NAUTILUS

The Invasion of Language

AN ESSAY BY CORMAC MCCARTHY p.22

US$12

MAR/APR 2017

Science Connected

NAUTIL.US


12 BILLION MILES AND COUNTING...
THE FARTHEST
The epic story of NASA's Voyager mission
to the outer planets and interstellar space
Feature film world premiere
THURS APR 20
TRIBECA FILM FESTIVAL
2017
OFFICIAL SELECTION
Television broadcast premiere
WED AUG 23 9/8c
PBS
hhmi
Tangled Bank Studios
Crossing the Line
Productions
ifb
IRISH FILM BOARD

The Character of the Unconscious

WHAT SUBJECT WOULD Cormac McCarthy tackle, if he were to write a non-fiction science essay?

Now we know, because we're publishing his first: the unconscious.

The subject may not come as a surprise to his fans, because to read McCarthy is to negotiate a series of dreamscapes. There is the 1950s Tennessee of *Suttree*, a "world beyond all fantasy, … the blown lightbulbs like shorn polyps semitranslucent and skullcolored bobbing blindly down"; the nameless, abducted infant of *Outer Dark* being pursued through dark forests by its mother; the higher faculties of reflection and justice faltering in the face of *Blood Meridian*'s animalistic, borderland violence.

What may be more surprising (it is to me) is the depth of McCarthy's academic interest in the unconscious. He has spent decades discussing and debating its nature with his colleagues at the Santa Fe Institute, the scientific research center where he is a senior fellow and trustee. In this issue's cover story, he presents the understanding that has emerged from these years of thought—a product, he tells us, mostly of his own unconscious, just like his writing.

"The actual process of thinking," McCarthy argues, "is largely an unconscious affair." But, the unconscious is also "not used to giving verbal instructions and is not happy doing so." Language, McCarthy concludes, is a newcomer, an invader that has forced itself onto an ancient brain—and not, contrary to certain "influential persons," something that evolved entirely from it.

The result is a scientifically informed, humanist take on a foundational question in science, and a remarkable window into the self-conception of one of America's greatest living writers.

Whether because of its content or of our expectations, McCarthy's take also seems vaguely familiar. The young interloper traveling from a distant place. An ancient, silent, unwelcoming landscape. A conflict. A conclusion full of question marks. Almost as if the scientific narrative wasn't that different, really, than the human ones that came before it.

Which is something we at *Nautilus* have believed in all along.

Welcome to the March/April 2017 *Nautilus* print edition.

—*Michael Segal*
Editor in Chief

Contents

AMANDA PHINGBODHIPAKKIYA

46

Balance

"The fear threatens to overwhelm us, motivating us into a state of extreme focus. It's a state between comfort and terror."

—Samantha Larson, p. 34

THEME ART Francesco Izzo

47

Consciousness

"I felt less like myself and more like everything around me."

—Lauren Marks p. 80

THEME ART Len Small

NAUTILUS

Nautilus has received financial support from:

John Templeton Foundation
Science Sandbox, Simons Foundation
hhmi Howard Hughes Medical Institute
Olin College of Engineering
Glenn Foundation for Medical Research
Carnegie Corporation of New York

Published by:

The MIT Press
Nautilus *think*

Letters

Reader responses to the Jan/Feb 2017 print edition.

“BIAS IN THE ER”
Good article, would love to see more examples (sprinkled throughout the article) about these confusing questions and what they say about the mind, and how to compensate.
—*Bob Helkse*

“HOW DESIGNERS ENGINEER LUCK INTO VIDEO GAMES”
Very valuable, and also scary piece. It seems to be saying that some of the methods used by game designers to make their products more addictive are also over time likely to increase players’ vulnerability to addictive behavior in general. I wonder if anyone has attempted to study this possibility, which has unfortunate implications as our society comes to consist more and more of people who spend hour after hour playing these games.
—*RSF*

“AGAINST WILLPOWER”
A very thoughtful and thought- provoking article. However, I find the use of drinking as your core example to be ultimately confusing, even off-putting. I find the concepts described here to be intriguing, and they strike me as quite right. I just wish you’d use examples other than addiction to make your case. You might look at, for example, procrastination, or shyness, or exercise, or studying. Just not drinking, in my humble opinion.
—*Charles H. Green*

None of your arguments suggest that willpower does not exist—only that we are having trouble understanding it and that it’s not always a helpful concept. We shouldn’t reject a notion simply because it’s inconvenient. But I think you have hit on something important by encouraging people, particularly those struggling with addiction, to look for other factors before writing themselves off as too weak.
—*Scott Baker*

“INVESTING IS MORE LUCK THAN TALENT”
This article fails to bring into consideration any of the factual details of investing or the skills necessary to make wise investments. All the author has succeeded in doing is introducing a mind-game where a certain path of logic makes sense and is therefore presented to be fact. Logic is not always truth.
—*Shang Pav*

CORRECTIONS
As originally published in the January/February 2017 print edition of *Nautilus*, “Time Is Contagious” incorrectly stated that the famous chess computer is called “Big Blue.” It’s really known as Deep Blue.

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

CONTACT
233 Broadway, Suite 720
New York, NY 10279
212 221 3870
info@nautil.us

SUBSCRIPTIONS
Visit subscribe.nautil.us

aging

is the climate change of human biology

GLENN FOUNDATION
FOR MEDICAL RESEARCH

Why Basic Science?

SCIENCE
PHILANTHROPY ALLIANCE

Advancing basic science—The foundation of our future

www.sciphil.org

Preludes

PHYSICS

How to Weigh the World

A delicate balance leads to a colossal result.

ATLAS KNEW THE ANSWER. Straining under the task of holding up the Earth, this Titan god likely got a good idea of how much the Earth weighed. But none of us are so conveniently situated. How could mere mortals carry out their own estimate of Earth's weight?

A firm answer didn't arrive until the Englishman John Michell figured out a way. Little known today, he was actually one of the cleverest clergymen of the 18th century. As a geologist, astronomer, mathematician, and theorist who hobnobbed with his fellow greats at the Royal Society of London, he was the first to many things: the first to suggest that earthquakes propagate as elastic waves through the Earth's crust (earning him the title "father of modern seismology"), the first to suggest that many stars were likely paired up as binaries, and the first to imagine a star so huge and massive that no light could escape its intense gravitational field—a black sun, the Model-T version of a black hole.

This West Yorkshire parson was a devotee of Isaac Newton's law of gravitation, introduced in 1687. While the law had found great success in predicting the motions of comets and cannon balls, by the 1780s the gravitational attraction between two small bodies in a laboratory had not yet been demonstrated. Michell had wanted to know for decades our planet's density—and hence its weight. So, he devised a scheme to measure those short-range gravitational forces, and in the process weigh the Earth. The apparatus Michell designed was simple, yet elegant. In fact, it involved only four balls of lead, a moveable rod, and a set of wires, all

SHUTTERSTOCK

PHOTOCOLLAGES BY FRANCESCO IZZO

encased to prevent interfering air currents. Physicists call this a "torsion balance," as rotation of the rod is the key to its function.

The final design had a 6-foot-long wooden rod suspended on a wire, with a pair of the 2-inch-wide balls attached to each end. Then a larger ball (a foot across) was separately suspended close to each of the smaller balls. The idea was that the minuscule gravitational attraction between each pair of large and small balls would gradually cause the supporting arm to move. But this rotation stops once the twisting force of the wire equals the force of attraction between the large and small lead spheres. This provides one bit of information. Already known is the gravitational force of the balls toward the Earth below; it's simply their weight. Crucial to Michell's concept was having these two sets of data. By comparing the two, separately measured forces on the balls, the experimenter can then calculate the one unknown in the gravitational equation—Earth's mass. A delicate balance leads to a colossal result.

Michell's apparatus eventually ended up with his Royal Society colleague Henry Cavendish, who was described by his biographers as "one of the richest men of the realm ... a scientific fanatic, and a neurotic of the first order." He was frightfully shy, especially of women. In his solitude, he completed the instrument with the final design that improved on Michell's original scheme. Cavendish now gets the lion's share of credit for the long-awaited test—and with good reason. With the apparatus shut up in a small shed on his estate, he had to manipulate the weights from the outside with pulleys and observe the arm's tiny movements (no more than two-tenths of an inch) through a hole at each end of the shed's wall with a telescope.

It was laborious and painstaking work. Over and over again, he measured torques, moments of inertia, and the angles of the rod's deflections, with the results inserted by hand into the proper mathematical formulas to find answers. His discovery paper, published in *Philosophical Transactions* in 1798, was described by a Scottish physicist at the time as "a model of precision, lucidity, and conciseness."

Cavendish's computed value for the density of the Earth—even with equipment we now consider ancient—was within 1 percent of today's value, now recognized as 5.513 grams/cm^3, or five-and-a-half times the density of water. Multiply that by the volume of the Earth (around 1.1x10^{27} cm^3), and you arrive at some six thousand trillion trillion grams for our planet's total mass.

Too bad Atlas isn't around these days to confirm the finding.

—Elizabeth Landau

ARTIFICIAL INTELLIGENCE

Would You Have Any Cosmetic Neurology Done?

LIKE SOME OTHER FUTURISTS, Ray Kurzweil thinks the best way to avoid aging is to avoid biology altogether. With a sufficient understanding of the brain, he says, we'll be able to upload our minds to non-organic structures and become digitally immortal. Who's going to rule out such an idea so early in the game?

Answer: Susan Schneider, philosopher and cognitive scientist at the University of Connecticut. "It would be silly to claim you can 'upload' your consciousness to a computer, " she says. "You wouldn't be conscious, and it wouldn't be you. Uploading would not be a route to digital immortality but suicide."

Schneider spoke to *Nautilus* about her thoughts on the mind and the potential promise and danger of artificial intelligence.

SHUTTERSTOCK

Why is Ray Kurzweil wrong about what we can do with the mind?
Kurzweil is a true visionary, but he believes that the development of AI will lead to a technological utopia. That may be the case, but I don't see how it could involve uploading your mind. It is too early to tell if machines will be conscious. If AIs that seem conscious—like Samantha in the film *Her*—aren't actually conscious, then a version of our uploaded minds may not be conscious either. In other words, we'd forfeit consciousness. On the other hand, if *Her*-like AIs are conscious, then so may uploaded minds be—but what can guarantee that the uploaded mind would be *you*, rather than just a digital copy of you that now exists while you're dead?

In any case, if someone is going to try to do this, they had better make sure that the type of computer your brain is supposed to be "uploaded" on is actually capable of being conscious. Silicon, for instance, may be capable of fast information processing, but perhaps not consciousness.

Is technology advancing too quickly for humanity's good?
One wouldn't want medical technology to advance any slower, and it's exciting to have so many developments in that field. I do agree with Kurzweil that the next 20 years will probably be marked by the development of Artificial General Intelligence and that superintelligence will follow. We already see signs that AI will change the face of warfare and will be a part of our everyday lives, from self-driving cars to brain enhancements.

However, I would be worried if artificial intelligence advanced too quickly. The recent successes of Google Deep Mind, such as Alpha Go, coupled with the open sourcing of AI by Elon Musk and others, suggests that superintelligence could be developed, and faster than we think. This is not science fiction—this is science fact. The problem is that it could rewrite its own programming. As a result, superintelligence could be impossible to control. At that point, it wouldn't be safe for humankind.

What science-fiction tales of AI do you think we should beware?
My favorite is Huxley's *Brave New World*, which warns us of the twin abuses of rampant consumerism and technology in the hands of an authoritarian dictatorship. The book depicts a technologically advanced society in which everyone is complacent, and the family has withered away and childbearing is no longer a natural process—something an unfeeling superintelligent AI might very well impose.

—Cole Little

LINGUISTICS

Mumbling Is a Clever Data-Compression Trick

MANY OF US WERE TAUGHT that pronouncing vowels indistinctly and dropping consonants are symptoms of slovenly speech, if not outright disregard for the English language. The Irish playwright St. John Ervine viewed such habits as evidence that some speakers are "weaklings too languid and emasculated to speak their noble language with any vigor." Happily, the science of mumbling offers a far less judgmental account of our imperfect pronunciations.

The idea is to keep only the information that has the greatest impact.

Far from being a symptom of linguistic indifference or moral decay, dropping or reducing sounds displays an underlying logic similar to the data-compression schemes used to create MP3s and JPEGs. These algorithms trim the space needed to digitally store sounds and images by throwing out information that is redundant or doesn't add much to our perceptual experience—for example, tossing out data at sound frequencies we can't hear, or not encoding slight gradations of color that are hard to see. The idea is to keep only the information that has the greatest impact.

Mumbling—or phonetic reduction, as language scientists prefer to call it—appears to follow a similar

PIXABAY

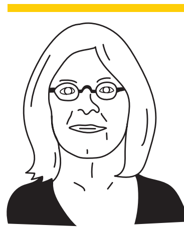
strategy. Not all words are equally likely to be reduced. You're more likely to reduce common words like "fine" than uncommon words like "tine." You're also more likely to reduce words if they're predictable in the context; the word fine would be pronounced less distinctly in a sentence like "You're going to be just fine" than "The last word in this sentence is fine." This suggests that speakers, at a purely unconscious level, strategically preserve information when it's needed, but often leave it out when it isn't.

While there are many reasons to believe language involves a great deal of data compression without catastrophic loss of meaning, scientists still know very little about how speakers figure out exactly what information they can leave out and when. The data-compression algorithms used to create MP3 files are based on scores of psychoacoustic experiments that probed the fine points of human auditory perception. Do speakers have implicit theories about what information is most essential to their listeners? If so, what do these theories look like, and how do speakers arrive at them?

We also don't know how well speakers tune their data-compression algorithms to the needs of individuals. Accurately predicting the information that a listener can easily recover sometimes requires knowing a lot about his previous experience or knowledge. After all, one person's redundancy can be another person's anomaly.

— Julie Sedivy

ONE QUESTION



"How much of the mind's knowledge is innate?"

Susan Carey

Developmental cognitive psychologist at Harvard University

That depends what you mean by knowledge. There are probably no innate beliefs. But there are innate representations of the world. If you take a representational computational theory of mind—which I think is the only game in town—all learning mechanisms are computational mechanisms that take information as input, and then transform it in some way. That's got to bottom out in some innate representations! For the Indigo Bunting bird, for instance, to calculate the center of rotation of the night sky, it must be able to identify the night sky. It must know, "That's the input that I'm supposed to be looking at successively in snapshots so that I can identify the center of it," right?

You can't have an innate learning mechanism without innate representations, just as a matter of logic! The question then just becomes: What are they? One view is that the innate representations are limited to proximal sensory representations, and the learning mechanisms are domain-general, statistical associations. The alternative point of view is the innate representational repertoire is vastly richer, and there's lots and lots of different kinds of learning mechanisms. That's the evolutionary psychology point of view, and the one that's clearly true for non-human animals. It would be kind of bizarre if we were the only animal that that wasn't true of.

PSYCHOLOGY

When Animals Started to Seem More Like People

Maybe your cat is more sentient than you think.

ANY PET OWNER WILL claim with confidence that their dog or cat (or rabbit, or gerbil) seems sentient, exhibiting a distinct temperament and emotional responses. I know my many beloved pets over the years could feel pain and fear, as well as love and trust. But are our pets truly conscious creatures?

It likely depends on what you mean by consciousness. On one end of the scale there is basic wakefulness and sentient awareness—which we share with all living creatures—and on the other, more sophisticated end there is self-awareness. But there are many other systems and terms advanced by various researchers to categorize and describe consciousness. Part of the confusion stems from the great complexity, largely still unknown, of how the brain gives rise to consciousness.

For a long time, scientists assumed that having a neocortex (the outer, and more recently evolved, part of mammals' brains) was necessary to be truly conscious in the human sense—not merely aware of one's surroundings but also self-aware. But there's good news for animal lovers, because that view is changing.

When we are just over one year old, we can look into a mirror and recognize the reflection as being "us." In the 1970s, Gordon G. Gallup devised a mirror test, in which he marked the face of an animal as it slept. If, when it woke and saw its reflection in a mirror, the animal tried to wipe away the mark, Gallup took this as evidence of a certain degree of self-awareness. Animals that have passed the mirror test include chimpanzees, orangutans, gorillas, dolphins, and elephants, all of which possess a neocortex—and magpies, which do not. So it turns out that a neocortex might not be essential after all.

Recognizing that we do share some basic neural structures and functions with many animals, a number of prominent neuroscientists signed a statement in August 2012 to that effect during a conference on animals and consciousness. The so-called Cambridge Declaration on Consciousness concluded that, while not self-aware in the human sense, "non-human animals"—including mammals and the octopus—possess sufficient brain structure and function to generate conscious states. The Cambridge declaration isn't talking about advanced metacognition or self-awareness; its focus is on the ability to distinguish between self and other.

But while the declaration suggests progress in understanding animal consciousness, the definitions and distinctions remain tricky. Neuroscientists have not yet pinpointed the specific mechanisms behind how the brain produces a distinct, persistent, subjective personal identity. That's a much tougher neuro-nut to crack. There is a fundamental layer we seem to share with animals, onto which human beings add a second, richer layer of self representation. That extra layer of meta-cognition might just be what separates animal and human consciousness.

Or not. Thomas Nagel famously opined that we could never really know what it's like to be a bat, for instance, regardless of what we can observe about its behavior and the structure of its brain. Maybe your cat is more sentient than you think, philosophizing about whether or not those giant humans exhibit consciousness.

— Jennifer Ouellette

PIXABAY

Meet Five Extraordinary Woman Scientists

A unique celebration of a neglected part of science history

BY AMANDA PHINGBODHIPAKKIYA

AMANDA PHINGBODHIPAKKIYA, a former neuroscientist-turned-designer, wants to galvanize us to safeguard science. Her solution? Put a human face on it. "To encourage the next generation of young minds to take on tomorrow's challenges and opportunities," she says, "we should celebrate that our world was built not just by men, but by brilliant women of all backgrounds."

And so, in honor of women's history month, she created a series of 32 posters drawing attention to a few remarkable women scientists. Her project, called "Beyond Curie," pairs photos of each scientist along with typography and graphic elements, highlighting the women and their scientific contributions. —*Regan Penaluna*

See more at beyondcurie.com

Rita Levi-Montalcini

An Italian neurobiologist whose academic work was interrupted by Mussolini's 1938 ban on Jews from participating in academia, she set up a laboratory in her bedroom to continue her research. In 1946, she was granted a fellowship at Washington University where she replicated her earlier work, and eventually won the Nobel Prize for her discovery of nerve growth factor.

Maryam Mirzakhani

This pioneer made mathematics history on Aug. 12, 2014 when she became both the first woman and Iranian honored with the Fields Medal, the most prestigious award in mathematics. Her research has implications for many fields, including engineering and theoretical physics as it applies to the origin of the universe.

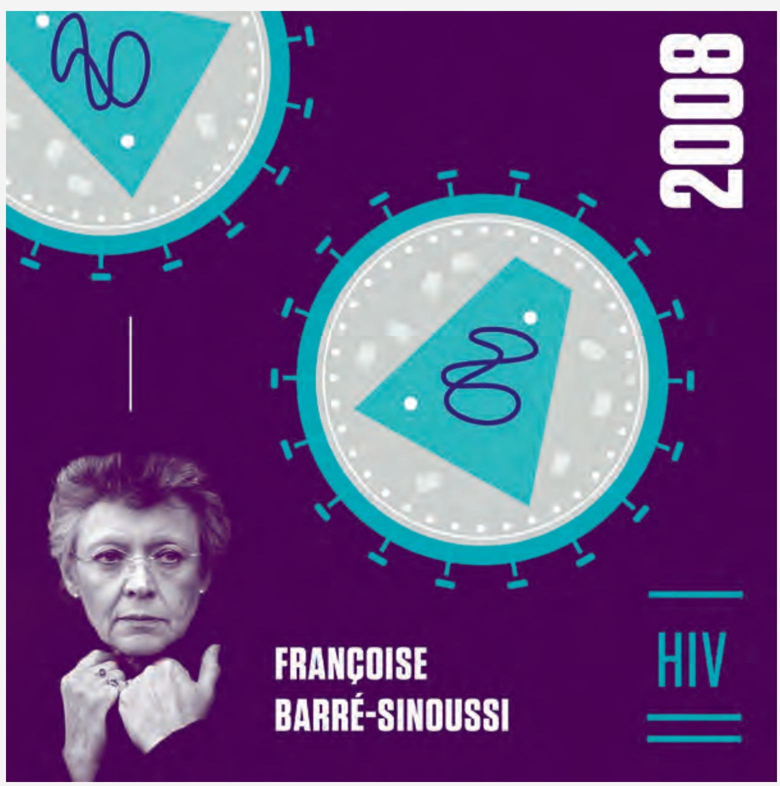
PREVIOUS PAGE:

Youyou Tu

A Chinese pharmacologist who won the Nobel Prize in 2015 for her discovery of artemisinin, a compound used to treat malaria, isolated from the sweet wormwood plant often found in traditional Chinese medicine. When others wanted to abandon the research, she found a solution in a millennia-old Chinese recipe—even first trying the drug on herself.

Mae Jemison
On Sept. 12, 1992, she flew into space on the shuttle Endeavour *for mission STS-47, becoming the first black woman to travel into space. While on board, she conducted scientific experiments exploring weightlessness, motion sickness, and bone cells.*

Françoise Barré-Sinoussi
A French virologist who discovered the human immunodeficiency virus (HIV) in 1983, which led to the identification of HIV as the cause of AIDS. In 2008, she won the Nobel Prize in Physiology or Medicine for this discovery, which has been fundamental to improving treatment for AIDS patients.



AMANDA PHINGBODHIPAKKIYA is the creator of Beyond Curie, a design project highlighting the rich history of women kicking ass in STEM fields and the founder and CEO of The Leading Strand.

The Kekulé

Problem

Where did language come from?

by Cormac McCarthy *Illustration by* Don Kilpatrick III

Cormac McCarthy is best known to the world as a writer of novels. These include Blood Meridian, All the Pretty Horses, No Country for Old Men, *and* The Road. *At the Santa Fe Institute (SFI) he is a research colleague and thought of in complementary terms. An aficionado on subjects ranging from the history of mathematics, philosophical arguments relating to the status of quantum mechanics as a causal theory, comparative evidence bearing on non-human intelligence, and the nature of the conscious and unconscious mind. At SFI we have been searching for the expression of these scientific interests in his novels and we maintain a furtive tally of their covert manifestations and demonstrations in his prose.*

Over the last two decades Cormac and I have been discussing the puzzles and paradoxes of the unconscious mind. Foremost among them, the fact that the very recent and "uniquely" human capability of near infinite expressive power arising through a combinatorial grammar is built on the foundations of a far more ancient animal brain. How have these two evolutionary systems become reconciled? Cormac expresses this tension as the deep suspicion, perhaps even contempt, that the primeval unconscious feels toward the upstart, conscious language. In this article Cormac explores this idea through processes of dream and infection. It is a discerning and wide-ranging exploration of ideas and challenges that our research community has only recently dared to start addressing through complexity science.

—David Krakauer
President and William H. Miller Professor
of Complex Systems, Santa Fe Institute

I call it the Kekulé Problem because among the myriad instances of scientific problems solved in the sleep of the inquirer Kekulé's is probably the best known. He was trying to arrive at the configuration of the benzene molecule and not making much progress when he fell asleep in front of the fire and had his famous dream of a snake coiled in a hoop with its tail in its mouth—the ouroboros of mythology—and woke exclaiming to himself: "It's a ring. The molecule is in the form of a ring." Well. The problem of course—not Kekulé's but ours—is that since the unconscious understands language perfectly well or it would not understand the problem in the first place, why doesnt it simply answer Kekulé's question with something like: "Kekulé, it's a bloody ring." To which our scientist might respond: "Okay. Got it. Thanks."

Why the snake? That is, why is the unconscious so loathe to speak to us? Why the images, metaphors, pictures? Why the dreams, for that matter.

A logical place to begin would be to define what the unconscious is in the first place. To do this we have to set aside the jargon of modern psychology and get back to biology. The unconscious is a biological system before it is anything else. To put it as pithily as possibly—and as accurately—the unconscious is a machine for operating an animal.

All animals have an unconscious. If they didnt they would be plants. We may sometimes credit ours with duties it doesnt actually perform. Systems at a certain level of necessity may require their own mechanics of governance. Breathing, for instance, is not controlled by the unconscious but by the pons and the medulla oblongata, two systems located in the brainstem. Except of course in the case of cetaceans, who have to breathe when they come up for air. An autonomous system wouldnt work here. The first dolphin anesthetized on an operating table simply died. (How do they sleep? With half of their brain alternately.) But the duties of the unconscious are beyond counting. Everything from scratching an itch to solving math problems.

Problems in general are often well posed in terms of language and language remains a handy tool for explaining them. But the actual process of thinking—in any discipline—is largely an unconscious affair. Language can be used to sum up some point at which one has arrived—a sort of milepost—so as to gain a fresh starting point. But if you believe that you actually use language in the solving of problems I wish that you would write to me and tell me how you go about it.

I've pointed out to some of my mathematical friends that the unconscious appears to be better at math than they are. My friend George Zweig calls this the Night Shift. Bear in mind that the unconscious has no pencil or notepad and certainly no eraser. That it does solve problems in mathematics is indisputable. How does it go about it? When I've suggested to my friends that it may well do it without using numbers, most of them thought—after a while—that this was a possibility. How, we dont know. Just as we dont know how it is that we manage to talk. If I am talking to you then I can hardly be crafting at the same time the sentences that are to follow what I am now saying. I am totally occupied in talking to you. Nor can some part of my mind be assembling these sentences and then saying them to me so that I can repeat them. Aside from the fact that I am busy this would be to evoke an endless regress. The truth is that there is a process here to which we have no access. It is a mystery opaque to total blackness.

There are influential persons among us—of whom a bit more a bit later—who claim to believe that language is a totally evolutionary process. That it has somehow appeared in the brain in a primitive form and then grown to usefulness. Somewhat like vision, perhaps. But vision we now know is traceable to perhaps as many as a dozen quite independent evolutionary histories. Tempting material for the teleologists. These stories apparently begin with a crude organ capable of perceiving light where any occlusion could well suggest a predator. Which actually makes it an excellent scenario for Darwinian selection. It may be that the influential persons imagine all mammals waiting for language to appear. I dont know. But all indications are that language has appeared only once and in one species only. Among whom it then spread with considerable speed.

There are a number of examples of signaling in the animal world that might be taken for a proto-language. Chipmunks—among other species—have one alarm-call for aerial predators and another for those on the ground. Hawks as distinct from foxes or cats. Very useful. But what is missing here is the central idea of language—that one thing can be another thing. It is the idea that Helen Keller suddenly understood at the well. That the sign for water was not simply what you did to get a glass of water. It was the glass of water. It was in fact the water in the glass. This in the play *The Miracle Worker*. Not a dry eye in the house.

The invention of language was understood at once to be incredibly useful. Again, it seems to have spread through the species almost instantaneously. The immediate problem would seem to have been that there were more things to name than sounds to name them with. Language appears to have originated in southwestern Africa and it may even be that the clicks in the Khoisan languages—to include Sandawe and Hadza—are an atavistic remnant of addressing this need for a greater variety of sounds. The vocal problems were eventually handled evolutionarily—and apparently in fairly short order—by turning our throat over largely to the manufacture of speech. Not without cost, as it turns out. The larynx has moved down

> Did language meet some need? No. The other five thousand plus mammals among us do fine without it.

in the throat in such a way as to make us as a species highly vulnerable to choking on our food—a not uncommon cause of death. It's also left us as the only mammal incapable of swallowing and vocalizing at the same time.

