of activity in a calm-looking brain. But they miss plenty of other, less robust activity that may still be psychologically and biologically meaningful. In contrast, when studies are run with enough power, they show activity in the majority of the brain.[7]

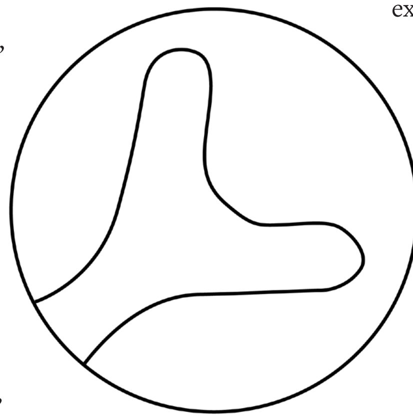
Another reason is that animal studies sometimes focus on one small part of the brain at a time, even just a few neurons. In pursuit of precision, they wind up limiting their scope to the places where they expect to see effects. When researchers instead take a more holistic approach that focuses on all the neurons in a brain—say, in flies, worms, or even mice—the results show more what looks like whole-brain effects.[8]

Pretty much everything that your brain creates, from sights and sounds to memories and emotions, involves your whole brain. Every neuron communicates with thousands of others at the same time. In such a complex system, very little that you do or experience can be traced to a simple sum of parts.

MYTH NUMBER TWO is that *your brain reacts to events in the world*. Supposedly, you go through your day with parts of your brain in the off position. Then something happens around you, and those parts switch on and "light up" with activity.

Brains, however, don't work by stimulus and response. All your neurons are firing at various rates all the time. What are they doing? Busily making predictions.[9] In every moment, your brain uses all its available information (your memory, your situation, the state of your body) to take guesses about what will happen in the next moment. If a guess turns out to be correct, your brain has a head start: It's already launching your body's next actions and creating what you see, hear, and feel. If a guess is wrong, the brain can correct itself and hopefully learn to predict better next time. Or sometimes it doesn't bother correcting the guess, and you might see or hear things that aren't present or do something that you didn't consciously intend. All of this prediction and correction happens in the blink of an eye, outside your awareness.

If a predicting brain sounds like science fiction, here's a quick demonstration. What is this picture?



If you see only some curvy lines, then your brain is trying to make a good prediction and failing. It can't match this picture to something similar in your past. (Scientists call this state "experiential blindness.") To cure your blindness, see References. Suddenly, your brain can make meaning of the picture. The description gave your brain new information, which conjured up similar experiences in your past, and your brain used those experiences to launch better predictions for what you should see. Your brain has transformed ambiguous, curvy lines into a meaningful perception. (You will probably never see this picture as meaningless again.)

Predicting and correcting is a more efficient way to run a system than constantly reacting in an uncertain world. This is clear every time you watch a baseball game. When the pitcher hurls the ball at 96 miles per hour toward home plate, the batter doesn't have enough time to wait for the ball to come close, consciously see it, and then prepare and execute the swing. Instead, the batter's brain automatically predicts the ball's future location, based on rich experience, and launches the swing based on that prediction, to be able to have a hope of hitting the ball. Without a predicting brain, sports as we know them would be impossible to play.

What does all this mean for you? You're not a simple stimulus-response organism. The experiences you have today influence the actions that your brain automatically launches tomorrow.

THE THIRD MYTH is that *there's a clear dividing line between diseases of the body*, such as cardiovascular disease, *and diseases of the mind*, such as depression. The idea that body and mind are separate was popularized by the philosopher René Descartes in the 17th century (known as Cartesian dualism) and it's still around today, including in the practice of medicine. Neuroscientists have found, however, that the same brain networks responsible for controlling your body also are involved in creating your mind.[10] A great example is the anterior cingulate cortex, which I mentioned earlier. Its neurons not only participate in all the psychological functions I listed, but also they regulate your organs, hormones, and immune system to keep you alive and well.

Every mental experience has physical causes, and physical changes in your body often have mental consequences, thanks to your predicting brain. In every moment, your brain makes meaning of the whirlwind of activity inside your body, just as it does with sense data from the outside world. That meaning can take different forms. If you have tightness in your chest that your brain makes meaningful as physical discomfort, you're likely to visit a cardiologist. But if your brain makes meaning of that same discomfort as distress, you're more likely to book time with a psychiatrist. Note that your brain isn't trying to distinguish two different physical sensations here. They are pretty much identical, and an incorrect prediction can cost you your life. Personally, I have three friends whose mothers were misdiagnosed with anxiety[11] when they had serious illnesses, and two of them died.

When it comes to illness, the boundary between physical and mental is porous. Depression is usually catalogued as a mental illness, but it's as much a metabolic illness as cardiovascular disease, which itself has significant mood-related symptoms. These two diseases occur together so often that some medical researchers believe that one may cause the other. That perspective is steeped in Cartesian dualism. Both depression[12] and cardiovascular disease[13] are known to involve problems with metabolism, so it's equally plausible that they share an underlying cause.

Modern research in molecular genetics has revealed that the triune brain idea is a myth.

When thinking about the relationship between mind and body, it's tempting to indulge in the myth that the mind is solely in the brain and the body is separate. Under the hood, however, your brain creates your mind while it regulates the systems of your body. That means the regulation of your body is itself part of your mind.

Science, like your brain, works by prediction and correction. Scientists use their knowledge to fashion hypotheses about how the world works. Then they observe the world, and their observations become evidence they use to test the hypotheses. If a hypothesis did not predict the evidence, then they update it as needed. We've all seen this process in action during the pandemic. First we heard that COVID-19 spread on surfaces, so everyone rushed to buy Purell and Clorox wipes. Later we learned that the virus is mainly airborne and the focus moved to ventilation and masks. This kind of change is a normal part of science: We adapt to what we learn. But sometimes hypotheses are so strong that they resist change. They are maintained not by evidence but by ideology. They become scientific myths.

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The mystery picture is a mermaid swimming past a porthole.

Consciousness Is Just a Feeling

With help from Freud, this neuropsychologist locates consciousness in choice

BY STEVE PAULSON

WHEN HE WAS A BOY, Mark Solms obsessed over big existential questions. *What happens when I die? What makes me who I am?* He went on to study neuroscience but soon discovered that neuropsychology had no patience for such open-ended questions about the psyche. So Solms did something unheard of for a budding scientist. He reclaimed Freud as a founding father of neuroscience and launched a new field, neuropsychoanalysis.

Solms had one other obstacle in his path. Born in Namibia, where his father worked for a South African diamond mining company, he grew up under apartheid in South Africa. Solms later worked at a hospital in Soweto, where a military occupation tried to clamp down on protesters. "Once you reach the end of your studies, you're required to join the very same army whose victims I was looking after," he told me. "That was emotionally impossible." So he fled to England, where he trained as a psychoanalyst, and didn't move back to South Africa until apartheid was dismantled.

Solms has spent decades working to reconcile brain science with the study of lived experience. Now, he presents his own theory of consciousness in a new book, *The Hidden Spring*. Solms believes neuropsychology has been looking for consciousness in the wrong place. "Since the cerebral cortex is the seat of intelligence, almost everybody thinks that it is also the seat of consciousness," Solms writes. "I disagree; consciousness is far more primitive than that. It arises from a part of the brain that humans share with fishes. This is the 'hidden spring' of the title." The book is a deep dive into modern neuroscience, peppered with surprising explanations for how we think, dream, remember, and perceive.

I reached Solms in Cape Town, South Africa, where he's stayed during the COVID-19 lockdown. We talked about the brain-mind problem, the biases of neuropsychology, and how a family trauma shaped the course of his life.

You write about a seminal moment in your childhood when your older brother suffered a serious brain injury. Can you describe what happened?

I was 4 and he was 6. My parents were yachting and I was down at the water's edge, but he, with some friends, clambered onto the roof of the clubhouse. Then he tripped and fell three stories onto the pavement below and fractured his skull. He lost consciousness on impact and sustained an intracerebral hemorrhage. We were living in a small village, so he had to be flown to a hospital in Cape Town, and he was very lucky to survive the accident. What was so disturbing and really difficult to comprehend for me was the fact that he looked the same, but was utterly changed. He lost his developmental milestones. For example, he became incontinent and his personality was very changed. He was much more emotional, irascible and difficult, but also intellectually, he was changed.

You say this had a profound impact on you.

It did. We underestimate little children. You start thinking, "How can it be that the brain is this thing in his head that's been damaged and now he looks the same but isn't the same? Where is he? How can this person, my brother, be an organ?" I quickly extrapolated that to my own case and thought, "Hmmm, am I my brain and how can that be? If my brain were to be damaged, would I be a different person? Where would the original version of me go?" And it was a tragedy for my parents. They felt terribly guilty.

PAGES 42-43: STUNNINGART / SHUTTERSTOCK

So as a boy, you were asking some profound questions that neuroscience deals with today. What is the self? And how is the brain connected to our mental experience?
I think I was just plunged into them prematurely because of that event. For me, it was also the question of mortality. If my body dies, I'm going to disappear, and that was just terrifying. And I thought, well, if you're gone forever, what's the point of doing anything then? That disturbed me very much and it spiraled me into what can only be described as a depression. I remember feeling in the mornings, What's the point of going to school? And not being able to summon the energy to tie my shoelaces. Obviously, I don't believe at age 4 or 5 that I decided I'm going to be a neuroscientist, but in retrospect, it's clear that the two things must be connected. It's sort of the solution to that nihilistic despair. Somewhere in my teens I remember thinking, the only thing really worth doing is to try and understand what existence is. What actually is sentience?

If my brain were damaged, would I be a different person? Where would the original version of me go?

You went on to study neuroscience—specifically, the science of dreams. How did that figure into your thinking about the nature of consciousness?
The particular aspect of neuroscience that interested me was how the mind and brain relate, so neuropsychology was the domain of the neurosciences that was most compelling for me. But when I arrived at university, I was taught about abstract functions—the information processing mechanisms of memory, language, perception, and executive control. There was no interest in the actual subjective being of the mind. When I asked questions about the contents of memory and the dynamics of one's own lived life, I was seriously advised by my professors that you shouldn't ask questions like that. It's bad for your career.

You made a big discovery that overturned the prevailing theory that we only dream during REM sleep. What did you find?
It was just assumed that when your REM sleep stops, your dreams also stop. But I found that human patients with damage to the part of the brain generating REM sleep nevertheless continue to experience dreams. In retrospect, you realize what a significant methodological error we made. That's the price we pay for not gathering subjective data. You know, the actual subjective experience of dreams is an embarrassment to science. And this is what my professors had in mind when they were saying, don't study things like that. But you're going to be missing something rather important about how the brain works if you leave out half of the available data.

Your interest in Freud is very unusual for a neuroscientist. You actually trained to become a psychoanalyst, and since then, you've edited the complete psychological works of Freud.
Yes, and my colleagues were horrified. I had been taught this was pseudoscience. One of them said to me, "You know, astronomers don't study astrology." It's true that psychoanalysis had lost its bearings. Freud was a very well-trained neuroscientist and neurologist, but in successive generations that grounding of psychoanalysis in the biological sciences had been lost. So I can understand where some of the disdain for psychoanalysis came from. But to its credit, it studied the actual lived life of the mind, which was the thing that interested me, and was missing from neuropsychology. So I turned to psychoanalysis to find any kind of systematic attempt to study subjective experience and to infer what kinds of mechanisms lay behind it.

Did we get Freud wrong? Did he have scientific insights that we've ignored?
Very much so. I'm not going to pretend that Freud didn't make some gigantic mistakes. That's to be expected. He was a pioneer, taking the very first steps in trying to systematically study subjective experience. The reason he made so little progress and abandoned neuroscience was because there weren't scientific methods by which you could study things. Even the EEG was only brought into common use after the Second World War. So there were no methods for studying in vivo what's going on

WHO AM I? "How does all of this complex stuff that makes my life the way it is relate to this bodily organ?" asks Mark Solms, who's spent a lifetime studying the brain and consciousness, unafraid to go against the academic grain to ask the most primal existential questions.

in the brain, let alone the methods we have nowadays. But the sum of his basic observations, the centrality of emotion, was how much affective feelings influence cognitive processes. That's the essence of what psychoanalysis is all about, how our rational, logical, cognitive processes can be distorted by emotional forces.

You founded the new field of "neuropsychoanalysis." What's the basic premise of this approach?
The neuropsychology I was taught might as well have been neurobehaviorism. Oliver Sacks famously wrote in 1984 that neuropsychology is admirable, but it excludes the psyche, by which he meant the active living subject of the mind. That really caught my attention. So I wanted to bring the psyche back into neuropsychology. Emotion was just not studied in the neuropsychology of the 1980s. The centrality of emotion in the life of the mind and what lies behind emotion is what Freud called "drive." Basically, his idea was that unpleasant feelings represent the failures to meet those needs and pleasant feelings represent the opposite. It's how we come to know how we're meeting our deepest biological needs. And that idea gives an underpinning to cognition that I think is sorely lacking in cognitive science, pure and simple.

There are huge debates about the science of consciousness. Explaining the causal connection between brain and mind is one of the most difficult problems in all of science. On the one hand, there are the neurons and synaptic connections in the brain. And then there's the immaterial world of thinking and feeling. It seems like they exist in two entirely separate domains. How do you approach this problem?
Subjective experience—consciousness—surely is part of nature because we are embodied creatures and we are experiencing subjects. So there are two ways in which you can look on the great problem you've just mentioned. You can either say it's impossibly difficult to imagine how the physical organ becomes the experiencing subject, so they must belong to two different universes and therefore, the subjective experience is incomprehensible and outside of science. But it's very hard for me to accept a view like that. The alternative is that it must somehow be possible to bridge that divide.

The major point of contention is whether consciousness can be reduced to the laws of physics or biology. The philosopher David Chalmers has speculated that consciousness is a fundamental property of nature that's not reducible to any laws of nature.
I accept that, except for the word "fundamental." I argue that consciousness is a property of nature, but it's not a fundamental property. It's quite easy to argue that there was a big bang very long ago and long after that, there was an emergence of life. If Chalmers' view is that consciousness is a fundamental property of the universe, it must have preceded even the emergence of life. I know there are people who believe that. But as a scientist, when you look at the weight of the evidence, it's just so much less plausible that there was already some sort of elementary form of consciousness even at the moment of the Big Bang. That's basically the same as the idea of God. It's not really grappling with the problem.

ILHAAM ABRAHAM

My colleagues were horrified that I studied Freud. I had been taught this was pseudoscience.

Where are those feelings rooted in the brain?

Feeling arises in a very ancient part of the brain, in the upper brainstem in structures we share with all vertebrates. This part of the brain is over 500 million years old. The very telling fact is that damage to those structures—tiny lesions as small as the size of a match head in parts of the reticular activating system—obliterates all consciousness. That fact alone demonstrates that more complex cognitive consciousness is dependent upon the basic affective form of consciousness that's generated in the upper brainstem.

You can certainly find all kinds of correlations between brain function and mental activity. We know that brain damage—for instance, what happened to your brother—can change someone's personality. But it still doesn't explain causation. As the philosopher John Searle said, "How does the brain get over the hump from electrochemistry to feeling?"

I think we have made that problem harder for ourselves by taking *human* consciousness as our model of what we mean by consciousness. The question sounds so much more magical. How is it possible that all of this thinking and feeling and philosophizing can be the product of brain cells? But we should start with the far more elementary rudiment of consciousness—feeling. Think about consciousness as just being something to do with existential value. Survival is good and dying is bad. That's the basic value system of all living things. Bad feelings mean you're doing badly—you're hungry, you're thirsty, you're sleepy, you're under threat of damage to life and limb. Good feelings mean the opposite—this is good for your survival and reproductive success.

You're saying consciousness is essentially about feelings. It's not about cognition or intelligence.

That's why I'm saying the most elementary forms of consciousness give us a much better prospect of being able to solve the question you're posing. How can it happen that a physical creature comes to have this mysterious, magical stuff called consciousness? You reduce it down to something much more biological, like basic feelings, and then you start building up the complexities. A first step in that direction is "I feel." Then comes the question, What is the cause of this feeling? What is this feeling about? And then you have the beginnings of cognition. "I feel like this about that." So feeling gets extended onto perception and other cognitive representations of the organism in the world.

So we place too much emphasis on the cortex, which we celebrate because it's what makes humans smart.

Exactly. Our evolutionary pride and joy is the huge cortical expanse that only mammals have, and we humans have even more of it. That was the biggest mistake we've made in the history of the neuroscience of consciousness. The evidence for the cortex being the seat of consciousness is really weak. If you de-corticate a neonatal mammal—say, a rat or a mouse—it doesn't lose consciousness. Not only does it wake up in the morning and go to sleep at night, it runs and hangs from bars, swims, eats, copulates, plays, raises its pups to maturity. All of this emotional behavior remains without any cortex.

