# NAUTILUS

**A NEW MOON THEORY**
Not a chip off the old Earth

**WHAT TREES TALK ABOUT**
Fiction by Richard Powers

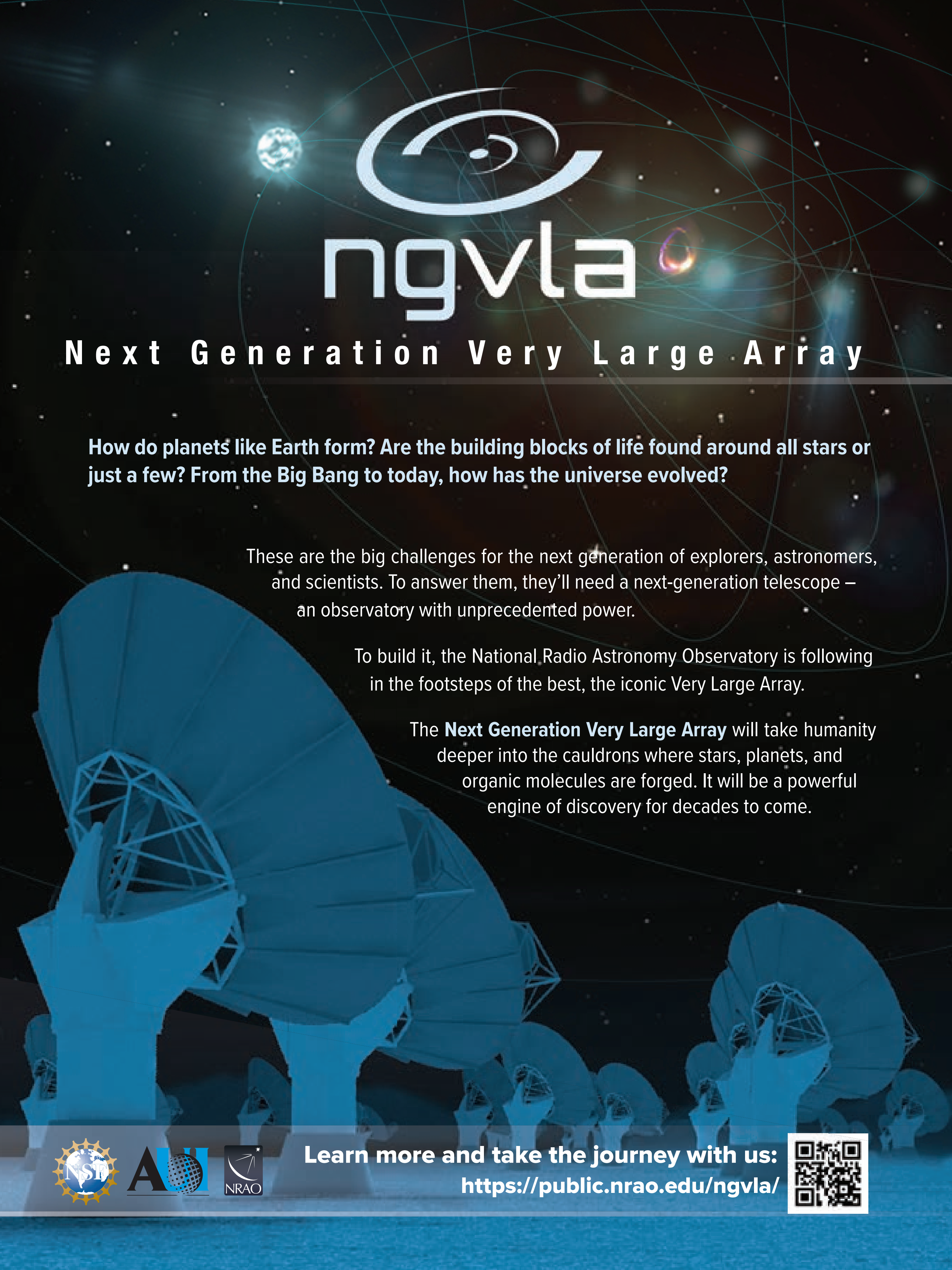
**HERBICIDES FOR DINNER**
What's hiding in our food

## 5 Cool Places to Live on a Hot Planet

**NO FLOODS, FAMINE, OR WAR. AND NICE PEOPLE** p.22

US$12

ISSUE 25 Science Connected NAUTIL.US


ngvla
Next Generation Very Large Array
How do planets like Earth form? Are the building blocks of life found around all stars or just a few? From the Big Bang to today, how has the universe evolved?
These are the big challenges for the next generation of explorers, astronomers, and scientists. To answer them, they'll need a next-generation telescope – an observatory with unprecedented power.
To build it, the National Radio Astronomy Observatory is following in the footsteps of the best, the iconic Very Large Array.
The Next Generation Very Large Array will take humanity deeper into the cauldrons where stars, planets, and organic molecules are forged. It will be a powerful engine of discovery for decades to come.
NSF
AUI
NRAO
Learn more and take the journey with us:
https://public.nrao.edu/ngvla/

ISSUE 25

# Contents



**COVER** Angela Hsieh

# Themes

Each print edition explores different themes in science from multiple perspectives. In this edition, you'll find stories from the April through December 2018 *Nautilus* online issues.

## Connections

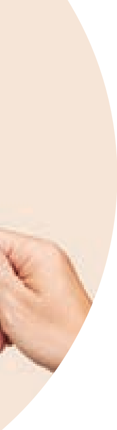


## Searches



## Coordinates





## Systems



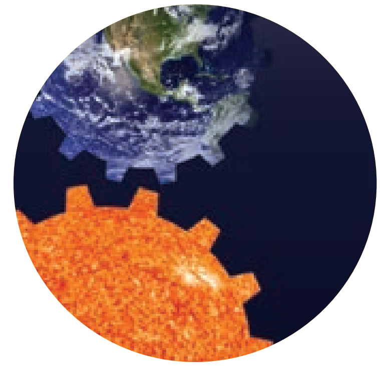
## The Unseen



## Horizons





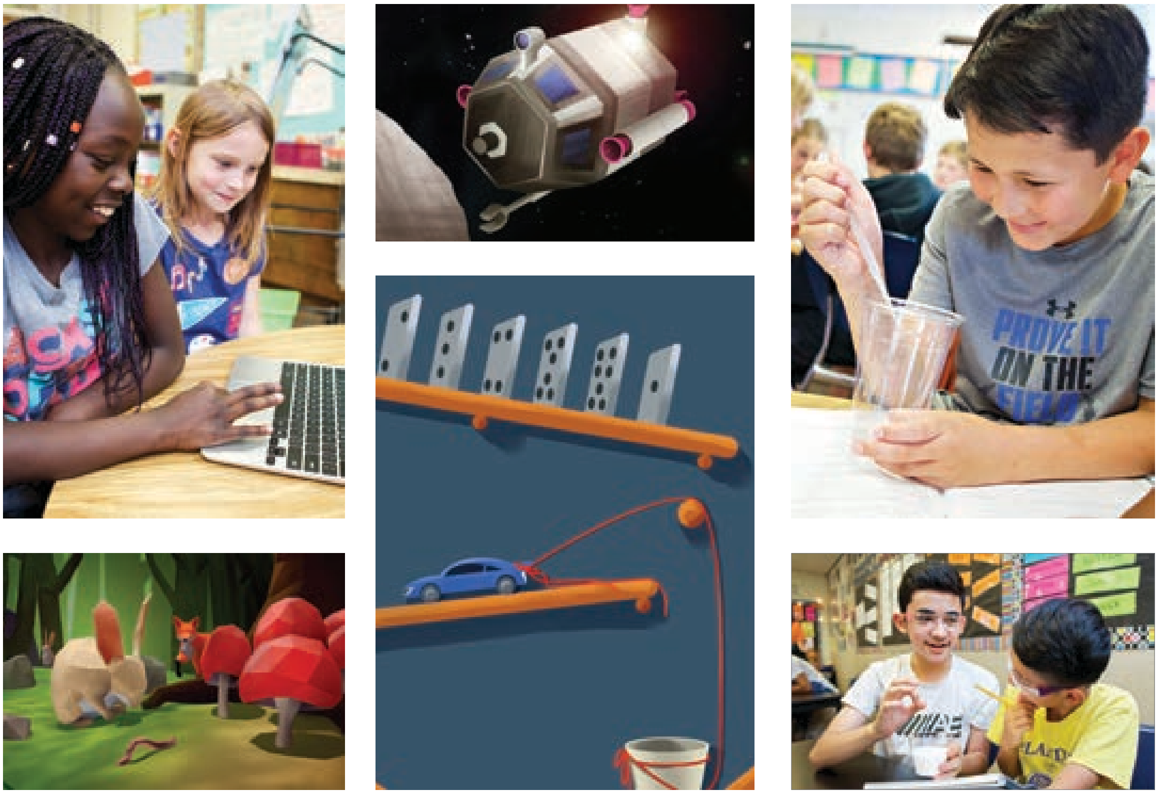
## In Plain Sight



## Clockwork



## Reboot


PROVE IT
ON THE

NAUTILUS



Published by:

NAUTILUS *think*

*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

# The Stars in Us

BY KEVIN BERGER

**IN THE 1970S,** Caleb Scharf was a boy in a rural England town. Most every night he'd wander outside his house and look up at the night sky. Under the canopy of stars, he felt terrified. "The sense of immersion was so vast and enormous that I felt absolutely microscopic, as if I was nothing," Scharf said.

Then his parents, both art historians, bought him a telescope. When he looked through it the first time, he was amazed. He could see the light of a single star up close, see the shadow of a mountain on the moon. "There was a tension in me between being nothing amid all of this and suddenly feeling it was all quite personal," Scharf said. He had felt lost in the universe, now he felt connected to it. "That encouraged me to become an astronomer."

Scharf is now director of astrobiology at Columbia University, and author of popular science books, including *The Copernicus Complex: Our Cosmic Significance in a Universe of Planets and Probabilities*. He is also a regular contributor to *Nautilus*.

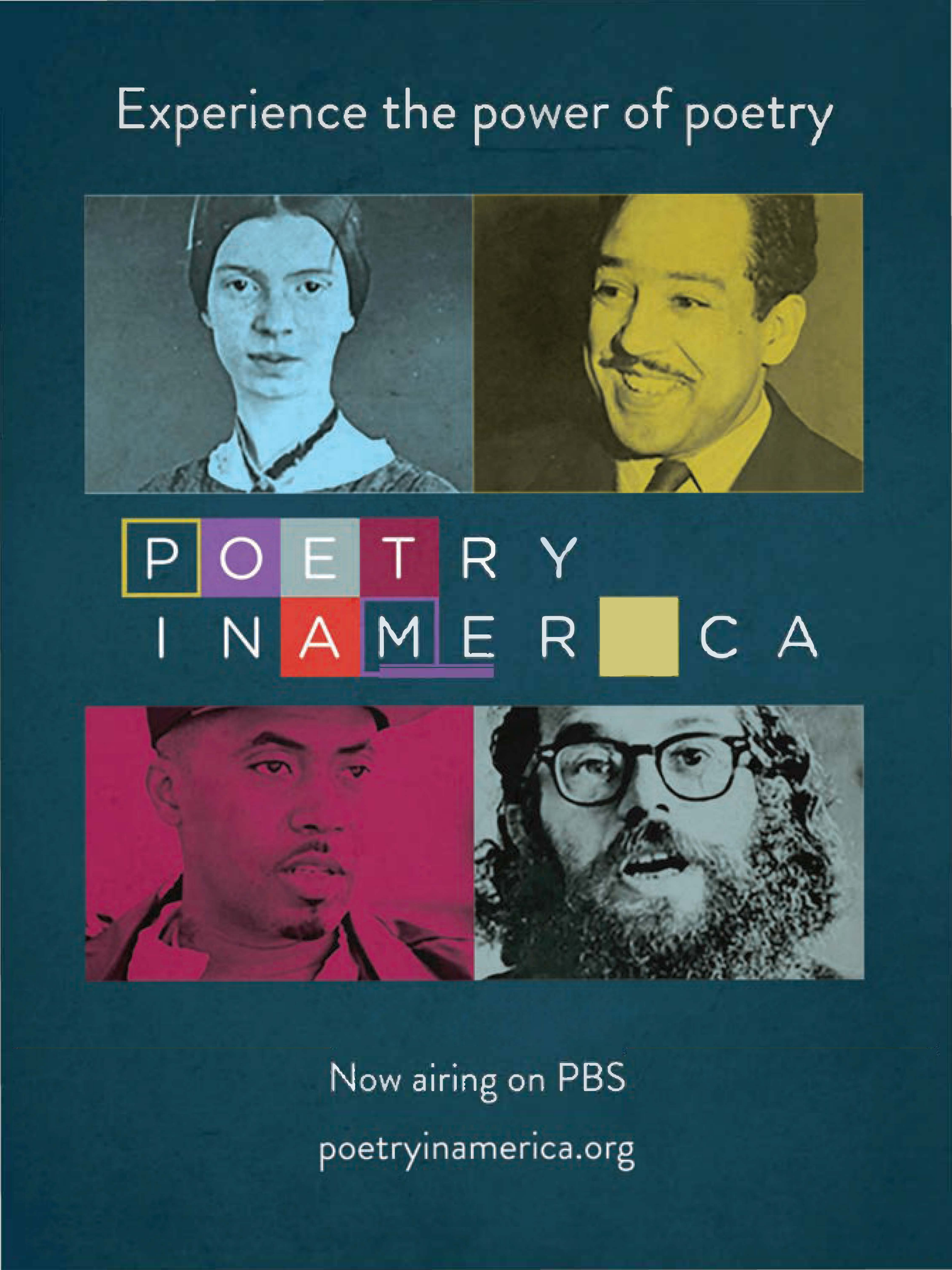
Scharf's boyhood experience is a powerful reminder of why science matters so much to us today. We know, of course, how much science means in daily life. Science gave us the medicines that cure us, the cars that carry us, the energy plants that sustain us, and the computers on which we spend way too much time. Innovation in technology charges the engine of the economy. A recent Stanford University report showed a jump in innovation can mean up to a 6 percent boost in the economy.

What we may not consider as often as we should is science can stir our deepest feelings. Hope Jahren, a geobiologist, whose memoir, *Lab Girl*, has won readers worldwide, once told us the true purpose of science is "not to build bridges or make new medicines that combat a lack of erection. It's to feed the soul in the same way that art does. The more you know about the world, the more you feel like you're part of it." And the more you feel part of the world, the more you feel a personal stake in it.

Taking you into the labs and fields of science and magnifying their consequences is our mission. Today that mission couldn't be more important. And we couldn't be more inspired. In this print issue of *Nautilus*, a selection of our articles, essays, and interviews from 2018, you'll enter the worlds of neuroscience and math, medicine and music. And be treated to a short story about what trees are saying to each other by 2019 Pulitzer Prize winner Richard Powers.

We're inspired for another reason. An investor group of *Nautilus* super fans has banded together to take us to the next level in our journalistic adventure. Following this issue, we'll be back on a regular print schedule.

After you read this issue, I have a suggestion, inspired by Caleb Scharf. Late at night, away from city lights, go outside and look up at the stars.

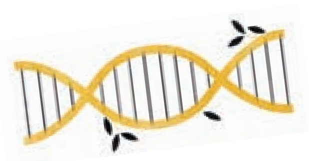

Experience the power of poetry
POETRY
IN AMERICA
Now airing on PBS
poetryinamerica.org

# Letters

*Reader responses to print issue 24.*

### "THE STICK IS AN UNSUNG HERO OF HUMAN EVOLUTION"

Wonderful essay illuminating the fascination of archeology (my former profession). The amazing things we can learn about our earliest forebearers are just a tantalizing hint of what is lost to us.
*—R.S.C.*



So our ancestors "Evolved" because a man can play Snooker, and that's the evidence? I just read another article from Australia that birds are purposely using sticks of fire to set ablaze patches of grass in order to force small game out so they can eat in a frenzy. They claim people have witnessed that for 40,000 years. I don't see that birds have evolved to play Snooker.
*—Karamoore*

### "ANTONIO DAMASIO TELLS US WHY PAIN IS NECESSARY"

I always thought Damasio's work was brilliant and pretty inspired. I find it puzzling that so much attention would be placed on the brain. The embodied brain view, is awesome in that it accounts for that simple observation—what's a brain when it's not situated in sensory system (at the very least) or a body?

Personally, I'm not so sure that the mind doesn't extend beyond the body. In fact, I think we often confuse the two: mind and sensory outputs … and that's been very problematic in philosophy leading to a lot of the confusion.
*—Adam InTae Gerard*

### "WAITING FOR THE ROBOT REMBRANDT"

Interesting, but probably naive, speculations. Learning goals not specifically programmed into an AI probably does not get you very far toward self-consciousness—which I would think is a prerequisite to what I would define as "Art." Nature at all levels has built some pretty impressive structures (consider coral reefs, beehives, or even spiral galaxies) that I consider beautiful, but they are not self-conscious artistic expression.
*—George Gantz*

### "IT'S TIME TO MAKE HUMAN-CHIMP HYBRIDS"

We don't even treat other humans as human, this would simply lead to a new form of slavery. Not a good idea. Just because we can do something doesn't mean we should.
*—Len Reinhart*


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

**CONTACT**
25 Broadway, 9th Floor
New York, NY 10004
212 221 3870
info@nautil.us

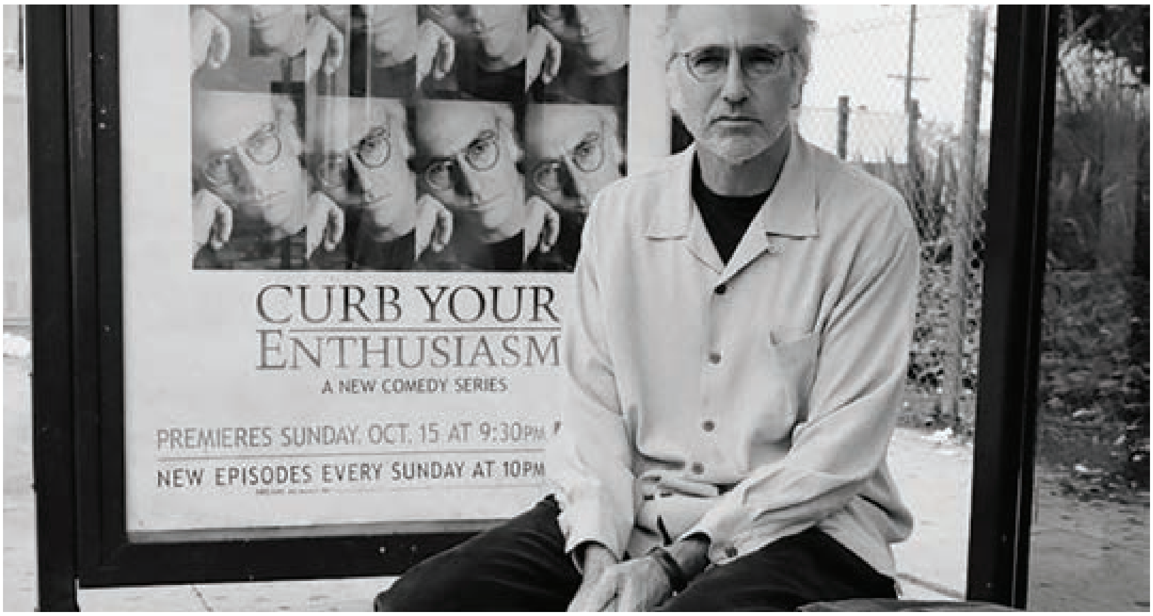
**SUBSCRIPTIONS**
Visit subscribe.nautil.us


SANTA FE INSTITUTE
www.santafe.edu

*Searching for order in the complexity of evolving worlds*

Image: *Cutaway view of a Stanford torus, a NASA design for a space habitat capable of housing 10,000 to 140,000 residents, proposed in 1975.*

# Preludes




DAVID HUME KENNERLY / GETTY IMAGES

SOCIOLOGY

## The Game Theory of Anonymous Donations

**In an episode of** *Curb Your Enthusiasm*, Larry David and his wife Cheryl attend a ceremony to celebrate a public donation he'd made. Little does he know that Ted Danson, his arch-frenemy, also donated money, but anonymously. David feels upstaged, as if his public donation has been transformed from a generous gesture to an egotistical one. He fumes, "You can't have it halfway! You're either anonymous, or you're not."