The sort of isolation that gave us tall and short and light and dark and other variations in our species was no protection against the advance of language. It crossed mountains and oceans as if they werent there. Did it meet some need? No. The other five thousand plus mammals among us do fine without it. But useful? Oh yes. We might further point out that when it arrived it had no place to go. The brain was not expecting it and had made no plans for its arrival. It simply invaded those areas of the brain that were the least dedicated. I suggested once in conversation at the Santa Fe Institute that language had acted very much like a parasitic invasion and David Krakauer—our president—said that the same idea had occurred to him. Which pleased me a good deal because David is very smart. This is not to say of course that the human brain was not in any way structured for the reception of language. Where else would it go? If nothing else we have the evidence of history. The difference between the history of a virus and that of language is that the virus has arrived by way of Darwinian selection and language has not. The virus comes nicely machined. Offer it up. Turn it slightly. Push it in. Click. Nice fit. But the scrap heap will be found to contain any number of viruses that did not fit.

There is no selection at work in the evolution of language because language is not a biological system and because there is only one of them. The ur-language of linguistic origin out of which all languages have evolved.

Influential persons will by now of course have smiled to themselves at the ill-concealed Lamarckianism lurking here. We might think to evade it by various strategies or redefinitions but probably without much success. Darwin of course was dismissive of the idea of inherited

“mutilations”—the issue of cutting off the tails of dogs for instance. But the inheritance of ideas remains something of a sticky issue. It is difficult to see them as anything other than acquired. How the unconscious goes about its work is not so much poorly understood as not understood at all. It is an area pretty much ignored by the artificial intelligence studies, which seem mostly devoted to analytics and to the question of whether the brain is like a computer. They have decided that it’s not, but that is not altogether true.

Of the known characteristics of the unconscious its persistence is among the most notable. Everyone is familiar with repetitive dreams. Here the unconscious may well be imagined to have more than one voice: He’s not getting it, is he? No. He’s pretty thick. What do you want to do? I dont know. Do you want to try using his mother? His mother is dead. What difference does that make?

What is at work here? And how does the unconscious *know* we’re not getting it? What *doesnt* it know? It’s hard to escape the conclusion that the unconscious is laboring under a moral compulsion to educate us. (Moral compulsion? Is he serious?)

The evolution of language would begin with the names of things. After that would come descriptions of these things and descriptions of what they do. The growth of languages into their present shape and form—their syntax and grammar—has a universality that suggests a common rule. The rule is that languages have followed their own requirements. The rule is that they are charged with describing the world. There is nothing else to describe.

All very quickly. There are no languages whose form is in a state of development. And their forms are all basically the same.

We dont know what the unconscious is or where it is or how it got there—wherever there might be. Recent animal brain studies showing outsized cerebellums in some pretty smart species are suggestive. That facts about the world are in themselves capable of shaping the brain is slowly becoming accepted. Does the unconscious only get these facts from us, or does it have the same access to our sensorium that we have? You can do whatever you like with the us and the our and the we. I did. At some point the mind must grammaticize facts and convert them to narratives. The facts of the world do not for the most part come in narrative form. We have to do that.

So what are we saying here? That some unknown thinker sat up one night in his cave and said: Wow. One thing can be another thing. Yes. Of course that's what we are saying. Except that he didnt say it because there was no language for him to say it in. For the time being he had to settle for just thinking it. And when did this take place? Our influential persons claim to have no idea. Of course they dont think that it took place at all. But aside from that. One hundred thousand years ago? Half a million? Longer? Actually a hundred thousand would be a pretty good guess. It dates the earliest known graphics—found in the Blombos Cave in South Africa. These scratchings have everything to do with our chap waking up in his cave. For while it is fairly certain that art preceded language it probably didnt precede it by much. Some influential persons have actually claimed that language could be up to a million years old. They havent explained what we have been doing with it all this time. What we do know—pretty much without question—is that once you have language everything else follows pretty quickly. The simple understanding that one thing can be another thing is at the root of all things of our doing. From using colored pebbles for the trading of goats to art and language and on to using symbolic marks to represent pieces of the world too small to see.

One hundred thousand years is pretty much an eyeblink. But two million years is not. This is, rather loosely, the length of time in which our unconscious has been organizing and directing our lives. And without language you will note. At least for all but that recent blink. How does it tell us where and when to scratch? We dont know. We just know that it's good at it. But the fact that the unconscious prefers avoiding verbal instructions pretty much altogether—even where they would appear to be quite useful—suggests rather strongly that it doesnt much like language and even that it doesnt trust it. And why is that? How about for the good and sufficient reason that it has been getting along quite well without it for a couple of million years?

REPRODUCTION OF CAVE PAINTINGS AT THE CHAUVET CAVE; VALLON-PONT-D'ARC, FRANCE, JEFF PACHOUD / AFP / GETTY IMAGES

To put it as pithily as possibly—and as accurately—the unconscious is a machine for operating an animal.

Apart from its great antiquity the picture-story mode of presentation favored by the unconscious has the appeal of its simple utility. A picture can be recalled in its entirety whereas an essay cannot. Unless one is an Asperger's case. In which event memories, while correct, suffer from their own literalness. The log of knowledge or information contained in the brain of the average citizen is enormous. But the form in which it resides is largely unknown. You may have read a thousand books and be able to discuss any one of them without remembering a word of the text.

When you pause to reflect and say: "Let me see. How can I put this," your aim is to resurrect an idea from this pool of we-know-not-what and give it a linguistic form so that it can be expressed. It is the *this* that one wishes to *put* that is representative of this pool of knowledge whose form is so amorphous. If you explain this to someone and they say that they dont understand you may well seize your chin and think some more and come up with another way to "put" it. Or you may not. When the physicist Dirac was complained to by students that they didnt understand what he'd said Dirac would simply repeat it verbatim.

The picture-story lends itself to parable. To the tale whose meaning gives one pause. The unconscious is concerned with rules but these rules will require your cooperation. The unconscious wants to give guidance to your life in general but it doesnt care what toothpaste you use. And while the path which it suggests for you may be broad it doesnt include going over a cliff. We can see this in dreams. Those disturbing dreams which wake us from sleep are purely graphic. No one speaks. These are very old dreams and often troubling. Sometimes a friend can see their meaning where we cannot. The unconscious intends that they be difficult to unravel because it wants us to think about them. To remember them. It doesnt say that you cant ask for help. Parables of course often want to resolve themselves into the pictorial. When you first heard of Plato's cave you set about reconstructing it.

To repeat. The unconscious is a biological operative and language is not. Or not yet. You have to be careful about inviting Descartes to the table. Aside from inheritability probably the best guide as to whether a category is of our own devising is to ask if we see it in other creatures. The case for language is pretty clear. In the facility with which young children learn its complex and difficult rules we see the slow incorporation of the acquired.

I'd been thinking about the Kekulé problem off and on for a couple of years without making much progress. Then one morning after George Zweig and I had had one of our ten hour lunches I came down in the morning with the wastebasket from my bedroom and as I was emptying it into the kitchen trash I suddenly knew the answer. Or I knew that I knew the answer. It took me a minute or so to put it together. I reflected that while George and I had spent the first couple of hours at cognition and neuroscience we had not talked about Kekulé and the problem. But something in our conversation might very well have triggered our reflections—mine and those of the Night Shift—on this issue. The answer of course is simple once you know it. The unconscious is just not used to giving verbal instructions and is not happy doing so. Habits of two million years duration are hard to break. When later I told George what I'd come up with he mulled it over for a minute or so and then nodded and said: "That sounds about right." Which pleased me a good deal because George is very smart.

The unconscious seems to know a great deal. What does it know about itself? Does it know that it's going to die? What does it think about that? It appears to represent a gathering of talents rather than just one. It seems unlikely that the itch department is also in charge of math. Can it work on a number of problems at once? Does it only know what we tell it? Or—more plausibly—has it direct access to the outer world? Some of the dreams which it is at pains to assemble for us are no doubt deeply reflective and yet some are quite frivolous. And the fact that it appears to be less than insistent upon our remembering every dream suggests that sometimes it may be working on itself. And is it really so good at solving problems or is it just that it keeps its own counsel about the failures? How does it have this understanding which we might well envy? How might we make inquiries of it? Are you sure?

CORMAC MCCARTHY is a board member and senior fellow of the Santa Fe Institute.

46

A GLACIER'S MASS BALANCE is the difference between how much snow and ice it accumulates, and what it loses to melting. A negative mass balance will, given enough time, skew other balances. As less sunlight is reflected by the shrinking glacier's bright ice, more is absorbed by the dark ocean, pushing temperatures up.

Warmer temperatures increase the amount of human-produced carbon dioxide stored in the atmosphere, which speeds ocean acidification and the dissolving of deep-water carbon deposits. These deposits make oceans more alkaline, balancing out their acidification.

Peel back one balance, and you find another. In this issue, each balance leans against the next: mental against physical, evolutionary against ecological, one infinity against another. The web of balances that make up our world is intricate, full of tiny stable points and unexpected transitions.

That can make it inscrutable. But, as living participants, we can still tell when it is broken. This February saw over 3,000 record high temperatures across the United States, compared to 30-odd record lows, the most lopsided ratio in history. This January was 1.6 degrees Fahrenheit above the 20th-century global average.

Which brings to mind another balance—a moral one.

Welcome to "Balance."

—MS

"Gravity, it seemed, was not quite what we thought it was."

PHILIP BALL
"The Fifth Force of Physics Is Hanging by a Thread" p.58

Balance

IN ALL THINGS

THIS IS MY BRAIN ON ROCK CLIMBING

The neurology of dread and desire on Half Dome

BY SAMANTHA LARSON

I **REACHED THANK GOD LEDGE** on the Regular Northwest Face, of Yosemite's iconic Half Dome climb, by mid-afternoon.

This 40-foot horizontal plank-like feature is the most famous part of the route: not for its physical difficulty, but for its stomach-churning exposure. When I reached it, the ledge looked undeserving of all the hype. All I had to do, it seemed, was walk right across it. No big deal.

The first few steps were, indeed, very easy. But then the ledge narrowed, and the slab of rock against my right side bulged out, seemingly pushing me out into the abyss. Scaredy-cat that I am, I quickly found myself on my knees, and I began to crawl.

Then the ledge narrowed even more. Soon, only my right knee would fully fit on top of the ledge; my left knee precariously dangled half on the rock, and half over the empty air below. My vision narrowed, my body grew hot, my mind became fuzzy and unable to focus. I fell into a full-on panic.

"I can't do it, Alaina!" I called out to my climbing partner.

"Yes, you can!" she immediately shouted back, in a tone closer to an order than a note of encouragement. Suddenly my whole being seemed to exist for the sole purpose of getting across that ledge. I buckled down, scurried forward, and made it to the other side. A wave of emotion that can only be described as euphoria washed over me. I let out a holler and laughed, in disbelief at what I had just done.

The best moments in climbing come when we're right on the edge of being completely overwhelmed, but somehow, even if just barely, manage to stay on the right side of the line. The fear threatens to overwhelm us, motivating us into a state of extreme focus. It's a state between comfort and terror, where we tap into what the University of Michigan neuroscientist Kent Berridge calls "the shimmering back and forth of desire and dread."

Berridge, whose career has revolved around figuring out the processes that govern what we want, what we like, and what gets us going, has even isolated one location in the brain key to striking this balance. It's called the nucleus accumbens, and it plays a role in both pleasure and terror, capable of producing either or both, depending on the circumstances. What's more, he has observed that the response of the nucleus accumbens is flexible, operating as if it had a switch that could flip between the two emotions, even given the same trigger.

In other words, Berridge has discovered in the lab what I discovered high up on Thank God Ledge: Desire and dread are deeply intertwined.

"EMOTION, PLEASURE, MOTIVATION … they've been not so much understood in psychology and neuroscience over the past 50 years," Berridge says. He has focused much of his research on the nucleus accumbens, the small area in the lower front of the brain that neuroscientists have long recognized as having a significant role in motivation, pleasure, and reward.

In the early 2000s, Berridge designed an experiment to study the neuroscience of wanting by injecting a dopamine-like drug (a neurotransmitter that plays a large role in reward-motivated behavior) into the nucleus accumbens of lab rats. When his doctoral student, Sheila Reynolds, placed microinjections in the front of the nucleus accumbens, the rats, as expected, demonstrated strong "wanting" behavior when presented with sugar.

When Reynolds placed the microinjections in the back of the nucleus accumbens, however, the reaction was quite different. Not only did the rats not show any interest in the sugar, they became frantic. They threw sawdust in the cage (anti-predator behavior) and, when Reynolds tried to pick them up, they would try to jump out of her hand or even bite her. "Normally they're very tame and friendly," Berridge says. Berridge and Reynolds realized that dopamine and the nucleus accumbens might be responsible not just for desire and motivation, but also for fear.

The effect was modulated by environment, with unfamiliar environments more likely to produce fear after the injections. When the rats were moved to a lab with harsh fluorescent lighting and played Iggy Pop songs for an hour, nearly all of their responses to microinjections produced fear, regardless of where in

DRAGON IMAGES / SHUTTERSTOCK

PHOTOCOLLAGE BY FRANCESCO IZZO

the nucleus accumbens the injections were made. In a quiet, dark space, on the other hand, nearly all of the microinjections produced wanting behavior regardless of injection location.

The different behaviors were associated with different dopamine receptors, called D_1 and D_2. Just D_1 was active in wanting behaviors in comfortable cages, but both were active in uncomfortable cages. "We think the same neurocircuit is producing both things, but it has different modes that can flip," Berridge says. "[Dopamine is] like a little tiny sledgehammer in the brain, but it's a changing sledgehammer each time." What it does depends on is what Berridge calls the "emotional ambience" of the animal's environment.

As a rock climber, this fickleness of fear makes a lot of sense to me. How much fear I feel while climbing can fluctuate in seemingly mysterious ways. Sometimes, the varying nature of fear does makes sense: for example, my experience climbing with a good friend on a route that I've done before versus when I'm climbing with a stranger on a route that's way too difficult for me. Other times, however, how much fear I feel seems to depend on factors less obvious to me in the present moment, like what's going on in my non-climbing life.

But what is most interesting to me is Berridge's interpretation of the most special climbing experience of all: when I'm able to gain control over all those other factors and a climb at my limit clicks into place, as it did on Half Dome, and feels like the most exciting thing in the world.

"It's possible that that kind of moment on the rock is triggering, and putting [the brain] into a flip-able state," Berridge tells me. "In some ways desire and dread are psychologically similar ... It's the same thing that's frightening you and that's making you love it at the same time." The line between pleasure and fear is thin, and sometimes you can place yourself right on it.

Berridge thinks that experiencing this in-between state requires the right personal balance of safety and comfort, much like the rush of riding a rollercoaster can be desirable—so long as you're buckled in—or how a lot of people get a kick out of seeing horror unfold—so long as they're watching it on a screen from the couch. In a sport like rock climbing, we find that balance through practice and the development of confidence in our abilities. "If I were up there, I would be terrified," Berridge says. "But your sense of control and confidence is much like the rats being in their homeroom."

The in-between also has a tendency to focus you. "The world kind of brightens up, and is inviting," Berridge says. You alternate between experiencing fear itself and the possibility of fear. It's one way to trigger what many athletes say they are really after: the experience of flow.

Flow is a condition of intense concentration and immersion in an experience. Named and popularized by the Hungarian psychologist Mihály Csíkszentmihályi, the condition has become one of the most studied in contemporary psychology. Books have been written about how to achieve flow, and some have argued that it enables happiness, or is even necessary for happiness.

Clearly, a state of extreme fear can enable concentration and immersion. But it doesn't allow for some of flow's other basic requirements: a sense of personal control, and a sense of reward. Conversely, an easy athletic activity can allow for a sense of control and reward, but doesn't require the same degree of concentration and immersion.

Flow, then, seems to require a balance—like the one between fear and desire. Eric Brymer is a professor at

PAIN AND PLEASURE Samantha Larson holds up bloodied fingers after climbing Serenity and Sons.

DESIRE AND DREAD ARE DEEPLY INTERTWINED.

THE EDGE OF FEAR My climbing partner, Alaina, crossing Thank God Ledge, a part of Yosemite's Half Dome climb.

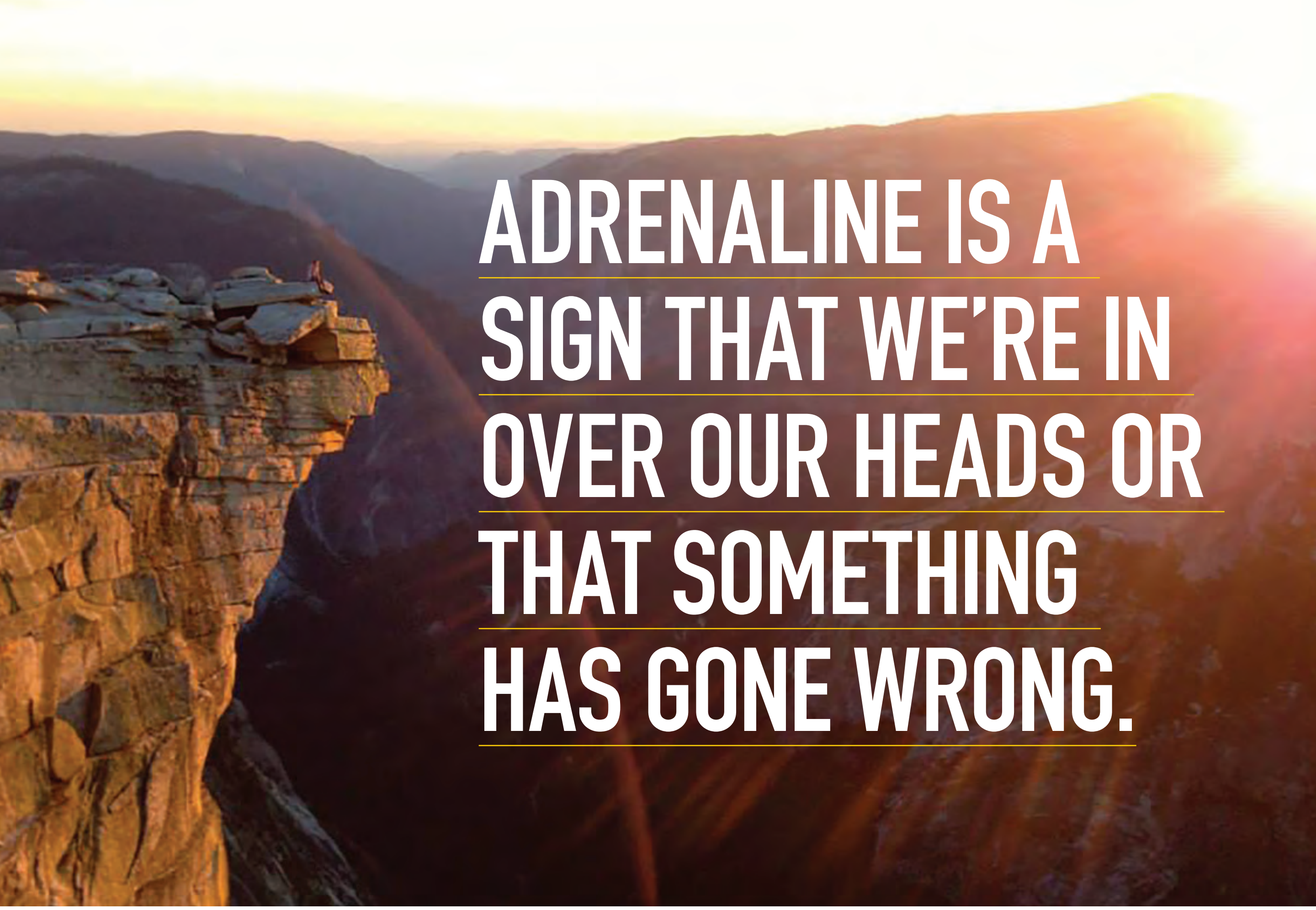
COURTESY OF THE AUTHOR

Leeds Beckett University whose research centers on athletes who do sports like BASE jumping or free solo (ropeless) rock climbing. Brymer says it's the committed nature of these endeavors that heightens the rewards felt by those brave and skilled enough to do them: "You're facilitated into a state where you are right there, right then, because if you mess up there's a good chance you're going to die," he says.

That's an experience Steph Davis and Alex Honnold both know well. They are two of the most famous free solo climbers in the United States. "It's liberating when you're able to manage fear and do things you otherwise would have been unable to do," Davis tells me. Honnold agrees with the premise that he free solos in order to unlock a flow-like state. "It forces you to go into that state more, because the higher consequences just demand more attention, more focus," he says.

Brymer points out that the flow-like state achieved by the extreme athlete differs from the more traditional definition of flow, for example in the experience of time. Both types of flow, though, rely on balance in their own way. Brymer has found that most people who do extreme sports aren't in it for the adrenaline, the hormone triggered by our innate fear response. Adrenaline is a sign that we're in over our heads—or that something has gone wrong. Instead, the drive to put oneself into uncomfortable, scary situations is about showing mastery in the face of extreme circumstance.

But you don't need to jump out of a plane or scale a granite wall to catch a glimpse of these sorts



ADRENALINE IS A SIGN THAT WE'RE IN OVER OUR HEADS OR THAT SOMETHING HAS GONE WRONG.

PAYOFF Samantha Larson at the top of the Half Dome climb.

COURTESY OF THE AUTHOR

of expansive experiences. Finding that sweet spot of the right amount of fear and challenge is an intensely personal affair. "I've seen people with what we would describe as low-level adventures having life-changing transformations," Brymer says. "If you come from a culture where tree climbing is just not a thing you do ... you might climb up to a branch that's three feet off the ground, and that's a life-changing experience because you never realized you could have done that, you just had no idea."

Even Honnold says the types of experiences he seeks out through free soloing aren't only possible when the stakes are life or death, so long as you feel that the stakes are high enough to warrant trying your hardest, and giving the present moment your full attention. It comes from "those moments in climbing where you just have to flip the switch and be like 'ok, now I'm going to preform,' " he says.

I COULDN'T FALL ASLEEP the night before I set out to climb Serenity and Sons, an iconic rock climb in Yosemite Valley. It's not that I doubted whether I would be physically able to do the climb. It was more about whether I would be able to keep my head together. I was afraid of being afraid.

As I lay in my tent in Camp IV, I recalled past climbs during which the dry-mouthed, sweaty palmed sensation of being frozen on the rock washed over me. My whole body had screamed at me not to move, every part wanting to be back down on the ground. It was an all-too-familiar feeling. As someone who struggles with the mental aspects of rock climbing, I'd had, by that point, many moments of wondering why I even bothered with the sport. There were a lot of things I loved about it—the movement, the places it brought me, the community—but being terrified was not one of them.

But I knew that panic didn't have to be a part of my climb—it wasn't for most of my climbing partners. I turned on my headlamp, dug out my journal and pen, and wrote "COMMIT" in large block letters. My rational brain knew I had the skills and equipment. I just had to convince my emotional brain to trust in them. If I could lean in to a confidence in my own abilities, I knew I could open the door to my favorite moments in climbing.

I had butterflies in my stomach as we walked up to the base of the climb the next morning. As I got ready to lead, I opened up my arms wide (a habit I've acquired after learning that research has shown such poses can make you feel more powerful and tolerant of risk). "This is going to be awesome!" I told my climbing partner. Though, of course, it was myself that I was really trying to convince.

I started climbing. My brain practically shut off as my body took over in the flow of the movement: Plug in a piece of gear for protection, sink my fingers into the crack, paste my feet against the granite. I glanced down at how high I was above my last piece of gear in order to gauge how far I would fall before the rope caught me should I slip off—a habit that usually inspired a certain amount of panic in me. This time, however, even though the fall could have been around 20 feet, I felt elated, alive. "Look where we are!" I shouted. "This is crazy! This is so cool!"

Letting out a laugh just because life just seemed absurdly wonderful, I kept on climbing. I had flipped the switch.

SAMANTHA LARSON is a Seattle-based writer who covers science, the environment, and adventure. At age 18, she became the youngest person to climb the highest mountain on each continent.

A Brief History of the Grand Unified Theory of Physics

It's the best of times or the worst of times in physics

BY LAWRENCE M. KRAUSS

PARTICLES #22, ACRYLIC AND PENCIL ON MYLAR, 54" X 42", 2016

PARTICLE PHYSICISTS HAD two nightmares before the Higgs particle was discovered in 2012. The first was that the Large Hadron Collider (LHC) particle accelerator would see precisely nothing. For if it did, it would likely be the last large accelerator ever built to probe the fundamental makeup of the cosmos. The second was that the LHC would discover the Higgs particle predicted by theoretical physicist Peter Higgs in 1964 ... and nothing else.

Each time we peel back one layer of reality, other layers beckon. So each important new development in science generally leaves us with more questions than answers. But it also usually leaves us with at least the outline of a road map to help us begin to seek answers to those questions. The successful discovery of the Higgs particle, and with it the validation of the existence of an invisible background Higgs field throughout space (in the quantum world, every particle like the Higgs is associated with a field), was a profound validation of the bold scientific developments of the 20th century.

However, the words of Sheldon Glashow continue to ring true: The Higgs is like a toilet. It hides all the messy details we would rather not speak of. The Higgs field interacts with most elementary particles as they travel through space, producing a resistive force that slows their motion and makes them appear massive. Thus, the masses of elementary particles that we measure, and that make the world of our experience possible, are something of an illusion—an accident of our particular experience.

As elegant as this idea might be, it is essentially an ad hoc addition to the Standard Model of physics—which explains three of the four known forces of nature, and how these forces interact with matter. It is added to the theory to do what is required to accurately model the world of our experience. But it is not required by the theory. The universe could have happily existed with massless particles and a long-range weak force (which, along with the strong force, gravity, and electromagnetism, make up the four known

PAINTINGS BY JONATHAN FELDSCHUH

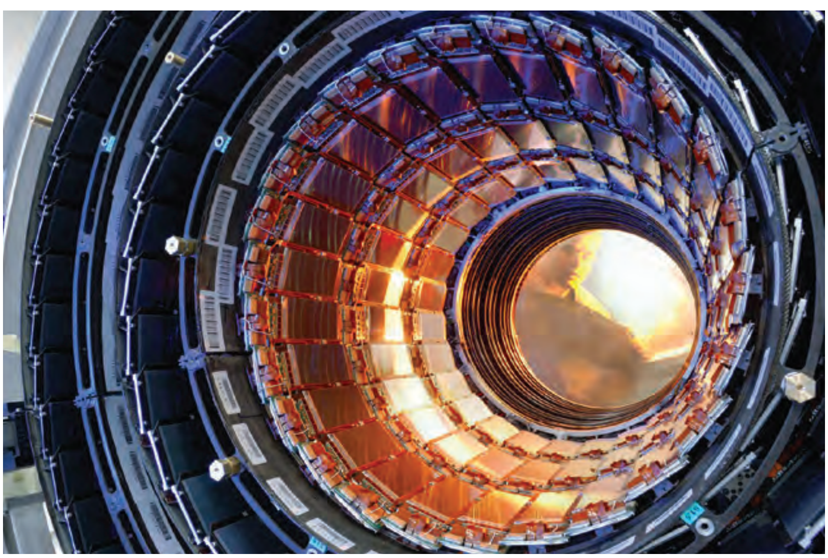
forces). We would just not be here to ask about them. Moreover, the detailed physics of the Higgs is undetermined within the Standard Model alone. The Higgs could have been 20 times heavier, or 100 times lighter.

Why, then, does the Higgs exist at all? And why does it have the mass it does? (Recognizing that whenever scientists ask "Why?" we really mean "How?") If the Higgs did not exist, the world we see would not exist, but surely that is not an explanation. Or is it? Ultimately to understand the underlying physics behind the Higgs is to understand how we came to exist. When we ask, "Why are we here?," at a fundamental level we may as well be asking, "Why is the Higgs here?" And the Standard Model gives no answer to this question.

Some hints do exist, however, coming from a combination of theory and experiment. Shortly after the fundamental structure of the Standard Model became firmly established, in 1974, and well before the details were experimentally verified over the next decade, two different groups of physicists at Harvard, where both Sheldown Glashow and Steven Weinberg were working, noticed something interesting. Glashow, along with Howard Georgi, did what Glashow did best: They looked for patterns among the existing particles and forces and sought out new possibilities using the mathematics of group theory.