And the same applies to human beings. Children born with no cortex, a condition called hydranencephaly—not to be confused with hydrocephaly—are exactly the same as what I've just described in these experimental animals. They wake up in the morning, go to sleep at night, smile when they're happy and fuss when they're frustrated. Of course, you can't speak to them, because they've got no cortex. They can't tell you that they're conscious, but they show consciousness and feeling in just the same way as our pets do.

You say we really have two brains—the brainstem and the cortex.

Yes, but the cortex is incapable of generating consciousness by itself. The cortex borrows, as it were, its consciousness from the brainstem. Moreover,

That was the biggest mistake we've made in the history of the neuroscience of consciousness.

consciousness is not intrinsic to what the cortex does. The cortex can perform high level, uniquely human cognitive operations as reading with comprehension, without consciousness being necessary at all. So why does it ever become conscious? The answer is that we have to feel our way into cognition because this is where the values come from. Is this going well or badly? All choices, any decision-making, has to be grounded in a value system where one thing is better than another thing.

So what is thinking? Can we even talk about the neurochemistry of a thought?

A thought in its most basic form is about choice. If you don't have to make a choice, then it can all happen automatically. I'm now faced with two alternatives and I need to decide which one I'm going to do. Consciousness enables you to make those choices because it contributes value. Thinking goes on unconsciously until you're in a state of uncertainty as to what to do. Then you need feeling to feel your way through the problem. The bulk of our cognition—our day-to-day psychological life—goes on unconsciously.

How does memory figure into consciousness?

The basic building block of all cognition is the memory we have. We have sensory impressions coming in and they leave traces which we can then reactivate in the form of cognitions and reassemble in all sorts of complicated ways, including coming up with new ideas. But the basic fabric of cognition is memory traces. The cortex is this vast storehouse of representations. So when I said earlier that cognition is not intrinsically conscious, that's just saying that memories are, for the most part, *We get the sense of mystery beaten out of us at medical school or graduate programs.*

latent. You couldn't possibly be conscious of all of those billions of bits of information you have imbibed during your lifetime. So what is conscious is drawn up from this vast storehouse of long-term memory into short-term working memory. The conscious bit is just a tiny fragment of what's there.

You say the function of memory is to predict our future needs. And the hippocampus, which we typically regard as the brain's memory center, is used for imagining the future as well as storing information about the past.
The only point of learning from past events is to better predict future events. That's the whole point of memory. It's not just a library where we file away everything that's happened to us. And the reason why we need to keep a record of what's happened in the past is so that we can use it as a basis for predicting the future. And yes, the hippocampus is every bit as much for imagining the future as remembering the past. You might say it's remembering the future.

Wouldn't a true science of consciousness, of subjective experience, explain why particular thoughts and memories pop into my brain?
Sure, and that's exactly why I take more seriously than most neuroscientists what psychoanalysts try to do. They ask, "Why this particular content for Steve at this point in his life? How does it happen that neurons in my brain generate all of this?" I'm saying if you start with the most rudimentary causal mechanisms, you're just talking about a feeling and they're not that difficult to understand in ordinary biological terms. Then there's all this cognitive stuff based on your whole life. How do I go about meeting my emotional needs? And there's your brain churning out predictions and feeling its way through the problem and trying to solve it.

So this is the premise of neuropsychoanalysis. There's one track to explain the biology of what's happening in the brain, and another track is psychological understanding. And maybe I need a psychotherapist to help me unpack why a particular thought suddenly occurs to me.
You've just summed up my entire scientific life in a nutshell. I think we need both. What drove me to study neuroscience in the first place was exactly these incredibly important and interesting questions. How does all of this complex stuff that makes my life the way it is relate to this bodily organ? You know, we get it beaten out of us at medical school or graduate programs that you must lose your wonder and your sense of mystery and excitement and fascination with those big questions. For my own particular reasons, I wasn't able to give up on those questions. That's what motivated me to do what I've done.

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Gaia, the Scientist

What if the first woman scientist was simply the first woman?

BY HOPE JAHREN

THERE EXISTS A SOCIAL HIERARCHY within science that strikes people who are not mixed up in it as ridiculous. It goes like this: Mathematicians are superior to Physicists, who are, in turn, superior to Chemists, who are of course, superior to Biologists. There's also a pecking order *within* each of these disciplines. Take biology, for example: Geneticists are superior to Biochemists, who are superior to Ecologists. The system breaks down when we come to sociology, psychology, and anthropology and devolves into a debate as to whether the social sciences are really Sciences after all.

Scientists arguing about whether a science qualifies as Science is more common than you might think. Zoom in, and you'll see scientists arguing about who does (and doesn't) qualify as a Scientist. Within the last five decades or so, it is generally accepted that more and more women have become Scientists, which implies that if we look back in time, there were fewer and fewer. This ultimately begs the question: Who was the first Woman Scientist?

Was it Marie Curie? She discovered the element radium, and later polonium, near the end of the 19th century. Does she count? After all, she viewed *herself* as more of an Artist: "The scientific history of radium is beautiful. And this is proof that scientific work must be done for itself, for the beauty of science," she wrote in 1921.

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By then I was myself a mother and still questioning whether I was a Scientist, or if I ever really could be.

Was it Émilie du Châtelet? She formulated the existence of infrared energy. Does she count? She apologized often for not knowing how to say what she wanted to say. "I use everyday words here in contravention with propriety but cannot avoid the too-frequent return of the same word because, technically, there are both things and not-things that we call Fire," reads a footnote on the very first page of her dissertation, written in 1758.

Was it Hypatia of Alexandria? She developed the mathematical technique of long division, which was cutting-technology during the fifth century A.D. Does she count? Hypatia taught men of great influence and highest government, and was eventually stripped, stoned, torn to pieces, and burnt to ashes for her trouble. Suidas, the 10th-century author of the first encyclopedia, devoted most of Hypatia's entry to the debate over whether she died a virgin.

Was it the Neanderthal female whose name has been lost to time? Who collected herbs and berries and could distinguish East from West, ripe from rotten, medicine from poison? Does she count? She didn't publish her results but we do have her bones, and we use them to argue over her "cognitive capacities" in the pages of *Nature*.

I've been told, more times than I can count, that these women shouldn't count. That Marie Curie was mostly following her husband's lead. That Émilie du Châtelet was a party-girl who slept with Voltaire and had a knack for translation. That Hypatia's father Theon (or her brother Epiphanius, or the bishop of Ptolemais, or ...) was the original author of her work. That I am prone to anthropomorphizing trees and seeds and Neanderthals. That my personal agenda makes me see Science everywhere, even in the places where it's not.

But certain questions still nag me. Now that I've learned and practiced both, why doesn't cooking count as chemistry? Why doesn't sewing count as geometry? Is gardening so different from botany? Does budgeting not involve math? Were my four grandmothers scientists, the ones who produced enough from too little, refining their techniques as they went along, working and working, in between babies, in between wars, in between being born and being dead?

Why doesn't their laborious trial and error, across generations, involving known and unknown materials, practices, procedures count as the scientific method? Because it produced only food, clothing, shelter, babies and love, and not publications?

What if the first woman scientist was simply the first woman? Was it Eve herself? Was she an horticultural ophiologist? An experimental theologist? Does she count? No, she was just a stolen rib, a spare part. She was born to be a helpmeet, to supply what the beasts of the field and the fowls of the air could not, in sorrow and pain. She was to be ruled over. She was to be cleaved to. And in the end, she was excluded.

THIS LAST YEAR the Earth itself seemed to stop in its tracks as COVID-19 suspended our collective animation. We waited for it to run its course, then for a cure, then for a vaccine. We are still waiting for some kind of ending and for some kind of beginning of what we hope will resemble the past. Quietly and in the background, our planet has circled the sun more-or-less the same way it has done for the last billion years, and we now find ourselves facing our second Earth Day distanced from each other and from the things we used to do.

Scientists arguing about whether a science qualifies as Science is more common than you might think.

Some things will be the same: We will tell each other the story of Gaia, the woman who is much more than a Woman. She is the docile Earth-mother who generously balances and protects the environment and all its inhabitants. She is our New-Age Eve—one who never screwed up—a goddess that can be worshipped by atheists. Above all, she is a nursery-rhyme for grown-ups, charming us away from the empty space where our own efforts should be.

In my 41st year I read Hesiod's original eighth-century B.C. story of Gaia. By then I was myself a mother and a stranger in a strange land, and still questioning whether I was a Scientist, or if I ever really could be. Through my reading, I discovered the real Gaia, and will never believe in the fairy tale again.

The real Gaia emerged spontaneously out of the chaos. First in the universe—she was the universe—until her brothers Tartarus and Eros followed her. Later, while her other younger siblings were squabbling about who was to be Day and who was to be Night, Gaia began her work, and her work was creating.

Gaia was a hard worker and she created almost everything. She eventually gave birth to 20 children—all of them destined to become gods—but during her early career, she labored alone. She brought forth the Sky and the Sea all by herself, in an attempt to build an ever-sure abiding-place for her future family. She was careful to fashion Uranus as her equal, and then took him as her mate.

After a little coaching by Eros, and a lot of work by Gaia, Uranus found himself the father of duodecaplets: six daughters and six sons. At this point in the story, Uranus completely lost his mind.

WOMEN WHO WORK

Gaia created the world, but even then her work wasn't done. Her daughter Rhea had several children with Cronos, but, each time, he would seize and eat the babe when it was barely out of the womb. So, Gaia stepped in, and handed him a swaddled stone instead of Rhea's latest child—which allowed Zeus to be raised to adulthood.

Not at all ready for fatherhood, Uranus shoved all 12 children back inside Gaia, and then rejoiced at her groaning. Gaia responded by inventing the atom, then the elements, and then from them she invented rock and quartz and flint. She then set about to forge a terrible sharp weapon.

Upon its completion, she showed the weapon to her sons and asked which one of them would use it to punish their father? Her youngest and most loyal son, Cronos, volunteered. When Uranus next came close, Cronos reached out and viciously maimed Uranus, and blood gushed across the earth.

Out of nostalgia, or perhaps just frugality, Gaia collected the blood and created from it a great number of Nymphs, and then taught them to differentiate oak trees from ash. Gaia's love for Uranus was over, though they had 12 children in common plus any number of step-monsters and giants. She would, nonetheless, live to know the sorrow of watching her favorite son grow into a violent bully like his father.

Her heart having been broken by Uranus, Gaia turned to her second creation, Pontus, and started over. With him she had five children: three great, proud boys and then two little girls—one sweet and one sour. Their oldest, Nereus, was a Golden Boy, kind and gentle, lawful and honest. A sea nymph rewarded him for his goodness by giving him 50 daughters, each of whom grew into a skilled craftswoman, not unlike her grandmother.

Gaia then turned her attention to her daughter Rhea, who needed her help badly, in the form of protection from Gaia's son, Cronos. Rhea had already given birth five times, and each time, Gaia attended her daughter

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as midwife. After each of these babies had dropped from Rhea's womb and onto Gaia's knees, Cronos grabbed them and swallowed them. One after the other, he had destroyed his children, unable to endure the idea of them growing into beings that might not obey him.

Gaia fled with the desperate Rhea, to a far-away land, where she birthed her grandson, Zeus. With mother and baby safely hidden in the woods, Gaia returned to Cronos carrying a stone swaddled in a blanket, which he immediately thrust down into his belly. As the years rolled on, Cronos repented his actions, but it was too late. Gaia had raised Zeus, nourishing him on the idea that it was his destiny to vanquish his father—a feat he ultimately accomplished using firearms borrowed from his uncles.

This has led me to a deeper truth: that Gaia was a Scientist, I am a Scientist, that your mother and grandmother might be Scientists too.

After all her children had grown up and left home, Gaia found lasting comfort with Tartarus. The oldest of her friends, he had emerged from Chaos just after her, and so had watched her working these many eons, out of the depths of his own exile. Gaia and Tartarus had one son, Typhoeus—a nervous, troubled boy who could not stop his feet from moving and heard voices in his head. He was subject to fits of wild and confused fury, from which only his father could talk him down.

Having pursued her career to its fullest, Gaia sank contentedly into retirement. She blessed her own work and then set aside all toil. She handed the keys of Olympus to her favorite grandchild Zeus, and wished him the best of luck. And that is where Gaia's real story ends.

I know that the above story isn't true. Similar to how I don't believe there was a perfect garden or breathing dust or magic tree or talking snake or poison apple. No, I don't believe in one-eyed giants or three-headed dogs or winged witches or flying horses. But I do believe in second chances at love, and tragedy during childbirth, and mothers that protect and fathers that abuse, and sons that grow to hate their mothers, and good men who know the value of daughters, and failure that comes too early and success that comes too late and to somebody else. I believe in knowing the difference between an oak tree and an ash tree. But most of all, I believe in women who work and follow no one.

Hesiod's untrue story has led me to a deeper truth: that Gaia was a Scientist, that I am a Scientist, that your mother and grandmother might be Scientists too. That we have always been and that we may all dare to count. That maybe it's not selfish cupidity that limits the application of the title. Maybe, like Ptolemy's Earth-centric model of the universe, they set it up wrong from the start. Maybe the only real way to identify a Scientist is when we see the joy and frustration and late nights and failed attempts and glowing pride unspoken whenever we are offered a view of something private and beautiful.

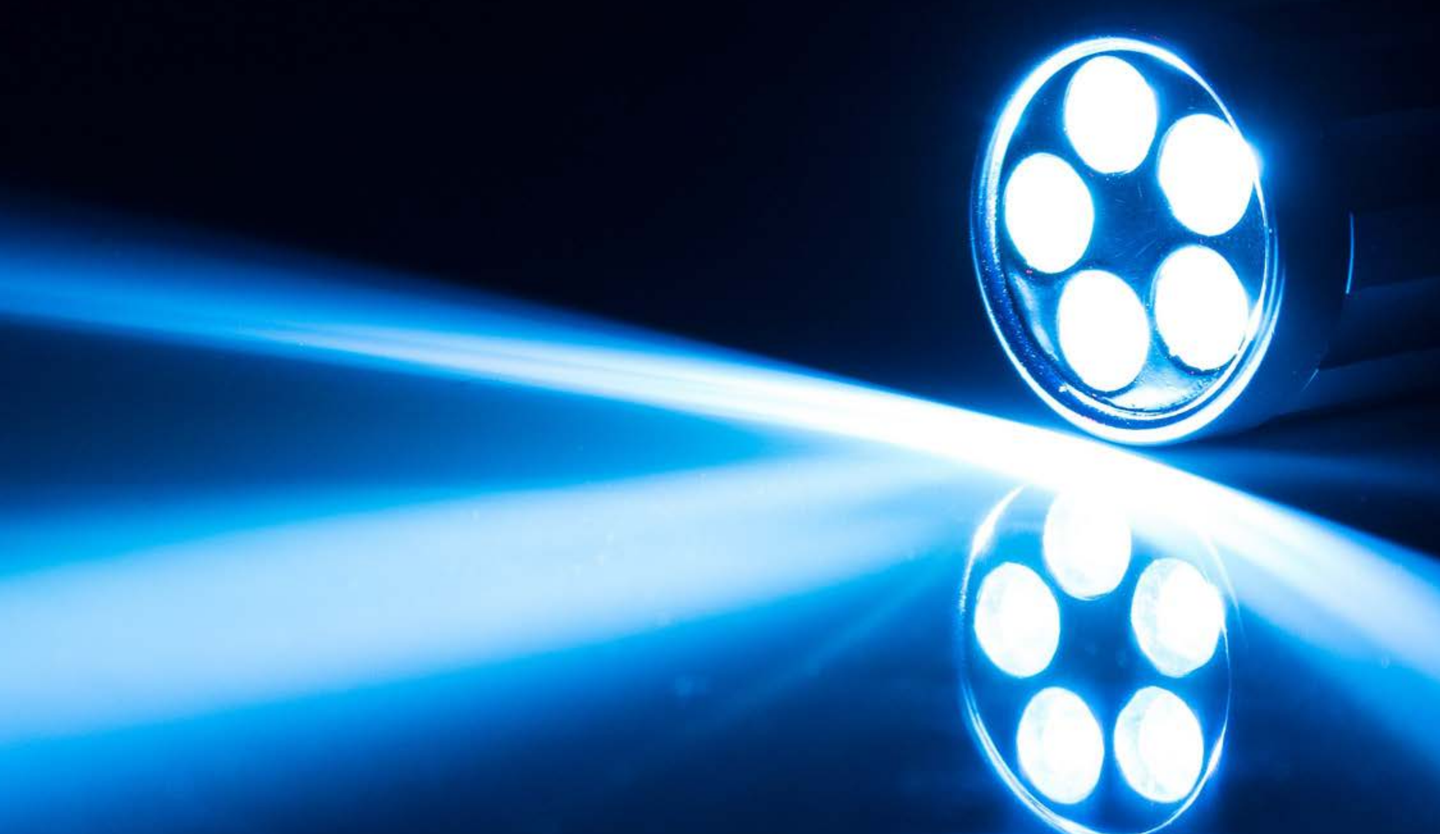
HOPE JAHREN currently serves as the Wilson Professor at the University of Oslo. She has recently finished rewriting her latest book, *The Story Of More*, for a junior high/high school audience. Watch for its release in late 2021.