I thought of this scene after reading a recent study in *Nature Human Behavior*. "People sometimes make their admirable deeds and accomplishments hard to spot, such as by giving anonymously or avoiding bragging," write authors Moshe Hoffman, Christian Hilbe, and Martin A. Nowak, evolutionary biologists from Harvard University and the Institute of Science and Technology Austria. But if "we give to gain reputational benefits, why would we ever wish to hide the fact that we gave?"

**Donation evolved because it granted a good reputation.**

"Donations are never fully anonymous," the authors write. "These donations are often revealed to the recipient, the inner circle of friends, or fellow do-gooders." What's intriguing about anonymous giving is that it's "hard to reconcile with standard evolutionary accounts of pro-social behavior." Donations fall under a form of cooperation called "indirect reciprocity." In other words, donation evolved because it granted a good reputation, which helped humans to secure mates and cement alliances. But if that's true, how did anonymous giving arise? The new paper's title suggests a solution: "The signal-burying game can explain why we obscure positive traits and good deeds."

In the signal-burying game, a sender and a receiver pair up randomly and are rewarded for the kind of match that is made. There are three types of senders (or donors)—low, medium, and high—and two types of receivers—weakly selecting and strongly selecting. A strong receiver corresponds to one of the donor's close friends or a fellow altruist, and a weak receiver to a member of the general public. The best payoff results from a strong receiver partnering with a high sender, while the worst payoff results from a weak receiver partnering with a high sender.

The players know their own type, but not each other's. So the sender aims for an optimum pairing by choosing the kind of signal to send, and the receiver chooses whether to partner with the sender based on the signal. The sender can choose to reveal their type by the costliness of their signal (the donation amount) and how it's sent (buried or clear, anonymous or public), or whether they send one at all. Clear signals are always spotted by both strong and weak receivers. Buried signals are more likely to be revealed by receivers, and tagged as buried, if they're sent by a high sender. The endgame is for the players to partner up for "some economic interaction." Senders always want to partner up, since the payoff is always positive, but "strong receivers get a positive payoff only from interacting with high senders, and weak receivers get a positive payoff only from interacting with high or medium senders."

The paper shows the conditions under which signal-burying can be maintained. "First, high senders need to prefer sending a buried signal to a clear signal," the authors write. "In equilibrium, burying allows high senders to gain access to some strong receivers (who would have rejected the clear signal but accept buried signals when they are revealed). However, burying also causes high senders to lose some weak receivers (who would have accepted the clear signal, but now may fail to notice the buried signal)." Second, medium senders need to prefer signalling clearly over burying. Third, medium and high senders need to be willing to pay the signalling cost.

To David, Danson's anonymity seems calculated. Perhaps it'd be cynical to assume that anonymous donors are all as covertly egotistical as Danson seems. Last year, 17 donations in the United States of more than $10 million were given anonymously. But these signal buriers aren't necessarily being shrewd about their reputation, the authors write. Self-effacing strategies are not necessarily consciously chosen, and can become natural and stable in a population if they prove adaptive, "as is arguably the case for our ideologies, tastes and emotions, including our artistic sense or moral intuitions related to anonymous giving."

*—Brian Gallagher*

EVOLUTION

# Why Social Science Needs Evolutionary Theory

**MY HIGH SCHOOL BIOLOGY TEACHER**, Mr. Whittington, put a framed picture of a primate ancestor in the front of his classroom—a place of reverence. In a deeply religious and conservative community in rural America, this was a radical act. Evolution, among the most well-supported scientific theories in human history, was then, and still is, deliberately censored from biological science education. Whittington saw me looking at the primate in wonder one day and said, "Cristine, look at its hands. Now look at your hands. This is what common descent looks like."

DAVID CARILLET / SHUTTERSTOCK

Human cognition and behavior is the product of the interaction of genetic and cultural evolution. This co-evolution has allowed us to adapt to diverse ecologies and produce cultural adaptations and innovations. It has also produced extraordinary cultural diversity. In fact, humans display a wider repertoire of behaviors within and across groups than any other animal. Social learning enables cultural transmission, so the psychological mechanisms supporting it should be universal. These psychological mechanisms must also be highly responsive to diverse developmental contexts and cultural ecologies.

Take the conformity bias. It is a universal proclivity of all human psychology—even very young children imitate the behavior of others and conform to group norms. Yet beliefs about conformity vary substantially between populations. Psychological adaptations for social learning, such as conformity bias, develop in complex and diverse cultural ecologies that work in tandem to shape the human mind and generate cultural variation.

Truly satisfying explanations of human behavior require identifying the components of human cognition that evolution designed to be sensitive to social or ecological conditions and information. For example, populations in which food resources show high variance (hunting is very hit or miss) tend to evoke cooperative adaptations for group-wide sharing compared to those in which food variance is lower and more dependent on individual effort, like gathered foods. Recent discoveries in cultural evolution have shown that our technological complexity is the outcome of our species' capacity for cumulative culture. It has set our genus *Homo* on an evolutionary pathway remarkably distinct from any other species. In a paper, I proposed that this was a result of psychological adaptations being universal but sufficiently flexible for innovations to build on each other, supporting the acquisition of highly variable behavioral repertoires.

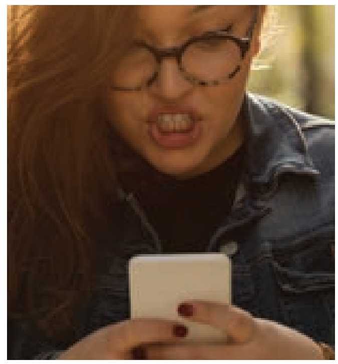
Applying evolutionary theory to social science has the potential to transform education and, through it, society. Evolutionary perspectives can help social scientists understand, and eventually address, common social problems, like schoolyard bullying, for example. Without an evolutionary understanding, interventions are likely to be ineffective, since they misdiagnose the causes. Bullying is not merely negative interpersonal behavior; it's goal-oriented and serves the function of gaining status and prestige for the bully, which must be understood to combat it. Bullying often occurs in front of an audience, suggesting that social attention drives, and may reinforce, the behavior. A 2015 paper suggests most interventions don't work because they remove the rewards of bullying—increased social status—without offering any alternatives. A deep understanding of the evolved functions of bullying provides a fulcrum for potential remedies.

If "nothing in biology makes sense except in the light of evolution," as evolutionary biologist Theodosius Dobzhansky argued in 1973, then nothing in human psychology, behavior, and culture does either. Social scientific research should reflect this fact.

*—Cristine H. Legare*

**SOCIOLOGY**

# How Social Media Exploits Our Moral Emotions



KITJA KITJA / SHUTTERSTOCK

A FEW YEARS AGO, Justine Sacco, then the senior director of corporate communications at the holding company InterActiveCorp, tweeted about the nuisances of air travel during a long, multi-leg journey from New York to South Africa. She started with sardonic observations—one about a smelly passenger at JFK Airport, another about London's peculiar food and predictably inclement weather. Then came this one, shortly before her final flight: "Going to Africa. Hope I don't get AIDS. Just kidding. I'm white!"

**We spend much of our online lives inside echo chambers.**

As she settled in to sleep, she had good reason to expect that that tweet would fade away into the hectic ether of Twitter. She had only 170 followers, after all. But no. While her phone was off, Sacco became the number one worldwide trending topic on Twitter, as tens of thousands of users across the globe filled her feed with their outrage. When she landed in Cape Town, she found herself receiving the full brunt of the online community's capacity for public shaming. Her public persona destroyed, Sacco was fired from her job and saw much of her social circle—both online and offline—wither away. "I thought there was no way that anyone could possibly think it was literal," she later told author Jon Ronson for his book, *So You've Been Publicly Shamed*.

This wasn't the first time caprice was punished with viral outrage. Sacco's tweet is just one of countless examples of provocative online behavior drawing a seemingly disproportionate social punishment. Why does this keep happening? Because the architecture of social media exploits our sense of right and wrong, reaping profit from the pleasure we feel in expressing righteous outrage. The algorithms that undergird the flow of information on social media are designed to maximize ad revenue by engaging consumers' attention to the fullest extent possible.

Columbia Law professor Tim Wu, author of *The Attention Merchants*, calls this "attention harvesting." And as a business model, it's extremely lucrative. Many are aware on some level that those persistent, weirdly personal ads on our devices have a lot to do with how Twitter, Facebook, and Google make money. What some may not be aware of, though, is exactly how those platforms manage to hold our attention well enough to make their ads so profitable.

Scientists have been at this question for several years, studying people's activity online and revealing trends as to what makes content eye-catching and more likely to go viral. Billy Brady from New York University analyzed hundreds of thousands of tweets in an effort to understand the role of moral emotions in social networks. Brady and his colleagues found that tweets about political topics were much more likely to go viral if they contained words that are both morally and emotionally charged, like "evil," "shame," "fight," "punish," and "faith." What's more, Brady's analysis revealed that viral political tweets propagated almost exclusively among people with similar ideological leanings, consistent with evidence that we spend much of our online lives inside echo chambers.

This constant flurry of moral-emotional content has turned much of Twitter—and, by the looks of it, other platforms—into what writer Samuel Ashworth described as "an endlessly self-renewing bonfire of outrage and confusion." And given how profitable it has become, social media companies have little financial incentive to scale it back. "I think it's really important to ask ourselves and to have a serious conversation about how we feel about our moral emotions being used to make a lot of money for tech companies," Molly Crockett, a psychology professor at Yale, said on the podcast Very Bad Wizards.

In a 2017 article in *Nature Human Behavior*, Crockett argued that the constant triggering of moral outrage—an ancient emotion that motivates the shaming and punishing of others—on social media not only makes money for tech companies, but also alters how we experience and express the emotion. Provocative content is ubiquitous, the tools to react to it have never been more accessible, and outrage expression is often positively reinforced by likes, retweets, and shares. All of this together, Crockett wrote, may cause people to undergo "outrage fatigue," whereby the intensity of the outrage they feel gradually fades. Or, in light of research showing that venting anger can stoke more anger, it may do the opposite, amplifying successive expressions of outrage. What's more, Crockett suggested that social media may uncouple the expression and experience of moral outrage. "[J]ust as a habitual snacker eats without feeling hungry," she wrote, "a habitual online shamer might express outrage without actually feeling outraged." Studies on social media activity could illuminate, she concluded, "how new technologies might transform ancient social emotions from a force for collective good into a tool for collective self-destruction."

There are no easy solutions, perhaps because moral outrage online is a mixed bag. "Digital media may promote the expression of outrage by magnifying its triggers, reducing its personal costs and amplifying its personal benefits," Crockett wrote. Simultaneously, she continued, digital media may reduce moral outrage's benefits for society. Until we find solutions, our moral emotions will remain subject to monetized technological forces that nobody fully understands. What an outrage.

—*Scott Koenig*

PSYCHOLOGY

## The Case Against Lectures

**GETTING "LECTURED" IS RARELY,** if ever, a pleasant experience. You're being told what to do and think, or even chastised. "Don't lecture me," we like to say. Having to "attend" a lecture, though—that's not so bad, depending on the speaker. Hell, on the go, I listen to lectures willingly.

Project-based learning helps deepen students' appreciation for what they learn.

Yet the efficacy of the lecture as a teaching method is in doubt. The latest salvo comes from a study published in *Science*, authored by just under 30 researchers who, a decade ago, began monitoring almost 550 lecturers as they taught over 700 courses at 25 universities in Canada and the United States.

The main conclusions: First, "Didactic practices"—various forms of lecture, using slides and so forth—"are prevalent throughout the undergraduate STEM curriculum," the researchers write. Over half of the classes didn't involve students except in the form of "sporadic questions" from and to them despite "ample evidence," they go on, "for the limited impact of these practices and substantial interest on the part of institutions and national organizations in education reform." Second, survey-based studies on faculty members have suggested that classroom layouts, like big amphitheaters with huge numbers of students, can be barriers to “instructional innovation”—the unalterable structure of the room caters to the status quo. But, the study found, when teachers have flexible layouts and fewer students they tend to fall back to lecturing. Third, you’ve got to sit in on a teacher at least four times to accurately assess their teaching method—how frequently they lecture versus have students, for example, answer quiz questions using wireless clickers or work together on a group project. Group work, an instance of “active” or “student-centered” learning, helps a lot, according to a 2014 meta-analysis of 225 studies. “These results indicate that average examination scores improved by about 6 percent in active learning sections,” the researchers found, “and that students in classes with traditional lecturing were 1.5 times more likely to fail than were students in classes with active learning.”

The researchers of the *Science* study say that it shouldn’t be too much to expect fields that prize empirical evidence to go where the evidence points. “These findings challenge institutions and STEM disciplines to reflect on practices and policies that sustain the status quo,” they write. “Specifically, institutions should revise their tenure, promotion, and merit-recognition policies to incentivize and reward” faculty of “all academic ranks,” to implement ways of instructing that have been shown to work.

Some fields are less lecture-heavy. “Relative to chance,” the researchers found, “mathematics and geology have more student-centered styles than expected, biology has more interactive”—clicker-grounded—“styles than expected, and chemistry has more didactic styles than expected.”

Olin College is one school that’s reducing the importance of lectures. Richard K. Miller, Olin’s president (he designed the school from scratch), told *Nautilus* that Olin avoids lecturing its students, engaging them in project-based learning instead. A criticism sometimes levied at Miller is that this only suits the brightest students. “That’s a worry we take very seriously,” he said. “We’ve been working specifically with other universities that don’t have especially precocious students or very demanding entrance requirements to see if the principles that we’re using will still work.”

Project-based learning doesn’t just help students “get” the material in time for a good grade on the test; it also helps deepen their appreciation for what they learn. “There is an enormous amount of work that has demonstrated that these (student-centered) strategies improve students’ learning and attitudes toward science,” said Marilyne Stains, lead author of the *Science* study and an associate professor in the chemistry department at the University of Nebraska. “It’s not just that they understand it better, but they also appreciate science more. They’re not as scared of it, and they engage more easily with it. When you see that kind of effect, it makes you say, ‘Why are we still doing it the other way?’”

—*Brian Gallagher*

PSYCHOLOGY

## Why Forests Give You Awe

**CAN YOU REMEMBER THE TIME** when you first felt awe, that feeling of being in the presence of something immense and mind-blowing? The natural world—with its domineering mountains, colossal trees, and tall waterfalls—is one of its main sources. I felt awe first when I was a young boy at the feet of the biggest tree in the world. I felt it next as a young man, when I walked in a tropical rainforest for the first time, in Sri Lanka. Here’s how I described it in my book *Gods, Wasps and Stranglers: The Secret History and Redemptive Future of Fig Trees*:

> It hugged all it contained in a humid, humming gloom. The trees towered over us, viscerally alive yet so alien to our animal ways. Their breath sweetened

the air we inhaled. It is hard to explain, but I could feel the concentration of life around me, as if its great density there had somehow reached into me physically. What struck me was the neutrality of that force. There was no malice or love there, just existence.

In 2003, psychologists Dacher Keltner and Jonathan Haidt wrote that "nature-produced awe involves a diminished self, the giving way of previous conceptual distinctions (e.g., between master and servant) and the sensed presence of a higher power. Natural objects that are vast in relation to the self ... are more likely to produce awe."

I asked Keltner what it might be about forests—as opposed to, say, single trees—that inspires awe. "I think it's the perception of collectivity in forests," he said, "where the eye doesn't focus on one object but on interconnections amongst many." That chimes with my experience. When you walk in a tropical forest, the sheer abundance and variety of life can have a powerful and somewhat disorienting effect.

In 1836, in his essay "Nature," Ralph Waldo Emerson hinted at this: "Standing on the bare ground, my head bathed by the blithe air and uplifted into infinite space, all mean egotism vanishes. I become a transparent eyeball; I am nothing; I see all; the currents of the Universal Being circulate through me; I am part or parcel of God."

Keltner's research shows that awe is good for our minds, bodies, and relationships. It may even make us kinder. It appears to encourage us to look beyond ourselves and to cooperate with others. Tapping into this power may be as simple as taking a walk in a forest; the less familiar, the better—Keltner and Haidt say nature is more likely to produce awe if it transcends one's prior knowledge.

Here's how Alfred Russel Wallace, co-discoverer of evolution with Charles Darwin, described his first experience of the forests of Southeast Asia. "When, for the first time, the traveller wanders in these primeval forests, he can scarcely fail to experience sensations of awe. There is a vastness, a solemnity, a gloom, a sense of solitude and of human insignificance which for a time overwhelm him."

With so much life vibrating in one place, it is hard not to feel some connection to the rhythm.

*—Mike Shanahan*

PAINTING BY CASPAR DAVID FRIEDRICH (CIRCA 1820-1821) / WIKICOMMONS

# The Argument Cemetery

BY ROBERT A. BURTON, M.D.

In the argument cemetery
Are the scattered bones
Of once bold mind leaps
Promising solutions to
Civilization's unraveling.

Long ago,
Worshippers and followers
Came to lay wreaths of grief
While historians sifted
Through the rotted remains
And marveled that
Fallen reason had insisted
Until the very end.

Now there is no one left
To mourn or blame,
Or appreciate
Nature's exuberant return.

In the lush overgrowth,
Oblivious to the mute exhortations,
New life forms experiment
With previously unimaginable ways of
Hearing,
Seeing,
Being.

If, against all odds,
Survivors pass this way,
Let us pray
They brush aside
The paralyzing crush of nostalgia
To find joy
In starting over.

# 5 Mind-Bending Perceptual Illusions

*What do you see?*

**BY STEVE STEWART-WILLIAMS**

EVERYONE LOVES a good optical illusion. Most people first come across them as kids and are instantly transfixed. And most of us never quite outgrow them. Even cats seem to enjoy the occasional optical illusion!

The good news, then, for humans and nonhumans alike, is that our illusions seem to be getting better over time. In the age of social media, lots of people are making and sharing them, and the best ones are quickly going viral and setting new standards. In effect, our illusions are evolving culturally to be more and more powerful.

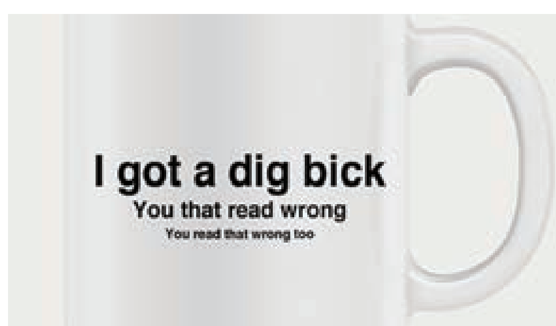
But although perceptual illusions are fun, they also have important philosophical implications. They show us in a clear and unambiguous way that we don't directly perceive the world around us. Perceptual experience is a simulation—a mental model—that doesn't always correspond to the reality it aims to depict.

The following illusions are some of my favorites. Enjoy!

## 1. The Power of Top-Down Processing

To get the ball rolling, here's a good example of how expectations guide perception.