In the Standard Model the weak and electromagnetic forces of nature are unified at a high-energy scale, into a single force that physicists call the "electroweak force." This means that the mathematics governing the weak and electromagnetic forces are the same, both constrained by the same mathematical symmetry, and the two forces are different reflections of a single underlying theory. But the symmetry is "spontaneously broken" by the Higgs field, which interacts with the particles that convey the weak force, but not the particles that convey the electromagnetic force. This accident of nature causes these two forces to appear as two separate and distinct forces at scales we can measure—with the weak force being short-range and electromagnetism remaining long-range.

Georgi and Glashow tried to extend this idea to include the strong force, and discovered that all of the known particles and the three non-gravitational forces could naturally fit within a single fundamental symmetry structure. They then speculated that this symmetry



SUPER SEARCHLIGHT Part of the inner tracker barrel of the CERN supercollider, where physicists continue the search for physical evidence that might lead to a Grand Unified Theory of physics.

Every time we open a new window on the universe, we are surprised.

could spontaneously break at some ultrahigh energy scale (and short distance scale) far beyond the range of current experiments, leaving two separate and distinct unbroken symmetries left over—resulting in separate strong and electroweak forces. Subsequently, at a lower energy and larger distance scale, the electroweak symmetry would break, separating the electroweak force into the short-range weak and the long-range electromagnetic force.

They called such a theory, modestly, a Grand Unified Theory (GUT).

At around the same time, Weinberg and Georgi along with Helen Quinn noticed something interesting—following the work of Frank Wilczek, David Gross, and David Politzer. While the strong interaction got weaker at smaller distance scales, the electromagnetic and weak interactions got stronger.

It didn't take a rocket scientist to wonder whether the strength of the three different interactions might become identical at some small-distance scale. When they did the calculations, they found (with the accuracy with which the interactions were then measured) that such a unification looked possible, but only if the scale of unification was about 15 orders of magnitude in scale smaller than the size of the proton.

This was good news if the unified theory was the one proposed by Howard Georgi and Glashow—because if all the particles we observe in nature got unified this way, then new particles (called gauge bosons) would exist that produce transitions between quarks (which make up protons and neutrons), and electrons and neutrinos. That would mean protons could decay into other lighter particles, which we could potentially observe. As Glashow put it, "Diamonds aren't forever."

Even then it was known that protons must have an incredibly long lifetime. Not just because we still exist almost 14 billion years after the big bang, but because we all don't die of cancer as children. If protons decayed with an average lifetime smaller than about a billion billion years, then enough protons would decay in our bodies during our childhood to produce enough radiation to kill us. Remember that in quantum mechanics, processes are probabilistic. If an average proton lives a billion billion years, and if one has a billion billion protons, then on average one will decay each year. There are a lot more than a billion billion protons in our bodies.

However, with the incredibly small proposed distance scale and therefore the incredibly large mass scale associated with spontaneous symmetry breaking in Grand Unification, the new gauge bosons would get large masses. That would make the interactions they mediate be so short-range that they would be unbelievably weak on the scale of protons and neutrons today.

MAXIMILIEN BRICE / CERN

As a result, while protons could decay, they might live, in this scenario, perhaps a million billion billion billion years before decaying. Still time to hold on to your growth stocks.

WITH THE RESULTS of Glashow and Georgi, and Georgi, Quinn, and Weinberg, the smell of grand synthesis was in the air. After the success of the electroweak theory, particle physicists were feeling ambitious and ready for further unification.

How would one know if these ideas were correct, however? There was no way to build an accelerator to probe an energy scale a million billion times greater than the rest mass energy of protons. Such a machine would have to have a circumference of the moon's orbit. Even if it was possible, considering the earlier debacle over the Superconducting Super Collider, no government would ever foot the bill.

Happily, there was another way, using the kind of probability arguments I just presented that give limits to the proton lifetime. If the new Grand Unified Theory predicted a proton lifetime of, say, a thousand billion billion billion years, then if one could put a thousand billion billion billion protons in a single detector, on average one of them would decay each year.

Where could one find so many protons? Simple: in about 3,000 tons of water.

So all that was required was to get a tank of water, put it in the dark, make sure there were no radioactivity backgrounds, surround it with sensitive phototubes that can detect flashes of light in the detector, and then wait for a year to see a burst of light when a proton decayed. As daunting as this may seem, at least two large experiments were commissioned and built to do just this, one deep underground next to Lake Erie in a salt mine, and one in a mine near Kamioka, Japan. The mines were necessary to screen out incoming cosmic rays that would otherwise produce a background that would swamp any proton decay signal.

Both experiments began taking data around 1982–83. Grand Unification seemed so compelling that the physics community was confident a signal would soon appear and Grand Unification would mean the culmination of a decade of amazing change and discovery in particle physics—not to mention another Nobel Prize for Glashow and maybe some others.

Unfortunately, nature was not so kind in this instance. No signals were seen in the first year, the second, or the third. The simplest elegant model proposed by Glashow and Georgi was soon ruled out. But once the Grand Unification bug had caught on, it was not easy to let it go. Other proposals were made for unified theories that might cause proton decay to be suppressed beyond the limits of the ongoing experiments.

On Feb. 23, 1987, however, another event occurred that demonstrates a maxim I have found is almost universal: Every time we open a new window on the universe, we are surprised. On that day a group of astronomers observed, in photographic plates obtained during the night, the closest exploding star (a supernova) seen in almost 400 years. The star, about 160,000 light-years away, was in the Large Magellanic Cloud—a small satellite galaxy of the Milky Way observable in the southern hemisphere.

If our ideas about exploding stars are correct, most of the energy released should be in the form of neutrinos, despite that the visible light released is so great that supernovas are the brightest cosmic fireworks in the sky when they explode (at a rate of about one explosion per 100 years per galaxy). Rough estimates then suggested that the huge IMB (Irvine-Michigan-Brookhaven) and Kamiokande water detectors should see about 20 neutrino events. When the IMB and Kamiokande experimentalists went back and reviewed their data for that day, lo and behold, IMB displayed eight candidate events in a 10-second interval, and Kamiokande displayed 11 such events. In the world of neutrino physics, this was a flood of data. The field of neutrino astrophysics had suddenly reached maturity. These 19 events produced perhaps 1,900 papers by physicists, such as me, who realized that they provided an unprecedented window into the core of an exploding star, and a laboratory not just for astrophysics but also for the physics of neutrinos themselves.

Spurred on by the realization that large proton-decay detectors might serve a dual purpose as new astrophysical neutrino detectors, several groups began to build a new generation of such dual-purpose detectors. The largest one in the world was again built in the Kamioka mine and was called Super-Kamiokande, and with good reason. This mammoth 50,000-ton tank of water, surrounded by 11,800 phototubes, was operated

LARGE HADRON COLLIDER #35, ACRYLIC AND PENCIL ON MYLAR, 78" X 156", 2012

in a working mine, yet the experiment was maintained with the purity of a laboratory clean room. This was absolutely necessary because in a detector of this size one had to worry not only about external cosmic rays, but also about internal radioactive contaminants in the water that could swamp any signals being searched for.

Meanwhile, interest in a related astrophysical neutrino signature also reached a new high during this period. The sun produces neutrinos due to the nuclear reactions in its core that power it, and over 20 years, using a huge underground detector, physicist Ray Davis had detected solar neutrinos, but had consistently found an event rate about a factor of three below what was predicted using the best models of the sun. A new type of solar neutrino detector was built inside a deep mine in Sudbury, Canada, which became known as the Sudbury Neutrino Observatory (SNO).

Super-Kamiokande has now been operating almost continuously, through various upgrades, for more than 20 years. No proton-decay signals have been seen, and no new supernovas observed. However, the precision observations of neutrinos at this huge detector, combined with complementary observations at SNO, definitely established that the solar neutrino deficit observed by Ray Davis is real, and moreover that it is not due to astrophysical effects in the sun but rather due to the properties of neutrinos. The implication was that at least one of the three known types of neutrinos is not massless. Since the Standard Model does not accommodate neutrinos' masses, this was the first definitive observation that some new physics, beyond the Standard Model and beyond the Higgs, must be operating in nature.

Soon after this, observations of higher-energy neutrinos that regularly bombard Earth as high-energy cosmic-ray protons hit the atmosphere and produce a downward shower of particles, including neutrinos, demonstrated that yet a second neutrino has mass. This mass is somewhat larger, but still far smaller than the mass of the electron. For these results team leaders at SNO and Kamiokande were awarded the 2015 Nobel Prize in Physics—a week before I wrote the first draft of these words. To date, these tantalizing hints of new physics are not explained by current theories.

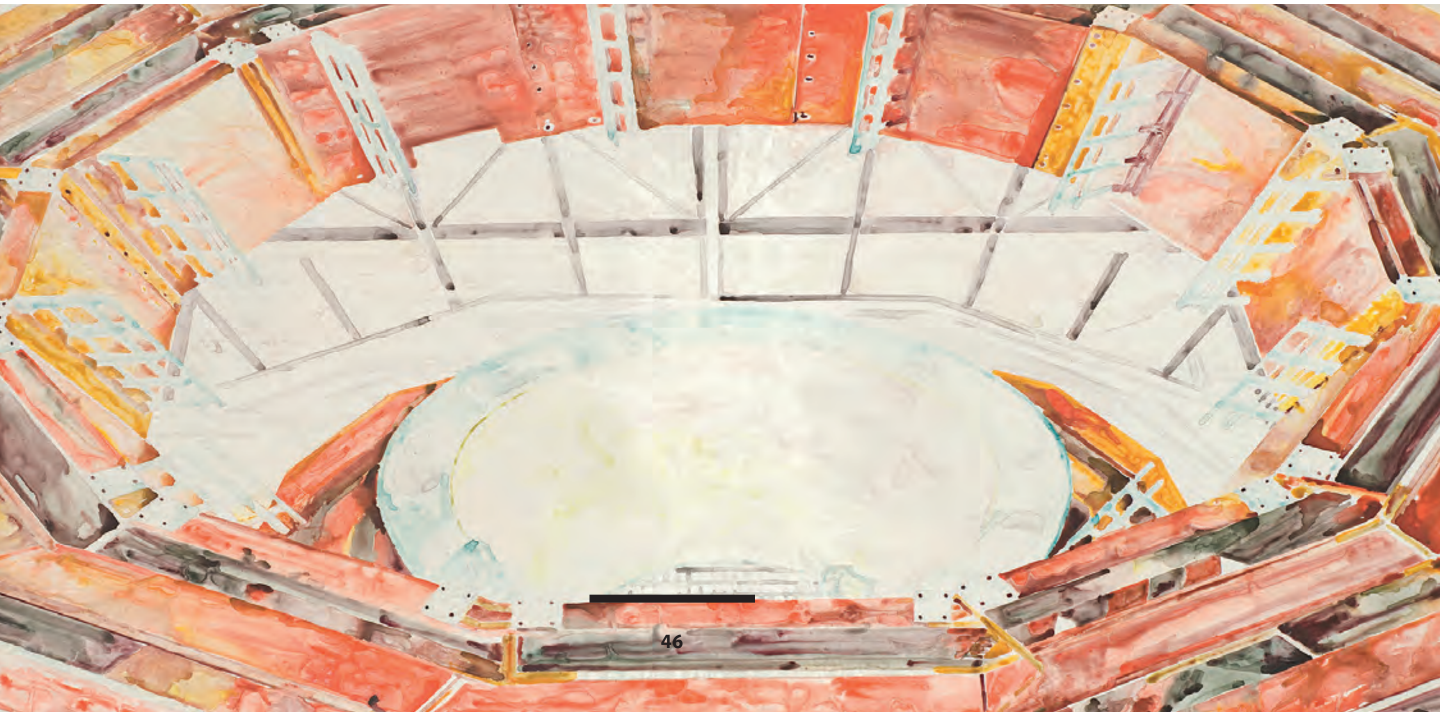
The absence of proton decay, while disappointing, turned out to be not totally unexpected. Since Grand Unification was first proposed, the physics landscape had shifted slightly. More precise measurements of the actual strengths of the three non-gravitational interactions—combined with more sophisticated calculations of the change in the strength of these interactions with distance—demonstrated that if the particles of the Standard Model are the only ones existing in nature, the strength of the three forces will not unify at a single scale. In order for Grand Unification to take place, some new physics at energy scales beyond those that have been observed thus far must exist. The presence of new particles would not only change the energy scale at which the three known interactions might unify, it would also tend to drive up the Grand Unification scale and thus suppress the rate of proton decay—leading to predicted lifetimes in excess of a million billion billion billion years.

As these developments were taking place, theorists were driven by new mathematical tools to explore a possible new type of symmetry in nature, which became known as supersymmetry. This fundamental symmetry is different from any previous known symmetry, in that it connects the two different types of particles in nature, fermions (particles with half-integer spins) and bosons (particles with integer spins). The upshot of this is that if this symmetry exists in nature, then for every known particle in the Standard Model at least one corresponding new elementary particle must exist. For every known boson there must exist a new fermion. For every known fermion there must exist a new boson.

Since we haven't seen these particles, this symmetry cannot be manifest in the world at the level we experience it, and it must be broken, meaning the new particles will all get masses that could be heavy enough so that they haven't been seen in any accelerator constructed thus far.

What could be so attractive about a symmetry that suddenly doubles all the particles in nature without any evidence of any of the new particles? In large part the seduction lay in the very fact of Grand Unification. Because if a Grand Unified theory exists at a mass scale of 15 to 16 orders of magnitude higher energy than the rest mass of the proton, this is also about 13 orders of magnitude higher than the scale of electroweak symmetry breaking. The big question is why and how such a huge difference in scales can exist for the fundamental laws of nature. In particular, if the Standard Model Higgs is the true last remnant of the Standard Model, then the question arises, Why is the energy scale of Higgs symmetry breaking 13 orders of magnitude smaller than the scale of symmetry breaking associated with whatever new field must be introduced to break the GUT symmetry into its separate component forces?

The problem is a little more severe than it appears. When one considers the effects of virtual particles (which appear and disappear on timescales so short that their existence can only be probed indirectly), including particles of arbitrarily large mass, such as the gauge particles of a presumed Grand Unified Theory, these tend to drive up the mass and symmetry-breaking scale of the Higgs so that it essentially becomes close to, or identical to, the heavy GUT scale. This generates a problem that has become known as the naturalness problem. It is technically unnatural to have a huge hierarchy between the scale at which the electroweak symmetry is broken by the Higgs particle



Following three years of LHC runs, there are no signs of supersymmetry whatsoever.

and the scale at which the GUT symmetry is broken by whatever new heavy field scalar breaks that symmetry.

The mathematical physicist Edward Witten argued in an influential paper in 1981 that supersymmetry had a special property. It could tame the effect that virtual particles of arbitrarily high mass and energy have on the properties of the world at the scales we can currently probe. Because virtual fermions and virtual bosons of the same mass produce quantum corrections that are identical except for a sign, if every boson is accompanied by a fermion of equal mass, then the quantum effects of the virtual particles will cancel out. This means that the effects of virtual particles of arbitrarily high mass and energy on the physical properties of the universe on scales we can measure would now be completely removed.

If, however, supersymmetry is itself broken (as it must be or all the supersymmetric partners of ordinary matter would have the same mass as the observed particles and we would have observed them), then the quantum corrections will not quite cancel out. Instead they would yield contributions to masses that are the same order as the supersymmetry-breaking scale. If it was comparable to the scale of the electroweak symmetry breaking, then it would explain why the Higgs mass scale is what it is.

And it also means we should expect to begin to observe a lot of new particles—the supersymmetric partners of ordinary matter—at the scale currently being probed at the LHC.

This would solve the naturalness problem because it would protect the Higgs boson masses from possible quantum corrections that could drive them up to be as large as the energy scale associated with Grand Unification. Supersymmetry could allow a "natural" large hierarchy in energy (and mass) separating the electroweak scale from the Grand Unified scale.

That supersymmetry could in principle solve the hierarchy problem, as it has become known, greatly increased its stock with physicists. It caused theorists to begin to explore realistic models that incorporated supersymmetry breaking and to explore the other physical consequences of this idea. When they did so, the stock price of supersymmetry went through the roof. For if one included the possibility of spontaneously broken supersymmetry in calculations of how the three non-gravitational forces change with distance, then suddenly the strength of the three forces would naturally converge at a single, very small-distance scale. Grand Unification became viable again!

Models in which supersymmetry is broken have another attractive feature. It was pointed out, well before the top quark was discovered, that if the top quark was heavy, then through its interactions with

LARGE HADRON COLLIDER #19, ACRYLIC AND PENCIL ON MYLAR, 36" X 84", 2009 other supersymmetric partners, it could produce quantum corrections to the Higgs particle properties that would cause the Higgs field to form a coherent background field throughout space at its currently measured energy scale if Grand Unification occurred at a much higher, superheavy scale. In short, the energy scale of electroweak symmetry breaking could be generated naturally within a theory in which Grand Unification occurs at a much higher energy scale. When the top quark was discovered and indeed was heavy, this added to the attractiveness of the possibility that supersymmetry breaking might be responsible for the observed energy scale of the weak interaction.

All of this comes at a cost, however. For the theory to work, there must be two Higgs bosons, not just one. Moreover, one would expect to begin to see the new supersymmetric particles if one built an accelerator such as the LHC, which could probe for new physics near the electroweak scale. Finally, in what looked for a while like a rather damning constraint, the lightest Higgs in the theory could not be too heavy or the mechanism wouldn't work.

As searches for the Higgs continued without yielding any results, accelerators began to push closer and closer to the theoretical upper limit on the mass of the lightest Higgs boson in supersymmetric theories. The value was something like 135 times the mass of the proton, with details to some extent depending on the model. If the Higgs could have been ruled out up to that scale, it would have suggested all the hype about supersymmetry was just that.

Well, things turned out differently. The Higgs that was observed at the LHC has a mass about 125 times the mass of the proton. Perhaps a grand synthesis was within reach.

The answer at present is … not so clear. The signatures of new supersymmetric partners of ordinary particles should be so striking at the LHC, if they exist, that many of us thought that the LHC had a much greater chance of discovering supersymmetry than it did of discovering the Higgs. It didn't turn out that way. Following three years of LHC runs, there are no signs of supersymmetry whatsoever. The situation is already beginning to look uncomfortable. The lower limits that can now be placed on the masses of supersymmetric partners of ordinary matter are getting higher. If they get too high, then the supersymmetry-breaking scale would no longer be close to the electroweak scale, and many of the attractive features of supersymmetry breaking for resolving the hierarchy problem would go away.

But the situation is not yet hopeless, and the LHC has been turned on again, this time at higher energy. It could be that supersymmetric particles will soon be discovered.

If they are, this will have another important consequence. One of the bigger mysteries in cosmology is the nature of the dark matter that appears to dominate the mass of all galaxies we can see. There is so much of it that it cannot be made of the same particles as normal matter. If it were, for example, the predictions of the abundance of light elements such as helium produced in the big bang would no longer agree with observation. Thus physicists are reasonably certain that the dark matter is made of a new type of elementary particle. But what type?

Well, the lightest supersymmetric partner of ordinary matter is, in most models, absolutely stable and has many of the properties of neutrinos. It would be weakly interacting and electrically neutral, so that it wouldn't absorb or emit light. Moreover, calculations that I and others performed more than 30 years ago showed that the remnant abundance today of the lightest supersymmetric particle left over after the big bang would naturally be in the range so that it could be the dark matter dominating the mass of galaxies.

In that case our galaxy would have a halo of dark matter particles whizzing throughout it, including through the room in which you are reading this. As a number of us also realized some time ago, this means that if one designs sensitive detectors and puts them underground, not unlike, at least in spirit, the neutrino detectors that already exist underground, one might directly detect these dark matter particles. Around the world a half dozen beautiful experiments are now going on to do just that. So far nothing has been seen, however.

So, we are in potentially the best of times or the worst of times. A race is going on between the detectors at the LHC and the underground direct dark matter detectors to see who might discover the nature of dark matter first. If either group reports a detection, it will herald the opening up of a whole new world of discovery, leading potentially to an understanding of Grand Unification itself. And if no discovery is made in the coming years, we might rule out the notion of a simple supersymmetric origin of dark matter—and in turn rule out the whole notion of supersymmetry as a solution of the hierarchy problem. In that case we would have to go back to the drawing board, except if we don't see any new signals at the LHC, we will have little guidance about which direction to head in order to derive a model of nature that might actually be correct.

Things got more interesting when the LHC reported a tantalizing possible signal due to a new particle about six times heavier than the Higgs particle. This particle did not have the characteristics one would expect for any supersymmetric partner of ordinary matter. In general the most exciting spurious hints of signals go away when more data are amassed, and about six months after this signal first appeared, after more data were amassed, it disappeared. If it had not, it could have changed everything about the way we think about Grand Unified Theories and electroweak symmetry, suggesting instead a new fundamental force and a new set of particles that feel this force. But while it generated many hopeful theoretical papers, nature seems to have chosen otherwise.

The absence of clear experimental direction or confirmation of supersymmetry has thus far not bothered one group of theoretical physicists. The beautiful mathematical aspects of supersymmetry encouraged, in 1984, the resurrection of an idea that had been dormant since the 1960s when Yoichiro Nambu and others tried to understand the strong force as if it were a theory of quarks connected by string-like excitations. When supersymmetry was incorporated in a quantum theory of strings, to create what became known as superstring theory, some amazingly beautiful mathematical results began to emerge, including the possibility of unifying not just the three non-gravitational forces, but all four known forces in nature into a single consistent quantum field theory.

However, the theory requires a host of new spacetime dimensions to exist, none of which has been, as yet, observed. Also, the theory makes no other predictions that are yet testable with currently conceived experiments. And the theory has recently gotten a lot more complicated so that it now seems that strings themselves are probably not even the central dynamical variables in the theory.

None of this dampened the enthusiasm of a hard core of dedicated and highly talented physicists who have continued to work on superstring theory, now called M-theory, over the 30 years since its heyday in the mid-1980s. Great successes are periodically claimed, but so far M-theory lacks the key element that makes the Standard Model such a triumph of the scientific enterprise: the ability to make contact with the world we can measure, resolve otherwise inexplicable puzzles, and provide fundamental explanations of how our world has arisen as it has. This doesn't mean M-theory isn't right, but at this point it is mostly speculation, although well-meaning and well-motivated speculation.

It is worth remembering that if the lessons of history are any guide, most forefront physical ideas are wrong. If they weren't, anyone could do theoretical physics. It took several centuries or, if one counts back to the science of the Greeks, several millennia of hits and misses to come up with the Standard Model.

So this is where we are. Are great new experimental insights just around the corner that may validate, or invalidate, some of the grander speculations of theoretical physicists? Or are we on the verge of a desert where nature will give us no hint of what direction to search in to probe deeper into the underlying nature of the cosmos? We'll find out, and we will have to live with the new reality either way.

LAWRENCE M. KRAUSS is a theoretical physicist and cosmologist, the director of the Origins Project and the foundation professor in the School of Earth and Space Exploration at Arizona State University. He is also the author of bestselling books including *A Universe from Nothing* and *The Physics of Star Trek*.

Why Evolution Is Ageist

Genetic mutation changes from adaptive to dangerous after reproductive age

BY AMY MAXMEN
ILLUSTRATION BY HANNAH K. LEE

EVERY TIME HE BENT over a freshly dead body, pathologist George Martin pondered the diversity before him. Although his cadavers almost always belonged to the elderly, they varied dramatically. One would have intestines pocked by polyps. Another's arteries were plugged with plaque. Variety even existed within the same types of disease. For instance, the location of beta amyloid deposits in the brains of people who'd suffered from Alzheimer's differed significantly. If each type of malady shared the identical underlying cause, bodies ravaged by that cause should look similar in death. But they didn't. "I never saw two people who had aged in the same way," Martin says.

Martin read everything he could on aging. He took particular interest in observations showing how organisms ranging from clonal yeast to human twins had wildly different lifespans. One of the more dramatic examples emerged from reports of tiny worms, *Caenorhabditis elegans*, that varied in lifespan by up to fivefold even when the worms were genetically identical and lived in identical laboratory surroundings.

Biologists know how chance events in the environment (such as getting hit by a bus) impact lifespan. And they understand the role of chance in genetics (such as inheriting genes for Huntington's disease and certain cancers). But it now seems a third realm of uncertainty emerges as animals grow older, causing them to age in different ways. Researchers are only beginning to figure out the basis of biological fluctuations that build up over time. Some result from mutations that slip into the genomes within cells as they replicate. Others occur because of changes in molecules that either shut off or activate genes.

The location of random variations within a cell's nucleus matters, and that too may be determined by chance. It's as if they were small tears forming on a blueprint that is sloppily folded, unfolded, and refolded over time. Depending on where the wrinkles occur, the building the blueprint encodes either remains intact or is rendered vulnerable to collapse.

Why would evolution have allowed such instability to persist in our biological makeup over the eons? Martin, now an 89-year-old researcher who studies the genetic basis of aging at the University of Washington, and a handful of other researchers who study aging, speculate that a limited amount of internal uncertainty is beneficial because it helps animals adapt to changing environments.

This notion fits with a broader picture of the vital role of diversity in evolution: Variation among individuals in a population provides options for natural selection to choose from. After all, natural selection cannot weed out excessive variations if they occur after an animal has passed on its genes, since survival in the evolutionary sense only means survival of that lineage in the next generation.

As Martin puts it, "Nature doesn't give a damn about us after we make our babies. Natural selection is pretty much gone around age 40—and that's where aging begins."

While mutations and fluctuations in gene expression within organisms can provide an adaptive boon, they become problematic late in life as mutations accumulate and the breadth of swings in gene expression grows wider. In turn, Martin says, these chance swings may lead to "geriatric disorders," including cancer and degenerative brain diseases.

THROUGHOUT OUR LIVES, chance slips into our bodies through tiny, accidental mutations. Somatic mutations occur in cells as they divide over time. During every division, mistakes are made in the new strand of DNA. Genes involved with DNA repair normally fix those mutations—but if enough time passes, a mistake will inevitably occur within one of those repair genes, too. When, exactly, is a matter of chance—although the risk increases over time. But once that error occurs, additional mutations will be sustained rather than fixed. Again, chance determines how much more time passes until one of the mutations randomly affects a cancer-causing gene.

"Imagine that you are throwing darts at DNA,"

JOHN B. CARNETT

Martin explains. “It might hit at some places where you’re lucky—and like me, you live until 89. Or you could be unlucky like my late wife who died of an aggressive form of cancer beginning in the brain. Even though she was in great physical shape, she got a hit in a dominant oncogene.”

Not all cancer is caused by chance. In January 2015, a biostatistician and a cancer geneticist estimated that about a third of cancer cases can be attributed to inherited defects and assaults from environmental factors ranging from sun rays to cigarettes. The rest, they wrote in *Science*, may be due to random internal events like chance mutations.

Recent studies have indicated how random mutations with seemingly negligible effects may be a problem as they accumulate over time. Some of these mutations might cause changes in how genes are expressed. State-of-the-art technology has permitted cell biologists to analyze minute differences in the expression of genes within individual cells. It appears that genetically identical cells within a body gradually become more dissimilar in terms of the expression of their genes as an animal grows older.

In a 2006 *Nature* study, researchers monitored the expression of a dozen genes in heart cells extracted from young, 6-month-old mice and elderly, 27-month-old mice. Gene activation was interpreted through levels of the corresponding RNA because RNA is the middleman in the molecular pathway between a gene and a protein. Levels of RNA were relatively similar between the cells from young mice. However, heterogeneity was elevated among cells from older mice. The researchers suggest this discordance provides an explanation for why the older mouse hearts functioned less well. “These results underscore the stochastic nature of the aging process,” concluded Jan Vijg, a molecular

“Nature doesn’t give a damn about us after we make our babies.”

geneticist at Albert Einstein College of Medicine, and his co-authors on the manuscript.

Roger Brent, a molecular biologist at the Fred Hutchinson Cancer Research Center in Seattle, agrees. "If the higher functions in a vertebrate depend on a population of cells within an organ or tissue responding in some way, then mutations mean that the response will be less coherent, and that may contribute to a decline in function," he explains. However, scientists have not yet proven that this noise causes diseases of aging, like heart disease. Vijg suspects it does, but says the evidence isn't simple to come by. "It's very hard to show precisely how variation among cells leads to, say, a loss of organ function," he explains.