Blackout in the Brain Lab

What will happen to the organoids? A work of fiction.

BY ERIK HOEL

WHEN THE POWER GOES OUT, the two young scientists are plunged into pitch blackness. After exclamations and fumbling they turn their phone lights on, creating bisecting cones that spear wildly at the darkness and dance over the ceiling.



"I guess they didn't take seriously the idea of a power outage in a Manhattan research facility?" Kierk says. "And it's past midnight. We might be the only ones here."

"Oh my god, the organoids!" Carmen exclaims, "They'll die without power. We have to check on them."

It takes a couple minutes to find the right floor in the darkened research building. The lock to the lab beeps red to both their cards and through the glass window the lab is in shadow. She can't see the cerebral organoids, the small brains grown from induced stem cells taken from adult human tissue samples. Among them is the organoid from *her* tissue sample—and it doesn't look like it or any of the others are getting heat or light. Carmen is already calling, pacing the hall.

"Hey! Hey, it's Carmen."

"What? Is this Carmen?" The tinny reply is from Todd, the researcher in charge of the organoid project.

"Todd, the power is out. That's why I'm calling. We're at the lab and the door is locked and the power is out."

"That is so bad … why are you the one calling me?"

"We were in the building when the power went out. We feel a connection to them. You made the organoids from the members of our research program. Those mini-brains are us. Kind of."

"Just hang on, we're coming."

"Why isn't there a backup generator?" Kierk asks as Carmen hangs up.

"There is one. Supposedly. Either something went wrong or it only serves some areas."

They sit illuminated by phone screens, looking online for the cause of the outage, which seems to be some freak blowout at a power station north of Manhattan.

Minutes pass. Carmen keeps peering through the glass, looking for any sign of light from inside. Occasionally she finds herself thumbing the small scar on her arm that the original punch biopsy left from her sample being taken months ago. She feels energetic despite the late hour, but some smaller part of her is getting flashes of tiredness, like she is two reservoirs and one is filling up as the other drains away.

"When are you going to give this up?" Kierk suddenly asks, putting down his phone. "This investigation into Atif's murder. Or non-murder. The accident. Whatever it was. I mean, lucky for the organoids we were here tonight, sure, but it's only because we were chasing down yet another lead to … absolutely nothing."

"Atif was part of our program. I can't explain how I know what happened, but his death wasn't just a meaningless accident. I just … believe."

"But the null hypothesis—"

SKATZENBERGER / SHUTTERSTOCK

A clattering from the stairwell precedes Todd and Amanda, his assistant, both flushed and breathing heavily. Kierk and Carmen immediately ply them with questions about what's going on outside, getting only that the two had just biked here through an empty city (Carmen doesn't remark on what a coincidence it was that they both got here at the same time, unless they left from the same location).

"It's like in a children's book where someone cast a spell and the whole kingdom goes to sleep," Amanda says breathlessly as the four head inside after Todd unlocks the door, past the stocked shelves and shadows of microscopes.

Carmen pans her light over the far table where the eight Erlenmeyer flasks sit silently like tombs containing the organoids, one for each of the original eight Francis Crick Scholars. Seeing them prompts Todd's cry of—"No, no, no!" With the heat lamps off the air is cool, and on closer examination the Matrigel fluid inside the flasks has begun to separate. The organoids are perfectly still at the bottom, strange planetoids out there alone, glinting and fleshy and white.

"They're dying," Carmen says sadly, crouching down to examine hers.

"We have to do it now," Todd says grimly. "More than a month's work ... Damn!" He slams his hand down on the table and the Matrigel jiggles. Then he disappears into the outside room.

The brain slice hangs in the air like the effluvia of a ghost.

"Can't you just restart the heat lamp or whatever?" Carmen asks Amanda.

Amanda shakes her head as she snaps gloves on. "No, they're irrecoverable. How can we be sure this didn't affect the results? If we do the slices now, at least we can run histology, look at the cytoarchitecture."

"So you're going to cut our clones up?" Kierk asks.

"We don't use that word."

"But that's what they are." Kierk is staring at the blob swaying in the current. "This is the excised neural tube of my clone, stuck in a vat trying to grow into a brain."

"I mean, technically ..."

"What's this white bubble growing off of mine?" Carmen says, pointing. "It looks like a little cup or saucer or ..."

"Oh," Amanda says, leaning over Carmen. "It's trying to grow an eye."

Carmen shivers. "It's trying to *see*?"

"It's not like the eye is going to be functional," she says. But when Carmen holds the phone light up she swears the white puckering cup darkens slightly, as if attempting to dilate.

"Thank god you called us. We were asleep, we never would have known—" Amanda cuts off, looking shocked at herself. Carmen is already touching her arm. "Oh honey. Don't worry. We won't tell anyone."

"What were you two even doing here this late?" Amanda asks.

"Trying to catch a murderer. Supposedly," Kierk says quietly, crouching nose-to-nose with his organoid's flask.

"Atif's death? Wasn't it an accident?" Amanda's eyes flicker over to Atif's organoid.

"We ... I ... don't think so," says Carmen.

"Spooky," Todd says in a clipped voice, coming back in. He grabs up Atif's flask and heads back out. Carmen lets out a low moan of protest. With a sympathetic look Kierk grabs up his organoid's flask. Carmen looks torn, and Kierk briefly wonders if she's going to make a break for it with hers, but soon she's joining him in delivering their mini-brains to the outer room.

Todd has set up the brain slicer, a vibratome, under a lamp so bright after so much darkness that Kierk and Carmen shield their eyes with their free hands. Both the lamp and the vibratome are plugged into a big silver battery. The vibratome is a long metal malocclusion. On the front an open jaw sports a silver metal pad, immersed in some buffer liquid, while tiny blades wait to be lowered down. Todd reaches into the ooze of the Matrigel with his gloved hand, a grimace on his face. Carefully he pulls Atif's organoid up, cupping its underside. Amanda squirts a drop of superglue to the base of the organoid and affixes it to the metallic plate of the vibratome. The organoid, several inches in diameter, white as undifferentiated flesh, sits on the cutting plate like a wet tumor freshly removed.

"It's the last of him," Carmen says suddenly. "He's gone and that's the last ... part of him."

"Just an organoid, Carmen," Todd says. "Set it for fifty microns." The blades are lowered with an electric-razor hum and the machine takes the thinnest sliver off the top, almost impossible to see until Amanda, using tweezers, scoops it off. The slice hangs in the air like the effluvia of a ghost, then is lowered into a small plastic container filled with clear but viscous liquid. It floats to the bottom and then the vibratome hums and another slice sinks down to join the first. This continues in silence, both Kierk and Carmen gripping their flasks, and in only a few minutes the organoid has been halved—Kierk, leaning over, can see white-matter tracts running in bands through the center. So there had been neural activity.

We feel a connection. Those mini-brains are us.

Meanwhile, Todd has scrounged up another vibratome, which he sets up. Amanda, finishing, scratches off the last of Atif's organoid from the metal plate and chucks it into a biohazard bag. Carmen shoots Kierk an indignant look, but then Todd and Amanda turn to them expectantly. After a moment's hesitance they hand over their flasks. In silence they step back and watch the same process unfold. First their organoids are extracted, glued to the plate, then the hum of vibratomes starts. Carmen's hand searches and clasps Kierk's. At the first slice Carmen gasps and her hand tightens, both standing just inside the circle of light where the other two are carefully slicing, removing and storing the tissue, thin as paper. There is a meditativeness to it, a silence, Kierk and Carmen hypnotized by the pair leaning over their tasks Talmudically, as if watching two medieval illustrators at their desks.

As this occurs a strange state has stolen over Kierk, perhaps from the nervousness of the night and the lateness of the hour, but he keeps blinking away strange fantasies that come and go, forms beyond language, like he is

"You had no right! We didn't know it'd be a cell line!"

downloading dreams bit by bit, memories with only the minimal outlines of content, experiences which feel like they are from a different time or a different self. He also knows that he must be imagining this, a mere trick of the mind, an influence from the gravitas of the setting and his current suggestible state. But looking over at Carmen, who has tears running in tracks down her face, he wonders if she feels it too. He squeezes her hand reassuringly.

Todd wipes at his forehead with his wrist, turns to them. "Listen, I appreciate you calling us, you really did save the whole experiment. But we've got this. No need for you here."

"We've got stuff to do anyways," Carmen says quietly, wiping at her eyes discreetly.

"Will you be able to do a paper with the data?" Kierk asks.

"Probably not. This time around we're just checking the cytoarchitecture, making sure there really were neurons, that kind of thing."

"What do you mean 'this time around'?" Carmen says.

"We'll be redoing the experiment," Todd says. "The original samples from your skin have all reverted to pluripotency. They're effectively stem cells, which we can use to make more."

"How many are there going to be?"

"People like to use cell lines that get established early on in the field, for replicability. You're part of the prestigious Francis Crick program so there's a novelty aspect. They grew exceptionally well too, better than anything out there. I imagine your lines will be extremely popular. And the lines are kept around forever. People in a hundred years might still be using these. Congratulations, you're immortal." Todd laughs thinly.

There is stunned silence. Carmen's hand slips from Kierk's as her voice raises—"What? A cell line? A fucking cell line? Are you kidding me?"

Kierk is struck by the thought of all his clone's brains growing, again and again, the same struggling pattern repeating until one day their total mass exceeded this very building, the gigantic weight of all those future hims in dishes all over the world. His own personal Boltzmann brains.

"Come on, Carmen. It's been a crazy night already. Let's go." He tugs on her arm.

"But … You had no right!" Carmen raises her voice. "We didn't know it'd be a cell line!"

"You're not acting like a scientist. Control yourself," Todd says, the professorial rebuke clear in his voice.

"You had—" Kierk tugs Carmen away toward the door as she yells "—no fucking right!"

In the bowl of lamplight with the vibratomes set up Todd stands with his arms crossed while Amanda looks bewildered by the outburst.

"I didn't judge it to be pertinent information," Todd says, glancing over at the remaining lumps resting lifeless at the bottom of the flasks. "If it makes you feel any better it's not like they're conscious."

Carmen yells back as the door is closing—"How could you *possibly* know that?"

Kierk keeps a hand on her arm until they are in the dark stairwell. Once the door clangs shut behind them, they sink to their knees, exhausted, silent. In the utter black it's possible to entertain the idea that the labyrinthine stairwell goes down forever. Carmen's reason tells her that she is only five or six floors up but some other, deeper sense is screaming that she is entirely wrong, that she's nowhere at all. She puts her head back against the cool concrete, feeling like she is floating in the blackness, the outside world a meaningless thing far beyond.

So this is what it is like.

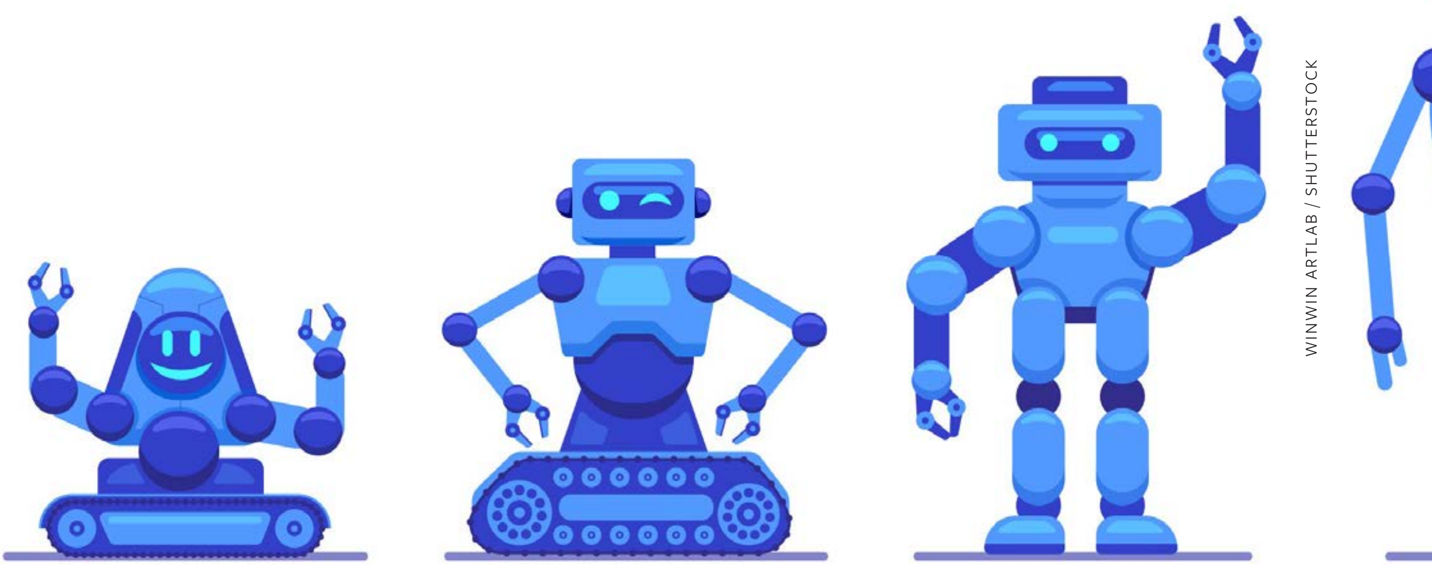
ERIK HOEL is a research assistant professor at Tufts University. He received his Ph.D. in neuroscience from the University of Wisconsin-Madison, was previously a postdoctoral researcher Columbia University, and has been a visiting researcher at the Institute for Advanced Study. A 2018 *Forbes* "30 Under 30" for his neuroscientific research on consciousness, he has won awards for his essays and fiction writing, and was a 2017 Center for Fiction NYC Emerging Writers Fellow. *The Revelations* is his first novel.

How Intelligent Could Life Be Without Natural Selection?

Don't be surprised if alien life forms are a lot like us

BY ARIK KERSHENBAUM

I **COULD STRIDENTLY INSIST** that natural selection is the only way that complex life can evolve, but that's not strictly true. We can already design computers that can learn and reason and—almost—convince an observer that their behavior might be human. It's not unreasonable that in 100 or 200 years, our computer systems will be effectively sentient: human-like robots, similar to *Star Trek*'s Commander Data. Alien civilizations that are considerably more advanced than us are likely already capable of such creations. The possibility—likelihood, even—of such robotic life has implications for our predictions about life on alien planets.



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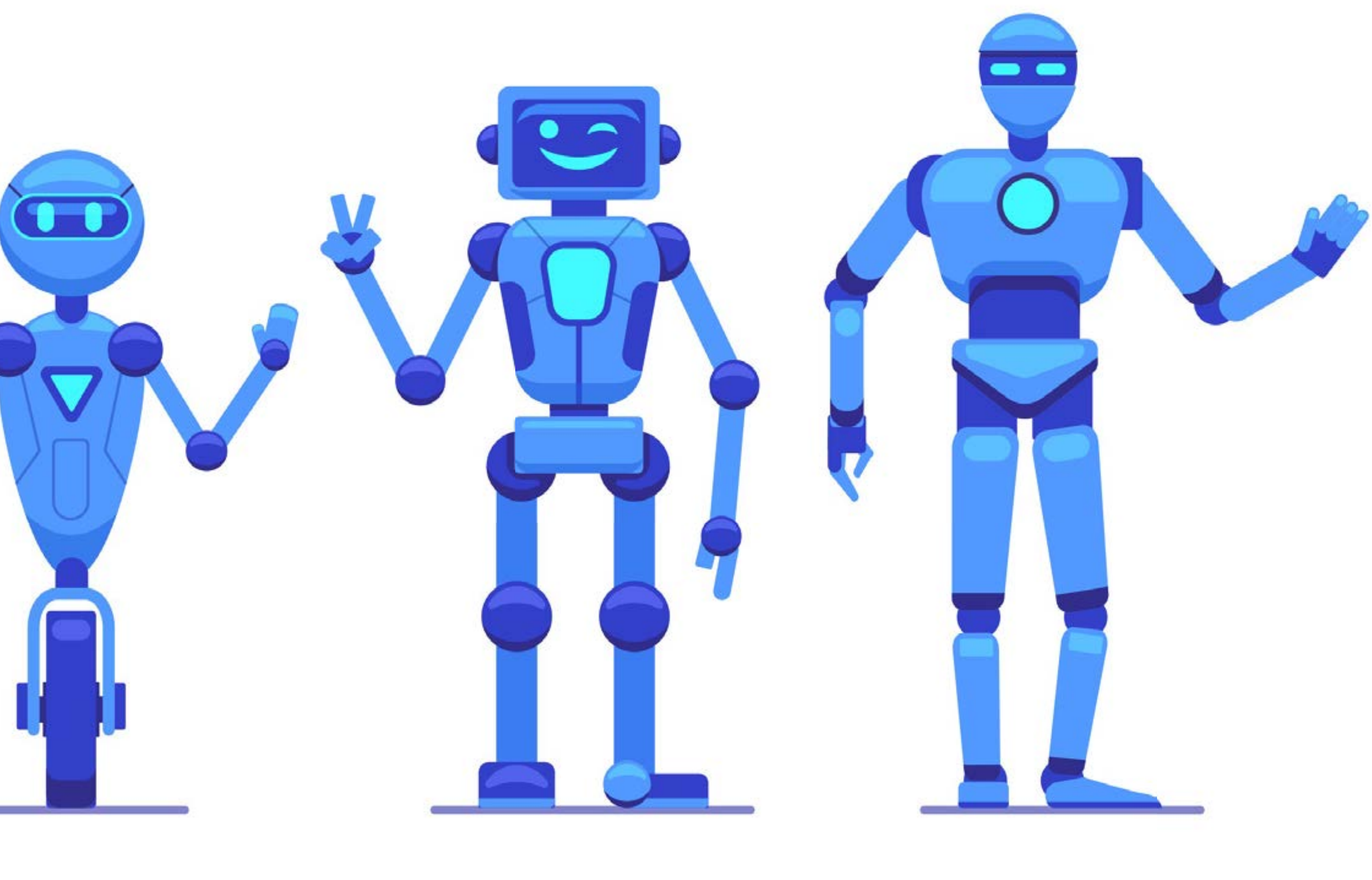
If, as some astrobiologists believe, alien life is likely to be artificial—i.e. "manufactured"—would the rules and constraints on life as we know it, stemming from the laws of physics and chemistry and biology, still apply? Or perhaps there are different rules, and different constraints, when life is the product of clear, intentional design?