We're so used to words being arranged in a certain order that, when the words are jumbled up, we often don't notice: We mistake our expectations for the world. That's why proofreading your own essays is so hard.

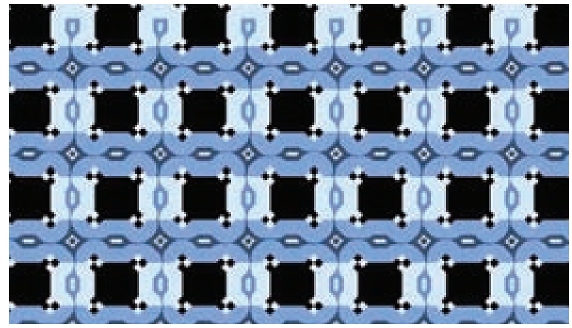



BREEZY CLOTHING

**2. The Skye Blue Café Wall Illusion**

This illusion, created by the artist Victoria Skye, was one of the top entries in the 2017 Best Illusion of the Year Contest. Believe it or not, the horizontal lines are all perfectly parallel. To prove this to yourself, just squint at the image or look at it from the side.

Notice that, even after you're completely convinced that the lines are parallel, the illusion continues to work. Perception is largely involuntary—and in many ways is walled off from our abstract knowledge of the world.

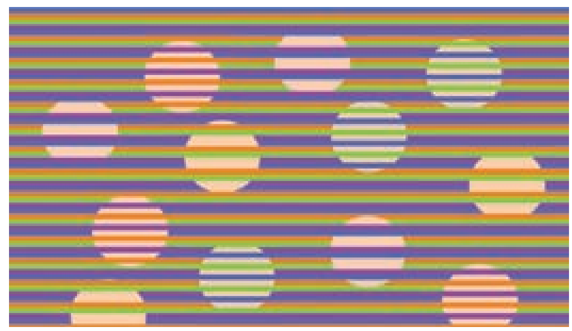


VICTORIA SKYE

**3. Confetti**

This one's a variation on the Munker Illusion, created by David Novick. The circles in the image are all the same color. The only thing that differs is the color of the lines around them.

The illusion is a vivid demonstration of the fact that we don't directly perceive the colors of objects in the world. Instead, the perceptual system takes an educated "guess," based on the objects' surroundings.

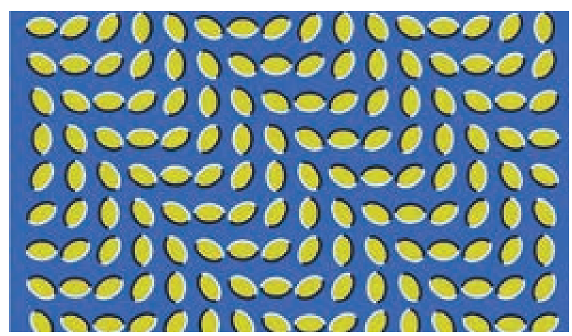


DAVID NOVICK

**4. The Rice Wave Illusion**

This might look an animated GIF, but it's not. The movement is all in your head.

The shading and sequencing of the yellow blobs triggers the motion areas of the brain, creating a perception of movement in a stimulus that's actually static. Interestingly, around 5 percent of people seem to be immune to this illusion.



AKIYOSHI KITAOKA

**5. The Tilted Road Illusion**

This looks like two photos of the same road, taken from different angles. But it's actually just the same photo twice.

Apparently, the visual system treats the image as if it were a single photo of two separate roads. The outlines of the two roads are parallel to one another in the two-dimensional image. For that to be the case in the image, the actual roads in the real world would have to be angling strongly away from each other. So, that's what the visual system infers.

DANIEL PICON

# The 5 Coolest Places to Live in 2100

*Where your children's children will call home*

BY JUSTIN NOBEL

VADIM NEFEDOFF / SHUTTERSTOCK

IT'S A SATURDAY NIGHT in August and another electric and endless Arctic sunset has cast the city of Iqaluit in gold. Downtown, on Niaqunngusiariaq Street, in an Inuit-themed bistro featuring tundra-fed musk ox and Arctic char, a host of young urban designers, dance choreographers, and writers, are discussing the plights of their parents, who immigrated to this northernmost province, Nunavut, in eastern Canada, in the 2070s. The smartly dressed friends, enjoying a flowery peach sauvignon blanc from China, are American and Spanish, Indian and African. Compared to their parents and grandparents, who fled deadly heat and droughts, endless forest fires and flash floods, the young artists, in the year 2100, can't believe they have it so good. In this perennially growing city, spread out across a series of mountain valleys, with homes that overlook the dynamic color-sweep of Frobisher Bay, they are never short of things to do when they are not at work. Under the eternal summer sun, they hike, bird-watch, kayak (which the Inuit like to remind the newcomers they invented)—the outdoor opportunities are thrilling.

That, anyway, is how a travel magazine devoted to the best places to live in 2100 might read. In fact, with the effects of climate change becoming more apparent every day in 2018, it might not be a bad idea to start planning for where our children's children might live. It's no surprise that the collective advice of climate scientists today is Go North, Young Man. "If, as many climate models suggest, our planet becomes one of killer heat waves, fickle rain, and baked croplands, might new human societies emerge in places currently unappealing for settlement?" asks Laurence C. Smith, a professor of geography at the University of California, Los Angeles, in his book, *The World in 2050—Four Forces Shaping Civilization's Northern Future*. "Could the 21st century see the decline of the southwestern United States and European Mediterranean, but the ascent of the northern United States, Canada, Scandinavia, and Russia?" According to the latest report from the Intergovernmental Panel on Climate Change, the international body that evaluates the science of climate change, the answer, for the year 2100, is "Yes." At that time, when Earth's atmosphere contains 1,000 parts per million of carbon dioxide—highly plausible, scientists say; today it's 410 ppm—places such as Greenland, Canada, Russia, and the northern U.S. would be significantly warmer and receive more precipitation than today. They would be downright livable. Based on today's climate science, here are five of the best places to live in 2100.

**Nuuk, Greenland**

One of the greatest challenges on a hot planet will be enough fresh water. Higher temperatures, says the IPCC, will "reduce renewable surface water and groundwater resources in most dry subtropical regions." Greenland has water literally pouring out of its core. A 2016 paper published in the journal *Geophysical Research Letters* estimates that from January 2011 to December 2014, the Greenland Ice Sheet lost an average of 269 gigatons of ice a year, or about 71 trillion gallons of water. The average American uses about 32,850 gallons a year, which means Greenland's annual melt can provide water needs for, get ready for it: more than 2 billion Americans. Put another way, a year of Greenland melt means sufficient water for one in three people on the planet.

So, Greenland will have water. (Don't worry, plenty of companies, like National Advisor Bureau Limited, based in the United Arab Emirates, are currently perfecting the technology to tow icebergs to shores and extract the water from them.) There will be water to use for hydroelectric power—five hydroelectric stations already utilize glacial melt in Greenland and the future will see many more. There will be water for heavy industry—Greenland is laden with valuable minerals such as iron, zinc, uranium, and rare-earth elements, and sits astride some of the Arctic's most massive oil and gas deposits, according to the U.S. Geological Survey. Greenland will have water to drink. Greenland will have water to sell.

Greenland will also have water for agriculture. Despite its epic (melting) ice cap, southwestern Greenland is dotted with ice-free fjords containing small towns and decent farmland. Elsewhere in Greenland potatoes, turnips, beets, carrots, parsnips, rhubarb, cabbage, tomatoes, cucumber, and cauliflower grow. And soon forests could be there, too. A 2013 paper published in the *Philosophical Transactions of the Royal Society B: Biological Sciences* explained that "future warming is likely to allow growth of trees and shrubs across much of ice-free Greenland by the year 2100."

The capital and largest city in Greenland is Nuuk, with 17,000 people, gourmet restaurants, a variety of cultural centers and museums, and famously strong coffee. All of that is overshadowed by the magnificent Sermitsiaq mountains and breaching humpback whales. Warmer weather and more vegetables will surely only enhance Nuuk's already booming foody scene. The tourism website, ATasteofGreenland.com, is already looking ahead. "Because of climate change the world's largest island has become even greener," it states. Just remember to do as the native Inuits do, not as the vanquished Vikings did. Sustainable farming and fishing, yes; perpetual walrus ivory hunting, no.

## Places like Greenland, Canada, Russia, and the northern U.S. would be downright livable.

BIGROLOIMAGES / SHUTTERSTOCK

SPACEPOTATO; GAMBITMG / WIKIPEDIA

**Egvekinot, Siberia**

Of course, we will want to eat well in a 1,000 ppm world. But as the atmosphere approaches that level of carbon dioxide, the IPCC states, the climate will "pose large risks to food security globally." Well, let's not beat around the bush. "This would not be a pretty world!" says Werner Kurz, a senior research scientist with Canada's Pacific Forestry Centre and a lead IPCC author. "One thousand ppm would be a very extreme outcome with catastrophic consequences for permafrost, forest fires, widespread tree mortality—providing more feedback to climate change—and sea level rise that would be ongoing for centuries."

But you can avoid the doom and gloom, and have your weekend farmer's market, by packing up the Container Store crates and moving to Siberia. Yes, presently, it's pretty damn cold. Oymyakon, in eastern Siberia, is considered the coldest populated place on earth. The 500-person town is sandwiched between two mountain ranges. The average high temperature in January is -45 degrees Fahrenheit. Residents put wool blankets over car engines to keep them warm so they'll start.

But the research of Elena Parfenova and Nadja Tchebakova, of the Siberian Branch of the Russian Academy of Sciences, has shown that by the 2080s, summer temperatures would rise by 9 degrees, winter temperatures would rise by 25 degrees, and precipitation would increase. A 2011 paper co-authored by the researchers and a scientist at NASA, published in the journal *Environmental Research Letters*, stated that from 50 to 85 percent of central Siberia is predicted to be climatically suitable for agriculture by the end of the century. "Crop production could increase twofold," said the paper. New crops like grapes, corn, peas, and sunflowers would be possible across the territory, and southern Siberia may even become suitable for warmth-loving crops such as melons, gourds, and berries.

Parfenova and Tchebakova use an index known as the Ecological Landscape Potential, or ELP, which characterizes conditions for human habitability. In particular, the ELP in the towns of Egvekinot and Anadyr, have the potential for their population density to increase by more than sixfold. While Parfenova and Tchebakova say the "best place to live" would remain along the Trans-Siberian railroad, where infrastructure is developed, Egvekinot, along Siberia's Arctic coast, "would likely be a growth point." Plus, Egvekinot is close to the Bering Strait and future Arctic trade routes, and being perched on the northwestern edge of the vast Pacific Ocean has good access to southeast Asia and the west coast of North America, too.

## Bangor, Maine

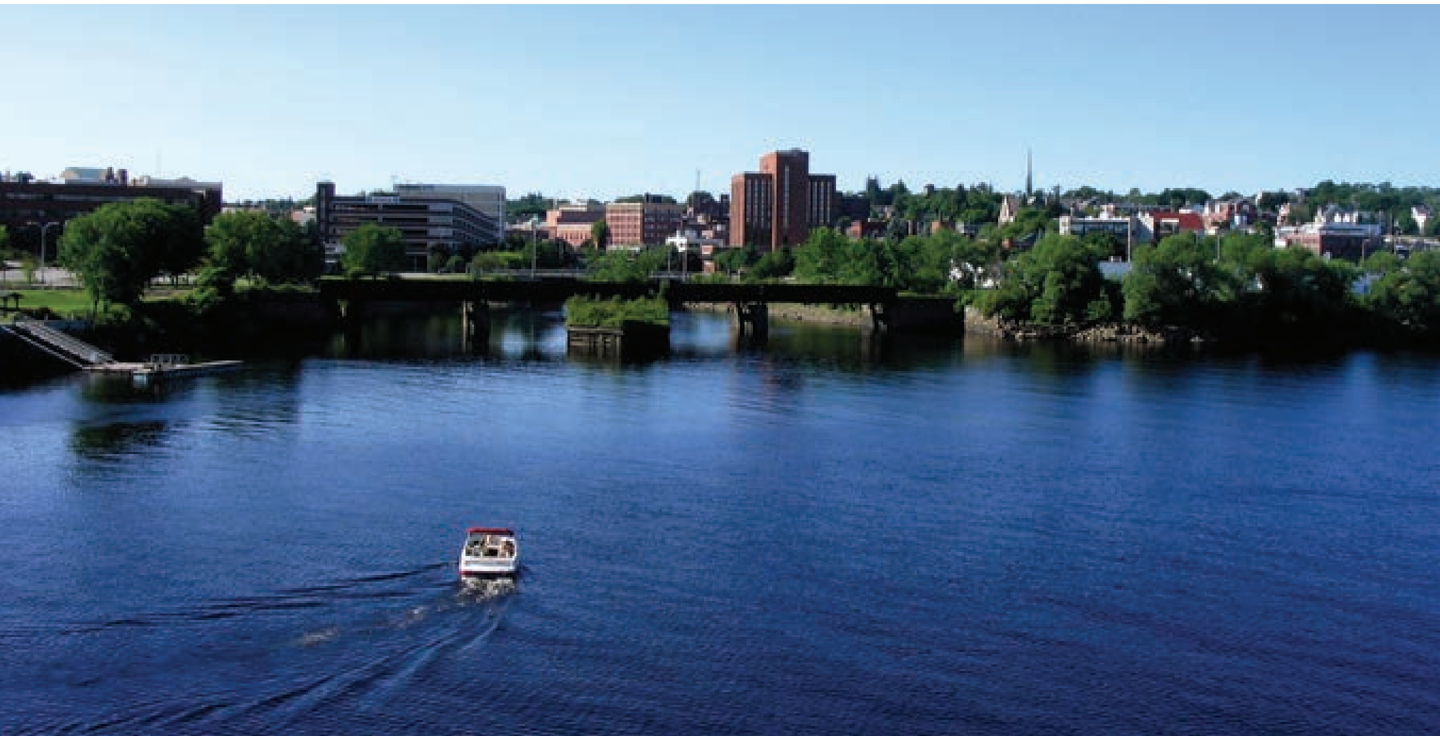
How to put this nicely? On a hot planet, with a paucity of fresh water and food, there will be war. Systems will be down. "Major transportation, command and control, intelligence, and deployment hubs may face unrelenting erratic outages or curtailment of operations," states a 2016 report by The Center for Climate Security, a D.C.-based group composed of former Marine, Navy, Army, and Coast Guard officers.

The United States Environmental Protection Agency has been looking out for us. It's been tallying a "Climate Resilience Screening Index." Basically, it's a color-coded map of the U.S. that conveys, on a county by county level, which areas are best suited to handle climate change. The EPA looked at environmental, economic, and societal aspects of climate resilience, and also assessed governance and social services. The state with by far the highest overall score is Maine.

With rocky coasts that would be difficult to attack and easy to defend, close enough to the ocean for trade and transport, but high and rocky enough to not lose all of their coastline to storms and sea level rise, Maine could be the place for peace. It could also, in fact, be further fortified. In 2016, the Union of Concerned Scientists reported that a three-foot rise in sea levels would threaten 128 coastal defense installations in the U.S., many located in the South and Mid-Atlantic. As the world moves north to escape the heat, and the melting Arctic opens up major shipping routes, Maine could well become a strategically important military outpost. The military has long been betting on Alaska to play a more strategic role in an Arctic-busy world, but recently Maine has become part of that conversation, too.

"As the climate changes and the Arctic continues to open, the strategic significance of the region will only grow more important," Maine Senator Angus King said in 2015. The year before, the Maine Maritime Academy received a $450,000 grant from the U.S. Department of Homeland Security. It was for the "development and delivery of maritime ice navigation and first responder courses to complement the U.S. Coast Guard's Arctic Strategy."

Just now in Maine, Portland typically tops the list of best cities with "great restaurants, scenery, and schools," writes Marina Schauffler of the *Portland Press Herald*. However, she notes, "The city's bustling Old Port, much of it built on fill, is highly vulnerable to sea-level rise and storm surge" and "parts of the gateway Bayside neighborhood are even lower in elevation than the Maine State Pier along Portland's waterfront." Sea level rise won't help any of this. So why not go even further north, to Bangor? The former timber hub is surrounded by forests, trails, parks, and breweries. And as the sea comes creeping up the Penobscot River, settlers can just keep on creeping further upstream.



**Buffalo, New York**

For a city to be able to take in potentially millions of new climate refugees it needs space. Meaning a metropolis laid out across relatively flat, relatively stable, grid-connected, non-flood-prone land that has been developed but not too developed and still a natural enough landscape to be pleasant. So where is there a city that has this—and also will have water, nearby farmland, and not be close enough to the ocean to be swamped by rising seas or superstorms?

Buffalo, says Jesse Keenan, a faculty member of Harvard University's Graduate School of Design. Keenan has studied the impact of climate change on cities around the world, notably Copenhagen, Hong Kong, and Miami. He coined the term "climate gentrification," based on his research showing that costs associated with climate change—such as rising home prices on higher elevations in coastal areas—are beginning to drive people from their longtime neighborhoods and homes. He says he's often asked by international investors where he would move in the future, and Buffalo is his regular answer.

"You first want to go where there's fresh water and moderate temperatures," Keenan says. "The Great Lakes for me make a lot of sense. Now, there are algal blooms in the Great Lakes, and those aren't easy problems to solve, but if you've got your algal loads under control and you manage that appropriately, Buffalo's going to be an area that I think we'll see a renewed economic investment because of its long-term capacity to accommodate density." Many Great Lake cities fit a similar mold: Duluth, Chicago, Cleveland. "Anywhere in the Great Lakes should be OK," says Keenan.

You can avoid the doom and gloom, and have your weekend farmer's market, by packing up and moving to Siberia.

NIKOLAY TRANOV / SHUTTERSTOCK;
LAGUNA DESIGN QAQQAQTUNAAQ / FLICKR

## Iqaluit, Nunavut

One of the most underrated losses to people fleeing their drowning or burning cities will be arts and culture. Both will be essential to help humanity deal with the inevitable pain of a 1,000 ppm future. Throughout history, cultural meccas have moved around the world, and although this might sound far-fetched, as most of us have never heard of Iqaluit, the northern Canadian town, population 7,000, is already showing signs of a burgeoning arts and culture scene. There are artists, bureaucrats, and hardworking new arrivals. A 2011 article in the *Nunatsiaq News,* the Canadian Arctic's main newspaper, profiled the story of 26-year-old Serge Lampron, who moved to Iqaluit from a smaller community "to make it big as a hip-hop artist." Nearby Cape Dorset, famous for its soapstone carvings, has been said to have more artists per capita than any other city in Canada.

Iqaluit is well positioned to take advantage of a climate change-inspired push north. The city began as an American cold war airbase in the 1950s and '60s, meant to track Soviet nuclear missiles headed across the Pole for America. Just last year Iqaluit opened a brand new international airport, and the city is located snug at the end of a long bay, making it better protected from notorious Arctic storms that have eaten away shorelines in places like Alaska. The city is presently above the tree line and soils are poor. But some 60 million years ago, at the start of the Cenozoic era, which scientists have called "a greenhouse world," vast temperate rainforest, similar to the coastal rainforests of the Pacific Northwest and Chile, existed across the Arctic Archipelago. That greenhouse world could come again. A 2003 paper in the research journal *Paleobiology* tells us that the Arctic climate "supported productive, high-biomass redwood-dominated forests." So come party in the forests of Iqaluit! And don't forget your guitars, paints, books, and Happy Light lamps. In the winter, sunrise is at 9:20 in the morning and sunset at 1:40 in the afternoon.