More than 60 years ago, C.H. Waddington predicted that too much fluctuation could be detrimental, and proposed the existence of a biological mechanism that kept fluctuation within a safe range. He coined the term "canalization" to describe the ability to remain stable. Currently, Martin's lab is searching for genes that maintain homeostasis. His hypothesis is that something occurs to these cells later in life that increases the molecular "drift" of old age that results in cell-to-cell variation. "This drift might take on a life of its own after the reproductive age," Martin says, "And if you get drift outside of a certain window of homeostasis, it's possible you can't come back."

> "Chance is something researchers have to deal with, whether they like it or not."

Martin says his research suggests that "drifts in gene expression become greater during aging," and can lead to "quasi-stochastic" geriatric disorders. He hastens to add, however, that while there is evidence of increased variability in gene expression with age, the precise mechanisms behind it remain to be discovered.

Meanwhile, Alexander Mendenhall, a researcher who studies age-related disease at the University of Washington, is trying to figure out which cells and organs are most sensitive to increasing incoherence. "We want to figure out what breaks first by chance," he says. To get there, the researchers in his lab observe individual cells of living *C. elegans* worms to understand when and how mitochondria, muscle cells, excretory cells, and other components fall apart. "Once there's data on which cell types fail, perhaps we can predict the probability of particular problems," he says.

AS THEY RESEARCH what goes wrong with cells, biologists are also learning how variability within individuals can be adaptive. Although cause-and-effect connections between non-heritable fluctuations and benefits have not been proven, analogous trade-offs occur within genetically identical populations of organisms in nature. Biologists call it bet-hedging—stealing a word from investors who want a cushion against monetary losses, and so put their money in opposing outcomes.

One example of bet-hedging occurs in single-celled, genetically identical populations of *Escherichia coli* bacteria. Many of the microbes die when exposed to antibiotics, but the slowest growing microbes among them seem to persist. Researchers don't know what causes the variation in gene expression among the microbial clones, but they suspect it has lasted through the generations since it helps the lineage survive. There are some hints that cancerous cell populations employ bet-hedging too: Fast-dividing cells seem more vulnerable to chemotherapy.

Likewise, Mendenhall and others have shown genetically identical *C. elegans* worms vary in the amount of "heat shock" proteins they produce. These particular proteins protect other proteins so they don't become misshapen or otherwise faulty in response to triggers, ranging from cancer to a flash of high heat. Those who produce more of the protein have fewer offspring, but survive environmental stress better than those who make more babies but produce fewer heat shock proteins. Mendenhall says this variation likely persists because it diversifies the physiologies of the worms within a population. He has identified genes controlling signaling systems that he thinks may underlie the variation.

When many researchers consider how the expression of genes varies or drifts, epigenetics comes quickly to mind. Through epigenetics, expression changes without mutations to the nucleotides comprising genes. Specifically, epigenetics has to do with two key processes. One component involves histone proteins, which DNA coils around within the nucleus of cells. The tightness of those coils exposes or hides certain genes so that they are or are not expressed—and this condition can be altered by the binding of "histone factors" in a process called histone modification. A second epigenetic component involves methyl compounds that attach to the DNA, activating or repressing the underlying gene from expression—a process called methylation.

In the past decade, scientists have documented changes in patterns of methylation and histone modification that vary as organisms age. Because these alterations cause deviations in gene expression, some researchers call the phenomenon "epigenetic drift."

In a 2012 report in the *Proceedings of the National Academy of Sciences*, researchers found that DNA from a 103-year-old was less methylated than DNA from a newborn. And not just a little less: The centenarian had almost 500,000 fewer points of methylation along their genome than the baby. In another study, researchers compared 3-year-old identical twins who had similar patterns of methylation and histone modification along their genomes to a pair of 50-year-old identical twins who differed dramatically in methylation, histone modification, and gene expression. No one knows what the effect of these different patterns in epigenetic modifications are—they simply indicate that epigenetic changes, known to alter gene expression, could be responsible for genetic drift.

Some external causes are known to underlie epigenetic changes, such as smoking. But the sheer extent of epigenetic drift observed between young and old organisms causes researchers to believe that other factors are at play—including those that are as random as a person being pelted by pigeon poop. "Chance is something that researchers have to deal with, whether they like it or not," Mendenhall says. "It doesn't make things so straightforward."

As with the gradual accumulation of mutations, methylation and histone deacetylation could alter the activation of genes that don't matter much—or those that dictate vital processes like DNA repair and cancer control. Like a gust of wind into a glass shop, chance dictates the extent of the damage. Researchers have found evidence that the damage can lead to diseases we associate with aging. For example, some cancers begin when genes that normally repress tumors are silenced through methylation.

However, Tom Johnson, a molecular biologist at the University of Colorado, worries about how little evidence drives the current wave of enthusiasm over the role of epigenetics in aging. Most variation in gene expression still exists without a documented cause. What's more, Johnson points out that *C. elegans* worms don't display methylation at all, despite enormous, unexplained variation in the way they age. He doesn't doubt that gene expression drifts over time—rather, he questions epigenetics as a main underlying cause. Another potential mechanism could be changes that occur to proteins during and after synthesis. "I'd rather just call [drift] stochastic, and not epigenetic," he says, "because when you say epigenetics you pretend you know what's going on."

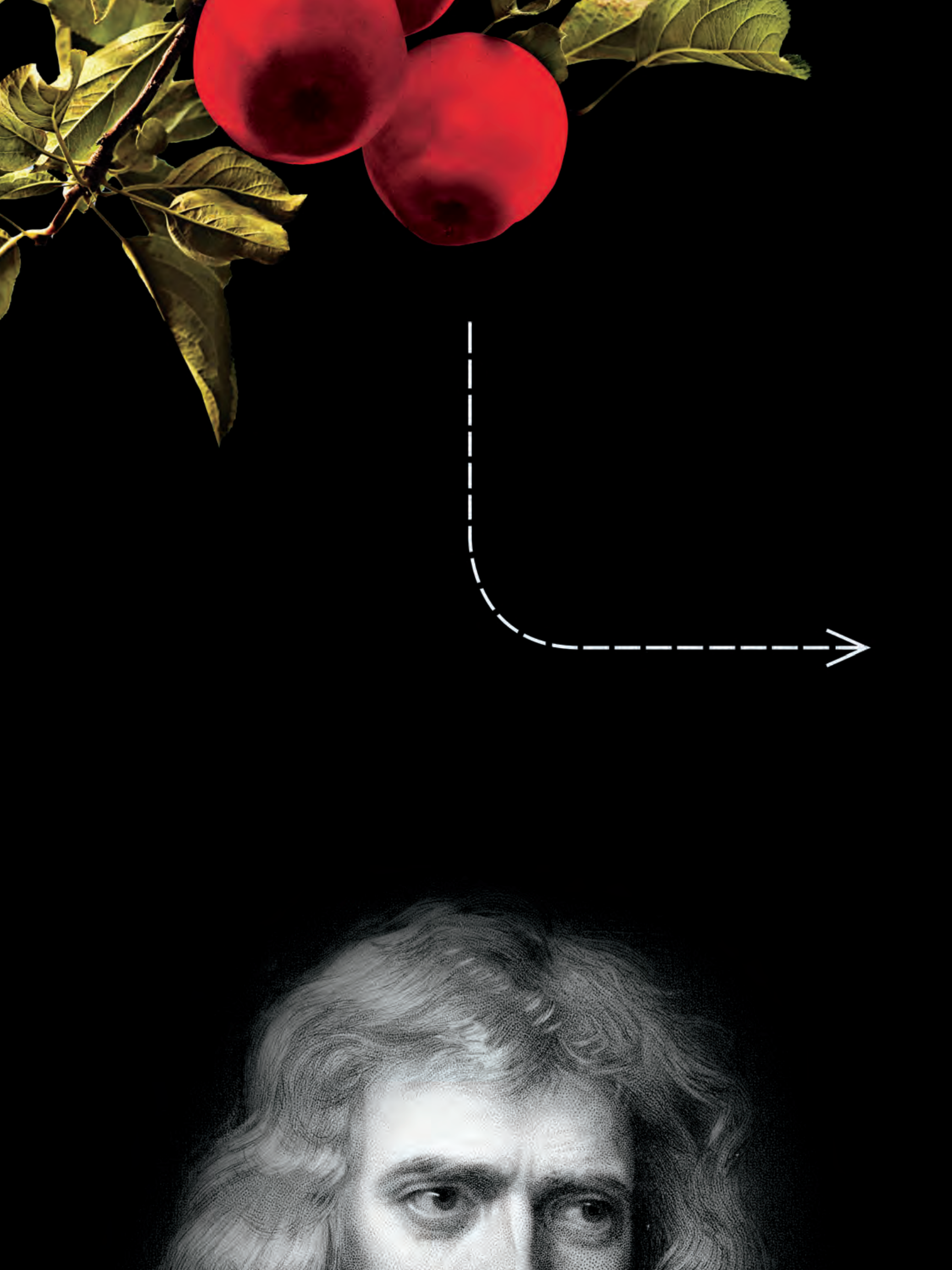
Johnson, who was a physics major for a year at the Massachusetts Institute of Technology, has never been shaken by the interference of chance in aging. "You can never measure where an atom is exactly because in measuring it you move it," he says, referring to

Heisenberg's Uncertainty Principle, which asserts a limit to precision. "You cannot be completely specific about anything, not even an individual atom."

Because Martin and his fellow researchers have yet to pinpoint the mechanisms of chance in aging, any mention of ways to address aging at a cellular level would be premature. ("If we really want people to live longer, we would work on our health system so that there is universal care," Martin says sharply.) Still, the scientists have painted a fuller picture of chance in nature. Before and during reproductive age, as Darwin showed, variability can help organisms adapt to changing environments and pass on their genes. After reproductive age, though, Martin and other researchers are beginning to feel that variation becomes increasingly unkind. Nature is indeed a cruel mistress. Having set us on our way with elementary instructions, she abandons us to the fates.

AMY MAXMEN is an award-winning science journalist with a Ph.D. in evolutionary biology from Harvard. Her *Nautilus* feature on the origin of humanity is featured in *The Best American Science and Nature Writing 2015*.

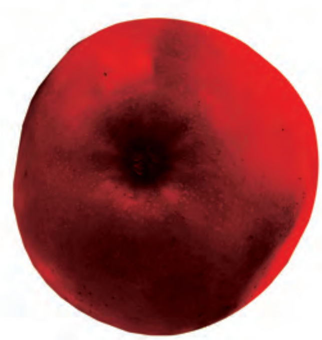
ILLUSTRATION BY **JACKIE FERRENTINO**



The Fifth Force of Physics Is Hanging by a Thread

As scientists chase tantalizing hints of a new force, modern physics hangs in the balance

BY PHILIP BALL



PORTRAIT OF SIR ISAAC NEWTON BY GODFREY KNELLER, 1689
VCG WILSON / CORBIS VIA GETTY IMAGES

HOW ABOUT THAT! Mr. Galileo was correct in his findings." That conclusion wasn't based on the most careful experiment you'll ever see, but it was one of the most spectacular in its way—because it was performed on the moon.

In 1971, Apollo 15 astronaut David Scott dropped a feather and a hammer from the same height and found that they hit the lunar surface at the same time. The acceleration due to gravity doesn't depend on a body's mass or composition, just as Galileo asserted from his (probably apocryphal) experiment on the Leaning Tower of Pisa.

Or does it? Jump forward to the front-page headline of *The New York Times* in January 1986: "Hints of 5th Force in the Universe Challenge Galileo's Findings." The newspaper was reporting on a paper in the premier physics journal *Physical Review Letters* by physicist Ephraim Fischbach and his colleagues, describing evidence that the acceleration due to gravity does vary depending on the chemical composition of the object in question. Gravity, it seemed, was not quite what we thought it was: its effects are modified by what the *The New York Times*' reporter John Noble Wilford christened a "fifth force," adding to the four fundamental forces we already know.

More than 30 years later, many experiments have sought to verify this putative fifth force. Yet despite their extraordinary accuracy, none has ever found convincing evidence for it. That search shows no sign of abating, however. Even in the past year a new tantalizing hint that such a force exists has emerged from experiments in nuclear physics, provoking fresh speculation and excitement.

What hangs in the balance are some of the foundational principles of modern physics. Some physicists believe that a fifth force is permitted, even demanded, by efforts to extend and unify the current fundamental theories. Others hope such a force might shed light on the mysterious dark matter that seems to outweigh all the ordinary matter in the universe. If it exists, says physicist Jonathan Feng of the University of California, Irvine, "it would imply that our attempts to unify the known forces have been premature, as now there will be a fifth one to unify, too."

WHY SPECULATE ABOUT ANOTHER fundamental force of nature, when there's no good evidence for it? The original motivation was appreciated even in Galileo's time: There are two ways of thinking about mass. One comes from inertia: An object's mass is its "resistance" to being moved, this being greater the more massive it is. The other comes from gravity: According to Isaac Newton's law of universal gravitation, the force of gravity experienced between two masses, such as an apple and the Earth, is proportional to the product of their masses divided by the square of the distance between them. This force causes a falling apple to accelerate. If, and only if, the two definitions of mass are the same, the gravitational acceleration doesn't depend on the amount of mass being accelerated.

Are they the same, though? If they aren't, then different masses would fall under gravity at different rates. The intuitive notion that a greater mass should "fall faster" had motivated tests before Galileo. The Dutch natural philosopher Simon Stevin is thought to have dropped lead balls from the clock tower in Delft around 1586, finding no detectable difference in how long they took to reach the ground. Newton himself tested the idea around 1680 by measuring whether pendulums of different mass but identical length have the same period of swing—as they should if gravitational acceleration is mass-independent. His studies were repeated with more accuracy by the German scientist Friedrich Wilhelm Bessel in 1832. Neither of them found any detectable difference.

The idea that inertial and gravitational mass are the same is known as the weak equivalence principle. It became a crucial issue when Einstein formulated his theory of general relativity around 1912-16, which rested on the central idea that the acceleration caused by gravity is the same as the acceleration of an object subject to the same force in free space. If that's not true, general relativity won't work.

"The equivalence principle is one of the basic assumptions of general relativity," says Stephan Schlamminger, who works at the Mecca of high-precision measurement, the National Institute of Standards and Technology in Gaithersburg, Maryland. "As such, it should be thoroughly tested. Tests of the equivalence principle are relatively cheap and simple, but could have a huge impact if a violation was found. It would be careless not to perform these experiments."

If the weak equivalence principle fails, then there are two possibilities. Either Newton's expression for the force of gravity between two masses (which is also what general relativity predicts if gravity is not extreme) is slightly inaccurate and needs tweaking. Or gravity might be fine as it stands—but there might be a new, fifth force that makes it look different. That fifth force would add to the four we already know to exist: gravity, electromagnetism, and the strong and weak nuclear forces that govern the interactions of subatomic particles inside atomic nuclei. Whether we think about "modified gravity" or a fifth force is, says Fischbach, in the end just a semantic distinction.

Either way, says Feng, there is "no reason at all that there can't be a fifth force that we have not noticed until now."

BY THE TIME EINSTEIN PINNED his new gravitational theory to it, the weak equivalence principle had already undergone some very exacting tests. At the end of the 19th century a Hungarian nobleman named Baron Loránd Eőtvős, working at the University of Budapest, realized it could be tested by placing two masses in delicate balance.

FISCHBACH, E. THE FIFTH FORCE: A PERSONAL HISTORY. THE EUROPEAN PHYSICAL JOURNAL H 40, 385-467 (2015).

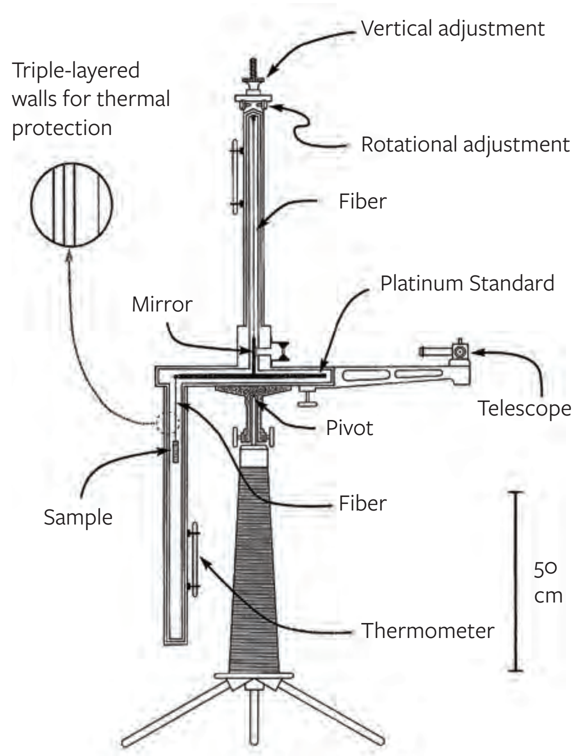
Eőtvős used an instrument known as a torsion balance. He attached two objects to the ends of a horizontal rod suspended by a thread. If the objects have the same weight—the same gravitational mass—then the rod is balanced horizontally. But the masses also experience a centrifugal force due to the rotation of the Earth, which depends on the objects' inertial masses. If inertial mass is the same as the gravitational mass, all the forces are in balance and the rod stays still. But if they differ, then the masses will tend to swing away from the horizontal because of the Earth's rotation.

And if the two masses experience a different "swing"—one possibility would be because the deviation from the weak equivalence principle is dependent on composition—then the rod will experience a net twisting force (torque), and it will rotate. Even if this rotation is very slight, it might be detected by, say, measuring the deflection of a light beam from a mirror attached to the rod.

Now, the fact is that the force of gravity does vary slightly from place to place on the Earth anyway. That's because the planet is not a smooth uniform sphere. Rocks have different density, and so exert a very slightly different gravitational tug. And at the precision of Eőtvős's experiments, even the presence of the nearby university buildings could disturb the results. One way of eliminating these local variations is to carry out the measurements for two different orientations of the dangling rod—say, east-west and north-south. Both should experience the same local effects of gravity, but the centrifugal forces will differ—and thus any deviation from weak equivalence would show up as a difference in torque between the two measurements. This approach fits with the general strategy of setting up the balance experiment to be sensitive to differences in gravitational acceleration between two test masses or configurations: That way, you don't need to worry about local effects or about how accurately you can measure absolute forces.

Local perturbations might, however, also vary in time: Even a passing truck could induce a tiny gravitational disturbance. So the researchers had to take care to rule out such things. In fact, even the presence of the observing experimenter might matter. So the Hungarian scientists would stand well off as the balance came to rest, then dash into the lab to make

Gravity might be fine as it stands—but there might be a new, fifth force that makes it look different.



DISTURBANCE IN THE FORCE The Eőtvős torsion balance was designed to be extremely sensitive to torque that could be evidence of a fifth force of nature.

a measurement before it had time to adjust to their presence (its twisting period was a slow 40 minutes).

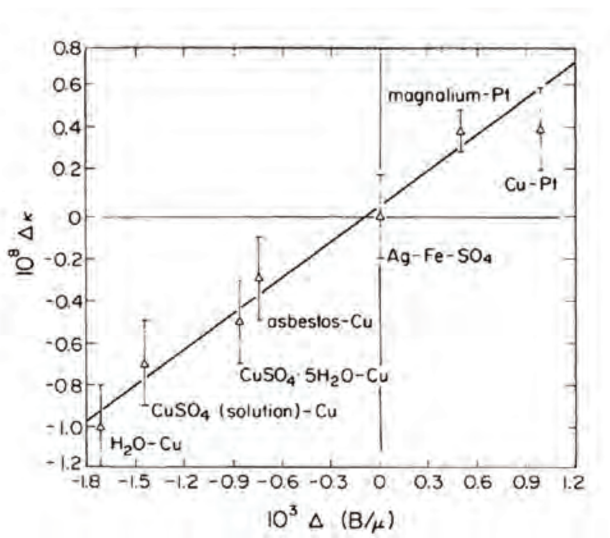
Eőtvős built a revised torsion balance that was a masterpiece of precision engineering. On one end of the hanging rod was a standard platinum mass, while the samples of other materials were suspended from the other end. The rod was mounted on a tripod that could pivot to alter its orientation. A telescope and mirror attached to the moving parts could show if any rotation of the rod had occurred. Tiny imbalances in temperature of the environment could induce warping of the apparatus, leading to spurious rotation, and so the whole assembly was encased in a sealed, insulated chamber. To make the experiments even more exquisitely accurate, the researchers later took to conducting them in a darkened, closed room, so that no light could produce temperature variations. What's more, they put the device inside a double tent insulated with seaweed.

The Hungarian researchers began their torsion balance experiments in 1889, when they found no detectable rotation due to deviations from inertial-gravitational mass equivalence for masses of several different materials, with an accuracy of one part in 20 million.

So by the end of the 19th century, there seemed to be no reason to doubt the weak equivalence principle. But at that very time, new reasons began appearing. For one thing, the discovery of radioactivity suggested the presence of an unknown source of energy locked inside atoms. What's more, Einstein's theory of special relativity offered a new perspective on matter and mass. Mass, it seemed, could be converted to energy—and it was sensitive to velocity, increasing as the speed of an object approached the speed of light. Mindful of all this, in 1906 the Royal Scientific Society of Göttingen in Germany offered a 4,500-mark prize for more sensitive tests of the equivalence of "inertia and gravitation,' citing Eőtvős' experiments as inspiration.

Eőtvős himself couldn't resist returning to the fray. "He was the world expert in this kind of experiment," says Fischbach. He and his students Dezső Pekár and Jenő Fekete in Budapest dusted off their torsion-balance experiments, devoting thousands of hours to testing different materials: copper, water, asbestos, dense wood, and more. They submitted their findings in 1909, claiming an improved accuracy of one part in 200 million. But the full report of the work wasn't published until 1922, three years after Eőtvős' death. Another of his students, János Renner, continued the work and published it in Hungarian in 1935, claiming to verify the weak equivalence principle to one part in 2-5 billion.

Was such sensitivity really possible back then? Physicist Robert Dicke, a specialist in general relativity, expressed doubts when he came to tackle the same question in the 1960s. Regardless of whether Dicke's criticisms are valid, he and his coworkers used a more sophisticated torsion balance that achieved an accuracy of one in 100 billion. They did it by measuring the acceleration of their test masses caused not by the Earth's gravity but by that of the sun. This meant there was no need to disturb the balance by rotating it: The direction of the gravitational attraction was itself being rotated as the Earth moved around the sun. Any



A SECOND LOOK Eőtvős and his coworkers measured very slight differences (Δk) in gravitational acceleration between two equal masses of different composition. But it was only half a century later when Fischbach and his colleagues plotted these against the difference in the baryon number *B* divided by the mass (μ) of the two samples that they ceased to look like random measurement errors and revealed what seemed to be a systematic relationship.

It began to seem as though Fischbach was the discoverer of something non-existent.

deviation from weak equivalence should have showed up as a signal varying every 24 hours in step with the Earth's rotation, giving a precise way to discriminate between this and false signals due to local gravitational variations or other disturbances. Dicke and his colleagues saw no sign of such deviations: No indication that Newton's law of gravity needed amending with a fifth force.

Were physicists satisfied now? Are they ever?

FISCHBACH BECAME INTERESTED in the fifth force after hearing about an experiment performed by his Purdue colleague Roberto Colella and coworkers in 1975, which looked at the effects of Newtonian gravity on subatomic particles. Fischbach wondered whether it would be possible to conduct similar experiments with subatomic particles in a situation where the gravity is strong enough to make general relativity, rather than Newton's theory, the proper description of gravity—that might then offer a completely new way of testing Einstein's theory.

He began to think about doing so using exotic particles called kaons and their antimatter siblings antikaons, which are produced in particle accelerators. Analyzing studies of kaons at the Fermilab accelerator facility near Chicago led Fischbach to suspect that some kind of new force might be affecting the particles' behavior, which was sensitive to a quantity called the baryon number, denoted *B*.

This is a property of fundamental particles that, unlike mass or energy, doesn't have any everyday meaning. It is equal to a simple arithmetic sum of the number of even more fundamental constituents called quarks and antiquarks that make up the protons and neutrons of atomic nuclei. Here's the thing, though: If this new force depended on baryon number, it should depend on the chemical composition of materials, since different chemical elements have different numbers of protons and neutrons. More precisely, it would depend on the ratio of *B* to the masses of the component atoms. Naively it might seem that this ratio should be constant for everything, since atomic mass comes from the sum of protons and neutrons. But actually a small part of the total mass of all those constituents is converted into the energy that binds them together, which varies from atom to atom. So each element has a unique *B*/mass ratio.

A force that depends on composition ... well, wasn't that what Eőtvős had been looking for? Fischbach decided to go back and look closely at the Hungarian baron's results. In the fall of 1985, he and his student Carrick Talmadge calculated the *B*/mass ratio for the substances in the samples of Eőtvős and his students. What they found astonished them.

The Hungarian team had found very small deviations for the measured gravitational acceleration of different substances, but apparently lacking any pattern, suggesting that these were just random errors. But when Fischbach and Talmadge plotted these deviations against the *B*/mass ratio, they saw a straight-line relationship, suggesting a force that induced a very small repulsion between masses, weakening their gravitational attraction.

The chemical composition of Eőtvős' samples wasn't always easy to deduce—for snakewood and "suet," who could be sure?—but as far as they could see, the relationship stood up. In one of the most striking cases, platinum and copper sulfate crystals turned out to have the same deviation. Everything about these two substances (density and so forth) are different—except for their near-identical *B*/mass ratio.

Fischbach and Talmadge presented these findings in their headline-grabbing 1986 paper, helped

FISCHBACH, E. THE FIFTH FORCE: A PERSONAL HISTORY. THE EUROPEAN PHYSICAL JOURNAL H 40, 385-467 (2015).

> That's simply the way physics has always worked: When all else fails, you place a new piece on the board and see how it moves.

by postdoc Peter Buck whose command of German enabled him to translate the original 1922 report by Eőtvős' team. The Purdue group's paper was reviewed by Dicke, who voiced some doubts but felt eventually that it should be published. Dicke later followed up with a paper claiming that the anomalies in the Eőtvős measurements could be explained by temperature gradients in the apparatus. It was hard, though, to see how such everyday environmental effects would end up producing such a convincing-looking correlation with a quantity as exotic as baryon number.

Once the word was out, the world came calling—not only *The New York Times* but also the legendary Richard Feynman, whose call to Fischbach's home four days after the paper was published he initially assumed to be a prank. Feynman was unimpressed, and said as much both to Fischbach and in the *Los Angeles Times*. But for him to show interest at all showed how the Purdue team's provocative result had got folks talking.

CONSIDERING THAT OUR PAPER was suggesting the presence of a new force in nature," wrote Fischbach, "it may seem surprising that the referring process went as smoothly as it did." But maybe the path was smoothed by the fact that there were already both theoretical and experimental reasons to suspect a fifth force might exist.

Back in 1955, the Chinese-American physicists T.D. Lee and C.N. Yang, who shared a Nobel prize two years later for their work on fundamental particle interactions, explored the idea of a new force that depended on baryon number, and had even used Eőtvős' work to set limits on how strong it could be. Lee met Fischbach just over a week after his paper was published, and congratulated him on it.