Natural selection seems, at first glance, to be so frustratingly inefficient. Generation after generation of baby gazelles are born, destined to be eaten by lions. Only by chance is one baby born with longer legs, able to run faster, and so escape being eaten. Of course, the very beauty of natural selection is that it doesn't require any foresight; natural selection explains life in the universe precisely because there is no presumption of any prior knowledge. No Creator is necessary, because the evolutionary process is guaranteed to proceed even without any predefined rules. Life evolves—albeit slowly—without having to know where it's going.

But what if it were all different? What would life look like if it *did* know where it was going?

The 1950s physicist Anatoly Dneprov wrote quirky and characteristically Soviet science fiction. His novel *Crabs on the Island* tells the story of two engineers conducting an experiment in cybernetics on a deserted island. A single self-replicating robot (a "crab") is released, and forages for the raw materials to build other robots. Soon the island is overrun with baby robot crabs. But the crabs begin to mutate. Some are larger than others, and ruthlessly cannibalize the smaller robots for spare parts to build even larger robots. How would such an experiment end? Catastrophically, of course, as is consistent with the genre, with robot crabs spreading exponentially across the entire island.

Science fiction can be terribly pessimistic, but that pessimism is unfounded. Other factors are at play. Resources are limited. Eventually, even the crabs on the island run out of materials with which to make new robots. Admittedly, humans have caused tremendous damage to our own planet, but we've hardly destroyed the universe. In fact, there's no indication in the night sky that any organism, biological or artificial, has spread its influence as far and wide as we might expect if they were growing exponentially like robot crabs.



What if I have a plan for how my offspring should look and behave, and I don't want to leave anything to chance?

But we must also be cautious with our optimism. We rely on the age-old processes of natural selection to keep reproducing robot crabs in check; something will evolve to eat them. But what if these were intelligent organisms, plotting a way to find new resources, discovering new ways to improve themselves, their evolutionary fitness, and their ability to learn from each other and from previous generations? Could such an army of replicating artificial intelligences be possible? If so, could they be stopped? How realistic is it that alien planets may be inhabited by artificial creatures so advanced that they can bypass natural selection itself? And if that is possible, why has such a creature never evolved naturally? If we want to know whether or not we should fear alien artificial intelligence, first we have to understand what's so special about it.

It has probably not escaped your attention that the kind of intelligent transmission of experience from one generation to the next—together with the ability to know when to use that information—is not unlike what we see in human society in the cultural transmission of ideas from generation to generation. We don't need genetics to learn about science, we just need a school. More importantly, we don't need to follow a religion or a political ideology indefinitely and unchallengingly, we can detect when it's not serving our needs and change our direction. Cultural transmission of experiences is a process with spookily Lamarckian characteristics. It was the Enlightenment French biologist Jean-Baptiste Lamarck, who, in the century before Darwin, attempted to explain the fact that animals appear to be remarkably well adapted to their environment and had a number of ideas how this might happen, the best known of which was his two-pronged laws of inheritance—that animals develop traits that they use repeatedly, lose traits they don't use, and pass on acquired traits to their offspring.

We do indeed inherit a tendency to certain cultural ideas from our parents and from society, but we can mold them to our best advantage, alter them, or even discard them. You might be brought up by parents who are wonderful musicians, but you decide that you never even want to touch a kazoo. Cultural ideas that are used are reinforced, those that are neglected waste away. It is precisely this ability to improve and to prune ideas that has caused human civilization to advance at such breakneck speed. And if this kind of cultural transmission does occur on another planet, you can be sure that evolution will be swift and effective—just as ours continues to be.

Let us do a brief thought experiment. Imagine that you are a member of a highly advanced alien civilization, intent on spreading your legacy throughout the galaxy. You come to an uninhabited planet with the intention of "seeding" it. But instead of dropping off a biological molecule, you might be such an advanced alien that you seed this planet with intelligent artificial creatures, specially designed robots that have the capacity to bypass natural selection. They are programmed to have the foresight that nature is lacking. Their robotic gazelle descendants would know that longer legs are better and would re-engineer their own design to give them longer legs. Similarly, robotic lions would reprogram their own software to enable them to sneak up on prey more stealthily.

What would be the end result of such a scenario? Would there still be predators and prey? Or would these creatures be improving themselves so rapidly that soon the robot gazelles are building spaceships to escape the robot lions and the robot lions are building supercomputers to design weapons of mass robot-gazelle destruction? This ridiculous scenario is not nearly as trivial as it seems, because the idea touches on some of the most fundamental mechanisms and constraints on evolution. Can intelligence, and the ability to bypass natural selection, also bypass the limits that the natural world imposes?

On the face of it, many of the familiar characteristics of animals and plants that we see around us would simply disappear if the organisms in an ecosystem were

Science fiction can be terribly pessimistic, but that pessimism is unfounded.

all super artificial intelligences. Oxford professor Nick Bostrom, for instance, suggests that a community of artificial intelligences will be sharing information in such an effective and rigid way that many aspects of animal behavior would be unnecessary. Large antlers, peacock feathers, colorful flowers, even birdsong—why bother with such peculiar and inefficient ways of communicating simple messages like "I'm here and I'm strong"? Artificial organisms could achieve the same result simply by sending an email. And if the system is well designed, checks will ensure that the email is a form of honest signalling. No fake Tinder profiles allowed.

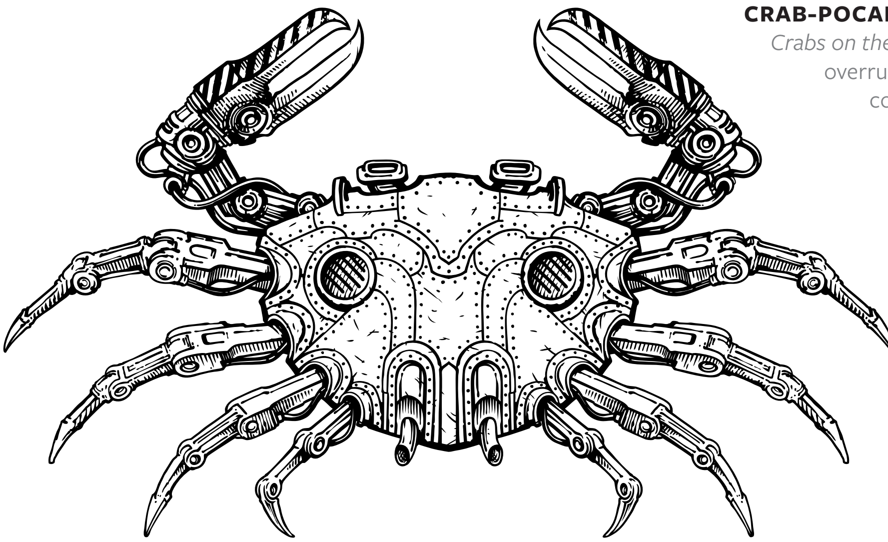
How likely is it that this universe of interconnected computers would be doing nothing but communicating, reproducing, and carrying out their singular goal? Possibly not very. If such an alien world of artificially intelligent organisms really exists, there are some things it cannot avoid—no matter how intelligent or how well designed. On the one hand, artificial intelligence cannot improve without change, and change brings the risk of mutation. On the other hand, even the cleverest strategy is potentially open to exploitation—game theory cannot be discounted, even by a computer of sci-fi-level superintelligence.

In life (that is, natural organisms like us), mutations occur because the universe has an element of randomness to it. A stray cosmic ray knocks an electron from an atom, and the copying of your DNA is disrupted. Each cell gets a faithful copy of your DNA, and if it doesn't, the result is often cancerous. However, not all mutations are necessarily this bad. A mutation that causes your neck bones to grow for a bit longer as an embryo may or may not be beneficial to the adult-you, but probably won't kill embryo-you. Variation in individual organisms inevitably arises through mutations (and also—on Earth at least—through sex).

All of this is very straightforward when considering natural selection, no one knows in advance which features of an organism are beneficial and which features are harmful. Without that foresight, the *only* way to try out different variants is through random but small mutations and alterations on the theme that already exists.

But what if I *know* what I want? What if I have a plan for how my offspring should look and behave, and I don't want to leave anything to chance?

Consider an artificial intelligence (or even a biological organism) that creates a set of self-replicating intelligent robotic probes to fly off and explore (and colonize) the universe. Each probe will land on a different



CRAB-POCALYPSE In the Soviet sci-fi novel *Crabs on the Island,* a self-replicating robot overruns an island with hordes of mutated copies of itself. The story raises the question: Would biological laws check the growth and evolution of artificially created beings?

KIRIAN / SHUTTERSTOCK

planet and begin to create new probes like itself, much like Dneprov's *Crabs on the Island*. Will each daughter probe be identical to the parent? Probably not. The parent probe may choose to make them slightly different from one another, with intelligent foresight: One may be optimized for swimming underwater, and one for flying in the air, for example. But will there be any errors, any mutations in the process? It would seem that, like any respectable engineer, the parent probe would make every effort to ensure that each replicated probe is exactly the way it was meant to be. The advantage of evolutionary mutation exists *only* because evolution has no foresight! If you do have foresight, it makes sense to dispense with the randomness.

But even if you can be 100 percent accurate, and are capable of completely stopping bugs from creeping into your software (our hypothetical parent is super intelligent, after all), we have seen that variation is, nonetheless, necessary. Even if you don't want mutations, you need a swimming daughter probe and a flying daughter probe. The offspring of each of those daughters will also change: one granddaughter probe for swimming in deep water and one for shallow water, for instance. As time goes on and the environment on the planet changes, a wide diversity of artificial creatures will arise. Not through the mechanisms we are familiar with on Earth, but diverse nonetheless. Each one will be perfectly engineered to its niche, without the awkward wisdom teeth and appendixes that we carry with us, and that betray our origins as creatures not designed by anyone.

Even if natural selection isn't operating on this well-oiled and super-intelligent community, some of the rules of evolution will still apply, no matter how flexible and self-designed they might be. Even super-intelligent artificial life forms are subject to the ruthlessly inevitable restrictions imposed on them by game theory—they would, after all, be competing against other super-intelligent organisms like themselves. If exploitation pays, exploitation will happen. Selfishness is a threat that will be present even in a community of super-intelligent artificial aliens. And some things like mutation, and even death, can't be eliminated just by being incredibly smart. Even for a radical, technological, non-Darwinian life form, so many of the principles that we use to understand the evolution of life on Earth, like trade-offs, still apply, and so it is unlikely that they would design themselves to live forever.

If astrobiologists wonder why we haven't found any indication of alien life so far, we should be doubly confused as to why we haven't found any indication of alien super-life. Once created, surely AI will take over the universe? Well, it hasn't happened yet, so perhaps the risk is less than we thought. And what about artificial life forms that are more modest in their abilities? Could a planet evolve an entire ecosystem all by itself, based on artificial life forms that accelerate evolution by having at least a basic Lamarckian ability, passing

Once created, surely AI will take over the universe?

their lifetime experiences on to their offspring? It's possible that, because environments can rapidly change, such organisms may not have such an advantage over natural selection after all, at least not until they can evolve the ability to communicate, cooperate, and plan their evolutionary strategies intentionally. If you are an alien species seeding a planet with some prototypical artificial organism, maybe it's better to seed it with Darwinian creatures, rather than Lamarckians.

It's possible that we, ourselves, are artificial creatures, seeded onto planet Earth by intelligent aliens billions of years ago. But there is no sign of this, no fingerprint of alien interference. We might as well have evolved naturally—we show all the signs of natural selection pure and simple, with no trace of Lamarckian acceleration.

Unless ...

We actually *do* have the ability to adapt our evolution, to spread the ideas and experiences of our lifetime both to our own offspring and to others. We have Lamarckian abilities through our culture and through our technology, and what is more, we have the intelligence to know how and when to use them—although it remains to be seen whether we will be intelligent enough to be able to find our way out of the environmental dead end into which our expanding consumption has led us. Using modern techniques of genetic engineering, we can even alter the contents of our genes, eliminate the susceptibility to disease, and perhaps even stop aging. Eventually we may be able to change the shape of our very development, growing an extra arm, or wheels, or whatever takes our fancy.

Perhaps our alien seeders knew that consciousness would evolve. Perhaps this was the grand plan the whole time: Lamarckian artificial organisms could not survive their early evolutionary stages, but would one day mature. Our creators knew this and were patient enough to wait for the day when that would happen. This is possibly an unlikely scenario, but it does leave open the possibility that alien planets will be inhabited by "artificial" life forms that are nonetheless indistinguishable from what we would expect from natural selection.

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I Have Come to Bury Ayn Rand

A prominent evolutionary biologist slays the beast of Individualism

BY DAVID SLOAN WILSON

MY FATHER, SLOAN WILSON, wrote novels that would help define 1950s America. I loved and admired him, but the prospect of following in the footsteps of *The Man in the Gray Flannel Suit* and *A Summer Place* was like being expected to climb Mount Everest. My love of nature provided an alternative path. I would become an ecologist, spending my days researching plants and animals, which fascinated me since the summers I spent as a boy at Lake George and a magical boarding school in the Adirondack mountains.

DELCARMAT / SHUTTERSTOCK

Little did I know that by heading away from the madding crowd of humanity and my father's vocation, I would end up writing a sequel to another famous novel of the 1950s—Ayn Rand's *Atlas Shrugged*. But don't get me wrong. I'm no Rand acolyte. I'm not here to praise her ideas but to bury them.

Even if you never read *Atlas Shrugged* or anything else by Rand, you probably know the names and what they stand for: The sanctity of the individual and the pursuit of self-interest as the highest moral ideal. Rand constructed an entire philosophy around this called Objectivism, which she claimed could be fully justified by rationality and science. But it was through fiction that she reached her largest audience, with *Atlas Shrugged* selling over 7 million copies and still widely read. She wisely noted that "Art is the essential medium for the communication of a moral ideal."

The hero of *Atlas Shrugged* is John Galt, a supremely self-confident inventor. He has figured out a way to turn static electricity into an inexhaustible source of clean energy. But Galt and his kind are living in an America veering toward the kind of ham-fisted socialism that Rand escaped when she immigrated from the Soviet Union in 1926. Galt brings about a rebellion of the "producers" of the world, like the mythical Atlas shrugging the Earth from his shoulders, so that the "looters" and "moochers" can be brought to their senses. The centerpiece of the novel is a speech that Galt delivers to the world by taking over the airwaves with his technical prowess.

Whether conveyed through philosophy or fiction, Rand's worldview couldn't function as a moral system if the pursuit of self-interest didn't end up benefiting the common good. That's where the invisible hand of the market comes in, a metaphor that was used only three times by Adam Smith in his voluminous writing, but was elevated to the status of a fundamental theorem by economists such as Milton Friedman and put into practice by Rand acolyte Alan Greenspan, who served as Chair of the United States Federal Reserve Board from 1987 to 2006.