JUSTIN NOBEL is a magazine writer on issues of science and environment. He's been published in *Rolling Stone, Popular Mechanics, Nautilus, Tin House, Oxford American*, and *the Virginia Quarterly Review*.

This story appeared online at Medium.com.

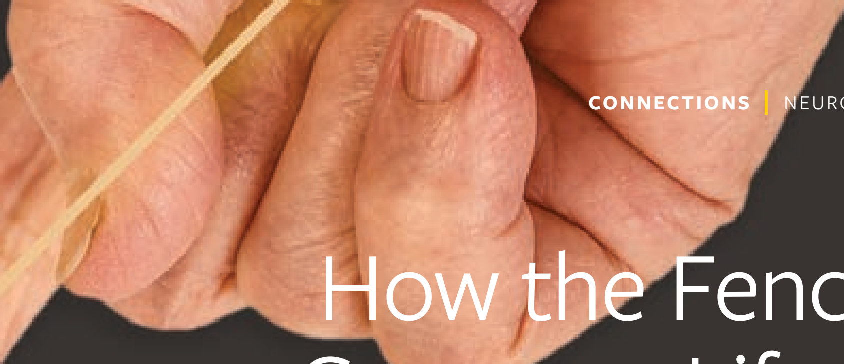
a new day in the neighborhood

the **nantucket** project

September 19 - 22, 2019

the nantucket project brings fresh ideas to curious people through live talks, original films and unforgettable experiences. this year's theme is neighborhood.

tnp**9**





# How the Fencing Reflex Connects Life and Death

*Primitive reflexes shepherd us into this world, and out*

BY AMANDA DARRACH

**BY THE SEVENTH MONTH** of my pregnancy, I sometimes felt a stroking motion on the inside of my abdomen, a repeated arc of movement traced by a tiny limb.

My daughter Lucy weighed 6 pounds when she was born two months later. My father's side of the family often produces small babies. Too small to regulate her own body temperature, she needed to be held in order to sleep. She was "living on" me, the pediatrician said.

Sometimes to free up my hands I would lay her along my thighs, the dip between them holding her snug. Her wrinkled arms and legs stayed drawn in to her chest, but then one arm and leg would extend, the arm reaching out in front of her and sweeping out to the side, taking in the expanse of the room until she lay twisted like an archer. The motion already was familiar to me: the asymmetrical tonic neck reflex.

When a baby's head is turned to one side, the asymmetrical tonic neck reflex prompts the infant into the archer's pose. One arm extends, while the opposite arm and leg flex. This reflex begins about 18 weeks after conception and helps the baby to make her way down the birth canal. Outside the womb, the fencing (or archer's) reflex allows the baby to discover her hands and develop hand-eye coordination.

When my parents came to New York to meet Lucy, she lay in the crook of my father's arm, tracing her lazy arcs across the ceiling. Dad's dementia was advancing, but he knew how to hold a baby. He'd raised six.

Lucy fell asleep on Dad, and I watched them together, remembering the smell of my father's skin as I had drifted off to sleep against him as a child. "Slow, steady heartbeat," said my mother. "That's what babies like."

I took a picture of Lucy's hand, uncurled in sleep against Dad's spotted skin. He had artist's hands, tools well-used. My mother said Lucy had "starfish hands," the tiny, translucent fingers tapered at the tips. "She's like a dancer," said my mother. "Our little archer."

**PRIMITIVE REFLEXES DEVELOP BEFORE** we are born and their primary function is to nourish or protect us. Neurologists call them "primitive" in part because the infant's brain has traditionally been seen as a primitive edition of an adult's. Also, primitive reflexes fade as we grow up. When neurologist Marshall Hall coined the term "reflex" in the 1830s, he positioned it in direct contrast to voluntarily activity—that is, activity controlled by the frontal cortex.[1] In the 1930s, the neurologist Gysbertus Rademaker reinforced this hierarchical view, describing primitive reflexes as basic units that gradually became hidden as higher brain centers became more active.[2] These neurologists saw the nervous system as separate compartments that slowly connected as a child grew, uniting under a "gradual increase of cortical influence."

The hierarchical understanding endures today. But, as the neurologist Bert Touwen wrote, primitive reflexes in infants belong in a different category than those that practitioners test in both children and adults during an annual physical. A tap on a patient's knee or elbow with a rubber hammer elicits a simple nerve circuit response. The suckle, grasp, or fencing reflexes are more complex and variable. Moreover, they have a way of coming back.

Primitive reflexes can be activated in patients with advanced dementia, coexisting with voluntary movement. Conventional wisdom holds that the work it takes the cortex to suppress them becomes too taxing in old age. Keeping the heart beating and the lungs inhaling and exhaling has to take priority. Traumatic brain damage and neurologic disease can also bring back primitive reflexes. Parkinson's disease, Alzheimer's disease, and other forms of dementia involving frontal cortex lesions can impair the connection between intention and action, making room for reflexes not seen since infancy. Deep anesthesia can produce this same effect. Doctors talk of patients who, under heavy sedation, grasp someone's finger, root for a breast to suckle, or twist into the archer's pose.

*Brocklehurst's Textbook of Geriatric Medicine and Gerontology* calls the phenomenon of primitive reflexes returning in adulthood "cortical release." To this day, cortical release is not well understood.

**WHEN DAD FIRST WENT** into the nursing home near his and my mother's home in western New Hampshire, we read him the *Just So Stories*, a favorite from his childhood. I would bring him wildflowers I picked on the hill where my parents lived. One morning in August, I walked in with a bouquet of goldenrod. "I

# There's a porous boundary between reflex and reaction.

didn't even know it was summer," he said, his voice swelling with sadness. It was a rare return of speech after months of silence.

A few evenings later, I was driving up to the nursing home and noticed children playing baseball. The warm summer light colored their white uniforms pink. "Can I wheel him down in a chair to watch?" I asked his nurse.

"I wouldn't advise that," she said. "Too risky."

I massaged Dad's hands and feet like he had taught me when I was young. He retired from the graphic design business when I was 3, so my family had breakfast together in my parents' bed every morning before school. Toast and jam. He'd use the tea cozy as a hat and pretend he was the pope. "Rub my hands before I go paint all day," he'd say.

After school, I'd visit him in his studio behind the house. "I just can't believe all the knowledge I've worked to acquire is going to die with me," Dad would say to me. "Why won't you let me teach you calligraphy, or how to sail, or how to build a box kite or a Japanese garden?" My awareness that he was older than other fathers, that it was already time to pass down knowledge, was too much to take on just yet.

A few weeks later, we got a call to come home again. "Only if it's not inconvenient," said my mother, reflexively reverting to English politeness in her pain.

The director of the nursing home met with me and my sister, our mother mute with sadness beside her. "His pneumonia is progressing," she said. "I'd give this a week. Everyone's different, but this looks like a week to me."

We went back to Dad's bed. "You're doing everything just right," my mother told him with a kiss.

He lay back and listened. After a while we were silent, and he stretched out his leg before tracing slow arcs in the air with his hand. Over and over again his arm gathered in and uncurled, taking in the scope of the room.

His eyes were wide and his face full of wonder, trying to show my mother what he could not say and what he seemed to know she could not see.

It was Dad's fencing reflex, the same gesture Lucy had practiced before her birth to ease her passage from one world to the next.

**THERE IS A VIDEO** of Dad and Lucy from the year before he went into the nursing home. In it, they are seated on opposite sides of the breakfast table in New Hampshire, surrounded by my mother's houseplants. They are drawing, though Dad hadn't been down to his studio to paint in a few years by that point. We had brought up some sketching pens, but he ignores them for a row of Lucy's chunky toddler crayons. Lucy, 2, uses a paint box.

They focus hard on their work, chins down, lips pursed with purpose. They both breathe through their noses. Dad's white beard, longer than he had kept it before his illness, rests on his chest. The dog walks through, sniffing under them, but they are busy and do not immediately notice.

Lucy stabs and swirls her brush, pushing the color across the page. Dad lifts his crayon like a conductor's

MEGAN MALOY / GETTY IMAGES

baton, each finger poised and light. He places it gently on the paper, just as he had handled a paintbrush in the past, and draws a complex purple squiggle. He pauses at the end to stroke his beard and squint at the paper as he had his canvases.

He shifts a white crayon to the back of the line and uses a bright pink one to trace above the path of the original purple. Then a blue, then an orange. With each pass, the loops swell higher, the sharp corners pinch more tightly.

There's a porous boundary between reflex and reaction. We sometimes think of our reactions to crises as reflexive, but they are behavioral, originating from the less ancient parts of our brains. Reflexes, too, can be colored by experience. The neurologist Karel Bobath wrote that he favored the word "reaction" to describe an infant's step reflex, in order to express the "variability and potentiality of adaptation to the different demands of the environment."[3] Touwen wrote that neurologists are not always strict about the separation between the terms "reflex" and "reaction." Reflexes, he argued, do not exist separately from the world. He preferred to view the nervous system as existing in a "dynamic state," one that grew "because of a continuous influx of energy and information." The rooting reflex, for example, begins with a rhythmic side-to-side motion before developing into a complex function, a gathering-in of the breast. Whether "reflex" or "reaction," Touwen wrote, these responses must be an "age-specific display adapted to the infant's needs."

Watching the video later, I couldn't help but wonder if a part of Lucy's drawings that day had grown out of her primitive reflexes, and if Dad's drawings weren't informing his remerging ones.

The evening after I got back to New Hampshire, I climbed into bed with Dad and curled my body around his. It was a protective gesture, but it was also full of longing, an effort to absorb all the time that was left. We watched Audrey Hepburn and Gregory Peck in *Roman Holiday*, both of us dozing on and off. Dad had grown up collecting bottles to pay the 11-cent entrance fee for Saturday afternoons at the Commodore movie theater in West Philadelphia. He and his brother Brad had taken acting classes together at night for fun when they were young men. Dad loved to tell a story of Laurence Olivier immersing himself so fully into a role that he had had no recollection of how the performance had gone once he came off stage.

Later that night, I leapt out of bed and stood in the stark light of the hall between our bedrooms, clasping hands with my mother and sister in a strange, impromptu circle. My mother was mute. We took a breath.

"Dad died," my sister told me.

"Already?"

**PRIMITIVE REFLEXES CAN BE USED** to determine brain death. The jaw is tapped with a reflex hammer. Response to pain and the cough reflex are assessed. In the cold calorics test, ice water is piped into the inner ear to check for eye movement.

Neurologists say that the loss of any meaningful consciousness is fairly sudden. Five minutes after the heart stops, neurons begin to die. There is a similarity between out-of-body experiences under deep anesthesia and in near death, but after 10 minutes at the outside, life is gone.

A reversion to primal reflexes easily explains away a deathbed hand squeeze. Another reflex associated with death is more rare. With activation of the truncal muscles, as when a braindead patient's chin is pushed toward the chest, or a respirator is disconnected, a

His eyes were wide and his face full of wonder, trying to show my mother what he could not say and what he seemed to know she could not see.

signal is sent to the spine and the patient raises their forearms up to their chest. It is caused by the same nerve signal that triggers us to snatch back our hands from something hot or sharp before our brain has had time to feel the pain. The brain plays no role at all. The cells sending the signal are in the spinal cord. Unlike the return of primitive reflexes, this motor response does not represent a cortical release. It can be the source of false hope and great doubt for families of patients whose diagnosis is brain death. It is known as the Lazarus reflex.

Dad waited to die until we were home in bed for the night. He looked hard at a nurse who came in to check on him some time after midnight. Thirty minutes later he was no longer breathing. There were no reflex checks, no respirator to detach. Dad died on Tylenol.

"Isn't that something," said my mother as we entered Dad's room. She had spent years in hospice work. "Once the person is gone, the body is just a shell."

I couldn't see that. Death did not seem so instantaneous to me. His hands and cheeks were cooling, but when I stuffed my hands between his shoulders and the bed, there was still warmth, energy. I sat beside him like that, feeling the warmth that was still left and looking down into his face.

"He just marched right on out of there," said my mother.

I was having a hard time leaving him. My sister chased an impatient undertaker away to the parking lot.

I couldn't think of one reason to get up and leave Dad, nor why my reluctance was out of the ordinary. I pressed my forehead into his chest, an instinctive, familiar gesture. He exhaled with a sigh.

"Dad is making noises when I lean on him," I said, like I was complaining that he was stealing my ice cream or had guessed the contents of a birthday gift before unwrapping it. My mother laughed, and for a moment the four of us were in bed together again.

The sun had been up for a while when I finally left to go pick up Lucy, now 4, from our babysitter.

We went home to the garden Dad had built and watched Lucy draw with chalk on the red brick. We sat there all day with blankets and looked at the woods like we were waiting for something.

AMANDA DARRACH is a journalist and filmmaker based in Brooklyn. She is a student at the Columbia Graduate School of Journalism.

**REFERENCES**

1. Hall, M. *On the Diseases and Derangements of the Nervous System, in Their Primary Forms and in their Modifications by Age, Sex, Constitution, Hereditary Preposition, Excesses, General Disorder and Organic Disease* H. Bailliére, London (1841).

2. Rademaker, G.G.J. *Das Stehen* Springer, Berlin (1931).

3. Bobath, K. *A Neurophysiological Basis for the Treatment of Cerebral Palsy* Lippincott, Philadelphia (1980).

**ADDITIONAL READING**

Fillit, H., Rockwood, K., & Woodhouse, K. *Brocklehurst's Textbook of Geriatric Medicine and Gerontology* Saunders, Philadelphia (2010).

Touwen, B.C.L. Primitive reflexes—Conceptional or semantic problem? In Prechtl, H.F.R. (Ed.) *Continuity of Neural Functions From Prenatal to Postnatal Life* Lippincott, Philadelphia (1984).

# The Woman Redeemed by Trees

*The data kept confirming. Life is talking to itself, through her.*

**BY RICHARD POWERS**

R**EAL LIFE STARTS** in graduate school. Some mornings in West Lafayette, Patricia Westerford's luck scares her. Forestry school: Purdue pays her to take classes she has craved for years. She gets food and lodging for teaching botany, something she'd gladly pay to do. And her research demands long days in the Indiana woods. It's an animist's heaven.

By her second year, the catch becomes clear. In a forest management seminar, the professor declares that windthrow should be cleaned up and pulped, to improve forest health. That doesn't seem right; a healthy forest needs dead trees. They've been around since the beginning. Birds use them, and small mammals. More forms of insects live on them than science has counted. She wants to raise her hand and say, like Ovid, how all life is turning into other things. But she doesn't have the data.

Soon, she sees. Something is wrong with the entire field. The men running American forestry dream of producing straight, clean grains at maximum speed. They speak of thrifty young forests and decadent old ones, of mean annual increment. These men will have to fall, next year or the year after. And up from the downed trunks will spring rich new undergrowth. That's where she'll thrive.

She preaches this covert revolution to her undergrads. "You'll look back in twenty years, amazed at what every person in forestry took to be self-evident. It's the refrain of all good science: 'How could we not have seen?' "

She abides her fellow grads. She goes to the barbecues and smiles at departmental gossip while remaining her own sovereign state. One night there's a dizzy, wild misunderstanding with a woman in plant genetics. Patricia puts the embarrassed fumble away in her heart's drawer and never takes it out again.

A suspicion sets her apart from the others. She's sure, on no evidence whatsoever, that trees are social. Motionless things that grow in mass communities

ILLUSTRATION BY PAULA SCHULTZ

must have evolved ways to synchronize. Nature knows few loner trees. But the belief leaves her marooned. Here she is, with her people, at last, and even they can't see the obvious.

Purdue gets hold of a prototype quadrupole gas chromatography-mass spectrometer. With such a device, she can measure which volatile organics the grand old eastern trees exude and what these gases do to the neighbors. She pitches the idea to her advisor. People know nothing about the stuff trees make. It's a green world, ripe for discovery.

"How will that produce anything useful?"

"It might not."

"Why do this in a forest? Why not the campus test plots?"

"You wouldn't study wild animals by going to the zoo."

"You think cultivated trees behave differently than trees in a forest?"

She's sure of it. His sigh is as clear as a public service announcement: Girls doing science are like bears riding bikes. Possible, but freakish.

The work consists of taping plastic bags over the ends of branches, then collecting them at intervals. She does this over and over, hour by hour, while the world around her rages with assassination, race riot, and jungle warfare. She works all day in the woods, her back crawling with chiggers, her scalp with ticks, her mouth filled with leaf duff, her eyes with pollen, cobwebs like scarves around her face, bracelets of poison ivy, her knees gouged by cinders, her nose lined with spores, the backs of her thighs bitten Braille by wasps, and her heart as happy as the day is generous.

She brings the samples to the lab and spends tedious hours determining which gases each of her trees exhale. There must be thousands of compounds. The tedium makes her ecstatic. She calls it the science paradox. It's the most brain-crushing work a person can do, yet it can spring the mind to see what else is out there. And she gets to work in the sun and rain, the stink of humus filling her nose with musky life.

It's a miracle, she tells her students, photosynthesis. All the razzmatazz of life on Earth is a free-rider on that mind-boggling magic act. She leads her charges into the heart of the mystery: Hundreds of chlorophyll molecules assemble into antennae complexes. Countless antennae arrays form into thylakoid discs. Stacks of these discs align in a single chloroplast. Up to a hundred such solar power factories power a single plant cell. Millions of cells may shape a single leaf. A million leaves rustle in a single ginkgo.

Too many zeros: their eyes glaze over. She shepherds them back over that ultrafine line between numbness and awe. "Billions of years ago, a single, fluke, self-copying cell learned how to turn a barren ball of poison gas and volcanic slag into a garden. And everything you hope, fear, and love became possible." They think she's nuts; that's fine with her. She's content to post a memory forward to their futures, futures that will depend on the generosity of green things.

Late at night, spent from teaching and research, she reads her beloved Muir. His prose floats her soul up to her room's ceiling. She writes her favorite lines inside the covers of her field notebooks and peeks at them when the cruelty of frightened humans get her down.

*The clearest way into the universe is through a forest wilderness.*

Plant-Patty becomes Dr. Pat Westerford, a way to disguise her gender in professional correspondence. Her work on tulip trees earns her a doctorate. It turns out that those thick, long lengths of vertical culvert are richer than anyone suspects. Liriodendron breathes out a repertoire of organic compounds that do all kinds of things. She doesn't yet know how the system works. She just knows it's rich and beautiful.

She lands a postdoc at Wisconsin. The postdoc turns into an adjunct position. She makes almost nothing, but life requires little. Her budget is blessedly free of those two core expenses, entertainment and status. And the woods teem with free food.

She studies sugar maples, in a forest east of town. Her breakthrough comes as breakthroughs often do: by long-prepared accident. Patricia arrives in her copse one June day to find one of her bagged trees under full-scale insect invasion. The last several days of data seem to be ruined. Improvising, she keeps the samples from the damaged tree, as well as several nearby maples. Back in the lab, she finds something even she isn't ready to believe.

Another nearby tree gets infested. She measures again. Again, she doubts the evidence. Fall begins, and the leaves of her chemical factories drop to the forest floor. She battens down for winter, double-checking

His sigh is as clear as a public service announcement: Girls doing science are like bears riding bikes.

her results, trying to accept their crazy implications. She wanders the woods, wondering if she should publish or measure for another year. The oaks in her forest shine scarlet, the beeches a stunning bronze. It seems wise to wait.

Confirmation comes the following spring. The trees under attack pump out insecticides to save their lives. That much is uncontroversial. But something else in the data makes her flesh pucker: trees a little way off, untouched by the invading swarms, ramp up their own defenses when their neighbor is attacked. They somehow get wind of the disaster and prepare. She controls for everything, and the results are always the same. Only one conclusion makes sense: wounded trees send out alarms that other trees smell. Her maples are linked together in an airborne network, sharing an immune system across acres of woodland. These brainless, stationary trunks protect each other.