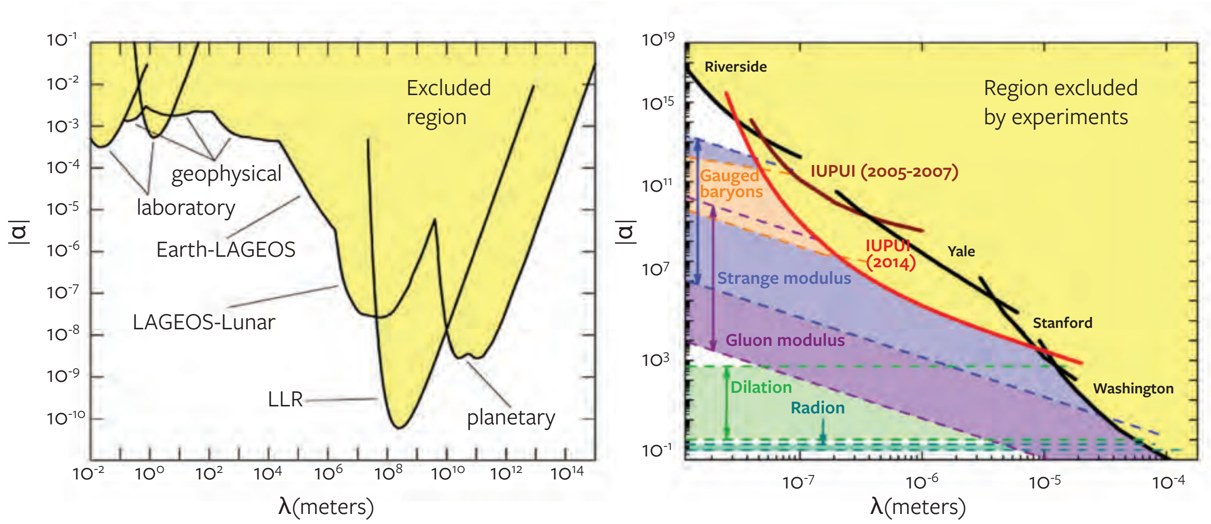
What's more, in the late 1970s two geophysicists in Australia, Frank Stacey and Gary Tuck, had made an accurate measurement in a deep mine of the gravitational constant that relates force to masses in Newton's equation of gravitational attraction. They reported a value significantly different from that measured previously in laboratories. One way of explaining those results was to invoke a new force that acted over distances of a few kilometers. Stacey and Tuck's measurements were themselves partly inspired by work in the early 1970s by Japanese physicist Yasunori Fujii on the possibility of "non-Newtonian gravity."

After 1986 the hunt was on. If a fifth force indeed acted over distances of tens to thousands of meters, it should be possible to detect deviations from what Newtonian gravity predicts about free fall high above the Earth's surface. In the late 1980s a team at the United States Air Force laboratory at Hanscom in Bedford, Massachusetts, measured the acceleration due to gravity up a 600-meter television tower in North Carolina and reported evidence for what seemed to be in fact a "sixth force," for in contrast to Fischbach's repulsive fifth force it seemed to enhance gravity. After subsequent analysis, however, these claims evaporated.

The most extensive studies were conducted at the University of Washington in Seattle by a team of physicists who, playing on the proper Hungarian pronunciation of "Eőtvős" (close to "Ert-wash"), called themselves the Eot-Wash group. They were co-led by nuclear physicist Eric Adelberger, who "has by now become the world's leading experimentalist in searching for deviations from the predictions of Newtonian Gravity," according to Fischbach. The Eot-Wash team used state-of-the-art torsion balances, taking all manner of precautions to eliminate artifacts from their measurements. Result: nothing.

One of the most evocative and suggestive experiments was begun right after the 1986 announcement, by Peter Thieberger of Brookhaven National Laboratory in Upton, New York. He floated a hollow copper sphere in a tank of water and placed it near the edge of

FISCHBACH, E. THE FIFTH FORCE: A PERSONAL HISTORY. THE EUROPEAN PHYSICAL JOURNAL H 40, 385-467 (2015).



PAINTED INTO A CORNER Limits on the possible strength of a fifth force at large (left) and small (right) scales. The yellow regions show the excluded zones, with boundary labels referring to individual experiments. The dashed lines for small scales show some possible magnitudes of a fifth force predicted by some theories.

a cliff. In 1987 Thieberger reported that the sphere consistently moved in the direction of the edge, where the gravitational attraction by the surrounding rock was smaller—just what you'd expect if there was indeed some repulsive force that counteracted gravity. This was the only corroborating evidence for a fifth force published in a prominent physics journal. Why did it alone see such a thing? That's still a mystery. "It is not clear what—if anything—was wrong with Thieberger's experiment," wrote Fischbach.

By 1988 Fischbach counted no fewer than 45 experiments searching for a fifth force. Yet five years later only Thieberger's had produced any sign of it. In a talk to mark the tenth anniversary of the 1986 paper, Fischbach admitted that "There is at present no compelling experimental evidence for any deviation from the predictions of Newtonian gravity ... the preponderance of the existing experimental data is incompatible with the presence of any new intermediate-range or long-range forces."

It began to seem as though, as Fischbach ruefully puts it, he was the discoverer of something non-existent. The mood was captured by physicist Lawrence Krauss, then at Yale University, who responded to the 1986 paper by formally submitting to *Physical Review Letters* a spoof paper claiming to have re-analyzed Galileo's experiments on the acceleration of balls rolling downhill under gravity, reported in his 1638 book *Discourses on Two New Sciences*, and to have found evidence for a "third force" (in addition to gravity and electromagnetism). The paper was rejected by the journal in the same spirit as it was submitted: on the basis of six spoof referees' reports clearly written in house.

AFTER A FEW DECADES of almost universal non-detection of a fifth force, you might think the game is over. But if anything, reasons to believe in a fifth force have become ever more attractive and diverse as physicists seek to extend the foundations of their science. "There are now thousands of papers suggesting new fundamental interactions that could be a source of a fifth force," says Fischbach. "The theoretical motivation is quite overwhelming."

For example, the latest theories that attempt to extend physics beyond the "standard model," which accounts for all the known particles and their interactions, throw up several possibilities for new interactions as they attempt to uncover the next layer of reality. Some of those theories predict new particles that could act as the "carriers" of previously unknown forces, just as the electromagnetic, strong, and weak forces are known to be associated with "force particles" such as the photon.

A group of models predicting deviations from Newtonian gravity called Modified Newtonian Dynamics (MOND) have also been put forward to account for some aspects of the movements of stars in galaxies that are otherwise conventionally explained by invoking a hypothetical "dark matter" that interacts with ordinary matter only (or perhaps almost only) via gravitational attraction. No clear evidence has been discovered to support MOND theories, but some physicists have found them increasingly promising as extensive searches for dark-matter particles have yielded no sign.

Alternatively, says Feng, a fifth force might help us find out about dark matter itself. As far as we know, dark matter only interacts with other matter through gravity. But if it turned out to feel a fifth force too, then, Feng says, "it could provide a 'portal' through which we can finally interact with dark matter in a way that is not purely gravitational, so we can understand what dark matter is."

What's more, some theories that invoke extra dimensions of space beyond our familiar three—such as the currently most favored versions of string theory—predict that there could be forces similar to but considerably stronger than gravity acting over short distances of millimeters or less.

That's the scale at which some researchers are now looking. It means measuring the forces, with extraordinary precision, between small masses separated by very small gaps. Three years ago Fischbach and colleagues set out to do this for tiny particles just 40 to 8,000 millionths of a millimeter apart. The difficulty with such measurements is that there is already a force of attraction between objects this close, called the Casimir force. This has the same origin as the so-called van der Waals forces that operate at even closer approach, and which stick molecules together weakly. These forces come from the synchronized sloshing of clouds of electrons in the objects, which give rise to electrostatic attraction because of the electrons' charge. Casimir forces are basically what van der Waals forces become when the objects are far enough apart—more than a few nanometers—for the time delay between the electron fluctuations across the gap to matter.

Fischbach and his coworkers found a way to suppress the Casimir force, making it about a million times weaker by coating their test masses with a layer of gold. They attached a gold-coated sapphire bead about 150 thousandths of a millimeter in radius to a solid plate, whose motions could be detected electronically. Then they rotated a microscopic disk patterned with patches of gold and silicon just below the bead. If there were any differences in the force exerted by the gold and silicon, that should produce a vibration of the bead. They saw no such effects, which meant they could place even more stringent limits on the possible strength of a material-dependent fifth force at these microscopic scales.

Torsion-balance measurements can be used in this region, too. Researchers at the Institute for Cosmic Ray Research at the University of Tokyo have used the device to look for deviations from the standard Casimir force caused by a fifth force. All they found were yet stricter lower limits on how strong such a force can be.

As well as detecting a fifth force directly, it might still be possible to spot it the way Fischbach originally thought to look: through the high-energy collisions of fundamental particles. In 2015 a team at the Institute for Nuclear Research in Debrecen, Hungary, led by Attila Krasznahorkay, reported something unexpected when an unstable form of beryllium atoms, formed by firing protons at a lithium foil, decays by emitting pairs of electrons and their antimatter counterparts positrons. There was a rise in the number of electron-positron pairs ejected from the sample at an angle of about 140 degrees, which standard theories of nuclear physics couldn't explain.

The results were all but ignored until Feng and his coworkers suggested last year that they could be accounted for by the ephemeral formation of a new "force particle" which then quickly decays into an electron and a positron. In other words, this hypothetical particle would carry a fifth force, with a very short range of just a few trillionths of a millimeter.

Although they haven't yet been replicated by other researchers, the Hungarian findings look pretty solid. The chance that they are just a random statistical fluctuation is tiny, says Feng: about 1 in 100 billion. "More than that, the data fit beautifully the hypothesis that they're caused by a new particle," he says. "If such a new particle exists, this is exactly how it would come to light." Schlamminger agrees that Feng's interpretation of the Hungarian observations was "one of the exciting things that happened in 2016."

"We have yet to confirm it is a new particle," admits Feng, "but it would be revolutionary if true—the biggest discovery in particle physics in at least 40 years." His theoretical work predicts that the putative new particle is just 33 times heavier than the electron. If so, it shouldn't be hard to make in particle collisions—but it would be hard to see. "It is very weakly interacting, and we've shown that it would have eluded all previous experiments," says Feng. Perhaps, he adds, it could be sought at colliders such as the Large Hadron Collider at the particle-physics center CERN in Geneva.

The hypothesis of a fifth force is, then, anything but exhausted. In fact it's fair to say that any observations in fundamental physics or cosmology that can't be explained by our current theories—by the Standard Model of particle physics or by general relativity—are apt to get physicists talking about new forces or new types of matter, such as dark matter and dark energy. That's simply the way physics has always worked: When all else fails, you place a new piece on the board and see how it moves. Sure, we haven't yet seen any convincing evidence for a fifth force, but neither have we seen a direct sign of dark matter or supersymmetry or extra dimensions, and not for want of looking. We have ruled out a great deal of the territory that a fifth force might inhabit, but there is still plenty of terrain left in shadow.

At any rate, the search continues. In April 2016, the European Space Agency launched a French satellite called Microscope that aims to test the weak equivalence principle in space with unprecedented accuracy. It will place two nested pairs of metal cylinders in free fall: One pair is made of the same heavy platinum-rhodium alloy, the other has an outer cylinder of lighter titanium-vanadium-aluminum. If the cylinders fall at a rate that depends ever so slightly on the material—so that deviations from the weak equivalence principle occur at a level of one part in a thousand trillion, about 100 times smaller than is detectable in current Earth-based experiments—it should be possible to measure the differences with electrical sensors on the satellite.

"String-theory models predict WEP violations below one part in 10 trillion," says Joel Bergé, a scientist at the French Centre for Aerospace Research (ONERA) that manages the Microscope project. He says that the scientific operations of the mission began last November and the first results should be published this summer.

Despite such high-tech studies, it's the Eőtvős torsion-balance experiments that Fischbach keeps returning to. Back then, the Hungarians had no theoretical motivation to expect a composition-dependent fifth force—nothing that could have subconsciously swayed them in their incredibly delicate work. "Whatever we need to explain their data simply didn't and couldn't conceptually exist then," says Fischbach. And yet they did seem to see something—not a random scatter of results, but a systematic deviation. "I keep thinking, maybe I'm missing something about what they did," says Fischbach. "It's still a puzzle."

PHILIP BALL is a writer based in London. His latest book is *The Water Kingdom: A Secret History of China*.

47

CONSCIOUSNESS IS A HARD PROBLEM because it is emergent, mixes software and hardware, and is dizzyingly self-referential. It's harder still because, in a sense, it impossible to study directly.

We can measure how some living (or even inanimate) thing interacts with the world. We can learn to recognize intelligence and reflexivity in that behavior. But how can we tell *what it is like* to be that thing?

Christof Koch, one of today's leading thinkers on consciousness, describes it as "physics from the inside." It's a different category of question than we're used to, and one that has a growing set of intersections with other sciences.

It is even a short distance from some common laments. Why don't we understand each other, or even ourselves? This issue is full of discovery, re-discovery and argument by analogy.

Because that's a good place to start.

Welcome to "Consciousness."

—MS

"If it feels like something to be a worm, then it's conscious."

CHRISTOF KOCH

"The Spiritual, Reductionist Consciousness of Christof Koch" p.70

Consciousness

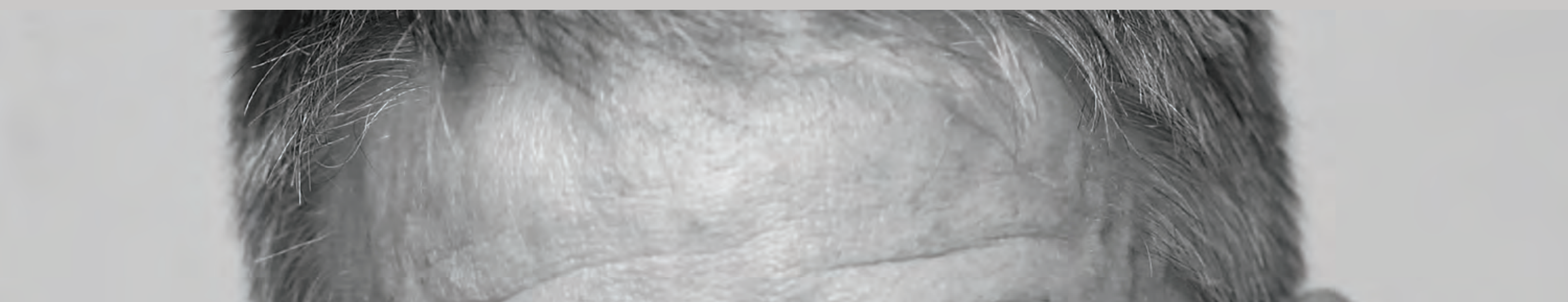
ON REFLECTION

The Spiritual, Reductionist Consciousness of Christof Koch

What the neuroscientist is discovering about consciousness is both humbling and frightening him

BY STEVE PAULSON

PHOTO BY ALLEN INSTITUTE



CONSCIOUSNESS IS A THRIVING industry. It's not just the meditation retreats and ayahuasca shamans. Or the conferences with a heady mix of philosophers, quantum physicists, and Buddhist monks. Consciousness is a buzzing business in neuroscience labs and brain institutes. But it wasn't always this way. Just a few decades ago, consciousness barely registered as a credible subject for science.

Perhaps no one did more to legitimize its study than Francis Crick, who launched a second career in neurobiology after cracking the genetic code. In the 1980s Crick found a brilliant collaborator in the young scientist Christof Koch. In some ways, they made an unlikely team. Crick, a legend in science, was an outspoken atheist, while Koch, 40 years younger, was a Catholic yearning for ultimate meaning. Together, they published a series of pioneering articles on the neural correlates of consciousness until Crick died in 2004.

Koch went on to a distinguished career at Caltech before joining the Allen Institute for Brain Science in Seattle. Today, as the president and chief scientific officer, he supervises several hundred scientists, engineers, and informatics experts trying to map the brain and figure out how our neural circuits process information. The Institute recently made news with the discovery of three giant neurons connecting many regions of the mouse brain, including one that wraps around the entire brain. The neurons extend from a set of cells known as the claustrum, which Crick and Koch maintained could act as a seat of consciousness.

Koch is one of the great thinkers about consciousness. He has a philosophical frame of mind and jumps readily from one big idea to the next. He can talk about the tough ethical decisions regarding brain-impaired patients and also zoom out to give a quick history of Christian thinking on the soul. In our conversation, he ranged over a number of far-out ideas—from panpsychism and runaway artificial intelligence to the consciousness of bees and even bacteria.

You've said you always loved dogs. Did growing up with a dog lead to your fascination with consciousness?
I've wondered about dogs since early childhood. I grew up in a devout Roman Catholic family, and I asked my father and then my priest, "Why don't dogs go to heaven?" That never made sense to me. They're like us in certain ways. They don't talk, but they obviously have strong emotions of love and fear, hate and excitement, of happiness. Why couldn't they be resurrected at the end of time?

Are scientific attitudes about animal consciousness simplistic?
The fact is, I don't even know that you're conscious. The only thing I know beyond any doubt—and this is one of the central insights of Western philosophy—is *Cogito ergo sum*. What Descartes meant is the only thing I'm absolutely sure of is my own consciousness. I assume you're conscious because your behavior is similar to mine, and I could see your brain if I put you in an MRI scanner. When you have a patient who's locked-in, who can't talk to me, I have to infer it. The same with animals. I can see they're afraid when it's appropriate to be afraid, and they display all the behavioral traits of being afraid, including the release of hormones in their bloodstream. If you look at a piece of dog brain or mouse brain and compare that to a piece of human brain the same size, only an expert with a microscope can tell for sure that this is a dog brain or a human brain. You really have to be an expert neuroanatomist.

We share much of our evolutionary history with dogs and even dolphins. But what about lizards or ants? What about bacteria? Can they be conscious?
It becomes progressively more difficult. The brain of a bird or a lizard has a very different evolutionary history, so it becomes more difficult to assert without having a general theory. Ultimately, you need a theory that tells us which physical systems can be conscious. By the time you get to a worm, let alone to bacteria, you

I'm not a mystic. I'm a scientist. But I find myself in a wonderful universe with a positive and romantic outlook on life.

can believe that it feels like something to be a worm because that's ultimately what consciousness is. If it feels like something to be a worm, then it's conscious. Right now, most people believe it doesn't feel like anything to be my iPhone. Yet it may well be true that it feels like something to be a bee. But it's not easy to test that assertion in a scientific way.

What do you mean when you say "it feels like something?"

It feels like something to be you. I can't describe it to you if you're a zombie. If you were born blind, I can never describe what it means to see colors. You are simply unable to comprehend that. So it is with consciousness. It's impossible to describe it unless you have it. And we have these states of consciousness unless we are deeply asleep or anesthetized or in a coma. In fact, it's impossible not to be conscious of something. Even if you wake up discombobulated in a dark hotel room, you're jet-lagged and your eyes are still closed, you are already there. Before there was just nothing, *nada*, *rien*. Then slowly some of your brain boots up and you realize, "Oh, I'm here. I'm in Beijing and I flew in last night." The difference between nothing and something is a base-level consciousness.

Is this self-awareness?

It's even much simpler. I might not even know who I am when I'm waking up. It takes time to boot up and realize who you are, where you are, what time of day it is. First, you open your eyes and just see darkness. Darkness is different from nothing. It's not that I see darkness behind my head; I just don't see at all. That's what consciousness is. It's a basic feeling.

You said bees could be conscious. They do amazing things, and yet they have tiny brains.

Yes, they do very complicated things. We know that individual bees can fly mazes. They can remember scents. They can return to a distant flower. In fact, they can communicate with each other, through a dance, about the location and quality of a distant food source. They have facial recognition and can recognize their beekeeper. Under normal conditions, they would never sting their beekeeper; it's probably a combination of visual and olfactory cues.

Their brains contain roughly a million neurons. By comparison, our brains contain about 100 billion, so a hundred thousand times more. Yet the complexity of the bee's brain is staggering, even though it's smaller than a piece of quinoa. It's roughly 10 times higher in terms of density than our cortex. They have all the complicated components that we have in our brains, but in a smaller package. So yes, I do believe it feels like something to be a honey bee. It probably feels very good to be dancing in the sunlight and to drink nectar and carry it back to their hive. I try not to kill bees or wasps or other insects anymore.

WHAT'S THE BUZZ Bees have all the complicated brain components that humans have, but in a smaller package. "So yes, I do believe if feels like something to be a honey bee," Christof Koch says.

PIXABAY

You're talking about the consciousness of an individual bee—not the hive, which has another level of complexity.

I'm talking about the potential for sentience in individual bees. Would we exclude them because they can't talk? Well, lots of people can't talk. Babies can't talk, impaired patients can't talk. Because they don't have a human brain? Well, that's completely arbitrary. Yes, their evolution diverged from us 250 million years ago or so, but they share with us a lot of the basic metabolism and machinery of the brain. They have neurons, ionic channels, neurotransmitters, and dopamine just like we have.

So brain size is not the key factor in consciousness?

That's entirely correct. In fact, there's no principal reason to assume that brain size should be the be-all and end-all of consciousness.

We also know Neanderthals had bigger brains than the *Homo sapiens* who lived near them in Europe. Yet we survived and they didn't.

Their brain was maybe 10 percent larger than our brain. We don't know why we survived. Did we just outbreed them? Were we more aggressive? There's some research showing that dogs play a role here. At the same time when *Homo neanderthalensis* became extinct—around 35,000 years ago—*Homo sapiens* domesticated the wolf and they became the two apex hunters. *Homo sapiens* and wolves/dogs started to collaborate. We became this ultra-efficient hunting cooperative because we now had the ability to be much more efficient at hunting down prey over long distances and exhausting them. So the creature with the larger brain didn't survive and the one with the smaller brain did.

Why were humans able to create civilizations that have transformed the planet?

We don't have a precise answer. We have big brains and are, by some measure, the most intelligent species, at least in the short term. We'll see whether we'll actually

> We might be surrounded by consciousness everywhere and find it in places we don't expect.

survive in the long term, given our propensity for mass violence. And we've manipulated the planet to such an extent that we are now talking about entering a new geological age, the Anthropocene. But it's unclear why whales or dolphins—some of which have bigger brains and more neurons in their cortex than we do—why they are not called smarter or more successful. Maybe because they have flippers and live in the ocean, which is a relatively static environment. With flippers, you're unable to build sophisticated tools. Of course, human civilization is all about tools, whether it's a little stone, an arrow, a bomb, or a computer.

So hands are crucial for their ability to manipulate tools.

You need not only a brain, but also hands that can manipulate the environment. Otherwise, you can think about the world but you can't act upon it. That's probably why this particular species of primate excelled and took over the planet.

There are fascinating questions about how deep consciousness goes. You've embraced the old philosophy of panpsychism. Isn't this the idea that everything in nature has some degree of consciousness or mind?

Yes, there's this ancient belief in panpsychism: "Pan" meaning "every," "psyche" meaning "soul." There are different versions of it depending on which philosophical or religious tradition you follow, but basically it meant that everything is ensouled. Now, I don't believe that a stone is ensouled or a planet is ensouled. But if you take a more conceptual approach to consciousness, the evidence suggests there are many more systems that have consciousness—possibly all animals, all unicellular bacteria, and at some level maybe even individual cells that have an autonomous existence. We might be surrounded by consciousness everywhere and find it in places where we don't expect it because our intuition says we'll only see it in people and maybe monkeys and also dogs and cats. But we know our intuition is fallible, which is why we need science to tell us what the actual state of the universe is.

Most scientists would dismiss panpsychism as ancient mythology. Why does this idea resonate for you?

It's terribly elegant in its simplicity. You don't say consciousness only exists if you have more than 42 neurons or 2 billion neurons or whatever. Instead, the system is conscious if there's a certain type of complexity. And we live in a universe where certain systems have consciousness. It's inherent in the design of the universe. Why is that so? I don't know. Why does the universe follow the laws of quantum mechanics? I don't know. Can I imagine a universe where the laws of quantum mechanics don't hold? Yes, but I don't happen to live in such a universe, so I believe our universe has certain types of complexity and a system that gives rise to consciousness. Suddenly the world is populated by entities that have conscious awareness, and that one simple principle leads to a number of very counterintuitive predictions that can, in principle, be verified.

So it all comes down to how complex the system is? And for the human brain, how its neurons and synapses are wired together?

It comes down to the circuitry of the brain. We know that most organs in your body do not give rise to consciousness. Your liver, for example, is very complicated, but it doesn't seem to have any feelings. We also know that consciousness does not require your entire brain. You can lose 80 percent of your neurons. You can lose the little brain at the back of your brain called the cerebellum. There was recently a 24-year-old Chinese woman who discovered, when she had to get a brain scan, that she has absolutely no cerebellum. She's one of the extremely rare cases of people born without a cerebellum, including deep cerebellar nuclei. She never had one. She talks in a somewhat funny way and she's a bit ataxic. It took her several years to learn how to walk and speak, but you can communicate with her. She's married and has a child. She can talk to you about her conscious experiences. So clearly you don't need the cerebellum.

Yet the cerebellum has everything you expect of neurons. It has gorgeous neurons. In fact, some of the most beautiful neurons in the brain, so-called Purkinje cells, are found in the cerebellum. Why does the cerebellum not contribute to consciousness? It has a very repetitive and monotonous circuitry. It has 69 billion neurons, but they have simple feed-forward loops. So I believe the way the cerebellum is wired up does not give rise to consciousness. Yet another part of the brain, the cerebral cortex, seems to be wired up in a much more complicated way. We know it's really the cortex that gives rise to conscious experience.

It sounds like you're saying our intelligence comes from this wiring, not from some special substance in the neurons. Could a conscious system be made of something totally different?

That's correct. There's nothing inherently magical about the human brain. It obeys all the laws of physics like everything else in the universe. There isn't anything supernatural that's added to my brain or my cortex that gives rise to a conscious experience.

Is it like a computer?

A computer shares some similarities with the brain, but this is a metaphor and that can be dangerous. One is evolved, the other one is constructed. In the one case you have software and hardware. It's much more difficult to make that distinction in the brain. I think we have to be cautious about comparisons between a brain and a computer. But in theory, a system that's complex enough could be conscious. It may be possible that human-built artifacts would feel like something and would also experience the world.

The Internet is an extremely complex system. Could it feel happy or depressed?

If a computer or the Internet has sentience, the challenge is how we relate its conscious state to ours because its evolutionary history is radically different. It doesn't have our senses or our reward systems. Of course, this is also a threat. The Internet and runaway AI will not have our value system. It may not care at all about humans. Why should it? We don't care about ants or bugs. Most of us don't even care about chickens or cows except when we want to eat them. This is a concern moving forward if we endow these entities not just with consciousness but intelligence. Is that really such a good idea?

The Internet and runaway AI will not have our value system. It may not care at all about humans. Why would it?

We're not the dominant species on the planet because we are wiser or swifter or more powerful. It's because we're more intelligent and ruthless. If we build intelligent systems that exceed even our intelligence, we may believe we can control them. "Oh yeah, I always have this kill-switch. Don't worry, it'll be OK." Well, one day somebody's going to say, "Oops, I didn't want that. I didn't mean that to happen." And it may be our last invention.

That's the scenario in a lot of science fiction. But you really believe artificial intelligence could develop a certain level of complexity and wipe us out?

This is independent of the question of computer consciousness. Yes, if you have an entity that has enough AI and deep machine learning and access to the Cloud, etc., it's possible in our lifetime that we'll see creatures that we can talk to with almost the same range of fluidity and depth of conversation that you and I have. Once you have one of them, you replicate them in software and you can have billions of them. If you link them together, you could get superhuman intelligence. That's why I think it behooves all of us to think hard about this before it may be too late. Yes, there's a promise of untold benefits, but we all know human nature. It has its dark side. People will misuse it for their own purposes.