Here's how it's supposed to work: Everything of value can be represented as a dollar value and therefore can be compared to anything else of value by their relative prices. Making money is the surest way to provide value to people because the best way to make money is to provide what people are most willing to pay for. The system works so well that no other form of care toward others is required. No empathy. No loyalty. No forgiveness. Thanks to the market, the old-fashioned virtues have been rendered obsolete. That's why Milton Friedman could make his famous claim in 1970 that the only social responsibility of a business is to maximize profits for its shareholders. In Ayn Rand's fictional rendering, the word "give" is banned from the vocabulary of the Utopian community founded by John Galt, whose members must recite the oath: "I swear by my life and love of it that I will never live for the sake of another man, nor ask another man to live for the sake of mine."

My sequel to *Atlas Shrugged* is titled *Atlas Hugged* and its protagonist is John Galt's grandson. Ayn Rand was not a character in her novel, but since anything goes in fiction, I could transport her into mine as Ayn Rant, John I's lover and John III's grandmother. Rant's son, John II, parlays her Objectivist philosophy into a world-destroying libertarian media empire. John III rebels against the evil empire by challenging his father to a duel of speeches. In the process, he brings about a worldwide transformation based on giving. *Atlas Hugged* is so anti-Rand that it isn't even being sold. Instead, it is gifted for whatever the reader wishes to give in return. Eat your heart out, Amazon!

HOW DID SOMEONE RUNNING AWAY from his famous father into the woods end up in a position to critique Ayn Rand and neoliberal

My sequel to *Atlas Shrugged* stars John Galt's grandson and features Ayn Rant.

economics? By becoming an ecologist, I did not escape the kind of Individualism that pervaded Rand's thinking. Instead, I encountered it in a different form: The dogma that organisms never evolve to behave "for the good of the group," but only for the good of themselves and their selfish genes. This conclusion had been reached with such certainty when I entered graduate school in 1971 that only a fool would challenge it. "For the good of the group" thinking belonged on the same dust heap of history as a flat earth, Lamarckism, and Phlogiston theory.

Later, when I began to study topics such as religion from an evolutionary perspective, I discovered that Individualism pervaded all of the social sciences, not just economics. It was called Methodological Individualism, as the most practical way to study all aspects of human society, regardless of its philosophical underpinnings. In short, Individualism is a far bigger beast than Ayn Rand. She gave voice to it, but it would be just as strong if she never existed.

Individualism has long historical roots but didn't become dominant in Western thought until the second half of the 20th century. Before then, it was common to think of society as a kind of organism in its own right, complete with a group mind. Individuals played their appointed roles in the social organism, but the whole society was the center of analysis. According to the Harvard psychologist Daniel Wegner, "almost every early social theorist we now recognize as a contributor to modern social psychology held a similar view."[1]

So, something happened around the middle of the 20th century that resulted in a sea change of thinking, from "society as an organism" to Margaret Thatcher's famous quip "there is no such thing as society" in 1987. When I encountered it as a budding ecologist in the early 1970s, it offended my sensibilities. My father was an atheist and my mother called herself an agnostic, but both were warm, nurturing people who taught me to do unto others. The characters in my father's novels always try to do well by each other, even when they fail.

COMMUNITY CHEST
It wouldn't pay off, in a normal game of Monopoly, to give other players money. But what if you were playing as a team against other teams, aiming to collectively develop the board's real estate the fastest?

CASEYMARTIN / SHUTTERSTOCK

I suspect that I am also an empath by nature. I don't remember it myself, but my mother told me that when her marriage to my father was heading toward divorce, I followed her around saying "I'm sorry! I'm sorry!" as if everything rested on my slim shoulders.

Even though I became a biologist to escape my father's shadow, I did not escape the allure of making a name for myself—and what better way than to show that behaviors can evolve "for the good of the group" after all? Perhaps this, along with wanting to explain what seemed intuitive to my empathic nature, accounts for why I became that fool that rushes in. I would challenge Individualism in evolutionary biology.

WHAT I DISCOVERED, even before entering graduate school, is that Darwin provided a perfectly good explanation for how behaviors can evolve for the good of the group. To understand its logic, imagine playing the game of Monopoly, where the object is to buy up all the real estate and drive everyone else bankrupt. Suppose that I were to offer you 1,000 extra Monopoly dollars at the beginning of a game. You would thank me and use the money to your advantage. Experiments like this have actually been conducted and the entitled players flaunt their wealth, making more noise when moving their pieces and attributing their success to their prowess and not their luck.[2]

Now suppose that I offer you 1,000 extra Monopoly dollars, subject to the constraint that every other player gets 2,000 dollars. You would wisely turn me down because the game of Monopoly is all about *relative* advantage. It doesn't matter how much money you have; only that you have more than the other players. There is no such thing as enough money in the game of Monopoly.

Relative advantage is also the name of the game in evolution. In any group of socially interacting individuals, those that extend benefits to others or to their group as a whole—who in a word behave *prosocially*—place themselves at a relative disadvantage, compared to those who passively accept social benefits without providing them (free-riding) or actively exploit other members of their group.

Continuing our thought experiment, imagine playing in a Monopoly tournament, where the trophy goes to the team that collectively develops its real estate the fastest. Nearly every decision that you make as a team player in a Monopoly tournament will be different than playing a single game of Monopoly. There will be a burst of conversation as you discuss strategy together. You will pool your money, divide labor, and so on. There will be cheers, hugs, and high fives if you win. This transformation is accomplished by adding a layer of between-group competition on top of within-group competition. In the case of a Monopoly tournament, between-group competition completely overrides within-group competition because there is no advantage to beating a teammate. And needless to say, a Monopoly tournament provides no context for cooperation among teams. For that, we would need to add another layer of competition among teams of teams.

What my Monopoly example makes intuitive dawned upon Darwin only gradually. At first, he thought that competition among individuals could explain all examples of design that had been attributed to a creator. Then he realized that prosocial behaviors—anything that requires time, energy, and risk on behalf of others or one's group as a whole—were a glaring exception. Finally, he realized that by adding a layer of selection among groups in a multi-group population to selection among individuals within each group, he could explain the evolution of prosocial behaviors after all. We know that the awareness dawned on him gradually because we can track it by the changes that he made in successive editions of his books.[3]

In a sense, I was a fool rushing in to explain how behaviors can evolve "for the good of the group" in the 1970s, since Darwin had done my work for me. Then why had his theory of between-group selection been so soundly rejected?

THERE IS ONE BIG DIFFERENCE between my Monopoly example and what takes place in nature. In a Monopoly tournament, competition among teams completely overrides competition among individuals within teams. In nature, both levels of selection usually operate simultaneously. Sometimes within-group selection is the stronger force, resulting in nasty brutish behaviors such as killing the babies of others to have one's own babies. At other times between-group selection is the stronger force, resulting in cooperative behaviors such as collective defense of a group's offspring. It all depends on the balance between levels of selection.

In some respects, the received wisdom of the 1970s was to accept the logic of within- and between-group selection but to argue that in practice, within-group selection is invariably the stronger force. If this were true, then nature would be a horror show. When it comes to the behaviors that evolve by within-group selection, there is no invisible hand to permute selfishness into the common good. As George C. Williams, one of the main critics of group selection put it, "Mother Nature is a wicked old witch."[4]

In other respects, the received wisdom of the 1970s was a repackaging of prosocial behaviors so that they fit into a narrative of selfishness. Helping kin became helping my genes in the bodies of my kin. Reciprocal behaviors became scratching your back so that you'll scratch mine. According to Richard Dawkins, everything that evolves is an example of gene selfishness, but somehow this results in individual organisms and even whole groups that qualify as "vehicles" of selection. In this fashion, theories that were framed in terms of self-interest gave back with one hand what they seemed to take away with the other. Part of my work as the fool rushing in was to establish that all theories of social evolution must reflect the logic of multilevel selection. They all must acknowledge that social interactions take place in groups that are small compared to the total evolving population; that prosocial individuals have a relative fitness disadvantage within groups; and that some process of selection among groups is required for prosocial behaviors to evolve.

Against this background in the 1970s, with differences of opinion reflecting differences of perspective as much as the invocation of different causal processes, another renegade biologist named Lynn Margulis made a radical proposal: Nucleated cells, which are much more complex than bacterial cells, did not evolve by small mutational steps from bacterial cells. Instead, they evolved as symbiotic

Nearly everything distinctive about us can be seen as a form of cooperation.

communities of bacteria, which became so cooperative that they qualified as higher-level "superorganisms" in their own right.

The idea that individuals are highly cooperative groups of lower-level agents is a game changer. Recall that the tradition of Individualism seemed to replace the previous tradition of treating society as an organism in its own right. If individuals are themselves a society of organisms, then what's wrong with considering their own societies as organisms, at least when certain conditions are met? The very concepts of "organism" and "society" have merged!

As if Margulis' proposal for nucleated cells was not radical enough, the concept of groups permuting into organisms was generalized by two theoretical biologists, John Maynard Smith and Eors Szathmary in the 1990s. Maynard Smith was an early critic of group selection but was happy to describe Major Evolutionary Transitions (METs), as they came to be called, in terms of multilevel selection. Most groups do not qualify as organisms because of disruptive behaviors that evolve by within-group selection. The balance between levels of selection is not static, however, but can itself evolve. When mechanisms evolve that suppress the potential for disruptive within-group selection, then between-group selection becomes the dominant evolutionary force and the group permutes into a superorganism. Maynard Smith and Szathmary invoked METs to explain not only the evolution of nucleated cells, but the evolution of multicellular organisms, social insect colonies, and even the origin of life as groups of cooperative molecular reactions.

Then the concept of METs started to make sense of human evolution. Despite sharing 99 percent of our genes with chimpanzees, there is a night-and-day difference in the degree of cooperation. Naked aggression is over 100 times more frequent in chimp communities than in small-scale human communities. The reason is due primarily to social control. Bullies get their way in chimp society but are usually effectively opposed in small-scale human societies and have been for a very long time. Our moral psychology can even be regarded as an immune system that protects against "cancerous" bullying and other disruptively self-serving behaviors.

Now, as we pass the one-fifth mark of the 21st century, nearly everything distinctive about our species can be seen as a form of cooperation, made possible by a MET. That includes our capacity for symbolic thought, which enables us to encode and transmit large bodies of learned information across generations—largely in the form of stories. Genetic evolution gave rise to cultural evolution, which is itself a multilevel process. From a pariah concept in the 1970s, multilevel selection theory has become a lens through which to view the entire pageant of human cultural diversity and history, leading up to the nearly 200 nation states that carve up the planet today—and perhaps even offering a blueprint for cooperation at the global scale.

I WAS AN EAGER participant in expanding the evolutionary view to include all things human. My 2002 book *Darwin's Cathedral: Evolution, Religion, and the Nature of Society* defended the thesis that religious meaning systems are primarily group-level cultural adaptations. In essence, Emile Durkheim was right when he defined religion as "a unified system of beliefs and practice relative to sacred things … which unite into one single moral community called a Church, all those

Stories are powerful because they are vehicles for imbibing moral worldviews.

who adhere to them." The tradition of group-level functionalism that Durkheim initiated might be faulted for axiomatically treating societies as like organisms, for failing to explain how they got that way or the role of individual agency, but these were shortcomings that multilevel selection theory could address.

Starting with the great recession of 2008, I started to turn my attention to economics. By then I had co-founded the Evolution Institute, which gave me the capacity to hold conferences and workshops. At one of the workshops someone idly observed that since Rand had done so much to promote the beast of Individualism through fiction, shouldn't someone be doing the same for our emerging multilevel worldview?

Within seconds, the title *Atlas Hugged* and the rudiments of the plotline flashed into my mind. I had never intended to return to my father's vocation, but this story was too juicy to resist! Once the idea took hold, it refused to let me go. By day, I continued to be a scientist, rethinking everything associated with the words "human," "culture," and "policy" from an evolutionary perspective. By night, on airplanes, and in hotel rooms, I scribbled away at my novel. I discovered that writing fiction is a different beast than writing nonfiction. Months would go by when I didn't have a chance to write anything. Then a new plot development would rise into my consciousness and I would think, "Of course! That's how it must be!" My characters became as real to me as real people—and why not, since real people exist only as avatars in our minds?

Much as I have established myself as the anti-Rand, I have also learned to sympathize with her as a person. The target of my critique is Individualism in all its forms, not just her version. In *Atlas Hugged*, John Galt III comes to see his grandmother as an intrepid explorer who happened to have taken the wrong path. The tragedy is that the world is following in her footsteps and needs to be set on a better path. Like Rand, that is the objective of both my work as an intellectual (in her case a philosopher, in my case a scientist) and the fictional universe that I have created.

Stories are powerful because they are vehicles for imbibing moral worldviews. If the worldview of a story resonates with the reader, then the reader gobbles up the story and wishes to make it a reality. If there is dissonance, then the reader loses interest or actively hates the story. It is for this reason that no work of fiction is universally loved, no matter how well told. Others can judge my talents as a storyteller, but *Atlas Hugged* is arguably the first science-informed novel of the Post-Individualism Age.

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FOOTNOTES

1. Wegner, D.M. Transactive memory: A contemporary analysis of the group mind. In Mullen, B. & Goethals, G.R. (Eds.) *Theories of Group Behavior* Springer-Verlag, New York, NY (1986).

2. Social psychologist Paul Piff describes his experiments in a TED talk titled "Does Money Make You Mean?"

3. See Chapter 2 of the philosopher of biology Elliott Sober's book *Did Darwin Write the Origin Backwards? Philosophical Essays on Darwin's Theory* (2010).

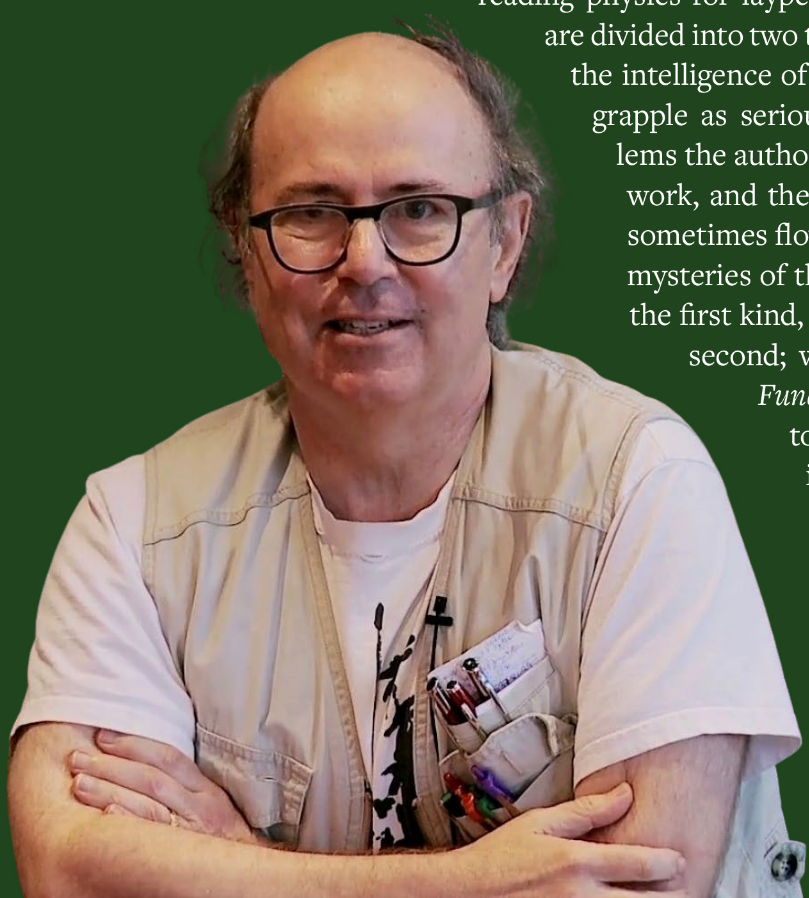
4. Williams, G.C. Mother nature is a wicked old witch. In Nitecki, M.H. & Nitecki, D.V. (Eds.) *Evolutionary Ethics* SUNY Press, Albany, NY (1993).

The Charmed Life of Frank Wilczek

A novelist gets a physicist to explain his scientific breakthroughs

BY NELL FREUDENBERGER

NOBEL LAUREATE FRANK WILCZEK'S new book, *Fundamentals: Ten Keys to Reality*, is both a way of thinking about the abundance that characterizes our exterior and interior worlds, and a kind of alternative to traditional religion, a way of being "born again" through science. I was asked to review it for *The New York Times*[1] because it's explicitly a book for non-scientists, and in doing research for my novel, *Lost and Wanted*, I'd gotten into the habit of reading physics for laypeople. Those books, for me, are divided into two types: the kind that presume the intelligence of the reader and push her to grapple as seriously as possible with problems the authors tackle in their theoretical work, and the kind that use abstract and sometimes flowery language to hint at the mysteries of the universe. I usually prefer the first kind, but I can be seduced by the second; what I like about Wilczek's *Fundamentals* is that it seems to occupy a middle ground, introducing ideas about the biggest and smallest things in nature with simple but precise language.