She can't quite believe. But the data keep confirming. On that evening when Patricia finally accepts the measurements, her limbs warm and tears run down her face. She may be the first creature in the expanding adventure of life ever to glimpse this small, certain thing that evolution made. Life is talking to itself, through her.

She writes up the results as soberly as she can. Chemistry, concentrations, and rates—nothing but what the gas chromatography equipment records. But in her paper's conclusion, she can't resist suggesting what the results spell out: *The biochemical behavior of individual trees may make sense only when we see them as members of a community.*

A reputable journal accepts her paper. The peer reviewers raise their eyebrows, but her data are sound and no one can find any problems except common sense. On the day the article appears, Patricia feels she has discharged her debt to the world. If she dies tomorrow, she'll still have added this one small thing to what life has come to know about itself.

The press latches onto her findings. She does an interview for a popular magazine. She struggles to hear the questions over the phone and stumbles with her answers. But the piece runs, and other newspapers reprint it. "Trees Talk to One Another." She gets letters from other researchers, asking for details. She's invited to speak at the midwestern meeting of the professional forestry society.

Four months later, the journal that ran the piece prints a letter signed by three leading dendrologists. The men say her methods are flawed and her statistics problematic. The defenses of the intact trees could have been activated by other mechanisms. Or these trees might already have been compromised in ways she didn't notice. The letter mocks the idea that trees send each other chemical warnings:

*Even if a message is in some way "received," it would not imply that any message has been "sent."*

Two Yale professors and a name chair at Northwestern, versus an adjunct girl at Madison: No one in the profession bothers replicating Patricia Westerford's findings. Researchers who wrote her for more information stop responding to her letters. Newspapers that ran wide-eyed articles follow up with accounts of her brutal debunking.

Patricia goes through with her talk at the midwestern forestry conference, in Columbus. The room is small and hot. Her hearing aids howl with feedback. Her slides jam in the carousel. Fielding hostile questions from behind the podium, Patricia feels her childhood speech defect returning to punish her for her hubris. For three agonizing days, people nudge each other as she passes in the halls of the conference hotel: There's the woman who thinks that trees are intelligent.

Madison doesn't renew her lectureship. She scrambles to line up a job elsewhere, but she can't even get work washing glassware. No other animal closes ranks faster than *Homo sapiens*. Without a lab, she can't vindicate herself.

At thirty-two, she starts high-school substitute teaching. Meaning drains from her like green from an autumn maple. After months in solitude replaying what happened, she decides it's time to shed.

She's too cowardly to give in to the scenarios that play in her head most nights as she lies sleepless. The pain prevents her. Not hers: the pain she'd inflict on her mother and brothers and remaining friends. Only the woods can help her. She tramps the winter trails, feeling the thick, sticky horse chestnut buds. She listens to the forest, the chatter that has always sustained her. But all she can hear is the wisdom of crowds.

Half a year passes at the bottom of a well. One crisp blue summer Sunday, Patricia finds several unexpanded caps of *Amanita bisporigera* in the bottomlands of Token Creek. She gathers them in her mushroom bag and brings them home. There, she cooks up a Sunday feast for one: chicken tenderloins in butter, garlic, shallots, and white wine, all seasoned with enough Destroying Angel to shut down both kidneys and liver.

She sits to a meal that smells like health itself. The beauty of the plan is that no one will know. Every year, amateur mycologists mistake young *A. bisporigera* for *Agaricus silvicola* or even *Volvariella volvacea*. No one will think anything but this: She was wrong in her controversial research, and wrong in her choice of fungal fruiting bodies for her dinner.

She brings the steaming forkful to her lips. Something stops her. Signals flood her muscles, finer than words.

*Not this. Come with. Fear nothing.*

The fork drops back to the plate. She rouses as from sleepwalking. Fork, plate, mushroom feast: everything turns, as she watches, into a fit of madness, lifted. The opinion of others left her ready to suffer the most agonizing death. She runs the entire meal down the disposal and goes hungry, a hunger more wonderful than any meal. Nothing in the years to come can do worse than she was ready to do to herself. Human estimation can no longer touch her. She's free now to experiment. To discover anything.

From the outside, yes: Patricia Westerford disappears into underemployment. Sorting storeroom boxes. Cleaning floors. Odd jobs leading from the Upper Midwest through the Great Plains toward the high

Only one conclusion makes sense: wounded trees send out alarms that other trees smell. These brainless, stationary trunks protect each other.

mountains. All her old friends add her to the roster of science roadkill. In fact, she's busy learning a foreign language. With few claims on her time and none on her soul, she turns back into the woods, the green negation of all careers. She no longer theorizes or speculates. Just watches, notes, and sketches into a stack of notebooks, her only persistent possessions. Her eyes go near and narrow. She camps out many nights, under the spruce and fir, sleeping on thick beds of brown needle pillow, the living earth beneath her bag, its fluid influence rising up into her fiber.

She drifts farther west. It's amazing how far a little war chest will go, once you learn how to forage. She glimpses her own face once, splashing water on it in the bathroom of a service station near a national forest in a state where she's the merest beginner. She looks weathered, old beyond her years. She has gone to seed. Soon she'll start scaring people. So be it. She has always scared people. Fear has its uses. The stepstool to wonder.

In the early eighties, Patricia heads northwest. Giants still grow there, in pockets of old growth scattered from Northern California on up to Washington. She wants to see uncut forest, while there's some left to see. The western Cascades in a damp September: Nothing prepares her. From mid-distance, with no clue for scale, the trees seem no larger than the biggest sycamores and tulip poplars out East. But up close the illusion disappears, and all she can do is look and laugh and look some more.

Hemlock, grand fir, yellow cedar, Douglas-fir: Monster conifers disappear in the mist above. Sitka

spruces bulge out in burls as big as minivans—pound for pound, a wood stronger than steel. A single trunk could fill a logging truck. Even runts here would dominate an eastern forest, and each acre holds five times as much wood. Beneath these giants, way down in the understory, her own body seems freakishly small, like one of those acorn-people she made in childhood.

Chatter disturbs the cathedral hush. The air is so twilight-green she feels like she's underwater. It rains particles—broken webs and mammal dander, skeletonized mites, insect frass, and bird feather ... Everything climbs over everything else, fighting for scraps of light. If she holds still too long, vines will overrun her. She walks, crunching ten thousand invertebrates with every step, watching for tracks in a place where at least one of the native languages uses the same word for footprint and understanding. The earth gives beneath her like a shot mattress. She swings her singing stick, and the temperature plummets as she passes through a thermal curtain. The canopy is a colander stippling the beetle-swarmed surfaces with specks of sun. Sword fern, liverworts, lichen, and leaves as small as sand grains stain every inch of the dank, downed logs. The mosses are as dense as thumbnail forests.

She presses on bark fissures and her fingers sink in. The rot is prodigious. Creature-riddled boles, decaying for centuries. Twisted snags, silvery as inverted icicles. The scent of ever-dying life woven together with fungal filaments and dew-betrayed spiderweb leaves her woozy. Mushrooms climb the sides of trunks in terraced ledges. Soaked by fog all winter long, spongy green stuff she can't name covers every wooden pillar in thick baize.

She sees the source of that forestry doctrine she so resisted in school. Looking at all this glorious decay, a person might be forgiven for thinking that old meant decadent, that such thick mats of decomposition were cellulose cemeteries in need of the rejuvenating ax.

Her kind will always dread these close, choked thickets, where solo trees give way to massed, crazed tangles. There are things in here worse than wolves and witches, primal fears that no amount of civilizing will ever tame.

Prodigious dying pulls her along, past an immense western red cedar. Her hand strokes the fibrous strips that peel from a colossal, fluted trunk reeking of incense. The top has sheared off, replaced by a candelabra of stand-in trunks. A grotto opens at ground level in the rotted heartwood, big enough for whole families of mammals. But the scaly sprays of branches, a thousand years on, still teem with cones. She addresses the cedar, in words of the forest's first humans. "Long Life Maker. I'm here. Down here." She feels foolish, at first. But each word is a little easier than the next.

"Thank you for the baskets and the boxes. Thank you for the capes and hats and skirts. Thank you for the cradles. The beds. The diapers. Canoes. Paddles, harpoons, and nets. Poles, logs, posts. The rot-proof shakes and shingles. The kindling that will always light."

Finding no good reason to quit now, she lets the gratitude spill out, following the ancient formula. "Thank you for the tools. The chests. The decking. The closets. The paneling. I forget ... Thank you for all these gifts that you have given." Not knowing how to stop, she adds, "We're sorry. We didn't know how hard it is for you to grow back."

She finds work with the Bureau of Land Management. Wilderness ranger. The job description seems as miraculous as the outsized trees: Help preserve and protect for present and future generations places where man is a visitor who does not remain. She must don a uniform. But they pay her to be alone, carry the welcome weight of a pack, read a topo map, dig a water bar, look for smoke and fire, follow the rhythms of the land, and live wholly within the arc of the year. To clean up after humankind, yes. To gather the endless twisties, six-pack rings, cans, and bottle caps strewn through meadows of wildflower, on remote scenic outlooks, and in cold running streams. It's expiation.

> As if forests were waiting these four hundred million years for people to come cure them.

Her supervisor apologizes for the cabin they give her, on the edge of an ancient cedar grove. There's no running water, and the varmint biomass outweighs her, many times over. She laughs at their embarrassment. It's the Alhambra.

She works for eleven blissful months. The wildlife never once threatens her, and deranged campers do so only twice. Monster trees suck up the downpour and respire it back into the air as steam. In the constant rain, everything grows mold. Spores spread across every damp surface. Both her legs sport athlete's foot up to the knees. Sometimes, when she closes her eyes, she feels that moss will cover her lids by the time she opens them again.

While she rehabs backcountry fire rings and cleans up illegal campsites fouled with beer cans and toilet paper, an article appears. It's published in a reputable journal, one of the best that humankind has managed. Trees trade airborne aerosol signals, the article says. Their fragrances alert their neighbors. They can sense an attacking species and summon an air force to come to their aid. The authors cite Patricia's earlier, much-mocked article. They reproduce her findings and extend them into surprising places. Words of hers that she has all but forgotten have gone on drifting, signals on the open air.

Out one day in a nearby drainage, sawing windthrow from a remote trail, Patricia sees a motion in the undergrowth. It's a couple of vagabond scientists from that loose confederation who gather every summer in the flimsy trailers full of lab gear in a clearing three miles from her own cabin. She dreads these run-ins with her old tribe, always saying as little as possible. Today, she holds back and watches. Through the woods, the two men look like upright circus animals in lumberjack costumes.

One of the men hoots softly, a perfect impersonation. She has often heard the call at night but has never seen the caller. The man calls again. Incredibly, something answers. A duet ensues: the bright, pert come-on, followed by the logy, obliging bird. A streak in the air, and the creature appears, the first *Strix occidentalis* Patricia has ever seen. Spotted owl. It settles, mythic, on a branch three yards from its seducers. Bird and men regard each other. One species takes pictures. The other just spins its head and blinks its enormous eyes. Then the owl is gone, followed, after further note-taking, by the humans, leaving Patricia Westerford wondering if she wakes or sleeps.

Three weeks later, she's near the same spot, pulling invasive plants. The furry ailanthus suckers leave her fingers stinking of coffee and peanut butter. She climbs a switchback at a good clip and runs into the two researchers, several yards up the slope, kneeling by a downed log. Before she can flee, they see her and wave. Caught, she waves back and hikes up to them. The older man is on the ground, on his side, popping tiny creatures into specimen bottles.

"Ambrosia beetles?" Two heads turn toward her, startled. Dead logs: her passion once, and she forgets herself. "When I was a student, my teacher told us that fallen trunks were nothing but fire hazards."

The man on the ground stares up at her. "Mine said the same thing."

" 'Clear them off to improve forest health.' "

" 'Burn them out for safety and cleanliness.' "

" 'Lay down the law and get the stagnant place producing again!' "

All three chuckle. But the chuckle is like pressing on a wound. Improve forest health. As if forests were waiting these four hundred million years for people to come cure them. Science in the service of willful blindness: How could so many smart people have missed the obvious? A person has only to look, to see that dead logs are far more alive than living ones. But the senses never have much chance, against the power of doctrine.

"Well," the man on the ground says, "I'm sticking it to the old bastard now!"

Hope pushes through Patricia, like a breeze through rain. "What are you studying?"

"Fungi, arthropods, reptiles, amphibians, small mammals, frass, webs, denning, soil. ... Everything we can catch a dead log doing."

"How long have you been at it?"

The two men trade looks. The younger man hands down another sample bottle. "We're six years in."

"*Six years*?" In a field where most studies last a few months. "Where on earth did you find funding?"

"We're planning to study this particular log until it's gone."

She laughs again, a little wilder. A cedar trunk on the wet forest floor: their grad students' great-great-great-grandchildren will have to finish the project. Science, in her absence, has gone as crazy as she always thought it should be.

The man on the ground sits up. "Dr. Westerford?"

She blinks, as baffled as any owl. Then she remembers her uniform badge, there for anybody to read. But *Dr*. He could only have gotten that from her buried past. "I'm sorry," she says. "I don't remember meeting you."

"You haven't! I heard you talk, years ago. Forest studies conference, in Columbus. Airborne signaling. I was so impressed, I ordered offprints of your article."

That wasn't me, she wants to say. That was someone else, lying dead and rotting somewhere.

"They hit you pretty hard."

She shrugs. The younger scientist looks on like a kid on a visit to the Smithsonian.

"I knew you'd be vindicated."

Her bewilderment is enough to tell him what she's doing here. Why she's in the uniform of a wilderness ranger.

"Patricia. I'm Henry. This is Jason." His voice is soft but urgent, like there's something at stake. And she knows what it is, before he can say. The story reaches her, on airborne pheromones. Science has come to drag her back, like Persephone, to the world of humans. "Come visit the station. You'll want to learn what your work's been up to, while you were gone."

---

**RICHARD POWERS** is the author of 12 novels, including *The Overstory*, which won the 2019 Pulitzer Prize for Fiction. He is the recipient of a MacArthur grant and the National Book Award, and has been a four-time National Book Critics Circle finalist. He lives in the foothills of the Great Smoky Mountains.

---

# Does Theranos Mark the Peak of the Silicon Valley Bubble?

*The lessons of a $1 billion fraud*

**BY MICHAEL SEGAL**

PHOTOCOLLAGE CREDITS: STUDIOVIN; IFONG / SHUTTERSTOCK

**SILICON VALLEY HAS A TERM** for startups that reach the $1 billion valuation mark: unicorns. The term is instructive. It suggests not only that hugely successful startups are rare, but also that there's something unreal about them.

There's no recent Valley startup that satisfies both dimensions better than Theranos. Founded by a 19-year-old Stanford University dropout, Elizabeth Holmes, who went on to become the world's youngest self-made female billionaire, it raised nearly $1 billion from investors and was valued at $10 billion at its peak. It claimed to have developed technology that dramatically increased the affordability, convenience, and speed of blood testing. It partnered with Safeway and Walgreens, which together spent hundreds of millions of dollars building in-store clinics that were to offer Theranos tests. Tens of thousands of Americans had their blood tested by its proprietary technology.

The problem was Theranos' technology was never close to ready. In a series of devastating articles published in the *Wall Street Journal* starting in 2015, reporter John Carreyrou reminded us that unicorns are found only in fairy tales. Theranos, he reported, was analyzing many of its blood samples with off-the-shelf blood analyzers. Samples analyzed with Theranos' own technology often produced inaccurate results. Some patients were rushed to a hospital on the basis of erroneous readings, only to be sent home when their blood was properly analyzed by the hospital. Even worse, Theranos was using brutal intimidation tactics against its own employees to stop the truth from coming out.

Carreyrou's book about the Theranos saga, *Bad Blood*, was released in May 2018. It reads like a page-turner in the finest tradition of Michael Crichton, complete with secondary and tertiary characters and finely detailed scene settings, with the tragic difference that everything in it is true. It has already been purchased by a Hollywood studio, which has cast Jennifer Lawrence as Holmes. In September 2018, Theranos ceased operations. Holmes has been charged by the federal government with conspiracy and wire fraud. She has pled not guilty.

# She got defensive at the probing questions and eventually left in a huff.

**If someone told you that your Theranos reporting would end up as a Hollywood movie, what would you have said?**

You know it's funny, because early on in my reporting I felt like I was in a movie, especially when Theranos started waging a scorched-earth campaign against me and my sources. Yeah, I wouldn't have believed it if someone would have told me it was going to be a Hollywood movie and Jennifer Lawrence was going to play Elizabeth Holmes.

**What was Theranos' vision?**

The vision to begin with was a portable blood testing device that could run the full range of lab tests, any tests you really needed, from a drop or two of blood pricked from the finger with results that you would get back very fast and at a fraction of the cost of traditional laboratories. The dream was to eventually have these machines in people's homes.

**Why is that a big deal?**

There are a lot of people who dread the hypodermic needle, and hate seeing tubes and tubes of blood drawn from their arm, and actually put off blood draws and don't get lab tests done as often as they should. Assuming what Theranos said it invented was real, it could have been a game changer, and could have resulted in people getting their blood tested more often. It could have changed the dynamics of the blood testing industry, where you have two giants—Quest and LabCorp—who essentially exercise a duopoly.

**Who was Elizabeth Holmes when she started the company?**

She was 19 years old and was midway through her sophomore year at Stanford. And she dropped out and incorporated the company, first as Real-Time Cures before later changing the name to Theranos, which was a combination of the words therapy and diagnosis. That was in reference to her very first idea, which was this futuristic arm patch that would draw blood through micro-needles, diagnose you, and then inject the appropriate drug to cure you. She and her cofounder realized very quickly that was essentially science fiction and not feasible, so they pivoted to something inspired by portable glucose monitors. Holmes wanted this new machine to do every blood test under the sun, not just blood sugar.

**Were other groups pursuing the goal of doing many blood tests from a drop of blood?**

There are thousands of scientists who have been

KRISTA KENNELL

working on this for 20 years in universities and academia. As far as I know based on my reporting, no one has yet cracked this nut.

**It took a bit of ego to walk in and say, "I'm going to do this on my own."**

It was a combination of fraud and hubris. She and Sunny Balwani [Theranos' president] didn't even have the curiosity to see what competitors were doing and how they were innovating. There was zero curiosity on their part and therefore zero knowledge about what others were doing to innovate in the space.

**Who's the leader in the space?**

Well, one instrument that has come up again and again as one that actually works is called Piccolo Xpress, from a company called Abaxis. It has been commercialized for a while, and can do about 30 or 31 general chemistry assays off a small sample. It's a semi-portable machine and looks like a miniature ATM. Holmes met with a firm called MedVenture Associates in the early days of Theranos that had a lot of experience in medical technology and had invested in Abaxis. They were familiar with microfluidics and they asked her questions about how her envisioned technology was going to differ from Abaxis.' She didn't even know that Abaxis had a device and she certainly didn't understand how it worked. She got defensive at the probing questions and eventually left in a huff.

**VISIONS OF GRANDEUR** Elizabeth Holmes in 2015.

**What technology did Theranos actually develop?**
Basically there were three iterations of the technology. The first one used microfluidics, which are basically the repurposing of the micro-fabrication techniques that the computer chip industry pioneered to move tiny volumes of liquid. Theranos tried to work on that for several years before Holmes lost patience in late fall 2007 and abandoned it.

At that point she pivoted to what was essentially a converted glue-dispensing robot. One of the engineers ordered a glue-dispensing robot from a company called Fisnar in New Jersey, studied its components and rebuilt a smaller version of it. It was a robotic arm on a gantry with three degrees of motion and a pipette stuck to its end, and it replicated what the scientist does at the bench. That ended up being called the Edison and it could do only one class of test, known as immunoassays. It was also error-prone.