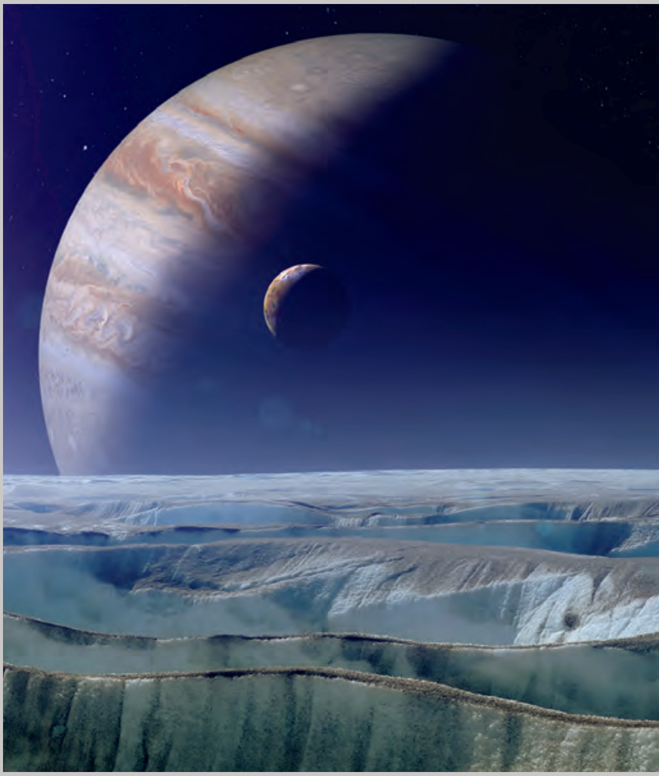
How do we build in those checks to make sure computers don't rule the world?
That's a very good question. The only reason we don't have a nuclear bomb in every backyard is because you can't build it easily. It's hard to get the material. It takes a nation state and tens of thousands of people. But that may be different with AI. If current trends accelerate, it may be that 10 programmers in Timbuktu could unleash something truly malevolent onto mankind. These days, I'm getting more pessimistic about the fate of a technological species such as ours. Of course, this might also explain the Fermi paradox.

Remind us what the Fermi paradox is.
We have yet to detect a single intelligent species, even though we know there are probably trillions of planets. Why is that? Well, one explanation is it's just extremely unlikely for life to arise and we're the only one. But I think a more likely possibility is that any time you get life that's sufficiently complex, with advanced technology, it has somehow managed to annihilate itself, either by nuclear war or by the rise of machines.

You are a pessimist! You really think any advanced civilization is going to destroy itself?
If it's very aggressive like ours and it's based in technology. You can imagine other civilizations that are not nearly as aggressive and live more in harmony with themselves and nature. Some people have thought of it as a bottleneck. As soon as you develop technology to escape the boundary of the planet, there's an argument that civilization will also develop computers and nuclear fusion and fission. Then the question is, can it grow up? Can it become a full-grown, mature adult without killing itself?

You have embraced Integrated Information Theory, which was developed by your colleague Giulio Tononi. What can this tell us about consciousness?
The Integrated Information Theory of consciousness derives a mathematical calculus and gives rise to something known as a consciousness meter, which a variety of clinical groups are now testing. If you have an anesthetized patient, or a patient who's been in a really bad traffic accident, you don't really know if this person is minimally conscious or in a vegetative state; you treat them as if they're conscious, but they don't respond in any meaningful way.

How can you be sure they're conscious?
You're never really sure. So you want a brain-based test that tells you if this person is capable of some experience. People have developed that based on this integrated information series. That's big progress. The current state of my brain influences what happens in my brain the next second, and the past state of my brain influences what my brain does right now. Any system that has this cause-effect power upon itself is conscious. It derives from a mathematical measure. It



NASA

FATAL INTELLIGENCE Given the probable existence of trillions of planets, why haven't we detected life elsewhere? It's likely, Christof Koch says, that sufficiently complex and intelligent life would destroy itself.

could be a number that's zero, which means a system with no cause-effect power upon itself. It's not conscious. Or you have systems that are "Phi," different from zero. The Phi measures, in some sense, the maximum capacity of the system to experience something. The higher the number, the more conscious the system.

So you could assign a number to everything that might have some degree of consciousness—whether it's an ant, a lizard, bacteria, or a vegetative human being?

Yes, you or me, the Dalai Lama or Albert Einstein.

The higher the number, the more conscious?

The number by itself doesn't tell you it's now thinking, or is conscious of an image or a smell. But it tells you the capacity of the system to have a conscious experience. In some deep philosophical sense, the number tells you how much it exists. The higher the number, the more the system exists for itself. There isn't a Turing Test for consciousness. You have to look at the way the system is built. You have to look at the circuitry, not its behavior, whether it's a computer or a biological brain. This has now been tested and validated in many patients, including locked-in patients who are fully conscious, people under anesthesia who are not conscious, people in deep sleep, and those in vegetative states or minimal-conscious states. So the question now is whether this can be turned into something practical that can be used at every clinic in the country or the world to test patients who've just been in a bad traffic accident.

JUST LIKE HEAVEN "In a cathedral, I get a feeling of luminosity out of the numinous," says Christof Koch. Gaudi's La Sagrada Familia is seen above. "You can get that feeling without being a Catholic."

PIXABAY

Obviously, there are huge implications. Do you turn off the life-support machines?

First, does the patient suffer or is nobody home anymore? In the famous case of Terri Schiavo, we could tell the brain stem was still functioning but there wasn't anybody home. Her consciousness had disappeared 15 years earlier.

Isn't there still the old "mind-body problem?" How do three pounds of goo in the human brain, with its billions of neurons and synapses, generate our thoughts and feelings? There seems to be an unbridgeable gap between the physical world and the mental world.

No, it's just how you look at it. The philosopher Bertrand Russell had this idea that physics is really just about external relationships—between a proton and electron, between planets and stars. But consciousness is really physics from the inside. Seen from the inside, it's experience. Seen from the outside, it's what we know as physics, chemistry, and biology. So there aren't two substances. Of course, a number of mystics throughout the ages have taken this point of view.

It does look strange if you grew up like me, as a Roman Catholic, believing in a body and a soul. But it's unclear how the body and the soul should interact. After a while, you realize this entire notion of a special substance that can't be tracked by science—that I have but animals don't have, which gets inserted during the developmental process and then leaves my body—sounds like wishful thinking and just doesn't cohere with what we know about the actual world.

It sounds like you lost your religious faith as you learned about science.

I lost my religious faith as I matured. I still look fondly back upon it. I still love the religious music of Bach. I still get this feeling of awe. In a cathedral, I can get a feeling of luminosity out of the numinous. When I'm on a mountain top, when I hear a dog howling, I still wake up some mornings and say, "I'm amazed that I exist. I'm amazed there is this world." But you can get that without being a Catholic.

Does that experience of awe or the numinous feel religious?

Not in a traditional sense. I was raised to believe in God, the Trinity, and particularly the Resurrection. Unfortunately, I now know four words: "No brain, never mind." That's bad news. Once my brain dies, unless I can somehow upload it into the Cloud, I die with it. I wish it were otherwise, but I'm not going to believe something if it's opposed by all the facts.

A few years ago, you and some other scientists spent a week with the Dalai Lama. Was that a meaningful experience?

Yes, it was. There were thousands of monks in the Drepung Monastery who were listening to our exchange. This particular Tibetan Buddhist tradition is quite fascinating. I'm not a scholar of it, but they view the mind primarily from an interior perspective. They've developed very sophisticated ways of analyzing it that are different from our way. We take the external way of Western science, which is independent of the observer. But ultimately, we're trying to approach the same thing. We're trying to approach this phenomenon of conscious experience. They have no trouble with the idea of evolution and other creatures being sentient. I found that very heartening—in particular the Dalai Lama's insistence on the primacy of science. I asked him, "What happens if science is in conflict with certain tenets of Buddhist faith?" He laughed and said, "Well, if this belief doesn't accord with what science ultimately discovers about the universe, then we have to throw it out."

But the Dalai Lama believes in reincarnation.

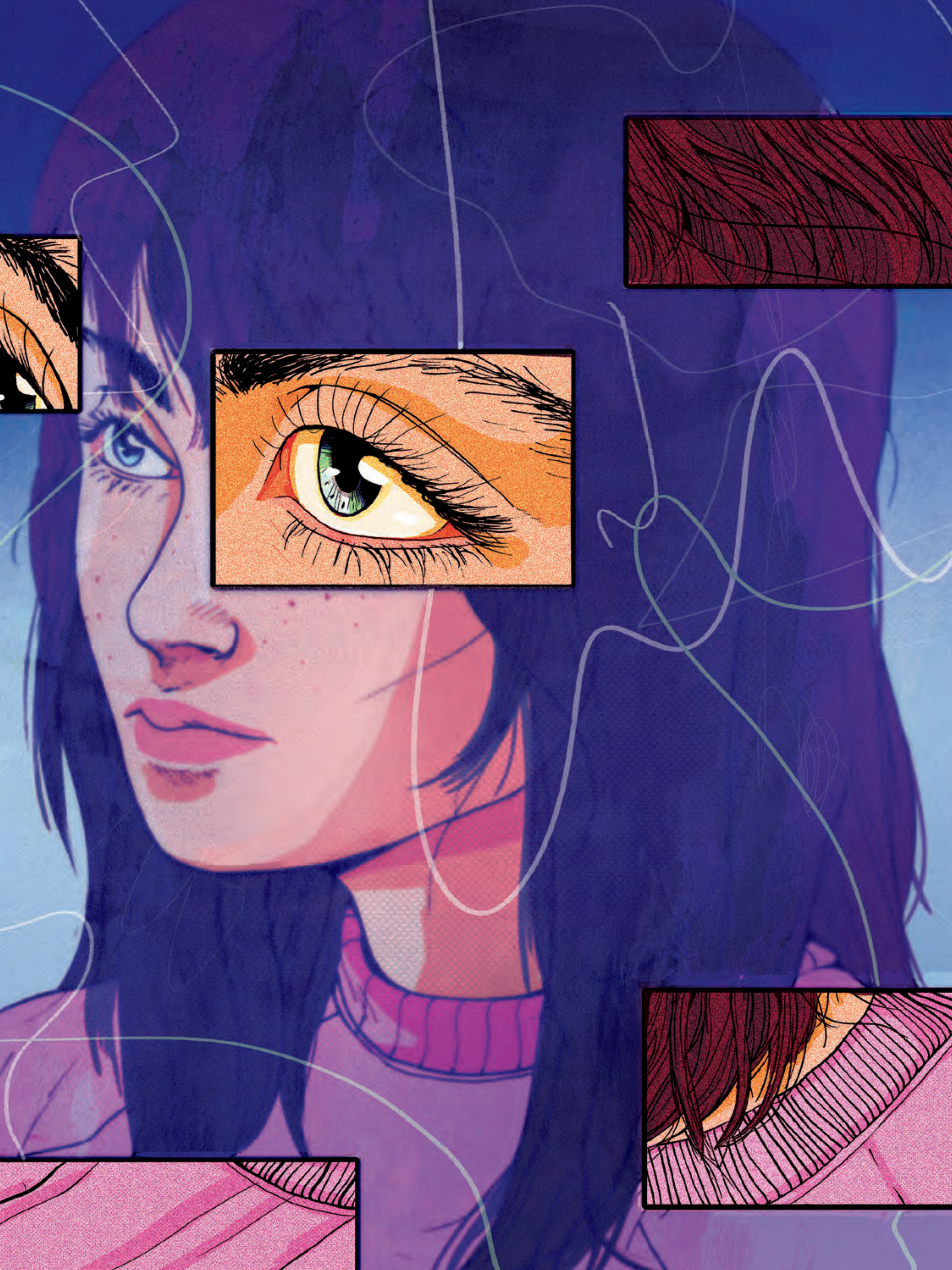
We talked about that. In fact, I said, "Well, I'm really sorry, Your Holiness, but I think we just have to agree that Western science shows that if there's no physical carrier, you're not going to get a mind. You're not going to get memory because you need some mechanism to retain the memory." I asked him, "Were you not reincarnated from the previous Dalai Lama?" And he just laughed and said, "Well, I don't remember anything about that anymore."

Has this scientific knowledge helped you sort out the deep existential questions about meaning, about why we're here?

My last book is titled *Confessions of a Romantic Reductionist*. I'm a reductionist because I do what scientists do. I take a complex phenomenon and try to pull it apart and reduce it to something at a lower level. I'm also romantic in the sense that I believe I can decipher the distant contrails of meanings. I find myself in a universe that seems to be conducive to life—the Anthropic Principle. And for reasons I don't understand, I also find myself in a universe that became conscious, ultimately reflecting upon itself. Who knows what might happen in the future if we continue to evolve without destroying ourselves? To what extent can we become conscious of the universe as a whole?

I don't know who put all of this in motion. It's certainly not the almighty God I was raised with. It's a god that resides in this mystical notion of all-nothingness. I'm not a mystic. I'm a scientist. But this is a feeling I have. I find myself in a wonderful universe with a very positive and romantic outlook on life. If only we humans could make a better job of getting along with each other.

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



What My Stroke Taught Me

The surprising, quiet nourishment of losing my internal monologue

BY LAUREN MARKS

IN MY MEMORIES of the Scottish hospital, the sky is always blue, though I know that can't be completely accurate. Summer was waning, and as my friends and I had already experienced, Edinburgh was prone to unpredictable storms. Yet, I can't think of a single moment of rain in the two weeks I lay in bed. My morphine-soaked haze only allowed glimpses and fragments: the bracing air coming in from an open window, the rough comfort of my mother's fingers wiping my fever-moist brow, my father's tears. All of that must have been confusing to me, but when I think of this time, I remember more clarity than confusion. I remember the Quiet.

This was not a Quiet I had known before. It was a placid current, a presence more than an absence. Everything I saw or touched or heard pulsed with a marvelous sense of order. I had a nothing mind, a flotsam mind. I was incredibly focused on the present, with very little awareness or interest in my past or future. My entire environment felt interconnected, like cells in a large, breathing organism. To experience this Quiet was to be it.

However, this sense of serenity was not shared by those around me. After I had collapsed in an Edinburgh bar while singing karaoke, and the medics had taken me away in an ambulance, my friends called my parents in the United States. It was the middle of the night in Edinburgh, but early evening in Los Angeles, and no one was overly worried about my fall from the stage, since it appeared I was suffering a simple concussion. That all changed two hours after my hospital admission—when the results of my CT scan showed the actual crisis unfolding. An aneurysm had ruptured in my brain and the hemorrhage was spreading. A neuroradiologist explained to my parents how precarious my situation was—how often people died the instant an aneurysm ruptured, and even after treatment, only slightly more than half of these patients actually survive the next few days. With every second being critical, the doctor was preparing for an emergency operation.

ILLUSTRATIONS BY JACKIE FERRENTINO

But my now-horrified parents were stranded in California. Their passports were in their safety deposit box, and the bank branch was closed for the night. My parents rattled on the windows of the bank the next morning, successfully convincing the bank to open early for them because there was no time to waste. My procedure was well under way when my parents boarded their flight the next morning, leaving my brother and grandmother behind at the house. The operation was already over when they got to Edinburgh. My parents and friends came together, relieved that I had survived the operation, but living with a keen awareness of how perilous my situation still was.

This was the very moment I became aware I couldn't read anymore.

It took a few days for me to wake up fully, under the influence of a combination of swollen brain tissue and heavy sedation. However, when I was more alert, the Quiet I found myself experiencing was much more interesting than my medical state. I had woken up to a new world, hushed and full of curiosities.

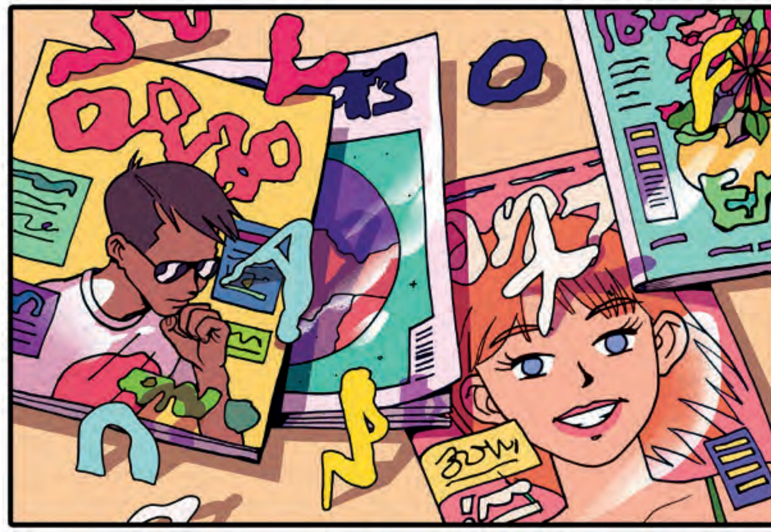
One of these moments of marvel took place during a move between the critical unit and the recovery ward. I was being transported in a mirrored elevator, and although there were no bandages on my face and my vision was clear, it was almost impossible for me to recognize my own reflection. Yet, somehow, this didn't disturb me. In fact, it made remarkable sense because I was quickly realizing that my reflection was not the only thing that was different. Transformation felt abundant. Once-fixed concepts, like "wall" and "window," weren't as easy to identify anymore, and the differences between "he" and "she" and "I" and "it" were becoming indistinguishable. I knew my parents were my parents and my friends were my friends, but I felt less like myself and more like everything around me.

I was wheeled to a bed by a westerly-facing window, with three other women in the room. My suitemates were often in discussion with one another. Even through their brogues, I understood what they were saying, but I rarely took part in the conversations. I just enjoyed the way their voices plodded and pattered like footsteps.

At this point I didn't know much about my brain injury at all. I wasn't in any pain, so my thoughts about my new condition were unfocused and fleeting. Instead of being occupied by questions about why I was in the hospital and what had happened to me, my mind was engrossed in an entirely different set of perceptions. The smallest of activities would enthrall me. Dressing myself, I was awed by the orbital distance between cloth and flesh. Brushing my teeth, I was enchanted by the stiffness of the bristles and the sponginess of my gums. I also spent an inordinate amount of time looking out the window. My view was mainly of the hospital's rooftop, with its gray and untextured panels, though I developed a lot of interest in a nearby tree. I could only make out the tops of the branches, but I'd watch this section of needles and boughs intently, fascinated by how the slightest wind would change the shape entirely. It was always and never the same tree.

Very few things disturbed me during this period of time. But even in this formless daydream I remember the moment that most closely resembled real distress. Or, at least, when I became aware of an actual loss.

It must have been midday because the sunlight was falling across my body, and that slat of light emphasized the white nightstand on my left. My parents had filled the shelves inside with clothing, and the nurses made sure there were plenty of liquids for me to drink in there, too. On this day, I noticed that there was a stack of magazines on the nightstand, as well as a book. I am not



sure how long they had been there—for all I knew, they could have even predated my arrival—but this was the first time they piqued my interest.

The high gloss of the magazine cover felt wet in my hands. And as I opened it up, I was instantly bombarded with photos of red carpet parades and illustrated makeup tips, a circus of color and distraction. I couldn't linger anywhere. It felt as if the magazine were shouting at me. Closing it was a relief.

I turned to the book. It was a novel by Agatha Christie, something I had probably read many years earlier. I opened to Chapter One and flipped slowly and evenly through the first few pages, a motion that seemed to come naturally to me. But on the third page, I stopped. I returned to the first page and started again. Slower this time. Much slower. My eyes focused and refocused in the bright sunlight, but I continued to only see the black, blocked shapes where words used to be.

Thinking about it now, I don't know how I could be so certain that it was an Agatha Christie novel, especially since this was the very moment I became aware I couldn't read anymore. With this simultaneously familiar and unfamiliar book in my hands, I first took in the actual loss of words. For my entire life, language had been at the forefront of every personal or professional achievement, and very few things had brought me as much joy and purpose. If I had ever been warned that I might be robbed of my ability to read, even for a limited amount of time, it would have been a devastation too cruel to bear. Or so I would have thought. But a day did come when I couldn't read the book in front of me, when paragraphs appeared to be nothing more than senseless jumbles, and the way I actually processed this massive loss was surprisingly mild. The knowledge of the failure was jarring, without a doubt, but was there any misery or angst? No. My reaction was much less sharp. A vague sense of disappointment swept through me, but then ... my inability to use words in this way just felt like transient information. Now that the ability was gone, I could no longer think of how or why it should have any influence on my life whatsoever.

It's shocking to reflect on that moment, and think about how the loss of something so crucial washed past me with such a vague wisp of emotion. But I was living so deeply in the present—and in the comfort of the Quiet—I couldn't fully realize how my sense of identity had shifted. It would be several weeks before I detected how much of myself had gone missing, and how hard I'd have to fight to regain it. However, the unpleasant sensations that came with holding that book drifted away as soon as I closed it. And with no effort at all, my attention settled back on the impossible blue sky.

A FEW DAYS AFTER the surgery and a battery of tests, Dr. Rustam Al-Shahi Salman, the consultant neurologist overseeing my case, made my parents aware of the short- and long-term issues at hand. Dr. Salman was slim and soft-spoken, his gestures and words thoughtful, and he was never rushed, a demeanor that fit nicely in the Quiet I now inhabited. He was also probably the first person who used the word "aphasia" with my family. However, he explained it in much more detail with my parents than with me.

He told my parents that aphasia did not attack a person's cognitive abilities and most often left a person's intelligence completely intact. But this condition could manifest quite differently in different people, and aphasia is generally divided into two categories: receptive and expressive. Expressive aphasia (also called "non-fluent" or "Broca's" aphasia) is characterized by word-finding difficulties, while receptive aphasia (also called "fluent" or "Wernicke's" aphasia) affects language comprehension. The expressive issues were most pronounced in my case, but in the beginning, I struggled with receptive issues, too, unable to detect the missing or garbled parts of my own language.

The speech and language therapist Dr. Salman appointed to me aimed to change that.

Anne Rowe was near my mother's age, with faded red curls cut close to her head. For a while, it seemed to me that her only job was to hand me worksheets. Piles and piles of worksheets. One of the first worksheets she gave me had a panel of faces. Every day I was instructed to point at the bald man in the images to tell her how I was feeling.

I feel fine, I said. Or thought I said. But Anne would insist on a more in-depth answer.

Why don't you just try to point to the picture that feels most appropriate for you? she would ask.

It didn't occur to me then that Anne was employing this image prompt not as an exercise but a necessity—because most of the time she couldn't understand my responses to her questions. While my expressive aphasia prevented me from speaking clearly, my receptive aphasia prevented me from knowing when my language was not clear. According to my parents, in the first two weeks I could only say 40 or 50 words.

THE QUIET After an aneurysm ruptured her brain, Lauren Marks lost her inner monologue.

BROOKS GIRSCH

Anne's records from our initial sessions mention that creating the sounds for speech was often challenging for me too: "Lauren is able to use fully intact phrases at times without hesitation, but has clear difficulties with word finding and motor planning for speech." This meant I had trouble shaping my mouth to make the right sounds—a condition known as speech apraxia, which often accompanies an onset of aphasia. Children go through a similar process, stuttering into speech while parents ask them to repeat and refine what they are saying until they do it correctly. Anne's worksheets had the same goal. Pointing at a drawing of a mouth, she'd say: The tip of the tongue goes here. ...

Then she would illustrate on her own face: T, T, T, Teh, is the tip of the tongue. Th, Th, Th is Thuh, the fat part of the tongue.

I wasn't disturbed when Anne asked me to take part in these articulation exercises. They didn't indicate to me that there was something especially wrong. In fact, they strongly resembled the routine vocal warm-ups I had been doing—and enjoying—since theater school. Asking an actor to demonstrate the difference between a P sound and a B sound over and over was nothing out of the ordinary. When I was instructed to do so in the hospital, I assumed I was excelling at it, flexing my muscle memory, until Anne subtly indicated my failures and misfires with her feedback throughout our sessions.

Very good, she'd say. Or: Not exactly, try again.

At some point, I realized that Anne was saying "not exactly" a lot. And if we hit too many "try agains," Anne would suggest we move on to something else for a while. It was a major hint that something was amiss. I didn't know exactly what was wrong, but I would try to fix it because I preferred positive feedback to negative.

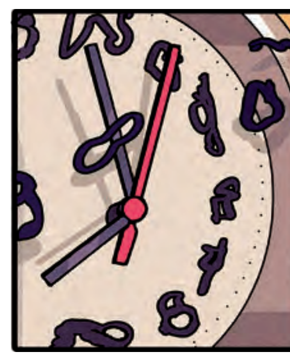
One week after the rupture, Anne administered the Western Aphasia Battery test on me. After the reading section, she made this note: "Testing was stopped as Lauren was becoming distressed. L. is very aware she could not do task." Though I have a hard time remembering this distress, I trust in Anne's reporting.

My best guess is that my anxiety was only skin-deep and short-lived. I also believe my awareness was more limited than Anne might have assumed. I probably wasn't thinking about my inability to do this task and how that might affect my limitations on future tasks. At the time, I had very little concern for the past or future; but in the present, I simply didn't like to disappoint. That, more than anything, was probably the source of my distress. Lucky for me, though, it didn't last long. In the way I perceived the world, negative impressions could pass very quickly, as if I had never even had them.

My trouble with spoken language was mirrored in my written language. I discovered as I progressed in my sessions with Anne that I had not completely forgotten the alphabet, but I had forgotten its order. If I isolated single letters at a time, I could still identify them on a page. It took a lot of guidance from Anne, but with her by my side, I could slowly sound out these letters, occasionally creating a very fragile word. Anne noted: "There are frequent errors reading aloud, especially words with irregular pronunciations, and Lauren finds it difficult to know if she is correct or not." So, while I had not lost my ability to read entirely, "reading" in this new iteration of my life involved a razor-sharp focus, accommodating only a word at a time. I also wasn't able to know my own accuracy without someone else's support. I would slowly sound out a word, but it took so long that when I went on to tackle the next one, I often would forget what I had just read. Perhaps that was what had happened with the Agatha Christie book I had attempted to read by myself. I had been expecting the language on the page to behave the way it used to, and when it didn't, the whole picture crumbled in front of me. Words could be approachable in small, isolated units. But a full sentence? That was beyond imagining.

I realize now that Anne was trying to address a systematic failure in me: my newly acquired aphasia. I just couldn't think of it like that. I could flip-flop in our exchanges and not hear the mistakes. When I did, I would assume I was simply tired or that the disturbances were all minor and temporary. And as soon as our session would end, I would gently be redelivered to the happy stillness of the pervasive Quiet.

Without language, I was paying attention to the world in a new way.



MY LIFE HAD ALWAYS been populated with big personalities, and I had created different approaches as a way to interact with each of them—as a daughter, as an older sister, as an actress, as a roommate, as a girlfriend. Before the stroke, my ability to appreciate the needs and desires of these complex characters around me came pretty easily. But after the stroke, my emotional sensitivity had dulled tremendously. It was hard to know what other people might be thinking, and I wasn't that interested in finding out. My general disinterest in interpersonal interactions was probably rooted in both emotional and anatomical aspects.

The rupture had originated on the middle cerebral artery in the left hemisphere of my brain, bleeding into the Sylvian fissures and my left basal ganglia. This cerebral artery supplies the blood for the two language centers of the brain—Broca's area and Wernicke's area. The basal ganglia are usually associated with motor control, but they also affect habits, cognition, and emotion. Some basal injuries can blunt emotional awareness and slow "goal-directed" activity. With such a wide range of influences, the alterations to the basal ganglia were probably affecting me in many ways at the time, but after the rupture, it was my faltering language that was my most visible symptom.

My aphasia had invisible effects, too, in ways that many people wouldn't even think about. It was not just my external language that was ailing. My inner monologue, my self-directed speech, had also gone almost completely mute. In its place was the radiant Quiet. The nourishing Quiet. The illuminating Quiet.

The Quiet was not something I spoke to anyone about. While my parents were on alert for signs of a secondary stroke (vasospasms are common after a rupture), I was happy enough floating in this meditative state. It felt deeply unique to me, but I later learned of other people (who also sustained damage to the left hemisphere of the brain) who have reported similar phenomena. Clinical psychologist Scott Moss describes waking up in the hospital with his own aphasia. His account is included in *Injured Brains of Medical Minds*. He writes:

> I did comprehend somewhat vaguely what was said to me. ... I didn't have any difficulty focusing: It was simply that the words, individually or in combination, didn't have meaning, and even more amazing, I was only a trifle bothered by that. ... I had also lost the ability even to engage in self-talk. ... I simply existed. ... It was as if without words I could not be concerned about tomorrow.

And Jill Bolte Taylor, a Harvard-trained neuroanatomist, who is well-known for being the author of the bestseller *My Stroke of Insight*, lost this inner monologue as well. She describes it as "brain chatter" that was "replaced by a pervasive and enticing inner peace." In addition, she writes that she "didn't think in the same way," partially because of the "dramatic silence that had taken residency" in her. Bolte Taylor specifically identifies her perceptual changes as related to a shift of attention between the two hemispheres of her brain.