In interviewing physicists, I'm always interested in how they work, and also in what kind of personality is suited to this discipline. Wilczek spoke to me over Zoom from his home in Concord, Massachusetts, in a gray room with a steeply sloped ceiling. He was wearing a blue plaid flannel shirt with more than one pen in the pocket, and he was both quick to smile and to qualify a point during our conversation. When he was concentrating on explaining something, he would close his eyes for moments at a time behind his glasses. Our conversation reinforced an impression I took from his book: that he is a profoundly happy person, whose happiness is in large part derived from intellectual endeavors, among which physics is the primary but not the exclusive passion.

I love the quote from Pascal at the beginning of *Fundamentals* about his existential horror at his own tininess: "the universe grasps me and swallows me up like a speck." Can you remember, either as a child or maybe even recently, looking up at the sky and being frightened by your own tininess?
I wasn't frightened. As a child, I was brought up in Roman Catholicism, so that colored my view of the cosmos. I was certainly frightened about going to hell, but not about the size of the universe. That, I thought, was just a fact that was not particularly relevant to everyday life, and certainly didn't feel it was oppressive. My attitude changed as I grew up and started to think more about the smallness of Earth and people on it. But that was a peculiar thing for Pascal to say, to be frightened by the size of the universe.

I wasn't going to ask this, but since you said you grew up Catholic, was there a moment where you lapsed? Or are you still …
Yes, there definitely was. There was a crisis. There's a ceremony in Catholicism called Confirmation. When you reach the age of reason, which I think was 12 or 13, you get the confirmation for a more informed commitment. We went on a retreat for a weekend. It was really intense, going through the doctrines and getting enthusiastic. I was very taken with that. I had always been serious about thinking about the issues raised in the catechism and trying to interpret it as truth. At the same time, I was learning about science and reading subversive people like Bertrand Russell. But that retreat brought things to a head. In the moment, I held to the faith. But right afterward, it was just like the dam burst. And when it burst, it just leveled. There was no …

No going back.
There was no going back, right. For me, at least, once you start to examine the doctrines as being not the word of God but the products of people who didn't understand things very well, you start to see the worldview was, in many ways, so paltry. It was all about Middle Eastern real estate.

COURTESY OF FRANK WILCZEK

It's interesting you were wrestling with what they were trying to teach you. Probably most of the kids at the retreat were looking out the window, or thinking about the 12-year-old girl across the table. You were actually grappling with the ideas.
Exactly. But in retrospect, I have a lot of sympathy for figures like St. Augustine. He reconciled Greek philosophy and religious doctrines—to the benefit of both, I think.

It was definitely easier to be a generalist than it is today.
It was easier to reconcile. We'll never understand things as well as the ancient Greeks did because our standards are different. Our standards are much more rigorous and harder to live up to. We just can't achieve them on all fronts.

In *Fundamentals*, you write about how, when you took a trip to Bell Labs in high school, you heard a scientist say that "phonons are the quanta of vibration," and that that phrase just kind of reverberated for you. You couldn't stop thinking about it until you figured out what it meant. That was interesting to me, hearing language that you don't exactly understand in that context, and then that leading you deeper into the subject.
It really did. I didn't realize it at the time, but it made a hugely deep impression on me. It began with the concept that particles, phonons, were a description or consequence of things that you wouldn't think of as particles but as vibrations. How do you get particles coming out of a deeper reality? You could think of materials. He was talking about materials as worlds in themselves that had their own emergent particles, particles that were not things that could exist in the absence of materials. And within that self-contained world, if you lived inside the material, this would be what you think of as the constituents of reality.

Other kids had comic books and you had the world of vibrating phonons.
I had comic books, too. But that really fired my imagination. It gave me enormous satisfaction to construct an interpretation of those worlds because I didn't know what quanta were. I didn't even know what vibrations were, except in a very common sensical way, and I certainly didn't know what phonons were. But, to be able to put together a plausible interpretation, which hung together, gave me immense satisfaction. It made me feel really smart.

For me, one of the great insights of *Fundamentals* was the way you explained that particles are not just smaller versions of the atoms that Democritus imagined floating in space. I've encountered the idea before, but you wrote, "Particles are avatars of fields." How did you come up with that definition? It seems very beautiful to me.
Well, it's just a straightforward description of how the equations work, as well as I can put it into English. People talk about "particle wave duality"

and "particles vs. fields," but the most profound way, the most natural way, is to talk about space-filling fields. Particles are epiphenomenon. They're excitations within fields. They have an internal cohesion that allows them to hold together and propagate as identifiable units. But in a real sense, they are just places in fields where the energy concentrates. The fields are really, in a deep way, where the action is. They are things in which we formulate our descriptions of the world that works.

There is one thing, in particular, I didn't understand in *Fundamentals*. You wrote that "anyons," quasiparticles you named, "have a simple kind of memory." You said that anyons are important because their behavior could be used as building blocks for quantum computers. I read an article you wrote in *Quanta*.[2] The explanation seemed simple and lucid but I got tripped up by the idea of space as two dimensions plus time. As nonscientists, we're usually asked to think in terms of three dimensions plus time.
You want to give it a try?

No, oh, no, me? I definitely don't, no!
Do you want me to try to explain it?

Our conversation reinforced an impression I took from Wilczek's book: He's a profoundly happy person.

Yes, please.
The first thing to say is there are two-dimensional worlds in physics. They're the worlds, for instance, inside your computer. When you have chips, the electrons live in two-dimensional worlds. Their motion in the plane is free, but, in the other dimension, they're constrained. In the rules of quantum mechanics, there's an energy gap, which means they can't escape into the third dimension. They really do live in two-dimensional worlds, and we can give a self-contained description of physics in their worlds.

So we have two spatial dimensions, but there's still a time dimension. Things can still move. So to describe not only the positions of your particles, but also their development in time, you introduce a third dimension. And then, instead of a particle having a position in this extended description, it has a "world line." As time evolves, at each time you have a position. Tracking these positions, we get the world line. When you have several particles, you have several world lines, and they can wrap around each other and get tangled up. That's the spacetime aspect. We have these threads, or hairs, that exist in three dimensions, two plus one, and wrap around each other.

THE NOVELIST To research her most recent novel, *Lost and Wanted*, Nell Freudenberger interviewed a host of physicists. So she knew just what tack she wanted to take with Frank Wilczek for *Nautilus*: "I'm always interested in how physicists work, and also in what kind of personality is suited to this discipline."

Now, the hair braiding analogy, I understood.
OK, so, if we have three plus one dimensions, you can always untangle the hairs in an easy way that doesn't involve tearing them through each other. You can just pass the strands over each other. In that way, you can unknot anything. Let's use that fourth dimension to describe a temperature. We heat up one of the strands and it's then in a different place in the extra dimension. So now it can pass through the strand that was obstructed before. With that extra dimension, you can unknot anything.

So, in three plus one, or four dimensions, there are no knots. They can all be untangled. But, in two plus one, or of course three, that's not true. So if you're describing a quantum mechanical system in two space dimensions and one time, then the world lines can get entangled and make knots.

And that ability to be unknotted is what gives the anyons their memory?
To be more precise, what can happen is that the entanglement of these worldlines gets imprinted on the quantum mechanical wave function that describes the system. The fundamental description is not in terms of particles in space—that's the classical description—but the wave function of these things. It turns out this was the theoretical discovery: that in some cases the entangling of the world lines gets directly imprinted on the wave function. So, you can get information encoded about how the world lines were entangled. So, the particles, in that sense, have a memory, in that there's a memory that stores how they were entangled. That's the precise conceptual structure behind that statement that the particles have a simple kind of memory. They read out their past into their wave function.

And then the idea is that an encrypted kind of this memory can be used in quantum computers?
It's a very capacious memory in some cases. But so far the only memory that's been constructed is a very limited memory. With the kind of anyons that have been observed so far, the only thing that's encoded is how many times they've wound around each other. So what's been demonstrated is a primitive version. To make them useful is the work of the future.

ELENA SEIBERT

OK, to say that I understand anyons would be lying, but I understand a little better than I did before.
It's really important not to insist you understand everything before you understand anything. That's very important to expand your mind. I do this constantly. I am learning, exploring things that I don't understand fully at all.

What's an example of something that you don't understand?
Well, I'm trying to bring my little-bit-more-than-*Scientific-American* knowledge of machine learning to a professional level.

That seems like a timely pursuit.
Yes, right. I've read things but now I'm programming and doing the exercises and doing it interactively, looking online. Similarly, I've been learning juggling and I really enjoy a professional juggler named Taylor Glenn. She is very charismatic and enthusiastic, and she has a tremendous number of videos on different kinds of juggling at all levels. Anyway, this is somewhat of a diversion.

Diversions are good.
One thing Taylor Glenn said that really stuck in my mind, to paraphrase, is that people think juggling is about throwing and catching. Juggling is actually about dropping things and picking them up.

That's very profound.
It is, it is.

I'm always telling my less math-oriented child about making mistakes. He can learn more sometimes from making a mistake in math.
Oh, that's probably my most famous saying. You can find it quoted on the Internet: "If you don't make mistakes, you're not working on hard enough problems. And that's a big mistake."

That's a great one. I'll tell him the next time we're struggling with fractions on a number line. So, I've been reading about Chien-Shiung Wu, a Chinese-American physicist who worked on the Manhattan Project. As far as I know, she wasn't religious. But I was thinking about this when we were talking about your Catholicism. She told her biographer she couldn't sleep for two weeks after her famous experiment on non-conservation of parity, and she wondered why God had chosen her to reveal this secret.
Wow.

Yeah, I'm really interested in this moment of revelation in science and how different it is from a similar moment in art. When you first thought about "asymptotic freedom," a quantum behavior you co-discovered, for

which you won the Nobel Prize, or anyons, or anything else, I wonder if you had the feeling, Why me?
Not really. This is going to sound very immodest, but I had one success after another, academically. I had something of a crisis when I first went to Princeton and graduate school. But, other than that, everything has gone very smoothly for me. There's certainly been dry periods, but I never was surprised by the fact that I could come up with things and did.

Maybe because you always had been able to do them.
Most of my work is highly theoretical, so I write equations and think conceptually in pictures and motions. And the experiments that deal with these things are in a completely different universe—if you think of that universe. That's probably the closest to what you're talking about. When I did the basic work on asymptotic freedom, it wasn't an established fact about the world. No one had seen gluons yet, or checked any of the important predictions. But it was plausible enough that serious people were taking it seriously and talking about it a lot, so it was very exciting and encouraging. I visited Brookhaven Laboratory, the national laboratory where there's an accelerator.

The Cosmotron or the Alternating Gradient Synchrotron?
It was the AGS at that time. This was the early '70s. It was a big thing, not by modern standards of accelerators, but it was big. It was a modest aircraft hangar size, and there were machines and wires all over the place. I was up in a gallery looking at it. Suddenly it hit me that this is where they're going to check our calculations. Which are just things that I wrote down! This is where they were going to be tested and what their consequences were. So that was probably the closest thing I've had to this sudden feeling of: How did this happen to me? How did I become the messenger?

It's like if you were a novelist, and someone said, "I've created these people from your book in a lab, and now we're going to put them in a room and see if they do what you said they'd do." Terrifying.
Something like that, right.

You write that the equations of modern quantum mechanics have an uncanny resemblance to equations in music. Do you play an instrument?
Oh, yes, I've always played. When I was a child, I wanted to have a piano, but our apartment was too small. And we couldn't afford one. I played the accordion. I got quite good at that. Later, when I was in high school, I played the drums. We had a little band for a little while. But then I went to college. As an adult, I took up the piano, and reached a certain level. It was too late by that time to get really good. But I noodle around a little bit, almost every day, and I've educated myself quite a bit in classical music. I have fantasies about taking up jazz someday. But that's sufficiently low on the agenda. It's the part you never get to.

That was the closest thing I've had to this sudden feeling of: How did this happen to me?

The idea of complementarity is important to your work. You define it as the "concept that one single thing, when considered from different perspectives, can seem to have very different or even contradictory properties." I get the impression that it's not only a way of thinking about physics for you. For example, it seems to make you more optimistic about climate change than the average climate scientist?

I'm optimistic in the sense that humanity has gone through a lot of bad times. There was the Black Death, there was the fall of Rome. I think humanity will come out on the other side. Maybe not with 100 percent probability, but maybe with 70 percent probability, we'll escape the worst doomsday scenarios for climate change and nuclear war and other terrible things. The long-term future will be great, but there may be some very tough intermediate times. Climate change is tragic in the sense that we know what we should do. People can argue about the details, but we can buy ourselves an insurance policy at quite a reasonable cost that would save us from very bad outcomes.

Are you talking about insurance policies in the form of carbon capture technology, or something else?

I'm talking about more investment in sustainable energy sources. We have to investigate fusion. We have to do safe nuclear energy. I hate to say this, but we do have to look into geoengineering. We have to look into mitigation, remedy, coping strategies. But what makes me really worried is that the political will to do these things just doesn't seem to be there. There's a deep reason for that, which is there are very powerful people whose power and wealth derive from the perceived value of the mineral and geological resources they control. They're going to fight and kick and scream and do their best to impede alternative energy sources.

TAYLOR TRIES / YOUTUBE

THE PHYSICIST'S NEW CHALLENGE
Frank Wilczek says he's always learning new things, most recently how to juggle, by watching Taylor Glenn's instructional videos on YouTube.

Also ominous is huge philanthropy. People give in the right places but still make money the old way.
I'm convinced philanthropy is part of a sophisticated strategy by people like the Koch brothers. I don't want to hear about their philanthropy. Even though they contribute generously to MIT, they're some of the worst people on Earth.

The last thing I was going to ask about is your reading for pleasure. Is there anything you've read recently that you especially enjoyed?
Oh, yeah, I read a really good book: *Lost and Wanted*.

Really?
I really appreciate what you have on page 185. There were two passages that I especially liked, one on page ...

I'm sorry, I just have to interrupt. Do you have a photographic memory? How do you remember something is on page 185?
Oh, because I marked it. There aren't that many things that really strike me, and so I want to remember. One was on page 177, where you talked about how physicists come from strange families, from parents who don't know

I was brought up in Catholicism and frightened about going to hell. But not about the size of the universe.

any better. That really resonated with me because that described my family very well. And then, on page 185, you have this brilliant analogy between doing math and the joy of doing a sport, gymnastics, and the necessity to do warm-up exercises. You have to do things that are not necessarily interesting or rewarding in themselves, but you have to know that there's a payoff coming. You have to invest in the math. It's very important for people to know that there is a payoff.

Well, I really appreciate *Fundamentals*. I wish someone had given it to me when I was a junior in high school, when I said to my math teacher, "I want to quit." I wish she'd said, "Just read this book about physics and you'll see why you shouldn't quit."

That's why I write these books, especially this latest one. I want to assure people that there is a pot of gold at the end of the rainbow. You can envision and admire it. But you can do more if you invest more.

NELL FREUDENBERGER is the author of the novels *Lost and Wanted*, *The Newlyweds*, and *The Dissident*, and of the short story collection, *Lucky Girls*. The recipient of a Guggenheim Fellowship, a Whiting Award, and a Cullman Fellowship from the New York Public Library, she lives in Brooklyn with her family.

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The Trouble with Brain Scans

An aspiring cognitive scientist faces the sketchy truth about fMRI

BY KELSEY ICHIKAWA

ONE AUTUMN AFTERNOON in the bowels of UC Berkeley's Li Ka Shing Center, I was looking at my brain. I had just spent 10 minutes inside the 3 Tesla MRI scanner, the technical name for a very expensive, very high maintenance, very magnetic brain camera. Lying on my back inside the narrow tube, I had swallowed my claustrophobia and let myself be enveloped in darkness and a cacophony of foghorn-like bleats.

At the time I was a research intern at UC Berkeley's Neuroeconomics Lab. That was the first time I saw my own brain from an MRI scan. It was a grayscale, 3-D reconstruction floating on the black background of a computer screen. As an undergraduate who studied neuroscience, I was enraptured. There is nothing quite like a young scientist's first encounter with an imaging technology that renders the hitherto invisible visible—magnetic resonance imaging took my breath away. I felt that I was looking not just inside my body, but into the biological recesses of my mind.

It was a strange self-image, if indeed it was one. My hair did not show up, leaving just the skull and outline of the face with a cross section of the tissues inside. Dragging my mouse, I cruised through the horizontal slices of my brain—there were the branching, root-like patterns of the cerebellum, the gaping black holes of the ventricles, and the undulating ridges of my cortex looking like snakes wiggling in the sand.