The third iteration of the technology was the miniLab, which Holmes wanted to be able to do more than just immunoassays. The miniLab didn't invent any new techniques to test blood with. It miniaturized existing laboratory instruments and packed them into one box. By the time Theranos went live with its tests, the miniLab was a malfunctioning prototype.

**What services did Theranos offer?**
Theranos offered 250 different blood tests. Twelve of them were handled by the Edison, and not well, because there were errors. The other 238 were done with regular, old laboratory machines bought from third parties like Siemens. Theranos kept up the illusion that they were running a lot of the tests from finger-stick blood draws by hacking the Siemens machines to work with small samples.

**How much money did Theranos raise?**
All together it was $900 million. If you count the $65 million in debt financing she got last year from Fortress Investment Group, the New York private equity fund, it's almost $1 billion in all. What's noteworthy is that the lion's share of that money was raised after 2013, after she went live with finger-stick tests in Walgreens stores. Getting the validation from making the technology commercial was really what enabled her to raise most of the funding. That's where the securities fraud part of this comes into play. Early investors like Larry Ellison and Tim Draper were not defrauded. They invested in a brand new startup with a vision, and they knew very well that most startups fail. The investors who came in after 2013 were presented with a company that was 10 years old and that was telling them it had a product that did the full range of tests.

**How is it possible that so many smart people got hoodwinked?**
Holmes was masterful at leveraging the credibility of people with good reputations who were older than she was. The first guy who vouched for her and gave her credibility when she was still a teenager was Channing Robertson, who was a star of the engineering faculty at Stanford and who had been an expert witness for plaintiffs against the tobacco industry. He accompanied her on some pitches to VC firms and gave her credibility. Then, she met Donald L. Lucas, who famously groomed Larry Ellison and helped him launch Oracle publicly. She wrapped Lucas around her finger. He became the chair of her board. He also put her in touch with other investors in the Valley. Then, when Lucas started getting addled by Alzheimer's Disease by 2011, she pivoted to another mark, another older guy—George Shultz, the former secretary of state. By all accounts, Shultz is passionate about science. When she presented her vision to him and told him about her technology, he was wowed and joined her board. Then he introduced her to all these other famous people, the likes of Henry Kissinger and Sam Nunn and Bill Perry, who had been secretary of defense under Clinton. They joined the board themselves, lured in part by shares that were worth millions of dollars. People thought, "Well she must be the real thing if she's got this fantastic board."

**But none of these people are scientists.**
Right. And that's where you can fault people for being too gullible. One of the first things I looked at when I started doing my digging into the company was how many of the dozen or so board members had any experience in medicine. The answer was two: William Foege, the former CDC director, and Bill Frist, who had been a surgeon before becoming a politician. Neither of them had any particular expertise in laboratory science or blood testing. The rest of the board were

statesmen between the ages of 65 and 90, and former military commanders. It's really not people that made sense to have on the board of a blood testing company.

**What were employees telling the outside world?**
There were quite a few negative, heartfelt reviews that were being posted anonymously by current and former employees about the company and its practices and culture. Sunny Balwani would have members of the HR department put out a steady stream of fake positive reviews to drown out the negative reviews. That was one of the very surreal aspects of this saga.

**How did you first come to suspect something was wrong at Theranos?**
The first tip was a third-hand tip. It was a practicing pathologist in Missouri who moonlighted as the writer of this obscure blog called the Pathology Blawg. He had read a profile in the *New Yorker* magazine about Holmes and wrote a short skeptical item about it. Then he was contacted by a group of people who had either feuded with Holmes or had reason to distrust her. The reason I persevered is I heard early on that there was a primary source out there who was gettable. I pulled on that string. If I hadn't known of any primary source, I'm not sure I would have spent as much time on it.

**What would you say to a science whistleblower today who maybe doesn't have access to someone like you?**
There's always the possibility of filing complaints quietly and secretly with the regulator, which is ultimately what one of my confidential sources did. Erika Cheung, who worked at Theranos for several months in late 2013 and early 2014, eventually got up the courage to go to a laboratory inspector at the CMS (Centers for Medicare and Medicaid Services), who then immediately launched an inspection of the company. That inspection proved crucial in backing up my reports in the *Journal*. You can also file complaints with the SEC and DOJ.

**Regulators certainly come off as heroes in the Theranos story.**
They do. You can fault them for maybe not ferreting out what Theranos was doing soon enough, but once they did get the feeling that things that were going on there were not good, they went in in force, the two agencies, one after the other, and essentially shut the company down. I wouldn't be too hard on the FDA (Food and Drug Administration) or CMS, because they were lied to. When the CLIA (Clinical Laboratory Improvement Amendments) inspector came to renew the CLIA certificate of the Theranos lab in early December of 2013, she was not shown the part

Assuming what Theranos said it invented was real, it could have been a game changer.

downstairs that Theranos referred to as Normandy, where they had the Edisons and the hacked Siemens machines. She was only showed the regular lab with the commercial machines. That's misleading the CLIA inspector. That's lying to federal officials.

**The role of lawyers in this story, by contrast, was fairly negative.**

Right. The lawyers were there to steamroll people and to intimidate them and to silence them. Holmes' lawyer, David Boies, was a stroke of genius on Holmes' part, because he was a real scarecrow for employees who had qualms and who had questions about the way the company was operating. The threat of litigation and of David Boies coming after them was always in the air. As a result, no one spoke up. That's really what enabled this to go on as long as it did.

**What did you learn about the culture of Silicon Valley while reporting this story?**

One thing I learned is that there's certainly a lot of innovation there, but there's also an unbelievable amount of arrogance and pretending. People in the Valley, just because they made some money, come to assume and to project an image of intelligence and knowing it all. Just because you made some money doesn't mean you're invaluable and doesn't mean that you can pioneer a field in which you have no training. I feel like Theranos is a cautionary tale about the hubris in the Valley.

**Is Theranos a sign of the peak of the Valley bubble?**

I was convinced that, when my story came out, it would mark the peak of the unicorn boom. Really the bubble hasn't deflated—maybe a little bit, but not all that much, not in the way that the dot-com bubble deflated in 2000 and 2001. We haven't seen that in part because these companies are mostly not publicly traded. It takes longer for the real evaluations to work themselves out. But would I maintain today that Theranos is a syndrome of peak Valley? Absolutely.

**Should we be surprised that Theranos happened, or surprised that it doesn't happen more?**

I don't think we should be surprised given what's gone on in Silicon Valley in the past 10 years with this gigantic flow of money into the Valley in large part triggered by the fact that the Fed kept interest rates so low and investors looked for new places to get returns. With that amount of money flowing in and founders being able to pick and choose who funds them and to turn down investors who do too much due diligence, you

There's certainly a lot of innovation in Silicon Valley, but there's also an unbelievable amount of arrogance and pretending.

have the ingredients for excess and for wrongdoing. I came up as a journalist in the '90s and reported on some of the corporate scandals around when Enron fell apart. Those, for the most part, were publicly traded companies. Now we have this ecosystem in Silicon Valley of private companies that don't have the same obligations of putting out quarterly reports and opening the kimono. As a result, I think the risk of things going wrong and of people cutting corners is greater. I don't think we should be surprised that it's come to this.

**What needs to change?**

The SEC needs to police these private companies more, and I think it's beginning to do that. It signaled with the charges filed against Theranos that it's going to do so, because private companies are going to argue, "Well, why is this the SEC's business? The SEC's supposed to police the public markets." But there are markets where you can buy the shares of these unicorns, so the shares of these unicorns are trading. It's the SEC's job to police this opaque market. The other thing that I would say is going to be important is whether or not the Justice Department files criminal charges in the Theranos matter. My sources are telling me that that investigation, which has been going on for more than two years, is drawing close to a conclusion and that indictments are likely. I think if indictments are handed up by the grand jury, that is going to be an enormous signal to the Silicon Valley ecosystem that there are consequences for wrongdoing and that it won't be as easy to get away with this stuff anymore.

MICHAEL SEGAL is the editor at large of *Nautilus*.

# Why New Antibiotics Are So Hard to Find

*A dispatch from the front lines of the war against antibiotic resistance*

**BY JULIAN G. WEST**

**AN 86-YEAR-OLD PATIENT ARRIVES** with a grisly foot injury.[1] It's badly infected—not a surprise, given his chronic untreated Type 2 diabetes. What is surprising is that meropenem, a broad spectrum antibiotic, and vancomycin, known as the antibiotic of last resort, have absolutely no effect.

The doctors know something bad is going on. But, even expecting the worst, the test results surprise them. The man's foot is infected with not one, but three different bacteria: *Staphylococcus aureus*, *Acinetobacter baumannii*, and *Acinetobacter lwoffii*. Each is multi-drug resistant. The hospital, located in Brazil, simply doesn't have the resources to deal with the situation. The patient is transferred to a larger hospital, but enough damage has already been done to his foot to require amputation.

This real story, reported in 2012, is one of many. There was also the 57-year-old woman in Washington, D.C. whose heart failure was caused by a penicillin-resistant bacteria.[2] Or the woman who died in quarantine after being admitted to a Nevada hospital with an infection resistant to every antibiotic the hospital had access to.[3]

An estimated 2 million Americans are infected with antibiotic resistant microbes every year and, of these, about 23,000 die.[4] Humans have known how to kill bacteria since before the dawn of civilization. So why is killing bacteria in patients resisting the combined efforts of modern science?

**THE FIRST STEPS** to antibiotic therapy were made by the British surgeon Joseph Lister in 1867.[5] Lister noticed that many of his surgical patients required amputations or died shortly after their procedures. Many credited this to the influence of "miasmas" (noxious, "bad" air) or oxygen on the open wound.

Lister had a different theory. He had been following the work of French microbiologist Louis Pasteur, who had shown that the spoilage of food was not due to oxygen, but to tiny, microscopic organisms. Lister hypothesized that these same organisms were responsible for

PHOTO COLLAGE CREDITS: KATERYNA KON; OZAIACHIN / SHUTTERSTOCK

his patients' terrible outcomes. Pasteur had given three options for avoiding this outcome: filtering the organisms away, cooking them to death, or killing them with a chemical. The first two options could be immediately ruled out, but the third proved intriguing.

Lister, being a curious and scholarly scientist, had recently heard of the use of creosote, or coal tar distillate, to prevent railway ties from rotting. Intuiting that these same troublesome microorganisms were to blame, he decided to try a component of coal tar distillate, carbolic acid, to treat his patients' wounds. The initial results were striking: Patients with compound fractures, who almost universally required amputation, were now able to make full recoveries with their limbs intact.

What Lister had found was the first medical antiseptic—not an antibiotic. Carbolic acid was poisonous to humans too, so it could only be applied sparingly to wounds. Paul Ehrlich, a prolific and brilliant German scientist, wanted to do better. He was fascinated with the old folktale of the Freischütz, a marksman who made a deal with the devil to receive six magic bullets that would hit a target and avoid everything that might get in the way. Would it be possible to make a chemical magic bullet that would kill bacteria but not human cells?

Ehrlich's background was in histology, particularly in staining samples for viewing under the microscope. Ehrlich discovered that certain dye molecules would stain some cells but not others, seeking out their targets like the mythical magic bullets. Ehrlich theorized that the right dye molecules might be able to realize his dream of a selective antibiotic.

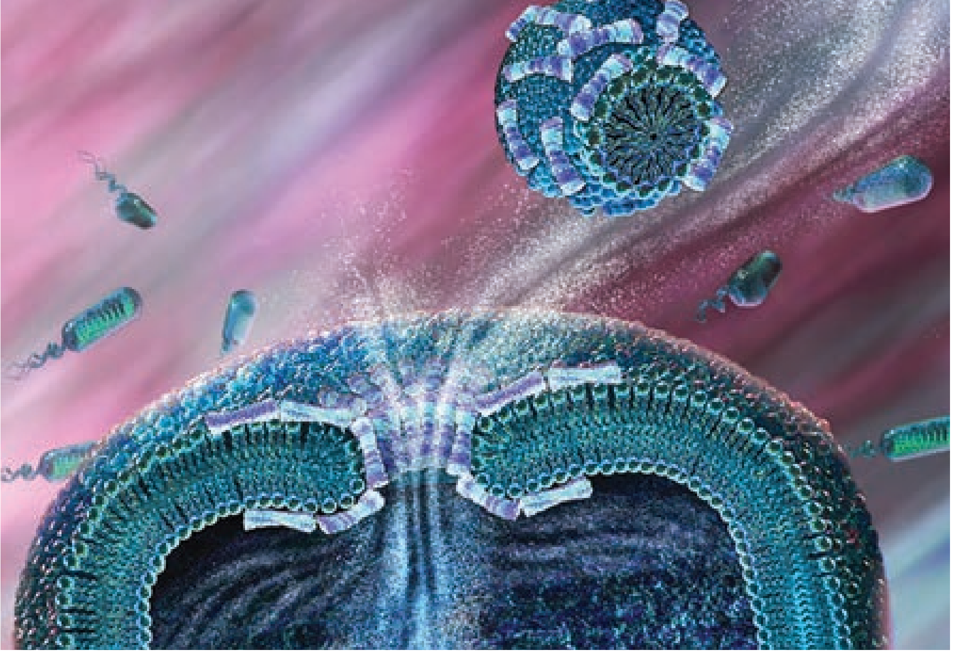
Finally, in 1909, Ehrlich's idea was achieved in arsphenamine, an arsenic-based dye able to kill syphilis bacteria without killing the patient. Arsphenamine was only really effective against syphilis, though. Researchers at the Bayer sector of the German conglomerate, IG Farben, wondered if this same approach could lead to an antibiotic for broader use. Chemists Josef Klarer and Fritz Miestzsch synthesized thousands of dyes that were tested on infected laboratory mice by Gerhard Domagk. After countless failures, one dye, prontosil, succeeded, delivering the first truly versatile antibiotic.

While the Bayer team assumed that Ehrlich's dye hypothesis was the reason for prontosil's effectiveness, subsequent research showed that it has nothing to do with its ability to stain cells.

So what makes an antibiotic tick?

**IT'S RELATIVELY EASY** to find new antiseptics, which can kill microbes on the skin and the surface of tissues.

# Chemicals that break an essential part of a bacterial cell will usually break the same part of human cells.



**ACTION HERO**
Computer illustration showing antimicrobial peptides penetrating a bacterium's membrane.

NICOLLE R. FULLER / SCIENCE PHOTO LIBRARY / SHUTTERSTOCK

But antiseptics make terrible antibiotics: Chemicals that break an essential part of a bacterial cell will usually break the same part of human cells. Luckily, sometimes there are bacterial parts not found in humans, or if they are, they are very different. This is the key to antibiotic function: exploiting the fact that bacteria are similar to human cells without being identical.

In the century or so since the first antibiotic was found, we've discovered a small library of bacteria-specific features to disrupt.[6] The antibiotic sulfanilamide, for example, targets a part of bacterial life that doesn't exist in humans. Folates like vitamin B9 are essential for DNA synthesis in all organisms. Humans get them by eating fruits and vegetables, but bacteria have to make them from scratch through processes foreign to human cells. Like other sulfa drugs, sulfanilamide plugs up one enzyme in one pathway of one process, stopping bacterial DNA synthesis in its tracks while having no effects on human metabolism.

Penicillin, serendipitously discovered by Alexander Fleming in 1928, and other beta lactam antibiotics (like meropenem) also target a part of bacteria that human cells don't have: the cell wall. Bacterial cells are a lot like an overstuffed roast being kept together by butcher's twine. When that butcher's twine—the cell wall—is removed, bacterial cells literally explode.

Bacteria build their cell walls a lot like how people build fences. After putting up some fence posts, the horizontal supports and boards are attached with the equivalent of a nail gun. What penicillin does is jam the bacteria's nail gun, preventing any of the posts in its cell wall from being connected. Glycopeptide antibiotics like vancomycin, on the other hand, wrap around the cell wall's fence posts like a thick bulletproof blanket. The nail gun still works, but none of the nails can get into the fence post.

These are the ideal cases. The other main classes of antibiotics target parts of bacterial life that are more similar to mechanisms in human cells—but still just different enough to allow them to be targeted. These differences can be very subtle, with the active walking a fine line between being selective antibiotics and antiseptics.

Many drugs target the manufacture of proteins, for example. Antibiotics can prevent tightly wound DNA from being unpacked and read, jam the RNA transcription process, or shut down the molecular factory that turns molecular RNA into proteins. In each case, the equivalent process in a human cell is performed by enzymes that are shaped differently and don't have the same handholds that the antibiotics need to do their work. It would be a problem if they did, however, as stopping any of these activities is just as deadly for human cells as for bacteria.

**THAT'S THE OFFENSE SIDE** of the story. There is also the defense: Bacteria have a tendency to fight back. One simple defense is to simply kick the antibiotics out before they can cause any damage. Like how a sump pump constantly removes water from a basement to keep it from flooding, bacterial efflux pumps constantly remove antibiotics to keep them from doing their work. One efflux pump might give multi-drug resistance by recognizing and removing several different kinds of antibiotics, making this a difficult resistance mechanism to deal with.

Bacteria can also make new proteins that break open and disarm antibiotics before they can act. Perhaps the most well-known example of this strategy is the bacterial manufacture of penicillinase, a new enzyme whose sole function is to break open the spring-loaded penicillin molecule before it can gum up the machinery that makes cell walls. These types of proteins are quite specific to one kind of antibiotic and don't usually give resistance to other classes. One way that we've been able to defeat this resistance mechanism is to package the original antibiotic with a new one for the new enzyme.

Another defense bacteria have is to make proteins that fit antibiotics with molecular straightjackets, preventing them from grabbing onto their targets and rendering them helpless bystanders. These enzymes work by attaching chemical groups known as phosphoryl, acetyl, nucleotidyl, glycosyl, or hydroxyl to key parts of the antibiotics, blocking them from interacting with the part of the bacteria they're supposed to disable. These enzymes are usually selective for members of one antibiotic family, so, again, cross resistance is often not a problem.

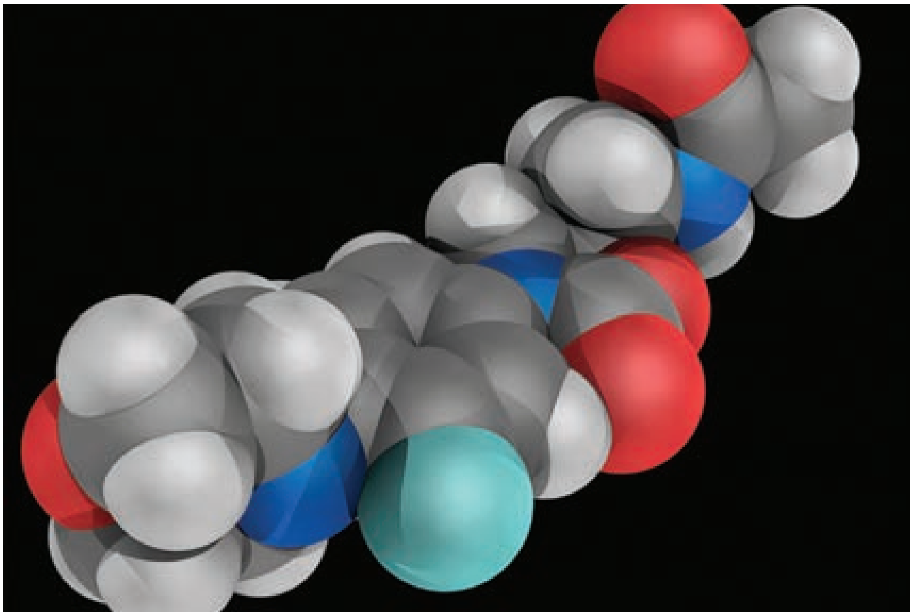
Perhaps the most obvious and confounding method of resistance bacteria have at their disposal is simply changing the target of an antibiotic so much that it no longer recognizes it. This method of resistance is very common, and there are many ways to accomplish it. For example, just changing the end-cap of the cell wall posts from the amino acid D-alanine to D-lactate, a very small adjustment, makes aminoglycoside antibiotics like vancomycin completely useless. Once the target has changed, it's impossible to hit it with the same magic bullet.