In *The Master and His Emissary: The Divided Brain and the Making of the Western World*, psychiatrist and writer Iain McGilchrist goes much further into detail about the differences between these hemispheres. The brain looks like a walnut split down the middle, and its two halves are called hemispheres. Each is a fully functional processing unit, like a PC and Mac side by side in the skull. Though they usually work together to create a seemingly uniform worldview, a human being can live with only one functional hemisphere, or one hemisphere can do the heavy lifting while the other is under repair (as is often the case for a person who has suffered a stroke). McGilchrist takes issue with the pseudoscience of people calling themselves "left-brained" or "right-brained," but that being said, the hemispheres do have different strengths, or as McGilchrist describes it, their differences deal with "competing needs" and "the types of attention they are required to bring to bear on the world." This bifurcated arrangement doesn't just exist in humans, but in most vertebrates, too. In a single moment, a bird, using its left hemisphere, must identify if an item is food or sand and using its right hemisphere, simultaneously be on guard for predators. McGilchrist mentions that these are "two quite different kinds of exercise, requiring not just that attention should be divided, but that it should be two distinct types [of attention] at once."

These hemispheric differences are not so divergent in humans, only more sophisticated. Our left hemisphere is much more detail-focused, and since both language centers exist on this side of the brain, it is much more verbal. But the right hemisphere has a keen awareness, too, and it is more vigilant than the left, more receptive to new information. McGilchrist writes:

> The left hemisphere's "stickiness," its tendency to recur to what it is familiar with, tends to reinforce whatever it is already doing. There is a reflexivity to the process, as if trapped in a hall of mirrors: It only discovers more of what it already knows, and it only does more of what it already is doing. The right hemisphere by contrast [is] seeing more of the picture, and taking a broader perspective.

This description resonates intensely with me. Without language, I was paying attention to the world in a new way. Without the talents and abilities I had once relied on—and used to identify myself—I was interacting with more ineffable senses. I had escaped from my old hall of mirrors, and with my language-dominant left hemisphere somewhat disabled, I was probably taking in a whole host of perceptions from the right hemisphere that were suddenly prioritized.

I was experiencing a near-constant sensation of interconnectedness, but my observations often lacked specific categories and dimensions, and a sense of my own personal preference. My "self" didn't seem at all pertinent in this kind of processing. It was all happening to me and through me, but not necessarily because of me.

I believe this temporary shift—changing the dominance from one hemisphere to the other and losing my inner voice for a while—was a huge part of what made the Quiet so quiet. The constant stream of language, which I had always assumed was thought, had stopped. It's hard to describe this voice exactly, and even harder to describe its lack. It is the internal monologue that turns on in the morning, when we instruct ourselves to "Get up" and "Make breakfast." It's a voice we use to monitor ourselves, to criticize or to doubt—and it can be pernicious this way. However, it can be an effective tool as well. We can motivate ourselves with it, understand our environment better, and sometimes modify our situations as well. My inner speech returned very slowly, not on a certain day, but in bits and bobs. In the hospital, though, I didn't realize that I no longer had access to it, only that something in me felt substantially ... different.

However, I certainly was able to think after the aneurysm's rupture. In many ways, my thinking had never been clearer. I retained the capacity for complex thought, but it was not represented by words or phrases, and my ideas didn't cluster or activate one another the same way. It wasn't ignorance, but there was an element of innocence.

And on the whole, this silence served me very well. With my internal monologue on mute, I was mainly spared from understanding my condition early on. Unable to ask myself: What is wrong with me? I could not, and did not, list the many things that were.

I was no longer the narrator of my own life.

TEN YEARS LATER, after another major surgery and countless hours of formal and informal language therapy, I have regained much of my linguistic capacity. How much is lost forever, I'll never know. I cannot promise that I am much like the person I was five years ago, or 15 years ago, or that I will be the same person 50 seconds from now. But I know experiences like this are not limited to people who have had brain injuries. Anytime we talk about our childhood, or any other distant period of our lives, we have to accommodate multiple versions of ourselves—even though we don't sound, or speak, or even think, like these people anymore. My changes were more swift than many. But we all contain these kinds of multitudes.

We are rarely prepared for the next stages in our lives, and we lurch forward into positions we are not equipped for, without the expertise we might sorely need. With that in mind, perfection can never be the goal. But fluidity might be. And sometimes without exactly realizing it, in the process of doing what we are doing, we become the people who are capable of doing it.

Language was both my injury and the treatment of that injury, and in many ways, I have been writing my way back to fluency. I suspect I will continue to keep reaching out for language, even when it falls short. Speech, overt or covert, can be such a gift, but sometimes it is at its best when it isn't being used at all.

How beautiful a word can be. Almost as beautiful as the silence that precedes it.

LAUREN MARKS is an advocate for those who live with language disorders like aphasia. In 2011, she was an Emerging Voices Fellow for PEN Center USA. *A Stitch of Time* is her first book.

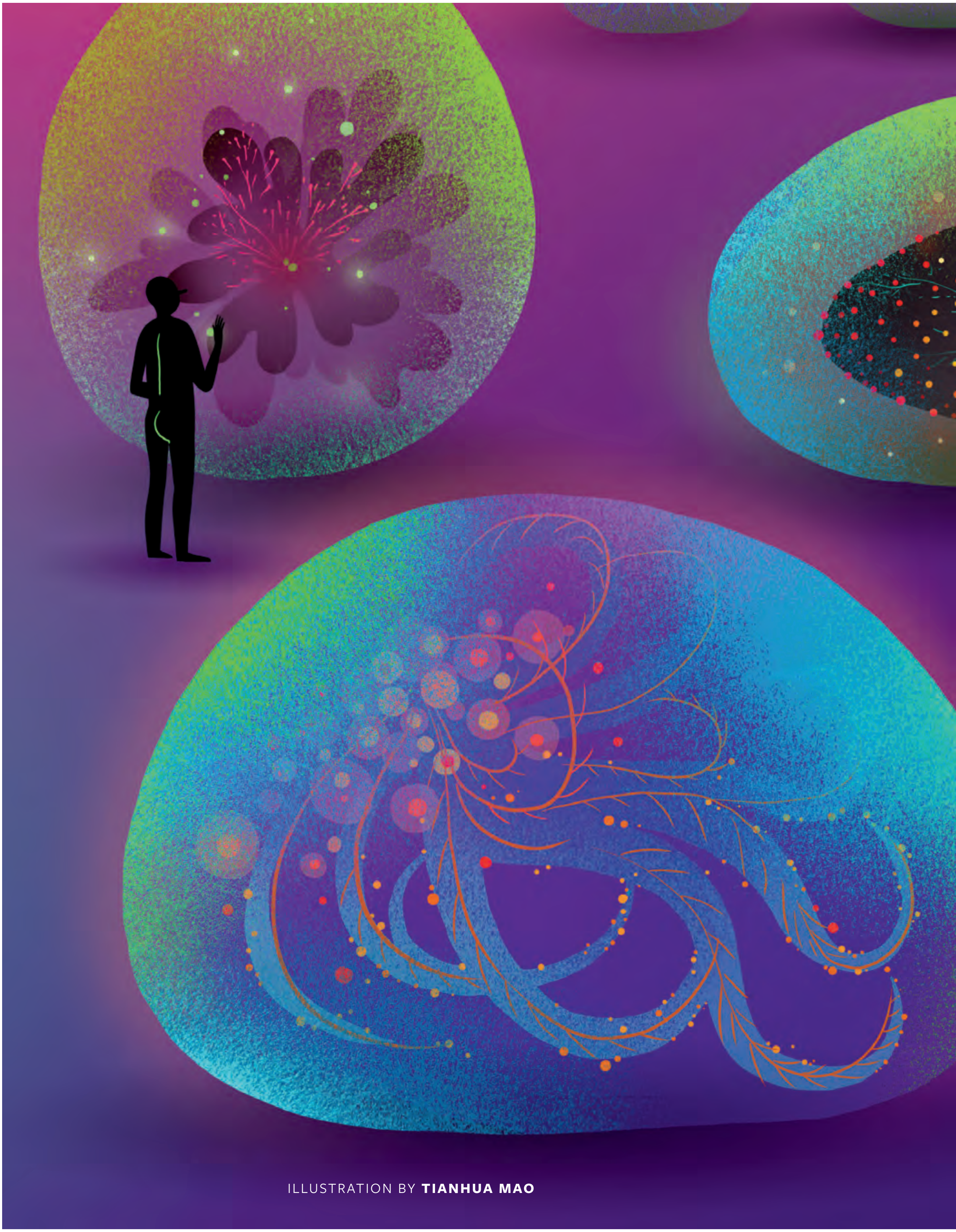
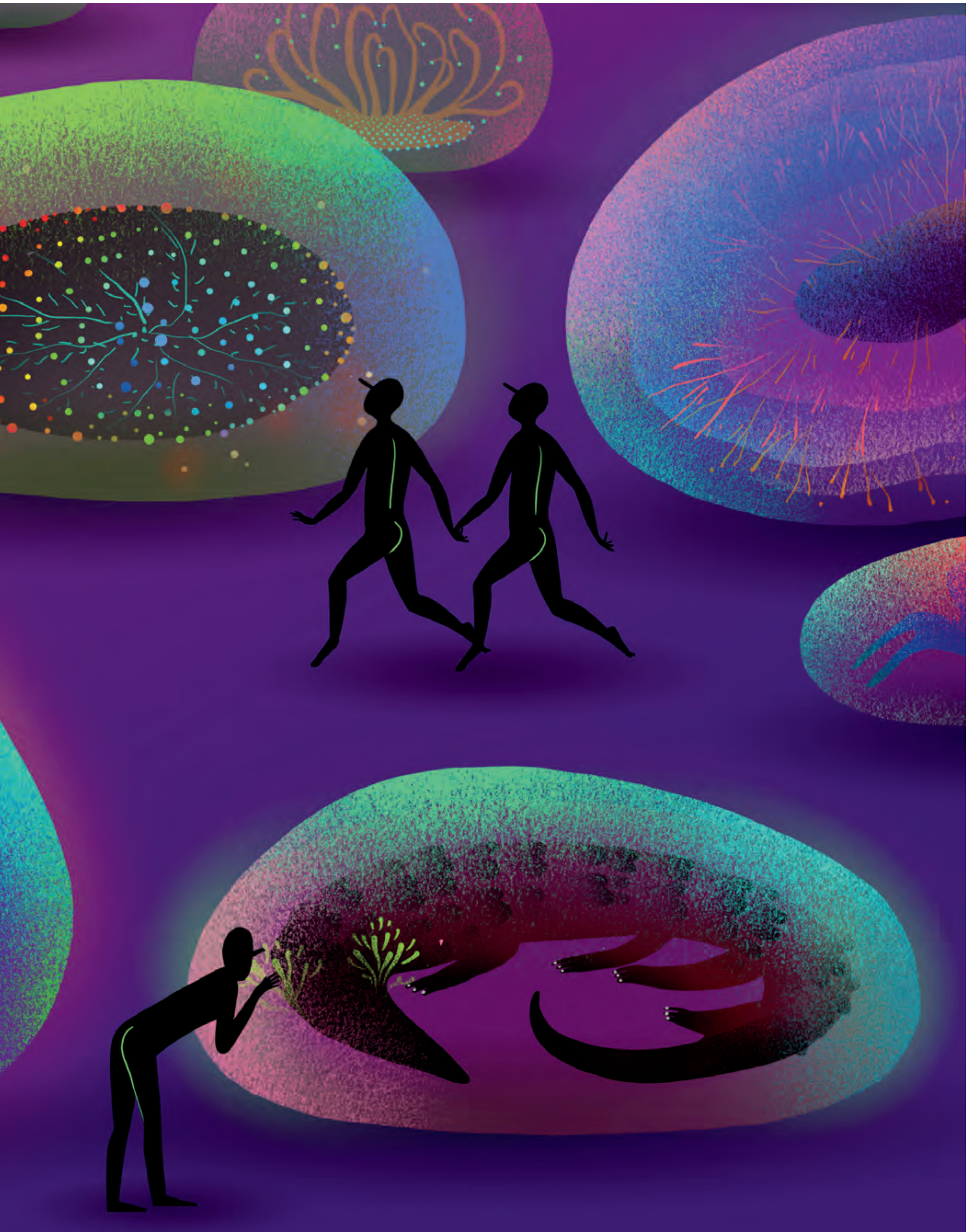


ILLUSTRATION BY **TIANHUA MAO**



Is Matter

Conscious?

Why the central problem in neuroscience is mirrored in physics

BY HEDDA HASSEL MØRCH

THE NATURE OF CONSCIOUSNESS seems to be unique among scientific puzzles. Not only do neuroscientists have no fundamental explanation for how it arises from physical states of the brain, we are not even sure whether we ever will. Astronomers wonder what dark matter is, geologists seek the origins of life, and biologists try to understand cancer—all difficult problems, of course, yet at least we have some idea of how to go about investigating them and rough conceptions of what their solutions could look like. Our first-person experience, on the other hand, lies beyond the traditional methods of science. Following the philosopher David Chalmers, we call it the hard problem of consciousness.

SSPL / GETTY IMAGES

But perhaps consciousness is not uniquely troublesome. Going back to Gottfried Leibniz and Immanuel Kant, philosophers of science have struggled with a lesser known, but equally hard, problem of matter. What is physical matter in and of itself, behind the mathematical structure described by physics? This problem, too, seems to lie beyond the traditional methods of science, because all we can observe is what matter *does*, not what it *is* in itself—the "software" of the universe but not its ultimate "hardware." On the surface, these problems seem entirely separate. But a closer look reveals that they might be deeply connected.

CONSCIOUSNESS IS a multifaceted phenomenon, but subjective experience is its most puzzling aspect. Our brains do not merely seem to gather and process information. They do not merely undergo biochemical processes. Rather, they create a vivid series of feelings and experiences, such as seeing red, feeling hungry, or being baffled about philosophy. There is something that it's like to be you, and no one else can ever know that as directly as you do.

Our own consciousness involves a complex array of sensations, emotions, desires, and thoughts. But, in principle, conscious experiences may be very simple. An animal that feels an immediate pain or an instinctive urge or desire, even without reflecting on it, would also be conscious. Our own consciousness is also usually consciousness *of* something—it involves awareness or contemplation of things in the world, abstract ideas, or the self. But someone who is dreaming an incoherent dream or hallucinating wildly would still be conscious in the sense of having some kind of subjective experience, even though they are not conscious *of* anything in particular.

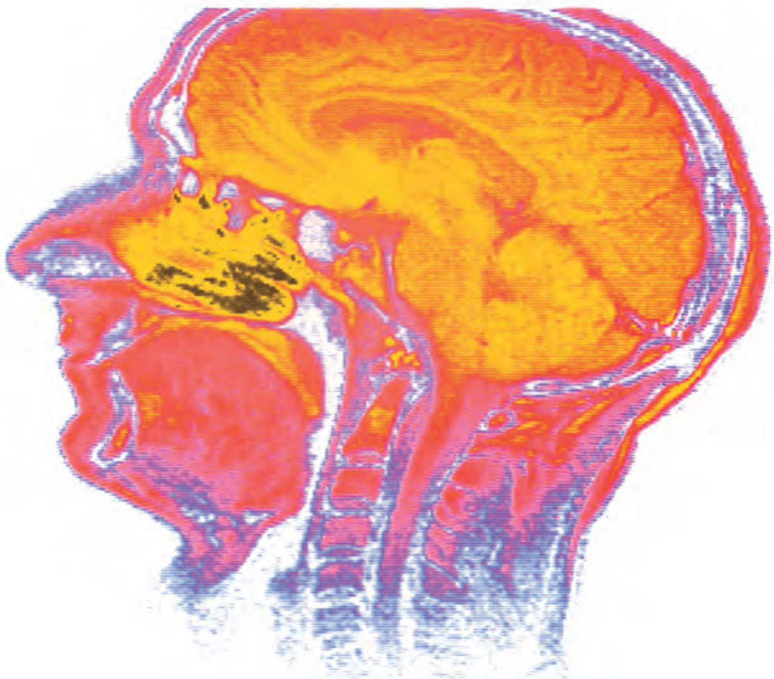
Where does consciousness—in this most general sense—come from? Modern science has given us good reason to believe that our consciousness is rooted in the physics and chemistry of the brain, as opposed to anything immaterial or transcendental. In order to get a conscious system, all we need is physical matter. Put it together in the right way, as in the brain, and consciousness will appear. But how and why can consciousness result merely from putting together nonconscious matter in certain complex ways?

This problem is distinctively hard because its solution cannot be determined by means of experiment and observation alone. Through increasingly sophisticated experiments and advanced neuroimaging technology, neuroscience is giving us better and better maps of what kinds of conscious experiences depend on what kinds of physical brain states. Neuroscience might also eventually be able to tell us what all of our conscious brain states have in common: for example, that they have high levels of integrated information (per Giulio Tononi's Integrated Information Theory), that they broadcast a message in the brain (per Bernard Baars' Global Workspace Theory), or that they generate 40-hertz oscillations (per an early proposal by Francis Crick and Christof Koch). But in all these theories, the hard problem remains. How and why does a system that integrates information, broadcasts a message, or oscillates at 40 hertz feel pain or delight? The appearance of consciousness from mere physical complexity seems equally mysterious no matter what precise form the complexity takes.

Nor would it seem to help to discover the concrete biochemical, and ultimately physical, details that underlie this complexity. No matter how precisely we could specify the mechanisms underlying, for example, the perception and recognition of tomatoes, we could still ask: Why is this process accompanied by the subjective experience of red, or any experience at all? Why couldn't we have just the physical process, but no consciousness?

Other natural phenomena, from dark matter to life, as puzzling as they may be, don't seem nearly as intractable. In principle, we can see that understanding them is fundamentally a matter of gathering more physical detail: building better telescopes and other instruments, designing better experiments, or noticing new laws and patterns in the data we already have. If we were somehow granted knowledge of every physical detail and pattern in the universe, we would not expect these problems to persist. They would dissolve in the same way the problem of heritability dissolved upon the discovery of the physical details of DNA. But the hard problem of consciousness would seem to persist even given knowledge of every imaginable kind of physical detail.

MANUEL LITRAN / PARIS MATCH VIA GETTY IMAGES



IN THIS WAY, the deep nature of consciousness appears to lie beyond scientific reach. We take it for granted, however, that physics can in principle tell us everything there is to know about the nature of physical matter. Physics tells us that matter is made of particles and fields, which have properties such as mass, charge, and spin. Physics may not yet have discovered all the fundamental properties of matter, but it is getting closer.

Yet there is reason to believe that there must be more to matter than what physics tells us. Broadly speaking, physics tells us what fundamental particles do or how they relate to other things, but nothing about how they *are* in themselves, independently of other things.

Charge, for example, is the property of repelling other particles with the same charge and attracting particles with the opposite charge. In other words, charge is a way of relating to other particles. Similarly, mass is the property of responding to applied forces and of gravitationally attracting other particles with mass, which might in turn be described as curving spacetime or interacting with the Higgs field. These are also things that particles do or ways of relating to other particles and to spacetime.

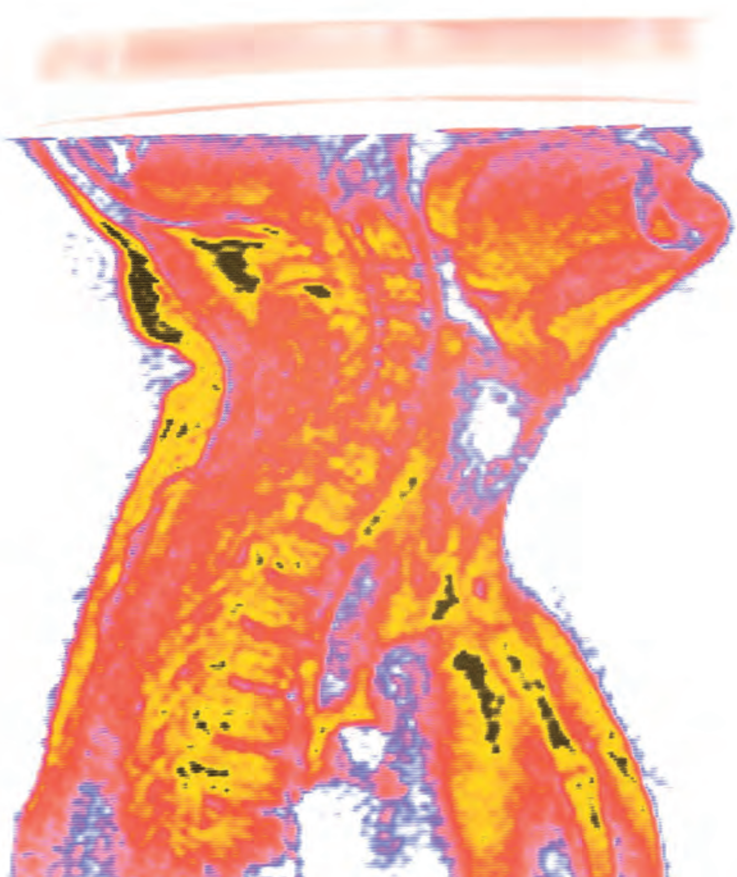
In general, it seems all fundamental physical properties can be described mathematically. Galileo, the father of modern science, famously professed that the great book of nature is written in the language of mathematics. Yet mathematics is a language with distinct limitations. It can only describe abstract structures and relations. For example, all we know about numbers is how they relate to the other numbers and other mathematical objects—that is, what they "do," the rules they follow when added, multiplied, and so on. Similarly, all we know about a geometrical object such as a node in a graph is its relations to other nodes. In the same way, a purely mathematical physics can tell us only about the relations between physical entities or the rules that govern their behavior.

One might wonder how physical particles *are*, independently of what they *do* or how they relate to other things. What are physical things like *in themselves*, or intrinsically? Some have argued that there is nothing more to particles than their relations, but intuition rebels at this claim. For there to be a relation, there must be two things being related. Otherwise, the relation is empty—a show that goes on without performers, or a castle constructed out of thin air. In other words, physical structure must be realized or implemented by some stuff or substance that is itself not purely structural. Otherwise, there would be no clear difference between physical and mere mathematical structure, or between the concrete universe and a mere abstraction. But what could this stuff that realizes or implements physical structure be, and what are the intrinsic, non-structural properties that characterize it? This problem is a close descendant of Kant's classic problem of knowledge of things-in-themselves. The philosopher Galen Strawson has called it the hard problem of matter.

It is ironic, because we usually think of physics as describing the hardware of the universe—the real, concrete stuff. But in fact physical matter (at least the aspect that physics tells us about) is more like software: a logical and mathematical structure. According to the hard problem of matter, this software needs some hardware to implement it. Physicists have brilliantly reverse-engineered the algorithms—or the source code—of the universe, but left out their concrete implementation.

The hard problem of matter is distinct from other problems of interpretation in physics. Current physics presents puzzles, such as: How can matter be both particle-like and wave-like? What is quantum wavefunction collapse? Are continuous fields or discrete individuals more fundamental? But these are all questions of how to properly conceive of the structure of reality. The hard problem of matter would arise even if we had answers to all such questions about structure. No matter what structure we are talking about, from the most bizarre and unusual to the perfectly intuitive, there will be a question of how it is non-structurally implemented.

Indeed, the problem arises even for Newtonian physics, which describes the structure of reality in a way that makes perfect intuitive sense. Roughly speaking, Newtonian physics says that matter consists of solid particles that interact either by bumping into each other or by gravitationally attracting each other. But what is the intrinsic nature of the stuff that behaves in this simple and intuitive way? What is the hardware that implements the software of Newton's equations? One might think the answer is simple: It is implemented by solid particles. But solidity is just the behavior of resisting intrusion and spatial overlap by



MANUEL LITRAN / PARIS MATCH VIA GETTY IMAGES

Conscious experiences are just the kind of things that physical structure could be the structure *of.*

other particles—that is, another mere relation to other particles and space. The hard problem of matter arises for any structural description of reality no matter how clear and intuitive at the structural level.

Like the hard problem of consciousness, the hard problem of matter cannot be solved by experiment and observation or by gathering more physical detail. This will only reveal more structure, at least as long as physics remains a discipline dedicated to capturing reality in mathematical terms.

MIGHT THE HARD PROBLEM of consciousness and the hard problem of matter be connected? There is already a tradition for connecting problems in physics with the problem of consciousness, namely in the area of quantum theories of consciousness. Such theories are sometimes disparaged as fallaciously inferring that because quantum physics and consciousness are both mysterious, together they will somehow be less so. The idea of a connection between the hard problem of consciousness and the hard problem of matter could be criticized on the same grounds. Yet a closer look reveals that these two problems are complementary in a much deeper and more determinate way. One of the first philosophers to notice the connection was Leibniz all the way back in the late 17th century, but the precise modern version of the idea is due to Bertrand Russell. Recently, contemporary philosophers including Chalmers and Strawson have rediscovered it. It goes like this.

The hard problem of matter calls for non-structural properties, and consciousness is the one phenomenon we know that might meet this need. Consciousness is full of qualitative properties, from the redness of red and the discomfort of hunger to the phenomenology of thought. Such experiences, or "qualia," may have internal structure, but there is more to them than structure. We know something about what conscious experiences are like *in and of themselves*, not just how they function and relate to other properties.

For example, think of someone who has never seen any red objects and has never been told that the color red exists. That person knows nothing about how redness relates to brain states, to physical objects such as tomatoes, or to wavelengths of light, nor how it relates to other colors (for example, that it's similar to orange but very different from green). One day, the person spontaneously hallucinates a big red patch. It seems this person will thereby learn what redness is like, even though he or she doesn't know any of its relations to other things. The knowledge he or she acquires will be non-relational knowledge of what redness is like in and of itself.

This suggests that consciousness—of some primitive and rudimentary form—is the hardware that the software described by physics runs on. The physical world can be conceived of as a structure of conscious experiences. Our own richly textured experiences implement the physical relations that make up our brains. Some simple, elementary forms of experiences implement the relations that make up fundamental particles. Take an electron, for example. What an electron does is to attract, repel, and otherwise relate to other entities in accordance with fundamental physical equations. What performs this behavior, we might think, is simply a stream of tiny electron experiences. Electrons and other particles can be thought of as mental beings with physical powers; as streams of experience in physical relations to other streams of experience.

This idea sounds strange, even mystical, but it comes out of a careful line of thought about the limitations of science. Leibniz and Russell were determined scientific rationalists—as evidenced by their own immortal contributions to physics, logic, and mathematics—but equally deeply committed to the reality and uniqueness of consciousness. They concluded that in order to give both phenomena their proper due, a radical change of thinking is required.

And a radical change it truly is. Philosophers and neuroscientists often assume that consciousness is like software, whereas the brain is like hardware. This suggestion turns this completely around. When we look at what physics tells us about the brain, we actually just find software—purely a set of relations—all the way down. And consciousness is in fact more like hardware, because of its distinctly qualitative, non-structural properties. For this reason, conscious experiences are just the kind of things that physical structure could be the structure *of*.

Given this solution to the hard problem of matter, the hard problem of consciousness all but dissolves. There is no longer any question of how consciousness arises from non-conscious matter, because all matter is intrinsically conscious. There is no longer a question of how consciousness depends on matter, because it is matter that depends on consciousness—as relations depend on relata, structure depends on realizer, or software on hardware.

One might object that this is plain anthropomorphism, an illegitimate projection of human qualities on nature. After all, why do we think that physical structure needs some intrinsic realizer? Is it not because our own brains have intrinsic, conscious properties, and we like to think of nature in familiar terms? But this objection does not hold. The idea that intrinsic properties are needed to distinguish real and concrete from mere abstract structure is entirely independent of consciousness. Moreover, the charge of anthropomorphism can be met by a countercharge of human exceptionalism. If the brain is indeed entirely material, why should it be so different from the rest of matter when it comes to intrinsic properties?

THIS VIEW, that consciousness constitutes the intrinsic aspect of physical reality, goes by many different names, but one of the most descriptive is "dual-aspect monism." Monism contrasts with dualism, the view that consciousness and matter are fundamentally different substances or kinds of stuff. Dualism is widely regarded as scientifically implausible, because science shows no evidence of any non-physical forces that influence the brain.