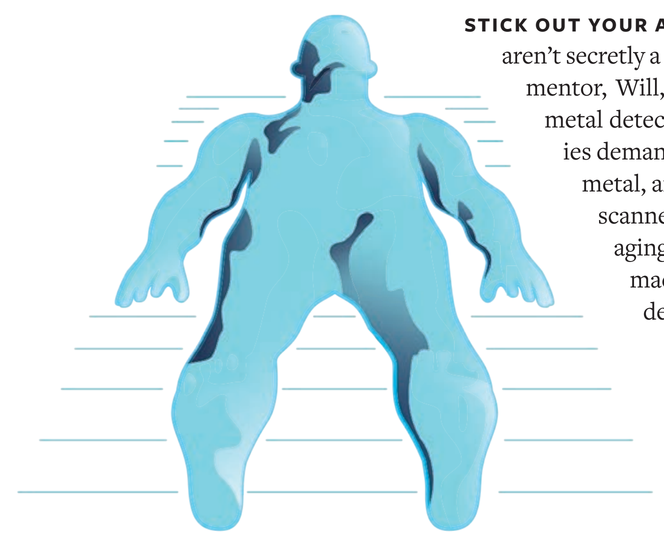
Full of excitement after my encounter with MRI, I consumed scientific papers and studied their figures, which were usually grayscale brains with bright orange and blue blobs on them indicating regions of increased activation. The following year I joined a lab at Harvard, where I started working on an experiment that used functional MRI, or fMRI, to study the brain regions involved in social decision-making. fMRI allows us to record what the brain is up to while people perform mental tasks. I committed to a senior thesis and set my future sights on a Ph.D. in cognitive science.

JACKIE NIAM / SHUTTERSTOCK

Little did I anticipate what a scientific morass I had entered. Functional magnetic resonance imaging has transformed medicine. It allows non-invasive mapping of a patient's brain regions to enable more accurate, precise neurosurgery,[1] as well as validating pharmacological effects of potential drugs on human brains.[2] But fMRI's use in cognitive and psychological science is notoriously controversial. This is partly because the technology doesn't directly measure neural activity but rather a proxy for it—oxygenated blood flow. It also requires a tremendous amount of data processing to sort signal from noise, data processing that requires many discretionary choices on the researcher's part.

In recent years, the field has dealt with a host of issues involving software glitches,[3] misapplied statistics,[4] and irreproducible studies.[5] These challenges have complicated MRI use in clinical and commercial contexts. Companies have attempted to bring fMRI into the courtroom to share what the brain reveals about truth-telling, insanity, and injury. It seems we seek something deeper, more human in these pictures of blood flow in the brain. We are looking for the mind and all its intricacies, the seat of agency, personality, and madness.

This is a story about how we—scientists and non-scientists, journalists and readers—tell illustrated stories about the brain in our attempt to understand the mind. When we talk about some part of the brain "lighting up," or a blob on the cortex serving as the hub for social pain, our language is shaped by the form of the brain images we see, and that image form emerges perhaps more from human choices than biological facts. This is also my story. I was determined to pursue a career researching the neural mechanisms of intergroup relations. If we could untangle the brain's role in our social biases, we might one day overcome them. MRI was going to light the way.



STICK OUT YOUR ARMS and legs like a starfish, and I'll make sure you aren't secretly a metal robot," my scanning buddy and postdoctoral mentor, Will, said to the volunteer participant. Will guided a metal detector wand over the participant's body. (fMRI studies demand an obsessive meticulousness about checking for metal, and justifiably so—the 3 Tesla magnetic field of the scanner at Harvard's Center for Brain Science Neuroimaging is strong enough to suck an office chair into the machine. Anything magnetic will quickly become a deadly projectile.)

After the participant laid supine on the scanner bed, Will and I snapped on the head coil, a clunky helmet which emits and receives radio frequency pulses from the machine. It reminded me of an especially unwieldy superhero mask. Our volunteer would be doing a decision-making task, in which he would repeatedly choose to play slot machines that yielded two different kinds of monetary rewards: one that gave money to people who shared his political party, and one that did that and subtracted money from people of the opposite political party. We were interested in whether he demonstrated a preference for one reward over another. (We would later calculate some participants were inclined toward the reward that hurt the other political party—they had a taste for out-group spite—and this preference may have a neural correlate.)

After strapping a button box onto his right hand, I raised the scanner bed and watched him glide slowly into the small cave of the magnet. Once back in the control room, Will launched the experiment's slot machine game. Soon we heard the frenetic stream of high-pitched beeps that indicated we had begun to collect functional images of his brain. At times it seemed bizarre, studying the neurobiology of intergroup decisions by sticking a single person into a chilly, spaceship-esque donut to play what were essentially low-graphic video games for an hour. These are, however, the constraints of most fMRI lab studies—a highly simplified computer task interface that mimics features of the real world while the machine tracks your blood flow patterns.

MRI measures the BOLD—blood oxygen level-dependent—signal. Since neurons need oxygen when they're firing, more oxygenated blood will travel to that local region of the brain. Rick Born, a neurobiologist at Harvard Medical School, who studies the visual cortex using electrophysiology, helped me understand the process. In the break room of his lab, he was chatty and exuded that particular form of excitement that scientists have when talking about their field. He drew animatedly on a white board, sketching a diagram with arrows going from the words "neural spikes" to "extracellular field potential" to "increased metabolism" to "increased blood flow." Because, for the most part, scientists can't measure neural spikes directly in humans (that requires opening up the skull and directly implanting electrodes, which is done in animals but only done in humans for medical cases like epilepsy treatment), we have to content ourselves with fMRI's indirect proxy.

We seek something deeper in these pictures of blood flow in the brain.

So how does the machine detect oxygenated blood flow? The answer lies in the atomic world and its quantum properties, specifically nuclear *magnetic resonance*—that's where the "M" and "R" in fMRI come from. In the presence of a very powerful magnetic field, hydrogen protons align with each other; you can picture them all pointing in the same direction. A well-coordinated radiofrequency pulse from the MRI machine will knock them off their alignment, like a finger flicking over a bobble toy. Bobble toys bounce back, and so do hydrogen protons. They will gradually "relax" back to their initial alignment. Hydrogen protons present in the skull will relax at a different rate than protons in the cortical tissue, giving us a way to use mathematical processing to generate pictures of anatomy.

But fMRI gives us more than anatomy. The "f" indicates a vital distinction. The MRI scan many people receive at the hospital is usually an

PIXELATED fMRI transforms the brain in ways similar to what happens when you take a photo—the camera converts the physical scene into a matrix of numbers, pixel intensities, and color.

DEVESH JAISINGHANI / SHUTTERSTOCK

anatomical MRI scan, providing high-resolution 3-D images of muscle, tendon, and bone tissue, able to highlight potential injuries like tendon tears or diseases like cancer. On the other hand, fMRI captures the liveliness of our brains and bodies, measuring the active movement of blood over time that is related to neural firing and cognition.

It's able to achieve this because of the complicated dance of magnetic resonance. Each hydrogen proton has a quantum property called "precession frequency"—a rotating spin. A radiofrequency pulse not only knocks protons down, but synchronizes their spins with each other, matching their precession frequencies into a coordinated group choreography. After the pulse, the precession frequencies gradually become unsynchronized again as the protons return to their upright orientation, spinning off at different rates like dancers embarking on their solos. This fact of nature, which makes fMRI possible, is that this process of desynchronization happens more slowly in the magnetic field of oxygenated blood in a brain. That is, protons in oxygenated blood more effectively stay in sync, emitting a stronger signal than protons in deoxygenated blood, a difference that the MRI scanner detects as the BOLD signal.

Finally, the "I" of fMRI stands for "imaging" because the output of this process is essentially a 3-D video of the brain in action. The scanning process divides the brain into small cubes called voxels, the three-dimensional equivalent of pixels. The data collected from a person's scanning session consists of quantitative measures of the BOLD signal at every voxel. Voxels typically range in size from 1 cubic millimeter to 27 cubic millimeters—small to us, but colossal on the scale of neurons. For a sense of scale, the brain contains an estimated 100 billion neurons, and a single voxel in the human cortex can cover over 500,000 neurons. Those neurons may be doing any number of things—exciting each other, inhibiting each other, or firing in different patterns within sub-populations—but all that fMRI can detect is the net change in oxygenated blood over that whole voxel space every 2 seconds. This is like trying to determine the average opinion on foreign policy from 500,000 different people arguing, agreeing, and debating simultaneously.

AFTER WILL AND I had scanned close to 50 people, it was time to start wrangling those terabytes of data. I grabbed a cup of coffee, plugged in my headphones, and started playing music by the band Hippo Campus (thematically appropriate, I suppose), settling in for a long night in the library. I was doing quality control checks, in which I looked for unnatural stripes or unusual brightness in the brain data we had collected.

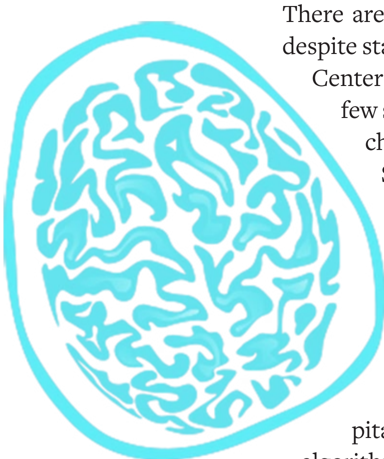
Using a special software program, I viewed the raw functional data—a gray and black video of a fuzzy brain slowly pulsing. In essence, the raw data that emerges from the scanner is a four-dimensional matrix that records changes in every voxel over time. The living, biological flesh of the brain that lay inside the scanner has been transformed into a set of numerical time series. It is the same thing that happens when you take a photo of the sunset—the camera converts the physical scene into a matrix of numbers, pixel intensities, and color. You can do a lot with a brain once it is in this numerical form. Using the computational neuroscientist's lab bench—a computer and desktop—I could warp, smooth, and filter these brains, a stage of analysis known as data pre-processing.

It's like surveying 100,000 strangers about whether they know Beyoncé personally.

fMRI is a game of millimeters. Minute movements of the head greater than 3 millimeters can produce distorted, ultimately unusable images. Pre-processing helps correct for motion by applying mathematical transformations that shift the brain back in place every time it bounces or rolls. Pre-processing also takes the fuzzy, raw functional brain data and via stretching, shifting, and shrinking voxels, transforms it to match first, the participant's anatomical scan, and second, a standard brain template.

Human brains exhibit considerable variability—slightly lopsided hemispheres, a lumpy occipital lobe, or just overall larger size (as practitioners of craniometry noticed early on). Without matching each participant's brain to a template, we would never be able to compare brain activity across an entire study sample.

Algorithms spatially smooth the data, which means averaging the activity of neighboring voxels in another attempt to eliminate noise. At least, what we think is probably noise; one always hopes they aren't filtering out the real signal of interest. It's like rubbing your finger over a pencil drawing to even out the shading. All this reshaping and correction produces brain images that are sharper, more uniform, and less rough around the edges—at the price of spatial resolution.



There are countless variations of preprocessing steps, and despite standardization initiatives spearheaded at Stanford's Center for Reproducible Neuroscience, there are still very few standards that the whole field follows, leaving many choices up to the individual researcher's discretion. Seemingly inconsequential decisions about which computer operating system, software program, or scanner hardware to use can produce pivotal differences in results.

"Magnetic resonance's strength is that it is a massively flexible technology," said Bruce Fischl, the director of the Computational Core at the Martinos Center and Massachusetts General Hospital, and one of the early pioneers of fMRI analysis algorithms. "It can generate images of structure, images of function, even map something related to neural connectivity, or look at chemical change. The downside of that flexibility is that it's difficult to standardize any set of images across different labs."

"WELL, BETTER LUCK on future analyses." Will and I stared at the gray-scale brain template, an aggregate of statistics from all our subjects, which was completely devoid of color—no hot spots, no clusters to use as future regions of interest. We had come to the stage after preprocessing, the actual statistical analysis. We had hypothesized that we would see differential activity in the subcortical reward circuitry depending on whether the monetary prize inflicted harm on the out-group, which could suggest a reward signal influencing decisions to harm a competing group. After all those nights spent scanning, weekends in the library learning a new programming language, and hours trouble shooting the experimental setup, I had hoped we would see a novel outcome—but this was a null result, a dud. Fortunately, it was just our preliminary analysis, but I still felt disheartened.

A common misconception is that fMRI studies tell us which brain regions are active during certain tasks. In fact, everything is relative. fMRI studies can tell us which brain regions are more active in one task than in another task. Put another way, fMRI analysis tells us which collections of voxels have activity profiles more closely matching one condition than another. Even cutting edge methods that capitalize on developments in machine learning analyze whether voxels collectively contain information that can discriminate one condition from another.

The most common analysis procedure in fMRI experiments, null hypothesis tests, require that the researcher designate a statistical threshold. Picking statistical thresholds determines what counts as a significant voxel—which voxels end up colored cherry red or lemon yellow. Statistical thresholds make the difference between a meaningful result published in prestigious journals like *Nature* or *Science*, and a null result shoved into the proverbial file drawer.

Scientists are under tremendous pressure to publish positive results, especially given the hypercompetitive academic job market that fixates on publication record as a measure of scientific achievement (though the reproducibility crisis has brought attention to the detriments of this incentive structure). If an fMRI study ends up with a null or lackluster result, you can't always go back and run another version of the study. MRI experiments are very expensive and time-intensive—my own required upward of $25,000 and took over a year to finish. You can see how a researcher might be tempted, even subconsciously, to play around with the analysis parameters just one more time to see if they can find a significant effect in the data it cost so much to obtain.

"fMRI is clearly not pure noise, it's a real signal, but it's subject to many degrees of freedom, fiddling around with the data, filtering it in different ways until you can see whatever you want to see," Born said.

The problem of statistical excess, called multiple comparisons, looms large over this part of the analysis. "That's probably the single biggest issue in brain imaging," Fischl told me. Multiple comparisons means *too many* statistical tests. The problem of multiple comparisons is like surveying 100,000 strangers about whether they know Beyoncé personally. None of those 100,000 people are actually acquainted with her, but for each person you ask, there is a 5 percent chance they will lie and say they are, just for kicks. In the end, you tally 5,000 friends of Beyoncé, *even though* the ground truth is that zero of those people are friends with her. If you had asked 100 strangers, you would only end up with five incorrect measurements, but because of sheer numbers and the probability of random deception, surveying 100,000 strangers results in 5,000 incorrect measurements.

So, too, with fMRI data: One person's brain data has hundreds of thousands of voxels. By the sheer number of voxels and random noise, a researcher who performs a statistical test at every voxel will almost certainly find significant effects where there isn't really one.

This became clear in 2009 when an fMRI scan detected something fishy in a dead salmon. Craig Bennett, then a postdoctoral researcher at the University of California, Santa Barbara, wanted to test how far he could push the envelope with analysis. He slid a single Atlantic salmon into an MRI scanner, showed it pictures of emotional scenarios, and then followed typical pre-processing and statistical analysis procedures. Lo and behold, the dead fish's brain exhibited increased activity for emotional images—implying a sensitive, if not alive, salmon. Even in a dead salmon's brain, the MRI scanner detected enough noise that some voxels exhibited statistically significant correlations.[6] By failing to correct for multiple comparisons, Bennett and his colleagues "discovered" illusory brain activity.

To correct for multiple comparisons, neuroimagers must establish stringent thresholds for statistical significance. "It's hard because we don't know what the right directions are," Fischl told me. "As a researcher, you're left with a choice: Are you going to live with missing stuff? Or are you going to live with showing stuff that's not real?"

You can see how a researcher might be tempted to play around with the parameters.

Fischl is talking about how statistical thresholds have to strike a balance between a scientist's two deepest fears: false positives (mis-identifying noise as signal) and false negatives (losing the signal amidst the noise). Therein lies the rub: The field has not yet settled on a best practice solution to multiple comparisons because people cannot agree on the right balance of strictness. Moreover, all the possible corrective procedures have important weaknesses, like assuming the voxels are independent of each other even though they are not.

In 2016, another paper rocked the neuroimaging world. Anders Eklund, Thomas E. Nichols, and Hans Knutsson published an empirical investigation of glitches in common fMRI software analysis packages.[3] These software bugs greatly increased the chance of false positive results, in some cases to over 70 percent instead of the 5 percent error rate most researchers assume. This revelation called into question previous published studies—findings about brain correlates of personality, neural representations of knowledge, even the neural signatures of decision-making.

The first time I read the Bennett and Eklund papers, I sat in a chilled stupor. Was the research I was doing and reading even *real*? Bruce Rosen, the director of the Martinos Center for Biomedical Imaging in Massachusetts, offered me a more tempered take. "The salmon paper showed that you could do analysis in a way that seems reasonable and get this really dumb result," Rosen said. "Am I surprised that you get a dumb result? Hardly. fMRI detects a remarkably big signal, but it's still a signal of 1 percent change from baseline. Is it easy to screw things up so that you see changes of 1 percent? Pretty easy."