In principle, the response to this kind of resistance is to simply find a new magic bullet. But many antibiotics have come from microorganisms themselves, where the fight for survival has forced one species to make weapons to defeat their competitors. The way these microorganisms typically make antibiotics is not very flexible: They are very good at making a specific key but have trouble adjusting it if it stops fitting into the target's lock. We have also discovered many of the obvious antibiotics derived from nature, and are running out of low-hanging fruit. All but one (ceftaroline) of the broad-spectrum antibiotics we use today were discovered over a decade ago, with almost half found in the "Golden Age" between 1950 and 1960.[7]

There are many other approaches. One that is attracting a lot of attention is the pursuit of cryptic antibiotics, which involves forcing bacteria to make molecules that they don't usually make.[8] The jury is still out on whether this approach will work. Our best option today is often to turn to organic chemistry, which has given us exquisite tools to tune molecules in ways otherwise unimaginable.[9] Linezolid, an antibiotic that stops the ribosome from laying the foundation for new proteins, was invented from scratch by human beings using the techniques of organic chemistry. We can also use organic chemistry to tweak antibiotics

**BETTER THAN REAL**

A molecular model of linezolid, a synthetic antibiotic used for the treatment of resistant infections. Grey, white, blue, red, and cyan atoms are carbon, hydrogen, nitrogen, oxygen, and fluorine respectively.



that we discover in nature. The company Tetraphase, for example, is working to adjust tetracyclines to fit a variety of resistant bacterial locks.

The one thing we can't do is give up, because bacteria never will. Pharmaceuticals have spent billions searching for new antibiotics, though many gave up after finding nothing but failure.[10] This is dangerous. We need to understand that the search will be slow and difficult. I've spent my career designing better organic chemistry tools for making molecules like antibiotics faster, but even with these new inventions, the process isn't easy. Antibiotic resistance is an arms race where humans are starting to fall behind. Unless we want to lose, we need to do more now. All our lives depend on it.

---

**JULIAN G. WEST** is a chemist and writer in Pasadena, CA. He is currently a postdoctoral fellow at the California Institute of Technology. Follow him on Twitter @pushingarrows.

## REFERENCES

1. Neto, R.M., Ansaldi Jr., M.A., da Costa, M.E.S.M., da Silva, S.M., & Luz, V.H.F. Report of a multi-drug resistant bacterial infection in a diabetic patient treated in northeast Brazil. *Diabetic Foot & Ankle* **3**, 18656 (2012).

2. Siegel, M. & Timpone, J. Penicillin-resistant *Streptococcus pnuemoniae* endocarditis: A case report and review. *Clinical Infectious Diseases* **32**, 972–974 (2001).

3. Chen, L., Todd, R., Kiehlbauch, J., Walters, M., & Kallen, A. Pan-resistant New Delhi metallo-beta-lactamase-producing *Klebsiella pneumonia*—Washoe County, Nevada, 2016. *Morbidity and Mortality Weekly Report* **66**, 33 (2017).

4. Centers for Disease Control and Prevention. Antibiotic Resistance Threats in the United States, 2013. Retrieved from https://www.cdc.gov/drugresistance/threat-report-2013/index.html

5. Rosen, W. *Miracle Cure: The Creation of Antibiotics and the Birth of Modern Medicine* Viking, New York, NY (2017).

6. Kapoor, G., Saigal, S., & Elongavan, A. Action and resistance mechanisms of antibiotics: A guide for clinicians. *Journal of Anaesthesiology Clinical Pharmacology* **33**, 300–305 (2017).

7. Davis, J. Where have all the antibiotics gone? *Canadian Journal of Infectious Diseases and Medical Microbiology* **17**, 287–290 (2006).

8. Rosen, P.C. & Seyedsayamdost, M.R. Though much is taken, much abides: Finding new antibiotics using old ones. *Biochemistry* **56**, 4925–4926 (2017).

9. Liu, J., Bedell, T.A., West, J.G., & Sorensen, E.J. Design and synthesis of molecular scaffolds with anti-infective activity. *Tetrahedron* **72**, 3579–3592 (2016).

10. Lowe, D. Antibiotics: Not As Easy As They Say. http://blogs.sciencemag.org (2015).

LAGUNA DESIGN

ILLUSTRATION BY **JACKIE FERRENTINO**

# What Time Feels Like When You're Improvising

*The neurology of flow states*

**BY HEATHER BERLIN**

**DON'T LOOK AT THE CLOCK!** Now tell me: How much time has passed since you first logged on to your computer today? Time may be a property of physics, but it is also a property of the mind, which ultimately makes it a product of the brain. Time measures out and shapes our lives, and how we live our lives in turn affects how we perceive the passage of time. Your sense of time is malleable and subjective—it changes in response to changing contexts and input, and it can be distorted when the brain is damaged, or affected by drugs, disease, sleep deprivation, or naturally altered states of consciousness. However, a new set of neuroscience research findings suggests that losing track of time is also intimately bound up with creativity, beauty, and rapture.

Time is most commonly manipulated by the kinds of things we do to fill it. When our minds are under-stimulated, time often feels like it is moving in slow motion, as in the scene in *The Simpsons* where Bart is made to lick envelopes for Principal Skinner all afternoon and groans when the clock starts ticking backward. On the other hand, when we are fully engaged, especially in the kind of "flow state" familiar to artists, athletes, and other top performers, our sense of time appears to speed up, or even to disappear entirely.

Many people describe being "enchanted" or "transfixed" when watching a live performance or viewing their favorite work of art. For example, when exploring the European paintings section of the Metropolitan Museum of Art, I enter into a kind of dissociated, transcendent state, which many people report experiencing. All of our cares and worries disappear and time seems to stand still or fade away as we become lost in the world of the story, or work of art, or the virtuosity of the performer. This loss of time-awareness mirrors the process occurring in the brains of the performers or artists while they create.

During what psychologists call "flow states," where one is completely immersed and absorbed in a mental or physical act, people often report an altered sense of

PIXABAY

time, place, and self. It's a transportive and pleasurable experience that people seek to achieve, and that neuroscience is now seeking to understand. A great example of flow state is found in many improvised art forms, from music to acting to comedy to poetry, also known as "spontaneous creativity." Improvisation is a highly complex form of creative behavior that justly inspires our awe and admiration. The ability to improvise requires cognitive flexibility, divergent thinking, and discipline-specific skills, and it improves with training.

Not surprisingly, the frontal regions of the brain that have been shown to be involved in time perception and impulse control are also involved in spontaneous creativity. Improvisation appears to take place in an altered state of mind/brain, and studies of the neural mechanisms of musical improvisation have identified a network of prefrontal brain regions linked to improvisation. The creative act of improvisation, at least in the musical realm, appears to be a result of changing patterns of activity in two key areas of the prefrontal cortex (PFC).

During musical improvisation, in jazz or freestyle rap, studies show a distinctive increase in medial prefrontal cortex activation. The medial prefrontal cortex (mPFC) is a brain area known to be involved in intentional, internally generated self-expression and the pursuit of goal-oriented behaviors. This makes sense, since improvised performance requires you to come up with new material in a rapid stream, and deploy it just as quickly for a listening or watching audience. The other aspect to this pattern is a decrease in lateral orbitofrontal cortex and dorsolateral prefrontal cortex activation (DLPFC). The lateral orbitofrontal cortex (OFC) and dorsolateral prefrontal cortex are brain areas involved in conscious self-monitoring, effortful problem solving, focused attention, and evaluation and regulation of goal-directed or planned behaviors. These lateral areas assess whether behaviors conform to social norms, and exert inhibitory control over inappropriate or maladaptive behavior. But as any skilled performer will tell you, inhibitions are the enemy of improvisation.

When mPFC activation is turned up, it encourages the internal generation of ideas. And when lateral PFC brain areas are simultaneously turned down, it allows novel thoughts and behaviors to emerge uninhibited, leading to divergent thinking and unfiltered creativity. In other words, the inner critic must be shut down, and the inner Picasso turned up. Deactivation of lateral PFC regions is associated with free-floating, defocused attention, allowing spontaneous associations between ideas to arise, and sudden realizations or insights to occur. Creativity appears to occur when the DLPFC decreases its regulation of the contents of consciousness, allowing for unconscious, unfiltered, or random sensations and thoughts to arise in the flow state. Just as children will play more wildly when the teacher isn't watching, when we reduce the influence of the DLPFC on our behavior, it allows us to think more like artists.

Future research could explore whether this pattern of brain activity is in fact a neural signature of improvisation that occurs across all art forms, for instance during painting, theater, comedy, and dance improvisation, or whether the signature is unique to the musical and verbal forms it has been found in so far. When the lateral PFC regions—where our sense of agency is created after ongoing actions take place—decrease in activation, a performer's moment-to-moment decisions and actions may feel as if they are occurring outside of time and without conscious intention, as if they are "coming from somewhere else." This is consistent with a sentiment many artists express: that their creative process is being directed by a "muse" or outside agent.

However, improvising performers are not oblivious; momentary "check-ins" to see how your performance is going can provide necessary environmental (or audience) feedback, helping to revise your approach and optimize performance in real time. Creative thought also involves the "default mode network" (DMN), a set of brain regions active when attention is directed internally and suppressed when a person engages in externally directed tasks. The DMN is active when you're daydreaming, but not when you're filling out an application form, which requires executive control areas like the DLFPC. Improvisation requires a balance in activation between these two networks, reflecting the extent to which creative thought and behavior needs to be responsive to environmental input, and constrained by certain rules to meet the specific goals of the task at hand. But if you become overly self-aware or self-conscious for too long, you can lose the flow state and

# Inhibitions are the enemy of improvisation.

the performance will suffer. Of course, you don't need a cognitive neuroscientist to tell you that. Just listen to Eminem:

> You better lose yourself in the music, the moment
> You own it, you better never let it go
> You only get one shot, do not miss your chance to blow
> This opportunity comes once in a lifetime

Luckily, you do not need to be able to improvise (or take drugs) to achieve flow states. Deactivation of the lateral PFC also occurs during other altered states of consciousness such as meditation, hypnosis, and daydreaming. And a similar pattern of dissociated activation in PFC has been identified during REM sleep, where dreaming usually occurs. Dreaming involves unplanned, irrational associations, defocused attention, an altered sense of time, and a feeling of lack of agency or volitional control (with the exception of lucid dreaming). These same characteristics are associated with creativity when one is fully awake.

The sense of time passing, producing its changes and progressions, is a capacity our brains evolved for adaptive reasons. How long have I been sleeping? How soon do the kids need to eat? How fast will I have to walk to make it home before dark? Keeping track of time is something we do instinctively, and our instincts have recently been supplemented by cultural inventions such as clocks and calendars, which train our brains to map its instincts onto scales and increments. However, we have also evolved the ability to turn off this constant time-keeping, in moments of artistic rapture or contemplation, and that adaptive sense of timelessness gives our lives much of its beauty and meaning. How we choose to spend our time, which remains our most limited and valuable resource, is one of the greatest gifts, and responsibilities, we are given.

HEATHER BERLIN, Ph.D., MPH is a cognitive neuroscientist and assistant professor of psychiatry at the Icahn School of Medicine at Mount Sinai. She practices clinical neuropsychology at Weill Cornell Medicine in the Department of Neurological Surgery, and is a visiting scholar at the New York Psychoanalytic Society and Institute. She hosts Startalk All-Stars with Neil DeGrasse Tyson, and has hosted series on PBS and the Discovery Channel.

# This Man Says the Mind Has No Depths

*Nick Chater argues our brain is a storyteller, not a reporter from an inner world*

**BY KEVIN BERGER**

A **WHOLE LOT OF BOOKS** on the brain are published these days and you can read yourself into a coma trying to make sense of their various messages. So it was with my usual low-burn curiosity that I starting reading *The Mind Is Flat* by British behavioral scientist Nick Chater. At least the title is intriguing. But as I started reading it, I perked right up. Maybe that's because it starts with a long riff on Anna Karenina and asks us to plumb the motivations of her suicide. Can we explain them? What if the great steam engine slammed on its brakes and Anna didn't die? Would she be able to explain her own motivations to a psychologist while convalescing in a Swiss sanatorium?

Chater writes it makes no difference that Anna is a fictional character. We would go through the exact same mental peregrinations with a real person. In fact, the surviving real person, struggling to find clarity in the muddle of her feelings, would only be telling the psychologist a story about why she wanted to take her life. Chater's point is a bold one: There is no deep truth about motivations to be found. "No amount of therapy, dream analysis, word association, experiment or brain-scanning can recover a person's 'true motives,' not because they are difficult to find, but because there is nothing to find," he writes. "The inner, mental world, and the beliefs, motives, and fears it is supposed to contain is, itself, a work of the imagination."

Well, then, I thought, if Chater keeps up this audacious tone, *The Mind Is Flat* is going to be anything but flat. Indeed, as it makes its way through a modern landscape of cognitive research and experiments, it shoots one dart after another at treasured cultural notions about truths lurking in the tangles of our brains. Emotions are not pre-formed feelings waiting to burst forth, Chater writes, they are momentary improvisations to bodily reactions. Our brains are jazz players, he tells us, cooking up the best thoughts and behaviors for the moment. Tapping into a higher consciousness may be a beloved idea, Chater writes, but it amounts to "nonsense on stilts." James Joyce's *Ulysses* is an exploration of the innermost workings of the mind, you say? "Quite the reverse," Chater writes. Joyce and Virginia Woolf's celebrated stream-of-consciousness styles are "outputs of successful cycles of thought." (OK, that's a little clunky.)

Nevertheless, I raced through *The Mind Is Flat* fascinated. I've encountered shades of Chater's ideas in other recent books, notably *How Emotions Are Made*, in which author Lisa Feldman Barrett, a neuroscientist, illuminates in detail how an "emotion is your brain's creation of what your bodily sensations mean." But I was consistently engaged by Chater's brazen points—"We have all been victims of a hoax, perpetrated on us by our brains"—even if I was never quite sure they were right. And so I was anxious to talk to Chater in person, see if I could get him to clear up some of my misgivings about his portrait of the unconscious. He answered my questions with a cheerful spirit and thoughtful insights, along with the wit I associated with his book, particularly when he called Jung's collective unconscious "the astrology of psychology." I began by asking about psychotherapy because if there is one pillar of thought that Chater seeks to topple it's the idea that voyaging into the unconscious can set us free.

**Are you saying psychotherapy that tries to alleviate pain by bringing unconscious motives to the surface is ...**

Doomed?

**Yes, doomed. Why?**

It's doomed by the fact that there is not a deep inner story that is hiding from you. Rather, you've got the first draft or a set of incoherent notes for a novel. You've got an incoherent muddle. And we're all incoherent muddles to some degree. But when some of those incoherencies cause us problems, when we're terrified of something we very much want to do, even something as narrow as a fear of spiders, these are conflicts in our thinking and reactions.

**Do you believe in the value of psychotherapy?**

I do, yes. And I think a reasonable goal should be to help a person understand the world in a more coherent,

ALEX_PO / SHUTTERSTOCK

consistent, integrated way. This is a tremendously creative act on the patient's part.

**If only it were that easy.**

Right, it's hard. It's not that the therapist can say, "I see a tangle there, and let's untangle it and everything will be fine." It requires a creative leap. It's like writing novels is hard. You might think if all you've got to do is make everything consistent and fit together and have the characters make sense, and that's easy. But of course it isn't. We struggle to do it with our own lives, which are at least as complex as novels.

In fact, our minds are not based on consistency. They are based on precedent, on a transmutation or extension of past experiences. Our past experiences are built on each other and they create habits of thought. Sometimes the past is going to equip us quite badly. We're going to have patterns of behavior, patterns of thought, that haunt us and are hard to break out of.

Now, you might say, "Well, if there are no hidden mental depths, psychotherapy ought to be a piece of cake." But that fact actually makes it more difficult. It's not that there's a coherent story and we just need to tweak it a bit. It's that the whole project of creating an integrated understanding of one's life is just a really hard thing to do.

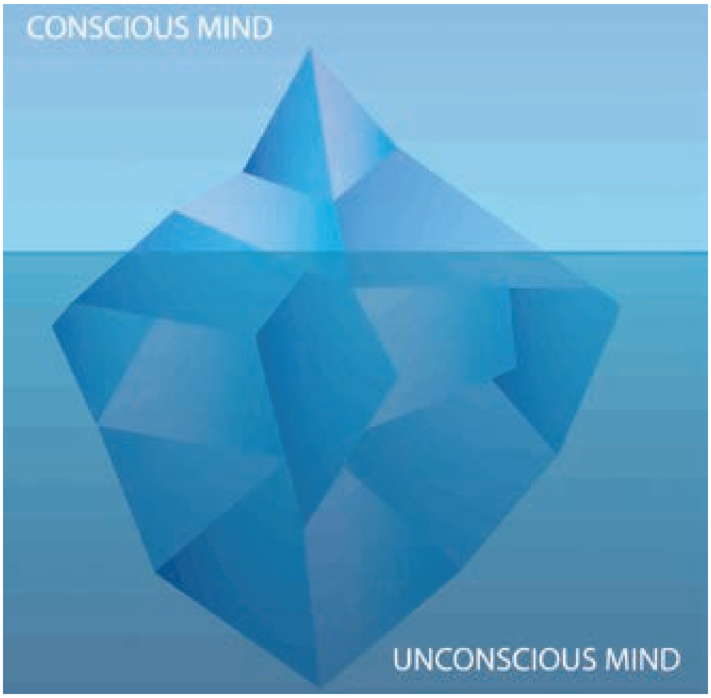
NICK CHATER

**Still, that sounds like we can just improvise our way out of problems. Let's consider grief. It overtakes your mind. How can a person think his way out of it?**

I don't think there's a winning solution to addressing any of life's problems in a particularly straightforward way. But what's likely happening in grief is a breakdown in one's understanding of one's life. If you think of something really awful like the loss of a child or a partner, one of the things that makes getting over

# If we imagine conscious thought is generated by hidden depths, we torture ourselves to find them.

COURTESY OF THE AUTHOR




**SURFACE THOUGHTS** Freud's iceberg/mind analogy couldn't be more misleading, Chater writes: "There are no conscious thoughts and unconscious thoughts ... There is just one type of thought, and each such thought has two aspects: a conscious read-out, and unconscious processes generating the read-out."

T AND Z / SHUTTERSTOCK

that really hard is the sense that this was not supposed to happen. This was not the script. Life is not supposed to do things like this. My life, my partner, my child's life, had a course, a direction. And now how do I make sense of what's happened? This makes no sense, it makes the world seem completely purposeless. A friend of mine whose marriage was breaking down said it's like someone's just taken the script and scrunched it up. The sense of the future is a void.

But once something unexpectedly awful happens, we need to rewrite that story. And I think when people are trying to change—grief being a big, difficult hurdle—a lot of that is creative re-imagining. We're trying to find a way of conceptualizing how the world can make sense when something as bad as this could happen. Maybe I can conceive of the departed person's life as a very good life. Shorter than I would have wished, but I can understand that there were many positive things.