Monism holds that all of reality is made of the same kind of stuff. It comes in several varieties. The most common monistic view is physicalism (also known as materialism), the view that everything is made of physical stuff, which only has one aspect, the one revealed by physics. This is the predominant view among philosophers and scientists today. According to physicalism, a complete, purely physical description of reality leaves nothing out. But according to the hard problem of consciousness, any purely physical description of a conscious system such as the brain at least appears to leave something out: It could never fully capture what it is like to be that system. That is to say, it captures the objective but not the subjective aspects of consciousness: the brain function, but not our inner mental life.

Russell's dual-aspect monism tries to fill in this deficiency. It accepts that the brain is a material system that behaves in accordance with the laws of physics. But it adds another, intrinsic aspect to matter which is hidden from the extrinsic, third-person perspective of physics and which therefore cannot be captured by any purely physical description. But although this intrinsic aspect eludes our physical theories, it does not elude our inner observations. Our own consciousness constitutes the intrinsic aspect of the brain, and this is our clue to the intrinsic aspect of other physical things. To paraphrase Arthur Schopenhauer's succinct response to Kant: We can know the thing-in-itself because we are it.

Dual-aspect monism comes in moderate and radical forms. Moderate versions take the intrinsic aspect of matter to consist of so-called protoconscious or "neutral" properties: properties that are unknown to science, but also different from consciousness. The nature of such neither-mental-nor-physical properties seems quite mysterious. Like the aforementioned quantum theories of consciousness, moderate dual-aspect monism can therefore be accused of merely adding one mystery to another and expecting them to cancel out.

The most radical version of dual-aspect monism takes the intrinsic aspect of reality to consist of consciousness itself. This is decidedly not the same as subjective idealism, the view that the physical world is merely a structure within human consciousness, and that the external world is in some sense an illusion. According to dual-aspect monism, the external world exists entirely independently of human consciousness. But it would not exist independently of any kind of consciousness, because all physical things are associated with some form of consciousness of their own, as their own intrinsic realizer, or hardware.

AS A SOLUTION to the hard problem of consciousness, dual-aspect monism faces objections of its own. The most common objection is that it results in panpsychism, the view that all things are associated with some form of consciousness. To critics, it's just too implausible that fundamental particles are conscious. And indeed this idea takes some getting used to. But consider the alternatives. Dualism looks implausible on scientific grounds. Physicalism takes the objective, scientifically accessible aspect of reality to be the only reality, which arguably implies that the subjective aspect of consciousness is an illusion. Maybe so—but shouldn't we be more confident that we are conscious, in the full subjective sense, than that particles are not?

A second important objection is the so-called combination problem. How and why does the complex, unified consciousness of our brains result from putting together particles with simple consciousness? This question looks suspiciously similar to the original hard problem. I and other defenders of panpsychism have argued that the combination problem is nevertheless not as hard as the original hard problem. In some ways, it is easier to see how to get one form of conscious matter (such as a conscious brain) from another form of conscious matter (such as a set of conscious particles) than how to get conscious matter from non-conscious matter. But many find this unconvincing. Perhaps it is just a matter of time, though. The original hard problem, in one form or another, has been pondered by philosophers for centuries. The combination problem has received much less attention, which gives more hope for a yet undiscovered solution.

The possibility that consciousness is the real concrete stuff of reality, the fundamental hardware that implements the software of our physical theories, is a radical idea. It completely inverts our ordinary picture of reality in a way that can be difficult to fully grasp. But it may solve two of the hardest problems in science and philosophy at once.

HEDDA HASSEL MØRCH is a Norwegian philosopher and postdoctoral researcher hosted by the Center for Mind, Brain, and Consciousness at NYU. She works on the combination problem and other topics related to dual-aspect monism and panpsychism.

What the Rat Brain Tells Us About Yours

The evolution of animal models for neuroactive medicine

BY ALLA KATSNELSON

A **LITTLE MORE THAN** a decade ago, Mike Mendl developed a new test for gauging a laboratory rat's level of happiness. Mendl, an animal welfare researcher in the veterinary school at the University of Bristol in England, was looking for an objective way to tell whether animals in captivity were suffering. Specifically, he wanted to be able to measure whether, and how much, disruptions in lab rats' routines—being placed in an unfamiliar cage, say, or experiencing a change in the light/dark cycle of the room in which they were housed—were bumming them out.

He and his colleagues explicitly drew on an extensive literature in psychology that describes how people with mood disorders such as depression process information and make decisions: They tend to focus on and recall more negative events and to judge ambiguous things in a more negative way. You might say that they tend to see the proverbial glass as half-empty rather than half-full. "We thought that it's easier to measure cognitive things than emotional ones, so we devised a test that would give us some indication of how animals responded under ambiguity," Mendl says. "Then, we could use that as a proxy measure of the emotional state they were in."

First, they trained rats to associate one tone with something positive (food, of course) and a different tone with something negative (hearing an unpleasant noise). They also trained them to press a lever upon hearing the good tone. Then, for the test, they'd play an intermediate tone and watch how the animals responded. Rats have great hearing, and the ones whose cage life wasn't disturbed were pretty good judges of where the new tone fell between the other two sounds. If it was closer to the positive tone they'd hit the lever, and if it was closer to the negative one they'd lay off. But the ones whose routine had been tweaked over the past two weeks judged this auditory information more negatively. Essentially, their negative responses bled into the positive half of the sound continuum.

ILLUSTRATION BY FRANCESCO IZZO

Since Mendl published his so-called judgment bias task in 2004, it's been shown to work in at least 15 other species, including dogs, sheep, bees, and even us humans. Some scientists—himself included—have begun to ask whether there's a role for it beyond animal welfare. Considering that it probes one of the core clinical measures of depression, could it be used to evaluate the efficacy of much-needed new medicines for that condition?

Drug discovery in neuroscience has hit a wall, with just 1 in 10 drugs tested in the final stage of clinical trials reaching the finish line of approval. With very few exceptions, no new types of drugs for mind disorders have been approved for decades. You might think drugs fail because they're found to be toxic, but most die in clinical trials because they aren't shown to work. Trace that back to the root of the problem, and one big stumbling stone along the drug development pathway is the point where animal tests—and most are done in rodents—wrongly predicted they would.

"We have lots of experience with this—15 to 20 years of failure," says Ricardo Dolmetsch, the global head of neuroscience at the Novartis Institutes for Biomedical Research. "I can name 14 or 15 examples [of tested drugs] that were just fantastic in animals and did not do anything at all in humans."

Even as these failures have accrued, neuroscientists armed with increasingly potent tools for pinpointing the genes that play a role in psychiatric disorders and the brain circuits those genes control are getting closer to understanding the pathologies of these illnesses. As drug companies—which had largely abandoned or strongly curtailed their efforts in neuroscience and mental health over the past several years—begin to dip their toes back into the water, it seems a fitting time to ask whether modeling aspects of the human mind in rodents is even possible.

ONE WORD EXPLAINS WHY testing neuropsychiatric drugs in animal models is hard, and that word is language. If we want people to tell us how they feel, we ask them. Animals, of course, have to show us—and it turns out some of our widely used methods for guiding them to do so haven't been that great. That's particularly true for depression. How do we know a rat is depressed?

An experiment called the "forced swim test" or "Porsolt test," after its founder Roger Porsolt, has been widely used since the late 1970s, at least by pharmaceutical companies and drug regulators.

"I can name 15 examples that were just fantastic in animals and did not do anything at all in humans."

RAT FUNK For years the pharmaceutical industry depended on the "forced swim test" to validate antidepressants. It showed rats given the drug would paddle longer in water before giving up than rats not doped.

FRANK GREENAWAY / GETTY IMAGES

It's a remarkable story. Before the mid 20th century, treatments for mental or psychiatric disorders consisted primarily of psychotherapy or interventions like sleep cures, insulin shock therapy, surgeries such as lobotomy, or electrical brain stimulation—most prominently, electroconvulsive therapy. Quite suddenly, spurred by the accidental discovery of an antipsychotic drug called chlorpromazine in 1952, these conditions were re-imagined as chemical imbalances that could be corrected with a well-designed pill.

Initially, these new compounds had their first runs in institutionalized patients. Medicinal chemists had a synthesizing frenzy, riffing off compounds that had seemed effective in the hopes of adjusting potency and side effect profiles, or of further expanding the cornucopia of psychoactive drugs. Soon, companies began freely giving out early-stage compounds to academic researchers who were up for observing how animals that ingested these novel chemical entities behaved.

By the 1970s, companies were deeply invested in conducting their own behavioral testing, primarily in rodents. Anti-anxiety medicines were big sellers, and there was a handful of ways to screen for them; for example, seeing whether experimental compounds could boost a rat's interest in exploring an unfamiliar environment, or its willingness to engage in a behavior that it had been conditioned to avoid. It's hard to say whether or how closely those tasks reflected anxiety as experienced by humans. Certainly, though, such drug testing drew on the relatively new fields of ethology and behaviorism, which generally assumed that behavioral principles gleaned from laboratory animals broadly applied to people.

For depression, however, as well as for conditions like psychosis, the tests weren't very good because they relied too strongly on pharmacology. Give a rat a drug known to induce a state that seems to have features of the disorder, and then see if an experimental compound reverses the effect. The problem was, this system was inherently rigged to find drugs that worked by the same mechanisms that the inducing agents did.

At the time, Porsolt was working at Synthelabo (later acquired by Sanofi), a French pharmaceutical company. While conducting a water maze experiment, he noticed that his rats had a propensity to just stop swimming in the middle of the task. He found it curious, and it reminded him of the work of another researcher, Martin Seligman. A few years earlier, Seligman had found that dogs trapped in adverse situations from which they couldn't escape eventually stopped trying—a phenomenon he termed "learned helplessness." What Porsolt observed with his rats looked similar.

Porsolt soon designed the forced swim test, which made its debut in a two-page report in *Nature* in 1977. It's very easy to perform. Researchers place a mouse or rat in a beaker of water from which there is no exit. Invariably, after a few minutes, it stops struggling to escape and simply hangs in the water, immobile. Animals given antidepressant drugs before undergoing the procedure a second time, Porsolt reported, struggle longer before apparently succumbing to what he poetically called "behavioral despair."

Pretty much right away, academic researchers studying depression and pharmaceutical companies developing new medicines began using it in full force. "There's not a single dossier of a newly introduced antidepressant in the last 20 years where they have not used the swimming test," Porsolt says now. "It's become the standard test."

The assay gave what you'd call the correct answer for the early antidepressants available in the 1970s, on which Porsolt validated it—that is, the drugs that kept the animals afloat longer also relieved depression in people. And by most accounts it worked great in predicting efficacy for the first serotonin reuptake inhibitors, specifically Prozac (fluoxetine), which was approved in the United States in 1987.

Porsolt concedes he made a hugely anthropomorphic leap in the reasoning that he attributed to the animals' experiences. But he doesn't see it as a problem. "You know, I'm a pragmatist," he says. "There's nothing wrong with engaging in anthropomorphism, provided you put it to the test."

What convinced Porsolt his assay was the real deal is the antidepressants available then tended to make animals sluggish, but in the context of the test they had the opposite effect. "That was the first big surprise—that you give the classical antidepressants of the time—tricyclics like imipramine—at doses which otherwise are sedative, and the animals become active again," he says. Because inducing this state didn't require pre-administering drugs, like earlier tests had, he believed his behavioral assay could in theory identify antidepressant effects in any type of chemical compound.

There is little to quibble with in the initial models. Neurobiology was in a larval state and the "animal assays were really smart," says Steven E. Hyman, director of the Stanley Center for Psychiatric Research at the Broad Institute of the Massachusetts Institute of Technology and Harvard, and director of the National Institutes of Mental Health from 1996 to 2001. But when psychiatric drugs went mass-market in the 1980s, companies doubled down on the strategy of relying on simple behavioral tests, like the forced swim test, to screen new compounds.

For a while, Hyman says, the drugs improved in terms of safety and side effects. Their efficacy, however, generally didn't, and it soon became clear that behavioral tests didn't help identify new types of chemical compounds. Yet companies kept turning the same animal model crank. "They were the accepted models and they were quick and easy to do," says Mark Tricklebank, who founded and, until a few years ago, directed Eli Lilly's Centre for Cognitive Neuroscience, an industry and academic partnership to improve animal models of cognition. "Too much focus on results and deadlines tends to push people to worry only about collecting data and not its quality," he says.

Today, 30 years after Prozac arrived on the market, it's remarkable how few novel types of antidepressants have been found. (Other psychiatric conditions, like schizophrenia, have fared no better.) The fact is, the forced swim test is a poor stand-in for depression. There's just no way to conclude why rats or mice cease swimming in the bucket. "It may be that those are actually the wise rodents, because they're conserving energy once they realize they're not drowning," says Hyman. "If you give them imipramine or a drug like it and they struggle longer, why is that better?" Emma Robinson, a psychopharmacologist at the University of Bristol, agrees. The Porsolt test may have been key to the development of Prozac and second-generation antidepressants, she says, but, "to be honest, I don't think we know what the forced swim test is measuring. It's given a lot of false data."

A BIG PART OF THE DIFFICULTY in judging what such behavioral tests in animals do and don't reveal about the human mind comes down to what we might call human errors of implementation. Take another ubiquitously used behavioral test, the Morris water maze, in which researchers release a rat or mouse into a pool of

DAMIEN LOVEGROVE / SCIENCE PHOTO LIBRARY / GETTY IMAGES

Today, 30 years after Prozac, it's remarkable how few novel types of antidepressants have been found.

JONATHAN NOUROK / GETTY IMAGES

water, then time how long it takes to find a submerged platform to stand on. Normally, over several trials the animal gets quicker at putting something solid beneath its feet, revealing its use of spatial memory.

But the test has also been adopted as a stand-in for clinically relevant memory loss, like the kind experienced in Alzheimer's disease—even though there is no evidence that it is applicable there. "It's a measure of fear-based, fear-motivated escape, which is of very little relevance to the disorders for which it's regularly used," says Joseph Garner, a neuroscientist at Stanford University who studies animal models. In fact, notes Garner, although the Morris water maze is one of the most widely used tests in behavioral research, a 2007 study found that an animal's performance correlates strongly with visual acuity, suggesting it is as much a test of vision as of memory.

Behavioral tests used in pain research provide another good example. One standard measure for whether an analgesic is effective in a mouse is how quickly it withdraws its paw from a heat lamp. Reflexively withdrawing from heat, though, is very different from the debilitating pain that generally troubles people—which tends to be chronic rather than acute, and to come from within rather than from outside the body. If a drug can treat one type of pain in an animal, says Jeffrey Mogil, a pain researcher at McGill University in Montreal, that doesn't mean it will work for the other types in humans. "It's a mismatch of the symptoms in humans and the choice of symptoms in animals," Mogil says. This dissociation has beguiled the search for novel pain medicines, but he explains that we shouldn't be surprised. "We use that test because it's convenient for us, and reliable."

With all these problems, a growing cadre of researchers says that the use of animal models in psychiatry needs a major rethink because the kinds of behavioral tests the field has relied on to probe rodent minds simply don't match up to the human mind. Behaviors in rodents and humans have been shaped by very different evolutionary trajectories, notes Hyman, and assuming they are supported by the same brain circuitry simply because they appear similar to us is "in the same intellectual ballpark as [classifying] insects, birds, and bats together because they all fly."

Does that mean that it's impossible to come up with tasks that do allow researchers to compare an animal's mental state directly with a human's? Perhaps not. Over the past few decades, neuropsychiatrists have developed standardized batteries of human cognitive tasks for probing processes like attention and impulsivity, with the aim of better understanding the cluster of symptoms that come together in any given disease. Because a strong focus was placed on tasks that don't rely on language, the field was able to build on that work by "reverse-translating" them—basically, recreating them as closely as possible in animal models.

Meanwhile, advances in neuroimaging—both in humans and in rodents—mean it's possible to make sure that the same brain regions and the same circuits are engaged in the human and the animal model. "If we see the same neural circuits involved in the rat as in the human, or if some particular task or drug strengths communication between different parts of the brain, then we know we have a translatable task," says Holly Moore, a neuroscientist at Columbia University who uses animal models to study the neural basis of schizophrenia. "We just now have the imaging chops to do that."

A few years ago, a grant from Pfizer launched Robinson—the University of Bristol psychopharmacologist—on an effort to build on Mendl's rat happiness task and develop one that's more suitable for drug testing. Rather than having the animals judge the similarity between different tones, Robinson has them dig for food, a task more relevant to their lives. She trains them to associate a specific digging material—say, sawdust, or sand—with the food reward. When asked to choose between the two types of digging material later, their choice is colored by whether or not they were having a good day, by lab rat standards, when they trained in it. Her lab has already begun to explore how to compare these rats' measured mental states to those of people trained to do a human version of such a task. But Robinson admits there's a lot left to do in determining what it means to make this match-up.

For now, nobody can say for sure whether all of this activity will produce novel medicines for people who need them. In schizophrenia, there have already been some positive effects for the field, Moore says. "I see the literature moving toward a more thoughtful approach to behavioral tasks and more widely questioning assumptions underlying both the human and animal research," she says. "I do know we won't be wasting as much time as we have been."

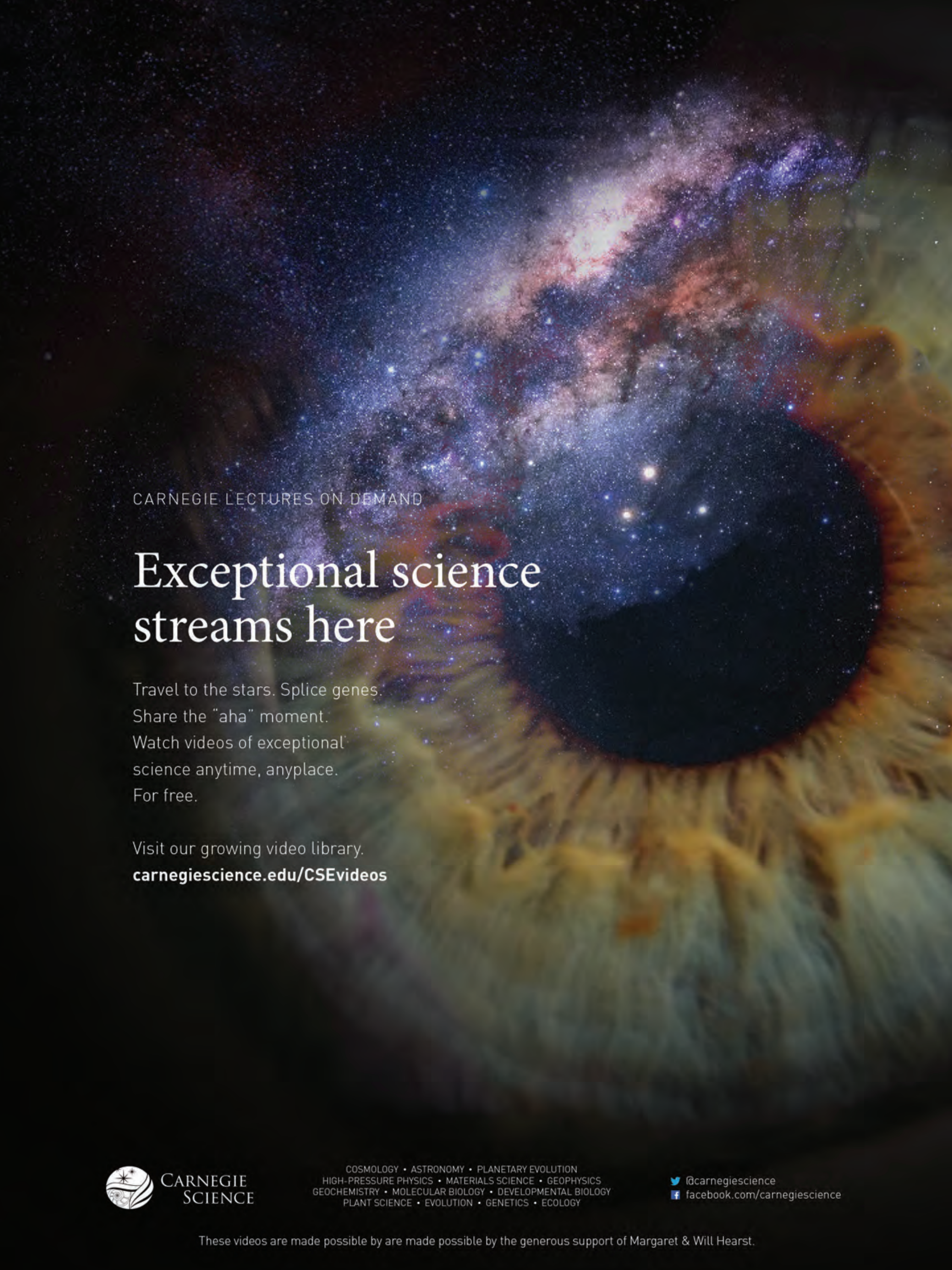
It could be the way forward is not to abandon rodent behavioral tests, but to refine them. Garner argues that for researchers who are well-versed in rat or mouse behavior, there is no *a priori* impediment to designing studies in which rodent cognitive faculties are directly compared to human ones. Many behaviors are in fact evolutionarily conserved, he says, and brain imaging or other techniques can be used to ensure that the same neural circuits are engaged across species. Even if the approach works, however, it's unclear whether drug companies will follow that route, since such tests would most likely be more complicated and time-intensive—and more expensive.

Novartis, for one, is taking a different route. The company plans to test new drugs in rodents. But rather than futz with behavioral tests that make assumptions about rodent minds and human diseases, they will use the animals just to determine that the drug hits the cells or brain regions it has been intended for. As for testing whether or not a drug treats some component of a psychiatric disorder, Novartis is going back to the future—that is, straight to humans. Dolmetsch guesses that other companies in psychiatry are doing the same. Some of the companies' leads will come through developing better versions of compounds like ketamine, serendipitously found to have psychiatric effects in humans. Others will come through dissecting neural circuits in people with rare mutations that point to some mechanism underlying brain and mind diseases.

"I think studying animal behavior is still valuable for its own sake," says Dolmetsch. "It's just not necessarily the best way of modeling psychiatric diseases."

ALLA KATSNELSON is a freelance science writer with a doctorate in neuroscience. She lives in Northampton, Massachusetts.

ILLUSTRATION BY **JACKIE FERRENTINO**


CARNEGIE LECTURES ON DEMAND
Exceptional science streams here
Travel to the stars. Splice genes. Share the "aha" moment. Watch videos of exceptional science anytime, anyplace. For free.
Visit our growing video library.
carnegiescience.edu/CSEvideos
CARNEGIE SCIENCE
COSMOLOGY • ASTRONOMY • PLANETARY EVOLUTION
HIGH-PRESSURE PHYSICS • MATERIALS SCIENCE • GEOPHYSICS
GEOCHEMISTRY • MOLECULAR BIOLOGY • DEVELOPMENTAL BIOLOGY
PLANT SCIENCE • EVOLUTION • GENETICS • ECOLOGY
@carnegiescience
facebook.com/carnegiescience
These videos are made possible by are made possible by the generous support of Margaret & Will Hearst.


Olin College
of Engineering
"At Olin I was fortunate enough to work one-on-one with so many faculty whose mentorship and teachings helped shape both my time at Olin and my career path afterwards. They inspired me to think big and follow my passions."
Brendan Quinlivan`14
PhD Candidate, Harvard University
Research Interest, Wearable Robotics
olin.edu


MPNeuro
BRAIN DISORDERS AND INJURY
COGNITION
DEVELOPMENT
INTEGRATIVE PHYSIOLOGY AND BEHAVIOR
MOTIVATION AND EMOTION
MOTOR SYSTEMS
NEURAL EXCITABILITY, SYNAPSES, AND GLIA
SENSORY SYSTEMS
TECHNIQUES

the nantucket project

{ what matters }

SEPTEMBER 14-17, 2017

NANTUCKET, MA

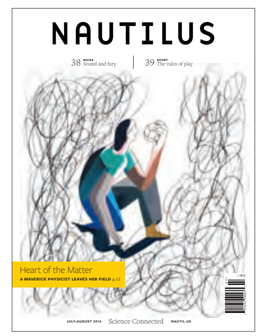
Our vision is a world where people think for themselves and can confidently ask questions, question answers, and understand the world around them.


NASA

Issue Index

Visit **subscribe.nautil.us** for single issues, subscriptions, and more.

Science Connected.



SEP/OCT 2015 | 10

JULY/AUG 2015 | 09

MAY/JUNE 2015 | 08

MAR/APR 2015 | 07

WINTER 2015 | 06

FALL 2014 | 05

SUMMER 2014 | 04

SPRING 2014 | 03

WINTER 2014 | 02

FALL 2013 | 01

SUBSCRIPTIONS
Nautilus (ISSN 2372-1758) is published bimonthly: Jan/Feb, March/April, May/June, July/Aug, Sept/Oct, Nov/Dec. Subscription and address changes should be addressed to *Nautilus*, 233 Broadway, Suite 720, New York, NY 10279; phone: 212-221-3870; email: cs@store.nautil.us

Visit subscribe.nautil.us for more information.

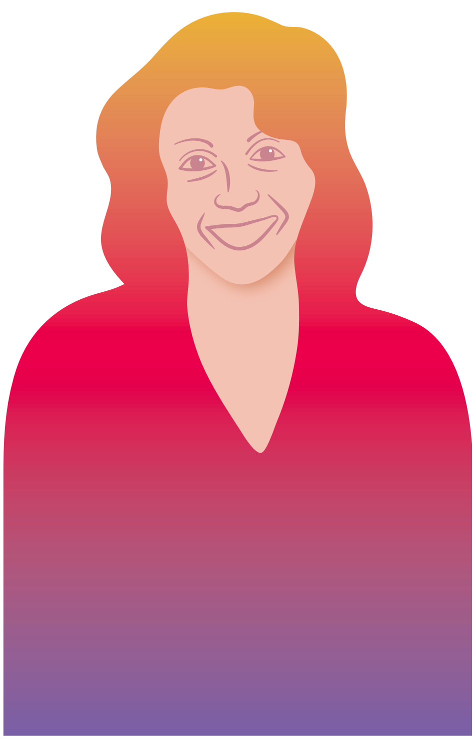
POSTMASTER
Send address changes to:
Nautilus
233 Broadway, Suite 720
New York, NY 10279

Lisa Feldman Barrett

The psychologist, neuroscientist, and author of How Emotions Are Made *reflects on the themes in* Nautilus

INTERVIEW BY KEVIN BERGER

BALANCE Your brain is like the financial sector of a company. Companies have many bank accounts. They move funds around to remain solvent and not go bankrupt. That's what your brain is doing. It constantly has to keep your body systems in balance. It's doing that as it's creating thoughts, feelings, and perceptions. You could argue it's creating thoughts, feelings, and perceptions in service of keeping your body in balance. The strongest feelings come when the brain's budget is out of balance—when you are overspent or faced with a big influx of resources. And when you feel strongly you're more likely to act. A bout of anger, for instance, is like a bout of exercise. Your brain is preparing you to do something and you'll go and you'll do it. It will cost you something, but presumably the revenues you get back will be worth your investment.



CONSCIOUSNESS Ancient philosophers bequeathed to us the idea the brain is divided into parts, one for each mental ability. They were concerned with morality, beauty, and truth. And many of our psychological faculties—thinking, feeling, perceiving—are linked to those concerns. But when scientists went searching for those categories, they realized there are no separate brain parts for thinking, feeling, or seeing. The brain is not as a collection of Lego blocks that fit together, but one big network of neurons bathed in a chemical system that influences the ease with which information is passed back and forth between neurons. Understanding the brain is a single structure with trillions of patterns is a good basis for addressing the hard problem—how this interaction of neurons produces consciousness—in a fresh way.

Your brain is like the financial sector of a company.

ILLUSTRATION BY FRANCESCO IZZO


Science Behind the Scene
VISIT SUBSCRIBE.NAUTIL.US