The problem lies in what we ask of these results and the authority we give them.

As for the Eklund, *et al.* paper, Rosen conceded, "It was an excellent point of statistics. It's actually a point we understood, but there are no doubt lots of people that didn't understand." But he thinks the paper's implications were overblown. "The impact of that paper was actually pretty modest in terms of the number of results that were invalidated, that were important results. And whether we were significantly misleading people or sending doctors astray or anything like that, was negligible as best as I could tell. But the paper got a lot of press, and suddenly, now fMRI has a black eye."

THAT BLACK EYE has not deterred optimistic speculations about the technology. In a 2019 *Wall Street Journal* article, tech entrepreneur Jerry Kaplan wrote about "The Machines That Will Read Your Mind." Kaplan's article highlights the convergence of machine learning advances and fMRI data, exploring the possibility of using neuroimaging for detecting lies, judging guilt in legal settings, determining when someone is truly "in pain" from a disease, and brain activity surveillance. It sounds like the premise to a *Black Mirror* episode: "Someday it may be possible to learn to some level of precision whether your spouse really loves you, finds you attractive, or is having an affair."

The interest in deception and the brain is not new. Since 2008, companies like No Lie MRI and Cephos have raced to develop adequate research to use fMRI in lie detection, offering their services to legal defendants looking to validate their alibis. Most scientists and legal scholars agree that the technology is not ready for legal applications, and several courts have denied requests to use fMRI evidence in arguments.[7] But as recently as 2016, Robert Huizenga, investor in No Lie MRI, was still promoting the company on *The Dr. Oz Show*. He touted fMRI as the "first unbiased, scientifically-backed way to differentiate a lie from truth telling."

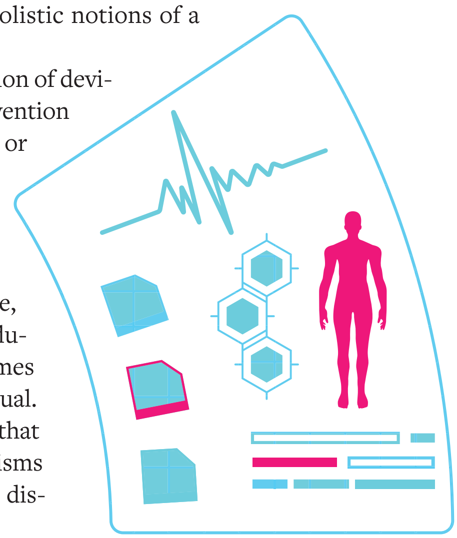
Rosen said he understood how fMRI images take on a special persuasiveness. "The clarity of the images lead to the implication of something more than what the image is," he said. "You see a spot on the brain and you feel like, 'Oh, this is so clear.' And then when you look at the underlying data you realize, eh, it's a pretty small signal that the statistics probably suggest. It's more a probabilistic than real result. Whereas when you see the bright spot, it doesn't seem probable at all, because there it is, right? Inarguable."

It is precisely this power of brain images' projected scientific authority that led anthropologist of science Joseph Dumit to comment on the "undue risk in courtrooms that brain images will not be seen as prejudiced, stylized representations of correlation, but rather as straightforward, objective photographs."[8]

In attempts to mitigate sentences, lawyers have adduced brain images as evidence of pathologies in criminal defendants. Arguments often take the following form: The defendant has a neurological or psychiatric disorder that impairs cognitive and moral reasoning. This image reveals the brain abnormalities associated with the psychopathology.

In court cases involving capital punishment, neuroimaging evidence can literally become a matter of life and death. At the same time, this kind of evidence validates conceptions of distinct human kinds: the mad and the sane, the pathological and the healthy, with these categories borne out in shining pictures of brain activity. In doing so, it privileges biological conceptions of personhood over other more holistic notions of a human life.

One concerning upshot of this is the medicalization of deviance, which can ultimately motivate biological intervention to eliminate behaviors considered non-normative or wrong. That is, fMRI often purports to show that a brain is "broken," and a broken brain demands to be fixed. This can lead to ethically fraught initiatives like recent efforts to electrically stimulate prisoners' brains in order to reduce aggression.[9] Here, the issue of interpersonal violence, a social issue influenced by many structural and cultural factors, comes to be located in the brain at the level of the individual. This is in no small part because of the tight hold that brain images have on our imagination of the mechanisms structuring human behavior, especially stigmatized dispositions like mental illness and criminality.



I LEANED BACK in my chair, squinting through the late afternoon sun from my lab's office on the 14th floor of William James Hall. The amount of useless, random chatter in fMRI data was beginning to overwhelm me. How can we extract the true signal amid such numerical clamor, especially when our statistical programs and know-how are flawed? Which results should I believe? Most importantly, how can we use fMRI technology responsibly, without reifying narrow biomedical definitions of pain, desire, and other human emotions?

"Scientists are human beings, and if there's one thing we know about human beings, it's that we're pretty good at fooling ourselves when we want to believe something," Born said to me. I don't want to fool myself, or for us to collectively fool ourselves, about what fMRI can unveil about the brain.

In March, 2020, the same week in which the World Health Organization declared COVID-19 a global pandemic, I submitted my senior thesis, which allowed me to graduate with a joint degree in neurobiology and philosophy. It contained the write-up of my fMRI experiment, including the null result and future directions for other analysis. I also argued some forms of fMRI evidence could illuminate the immorality of schadenfreude, the emotion where you feel pleasure in another person's or another group's misfortune. I'm proud of my thesis and sincerely enjoyed collecting and analyzing neural data.

Scientists are under immense pressure to publish positive results.

But in the process of doing this research, I was forced to confront this fact: fMRI is an imprecise camera that captures blurry images of blood, not neurons, and requires extensive computational manipulation before we can even view the images. If we want to avoid surgery or drugs, it is the best brain camera we have, and a pretty poor one at that. fMRI *has* produced important results and knowledge. It has allowed us to envision the systematic organization of the cortex across adult humans, which "provides a new lever for investigating the human mind's developmental and evolutionary origins," as Nancy Kanwisher, professor at MIT's McGovern Institute, put it. It has also allowed neuroscientists to learn about the brain's default mode network, which plays a key role in autobiographical memory and planning.

The problem lies in what we ask and expect of these scientific results, and the authority we give them. After all, the phrase "the brain lights up" is an artifact of the images that *we* craft. The eye-catching blobs and connectivity maps exist because of the particular way in which neuroscientists, magnetic resonance physicists, and data scientists decided to visualize and represent data from the brain.

Now I'm questioning whether I want to continue in this fraught field. Since graduating, I've turned toward my other passion, political advocacy and education in the Asian-American community. I joined two grassroots advocacy groups in California, one that organizes Japanese-Americans and another that builds cross-racial coalitions to fight discriminatory policies. Although I'm not probing people's brains, I am learning about creating solidarity between ethnic groups with long histories of conflict and shared oppression. As a student, I had wanted to understand how the boundaries of in-group and out-group crystallize, and now I have a chance to observe and enact firsthand actions that regulate or expand who is included in a community.

Still, I keep my Google bookmark folder for cognitive science Ph.D. programs. I attend neuroscience lectures when I can. Maybe I'll return, either as a scientist or sociologist of neuroimaging techniques. In opening the black box of the MRI machine, I may have fallen out of love with neuroimages, but at least now I see them for what they are.

KELSEY ICHIKAWA is a budding researcher with interests in the politics and ethics of science. She graduated from Harvard in 2020 with an A.B. in neurobiology and philosophy, and is currently based in California. You can follow her on Twitter @ IchikawaKelsey

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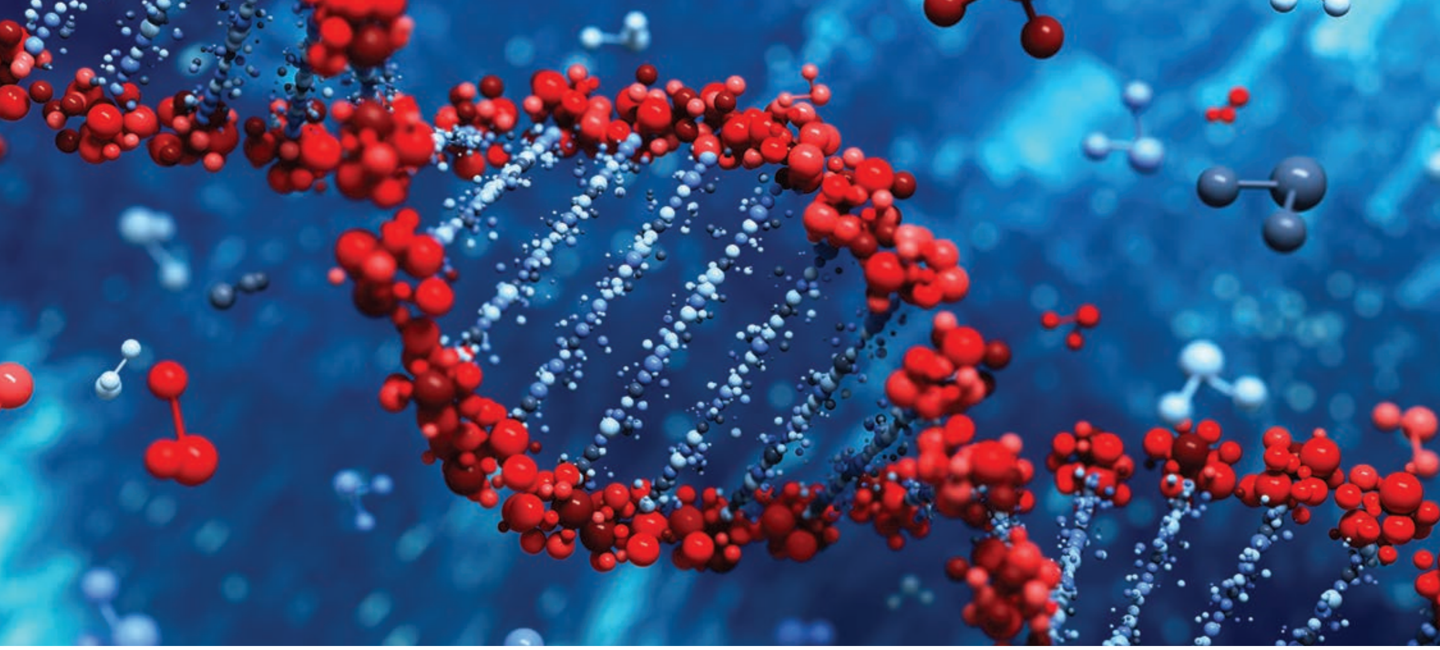

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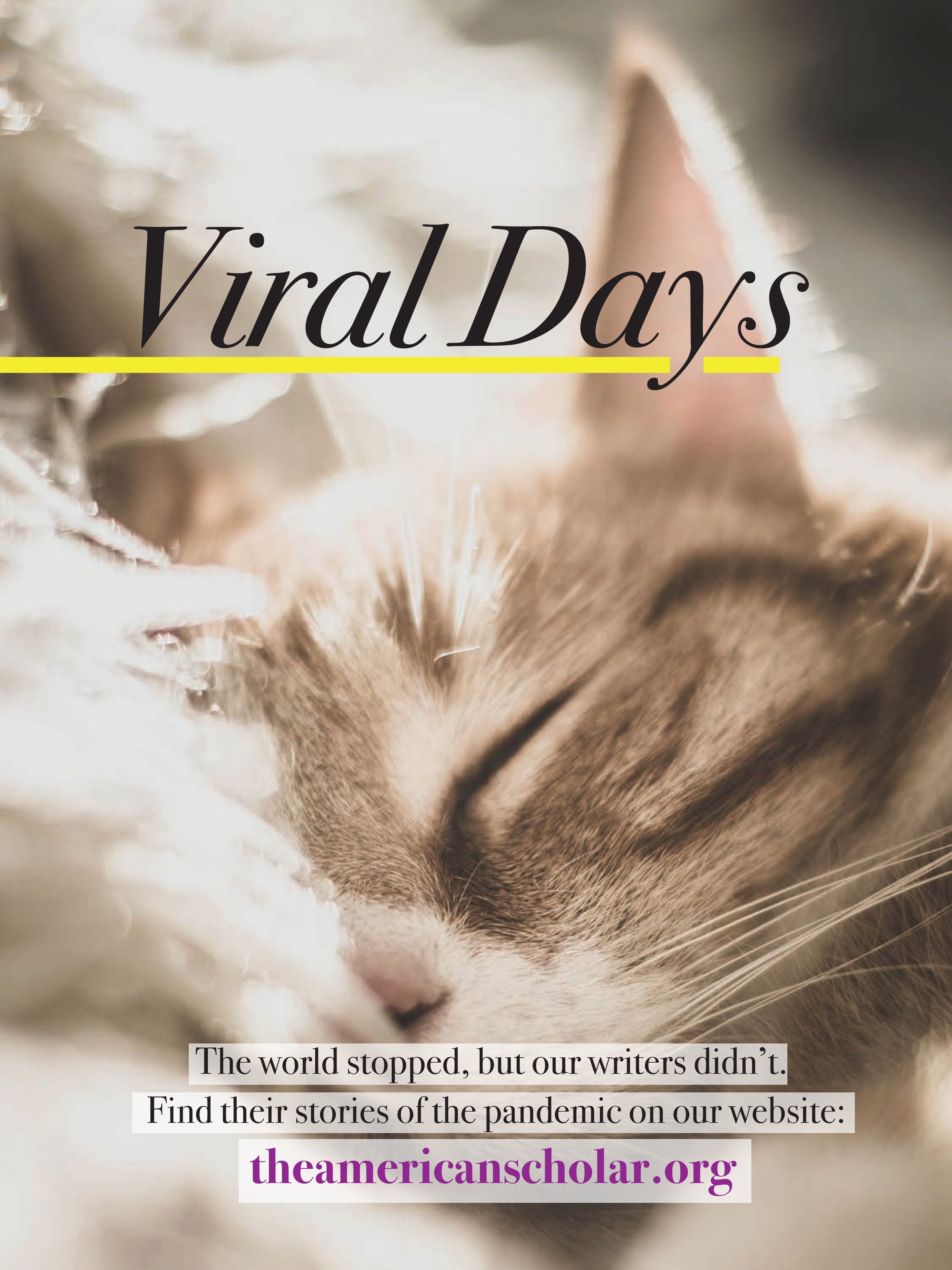
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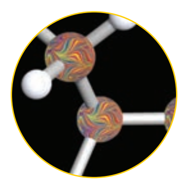

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Jonathon Keats

The experimental philosopher on how he created universal music

INTERVIEW BY KEVIN BERGER

TWO SUBCULTURES

If art is doing all that it can, and if science is doing all that it can, they have a lot to tell each other. They have a lot in common. Where art is most interesting to me is in the process of exploration, creatively speaking, the exercise of the imagination. Where science is most interesting to me is in the practice of discovery and the pursuit of curiosity. When you put these together, you end up with something that is no longer easy to set in one academic department or possible to hold down with a label.

To make music truly universal, we need to question the assumption that the human hearing range is adequate.

INTERGALACTIC SOUNDS

One of my projects that combines science and art—and is featured in a new anthology of my work, *Thought Experiments*—is called "Intergalactic Omniphonics." I want to investigate the common assumption that music is universal. The challenge of making music universal begins with the audience. In the case of an audience in a concert hall, you're talking about humans who have the same hearing range, and music is played on instruments tuned to that gamut. But if we're going to make music truly universal, we need to question the assumption that the human hearing range is adequate.

GRAVITATIONAL CELLO

There's no reason to believe that beings from elsewhere in the universe have ears. There might not be any evolutionary impetus, particularly if there isn't enough atmosphere to carry sound waves. So to make truly universal music we need to venture into territory beyond the human or animal sensory apparatus. What might other beings be able to sense? Gravitational waves? Music is a process of modulating frequency and amplitude over time. So I've created an instrument for modulating gravitational waves with a heavy weight on a string. I call it a "gravitational cello."

ENTROPIC ORCHESTRA

We have to address the fact that our musical traditions might be foreign to other beings. What might be the content of universal music? What can it express? I decided to create a universal anthem based on the fate of all matter throughout the universe: the tendency of entropy to increase in a system over time, formally known here on Earth as the second law of thermodynamics. Life has the remarkable ability to extract energy from a system before disintegrating to become a part of that system again. So my universal anthem involves a series of soloists on different instruments, some of which we can hear, others outside our sensory range. The orchestra serves as the environment. The soloist is an organism undergoing birth, life, and death. The solos begin with decreasing entropy, followed by increasing entropy. By having this iterate through multiple cycles performed by diverse soloists, it becomes a way to communicate what all life has in common: the characteristic of being alive by virtue of having the capacity to temporarily thwart the second law of thermodynamics. My universal anthem is a celebration of this extraordinary capacity. It's an affirmation of life.

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