**If you were a psychotherapist, what would you tell people?**

I suppose I would start by saying that how we interpret the people of the world around us, and the behavioral and mental habits that shape us, can crucially affect how we feel about our lives, and how well we can cope with them. So one aim of therapy is to help people construct new thoughts and patterns of behavior that can help them move forward. It is not, for example, about uncovering or correcting unconscious motives or beliefs—it is about helping the conscious mind move forward.

A better understanding of the shallow and improvised nature of our thinking may help—often, attempting to look deep inside ourselves can create some illusory problems for ourselves. If we imagine that our conscious thought is generated by hidden mental depths, we can start to torture ourselves about what those mental depths might contain. In the case of grief, we may wonder: "Am I feeling sad enough? Should I be feeling better this soon? Does that mean I didn't love my partner or child enough?" You become tormented by a search for what your true inner reality is, and I think that really hamstrings us.

People tear up relationships on similarly thin grounds. Suppose, for example, we look inside ourselves for the love I feel I ought to be feeling for my partner. But now I'm looking for it, where is it? Is it there at all? Or maybe it's not enough or maybe it's too much. You can get to a pathological state with this line of thinking. And that comes from this misconception that there's a true inner reality within me and my reality may not be as it should be. Indeed, the whole idea of the authentic feeling is dangerous because it presupposes there's a true feeling, and some fake ones, and the true ones are really deep inside me. And then we can worry endlessly about which of our feelings is true, and which isn't. We should be skeptical about those feelings.

**Why?**

Because to answer such questions about our inner world, our brain is creatively concocting an answer at the very moment we ask the question—not reading out from an inner library of preformed thoughts, feelings, and motivations. We can tell this because if we ask ourselves the same question in even subtly different ways we will get often flatly contradictory answers—our brain is an inveterate, and not entirely consistent, story spinner, not a reporter from an inner world. Yet the brain is such a fluent and compelling storyteller that we can so easily believe it is reporting fact, rather than creating fiction.

**OK, I see what you're saying. But I don't quite understand why you're dismissive of the unconscious. Our conscious thoughts and behavior are influenced by past memories and ingrained habits. So how can you say that the unconscious is a dangerous illusion?**

The reason I think the unconscious is a dangerous metaphor is because it gives you the impression that mental things that are unconscious *could* be conscious. This whole idea of uncovering things from the unconscious and making them conscious has the presupposition that they are of the same type. It's the iceberg metaphor of the mind. The tip of the iceberg is made of the same stuff as the rest of the iceberg, which is an invisible mass. And I think that's really a mistake. The reality is that the things we're conscious of—experiences, thoughts, fragments of conversation—are completely different in type from the things we're unconscious of—all these mysterious brain processes, which lay down and retrieve memories, piece fragments of information together, and so on. The brain is doing lots of unconscious work—but it is not thought in any way we understand it. At the everyday level, thought is what flows through my mind—images, pains, fragments of language. But the unconscious brain activity that generates such thoughts is not more of the same. If we could understand the processes by which billions of neurons cooperate to help us recognize a face or interpret a fragment of speech, we would find these as unrelated to the stream of consciousness as the operation of the liver.

**Maybe you should define "thought" for us.**

Well, that's a tall order of course! But roughly the stuff of conscious experience: the pains, prods, shapes, movements, noises, and scraps of language that flow through our conscious mind. Until Freud, the very idea that there could be thoughts we are not aware of would have seemed bizarre to most people. The idea that the brain is teeming with activity which is just like conscious thought, but not actually conscious, was a radical idea—but a false trail, I think.

**Is your problem with the unconscious a semantic one? Maybe you don't like the common usage of the term.**

I think it is really a substantive issue, not a semantic one. The unconscious thought viewpoint actually is a rather parochial view on how the brain works—it assumes that the thoughts that inhabit my conscious mind are a pretty good representation of how my brain operates of which, of course, I have no awareness. But the operation of the brain is much stranger than this: The brain mechanisms of perception, language processing, motor control, and memory help generate conscious thoughts—but they are nothing like hidden "copies" of conscious thoughts.

So the brain's activity is unconscious all right—it is just not *thought* in any way we commonly understand it. The trap we fall into is thinking, "Well, if brain activity is not conscious, the brain must be doing unconscious things, and those things must be thinking." And thinking is about beliefs and reasoning and motives and planning and pains—the things that flow through our conscious minds. So we suddenly start to think,

# Suppose we look inside ourselves for the love we ought to be feeling. Where is it?

"Yes, the brain has two types of thought, divided by some mysterious boundary of consciousness." I think that's a big mistake. You're quite right that we have brain processes of which we're not conscious. But it's not right that those brain processes are doing unconscious *thinking*.

**But they do influence our conscious thinking.**
Yes, absolutely. They completely determine it. Yes, they are the machinery that is generating conscious experiences and conscious thoughts.

**Here's a simple example of influence. Hearing an old David Bowie song will instantly trigger emotional memories in me. That sure doesn't feel like a conscious action.**
Yes, that's right. But think about the brain processes involved in even realizing that the song is familiar; or recognizing that the singer is David Bowie. We have no introspective access to these brain processes. And this is always true: we are only ever aware of the results of the brain's processing—"Oh, that's Bowie"—and never of the processing itself. The unconscious operation of the brain is crucially related to thought, but it's not thought.

**I don't see how you can separate the two. For instance, you write that the inventiveness of the human brain is best exemplified by "the centrality of metaphor in our thoughts." Yet the things that make up metaphor—language and symbols—are acquired through evolution and genetics and culture. I don't see how those unconscious influences can be separated from thoughts. So don't you think it's also dangerous, or even misleading, to say that the unconscious is a myth?**
Well, yes, unconscious influences on thought are everywhere—genetics, experiences, mental habits, the language and metaphors we use, and much more. But the unconscious influences—including the activity of our brains which underpin our thoughts—aren't themselves thoughts. That's the mistake we can so easily make. And the second mistake is thinking that, by looking inside ourselves, or through therapy or brain imaging or some other method, we can bring these supposed unconscious thoughts into the light of consciousness. But this is a hopeless project—we can no more bring to consciousness the operation of our brain than we can bring to consciousness other aspects of our own biology. We can invent stories about what the liver is trying to achieve, speak as if the immune system is confused by tissues from our own bodies, or talk of

# Our brains are no more engaged in unconscious thought than our livers, immune systems, or genes.

genes being selfish. And we can invent stories about our brain too—suggesting that it might be suppressing beliefs, harboring hidden motives, tapping into the collective unconscious, or whatever we like. But this is metaphor, not literal truth. Our brains are no more engaged in unconscious thought than our livers, immune systems, or genes.

**How do you define emotions?**
I think emotions are interpretations. Understanding one's own emotions, or another person's, is very much like understanding the emotions of a fictional character. You're in a situation, you have a physiological reaction, and you need to make sense of that. If you see someone sweating profusely and looking tense on a high ledge, you think, "That's bad, they're afraid of falling, they're feeling fear." You do the same with yourself. If you're on a high ledge, you have the experience of being afraid; you're thinking, "My goodness, my heart's going like crazy, I'm full of adrenaline, I'm sweating profusely," and, "Help, I'm on this high ledge.' But you might experience the same physiological symptoms at the starting blocks of a 100-meter race. So your physiological state is highly ambiguous. The point is feelings don't burst forth from some mental depths. They don't pre-exist at all. They're our brain's best momentary interpretation of feedback about our bodily state, in the light of the situation we're in.

**Let's apply your theory about how the mind works to something important in people's everyday lives, like religion.**
I think religion is quite an interesting illustration of the viewpoint, actually.

**OK. How so?**
If you ask people about the religious doctrines they subscribe to, they'll say I totally believe these doctrines. But if you try to elucidate how their beliefs and doctrines fit together, that will be a tough thing to do. I'm not saying it wouldn't be tough to probe our beliefs about science. Our thinking in almost everything is incoherent. Maybe that's because the world is too complex for us. But let's take the doctrine of

transubstantiation. Somebody who holds this doctrine would say the actual blood and body of Christ is in this wine and wafer. If you try to unpick this and make sense of it, you can't do it, they can't do it. It's just not a doable thing. But that reveals, I think, that what it means to think of yourself as believing something very strongly is to adhere to the surface. What you're saying, given my loose perspective and background and so on, this is something I will hold to. I might even die at the stake for this thing.

**What makes one belief over another so persuasive to us?**

In my perspective, it comes from this central idea that the brain is a sequential processor, thinking one thought at a time. With each thought, you're taking up massive fragments of information and trying to pull them together. It could be perceptual information, it could be linguistic information, it could be fragments of memory. And one of the things that presumably religion's good at doing is giving us the sense that it all somehow fits. It has the sense that all these different aspects of life click into place. Rather like when you see a hard-to-process image and suddenly think, "Oh, I see, it's a cow's face" or "It's a dog."

Now, maybe all the bits don't quite fit together, but it has a sense of being coherent. Once you start to disturb that coherence, then your life feels less meaningful. So people will defend a particular perspective of the world and not want to deviate from it. By doing that, the world, the ability to creatively understand their lives, their purpose, and the world around them, is reduced. Maybe there's another way of thinking about things, which would be at least as appealing. But, at least temporarily, the questioning is painful. Questioning anything we believe, not just religion, is actually quite disturbing.

**Ultimately, what's the benefit of thinking our minds are flat?**

It's about focusing on the creative project of understanding one's own life, rather than trying to unpick one's own psyche. How do we live our lives more happily and better? How do we think more coherently and better? How do we solve problems going forward? Sometimes solving problems requires going backward, like when you're trying to write a novel or produce a proof in mathematics. Sometimes you need to go back and think, Wait a minute, I made a mistake here, I did the wrong character development, I made a calculation error. But it's important to think of the project as going forward, rather than thinking that I and everyone else are in the grip of a mysterious force that's controlling us and we need to voyage inward to find it. It's just an unconstructive direction to be looking inward instead of outward. A forward-looking approach to our lives is the positive benefit.

---

KEVIN BERGER is the editor of *Nautilus*.

# Kolmogorov Complexity and Our Search for Meaning

*What math can teach us about finding order in our chaotic lives*

BY NOSON S. YANOFSKY

**WAS IT A CHANCE ENCOUNTER** when you met that special someone, or was there some deeper reason for it? What about that strange dream last night—was that just the random ramblings of the synapses of your brain or did it reveal something deep about your unconscious? Perhaps the dream was trying to tell you something about your future. Perhaps not. Did the fact that a close relative developed a virulent form of cancer have profound meaning or was it simply a consequence of a random mutation of his DNA?

We live our lives thinking about the patterns of events that happen around us. We ask ourselves whether they are simply random, or if there is some reason for them that is uniquely true and deep. As a mathematician, I often turn to numbers and theorems to gain insight into questions like these. As it happens, I learned something about the search for meaning among patterns in life from one of the deepest theorems in mathematical logic. That theorem, simply put, shows that there is no way to know, even in principle, if an explanation for a pattern is the deepest or most interesting explanation there is. Just as in life, the search for meaning in mathematics knows no bounds.

First, some preliminaries. Consider the following three strings of characters:

**1.** 10010010010010010010010010010010010010010
0100100100100100100100100100

**2.** 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

**3.** 38386274868783254735796801834682918987459817
0871067014095819804l8.

How can we describe these strings? We can easily describe them by simply writing them down as we just did. However, it is pretty obvious that there are shorter descriptions of the first two strings. The first is simply the pattern "100" over and over. The second pattern is simply a listing of the first few prime numbers. What about the third string? We can describe it

by just printing the string. But is there a better, shorter description?

In the early 1960s, an American teenager named Gregory Chaitin, the world famous Russian mathematician Andrey Kolmogorov, and the computer science pioneer Ray Solomonoff independently formulated a way to measure the complexity of strings of characters. Their ideas have come to be called Kolmogorov Complexity Theory, or Algorithmic Information Theory. They posited that a string is as complex as the length of the shortest computer program that can produce it. That is, take a string and look for a short computer program that produces that string. The program is a type of description of the string. If the shortest such program is very short, then the string has a simple pattern and is not very complex. We say that string "has little algorithmic content." In contrast, if a long program is required to produce the string, then the string is complicated and "has more algorithmic content." For any string, one must look for the shortest program that produces that string. The length of that program is called the Kolmogorov complexity of the string.

Let us look at the above three strings. The first two strings can be described by relatively short computer programs:

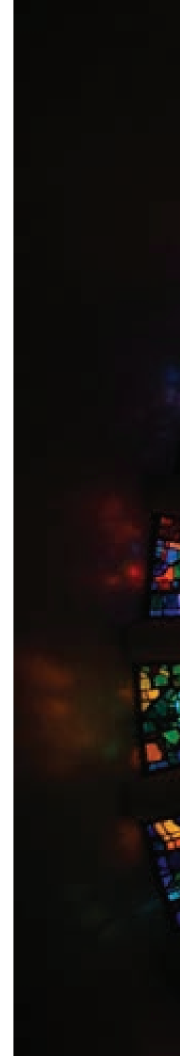
1. Print "100" 30 times.
2. Print the first 25 prime numbers.

The Kolmogorov complexity of the first string is less than the Kolmogorov complexity of the second string because the first program is shorter than the second program. What about the third string? There is no obvious pattern for this string. Nevertheless, there exists a silly program that prints this sequence:

3. Print "38386274868783254735796801834682918987459817087106701409581980418"

While this program will do the job, it is not very satisfying. Perhaps there is a shorter program that shows the string has a pattern. When the shortest program to produce a string is simply "Print the string," we say that the string is very complicated and has no known pattern. A string that lacks any pattern is called random. While we do not see any pattern, there could still be one. In mathematics, like in life, we are confronted with many seemingly random patterns.

We might try to use the amazing powers of modern computers to find a pattern and a shortest program. Wouldn't it be lovely if there were a computer that would simply calculate the Kolmogorov complexity of any string? This computer would accept a string as input, and output the length of the shortest program that can produce that string. Surely, with all the newfangled computer tools like AI, deep learning, big data, quantum computing, etc., it would be easy to create such a computer.



We will simply never know if the pattern that we have found is the best one.

PIXABAY

Alas, no such computer can exist! As powerful as modern computers are, this task cannot be accomplished. This is the content of one of the deepest theorems in mathematical logic. Basically, the theorem says that the Kolmogorov complexity of a string cannot be computed. There is no mechanical device to determine the size of the smallest program that produces a given string. It is not that our current level of computer technology is insufficient for the task at hand, or that we are not clever enough to write the algorithm. Rather, it was proven that the very notion of description and computation shows that no such computer can ever possibly perform the task for every string. While a computer might find some pattern in a string, it cannot find the best pattern. We might find some short program that outputs a certain pattern, but there could exist an even shorter program. We will never know.

The proof that the Kolmogorov complexity of a sequence is not computable is a bit technical. But it is a proof by contradiction, and we can get a sense of how that works by looking at two cute little paradoxes.

The interesting number paradox revolves around the claim that all natural numbers are interesting. 1 is the first number, so that is interesting. 2 is the first even number. 3 is the first odd prime number. 4 is interesting because $4=2\times2$ and $4=2+2$. We can continue in this fashion and find interesting properties for many numbers. At some point we might come to some number that does not seem to have an interesting property. We can call that number the first uninteresting number. But that, in itself, is an interesting property. In conclusion, the uninteresting number is, in fact, interesting!

# We want to know that there is some meaning, purpose, and significance in the world around us.

The ideas inside the Kolmogorov proof are also similar to those in the Berry paradox, which is about describing large numbers. Notice that the more words you use, the larger the number you can describe. For example, in three words you can describe "a trillion trillion," while in five words you can describe "a trillion trillion trillion trillion" which is much larger. Now consider the number described by the following phrase:

> "The smallest number that cannot be described in less than 15 words."

This number needs 15, or 16, or even more words to describe it. It cannot be described by 12 words, or 13 words, or 14 words. However there is a major problem: The above phrase described the number in only 12 words. Our description of the number violated the description of the number. This is a contradiction.

In both the interesting number paradox and the Berry paradox, we arrive at contradictions by assuming there is an exact way of describing something. Similarly, the proof that Kolmogorov complexity is not computable springs from the fact that if it was, we would find a contradiction.

The fact that Kolmogorov complexity is not computable is a result in pure mathematics and we should never confuse that pristine realm with the far more complicated, and messy, real world. However, there are certain common themes about Kolmogorov complexity theory that we might take with us when thinking about the real world.

Many times we are presented with something that looks totally chaotic. This randomness is unnerving, and so we search for a pattern that eliminates some of the chaos. If we do find a pattern, it is not clear that it is the best pattern to explain what we see. We might ask ourselves if there exists a deeper pattern that provides a better explanation. What Kolmogorov complexity theory teaches is that, at the deepest level, there is no sure way to determine the best pattern. We will simply never know if the pattern that we have found is the best one.

But that makes the search eternally interesting. By definition, something is interesting if it demands more thought. A fact that is obvious and totally understood does not require further thought. The fact that 6 times 7 is 42 is totally comprehensible and uninteresting. It's when we are not certain about ideas that we need to confirm them and think about them. The search for better patterns will always be interesting.

There is an added complexity in the real world. Whereas in the world of strings and computer programs there are no mistakes, in the real world we can, and do, make mistakes. We can easily see if a certain program prints out a string or not. While we might not be able to determine the optimal program to print a certain string, we can determine if the program prints the required string. In contrast, the real world is much more complicated. We can think we recognize a pattern when, in fact, we are mistaken.

Now our understanding of our search for meaning is starting to come together. We abhor randomness and love patterns. We are biologically programmed to find some patterns that explain what they see. But we can never be certain that the pattern we've identified is the right one. Even if we could somehow be assured that we haven't made a mistake, and we are exhibiting a computer-like perfection, there may always still be a deeper truth to unearth. This tension helps drive our love of literature, theater, and the cinema. When we read a novel, or watch a play, the author or director is presenting us with a sequence of events that has a common theme, pattern, or moral. Literature, plays, and the cinema offer us a delightful escape from the usual unintelligible, meaningless chaos that we find in the real world around us. Really good literature goes further, and leaves us with the possibility of many interpretations. We come face to face with the incomputability of the Kolmogorov complexity.

This tension also defines how we engage with our own lives. While we travel through the seemingly random events in our life, we are searching for patterns, and structure. Life is full of "ups and downs." There are the joys of falling in love, giggling with your child, and feeling a sense of great accomplishment when a hard job is completed. There is also the pain of a crumbling relationship, or the agony of failing at a task after great effort, or the tragedy of the death of a loved one. We try to make sense of all this. We abhor the feeling of total randomness and the idea that we are just following chaotic, habitual laws of physics. We want to know that there is some meaning, purpose, and significance in the world around us. We want a magical story of a life, so we tell ourselves stories.

Sometimes the stories are simply false. Sometimes we lie to ourselves and those around us. And sometimes the patterns we identify are correct. But even if the story is correct, it is not necessarily the best one. We can never know if there is a deeper story that is more exact. As we age and suffer from ennui, we gain certain insights about the universe that we did not see before. We find better patterns. Maybe we get to see things more clearly. Or maybe not. We will never know. But we do know that the search is guaranteed to never end.

NOSON S. YANOFSKY has a Ph.D. in mathematics from The Graduate Center of The City University of New York. He is a professor of computer science at Brooklyn College of The City University of New York. In addition to writing research papers he has co-authored *Quantum Computing for Computer Scientists* and authored *The Outer Limits of Reason: What Science, Mathematics, and Logic Cannot Tell Us*. Noson lives in Brooklyn with his wife and four children.

# The Ethics of Consciousness Hunting

*How fMRI has become an ethical obligation*

**BY MACKENZIE GRAHAM**

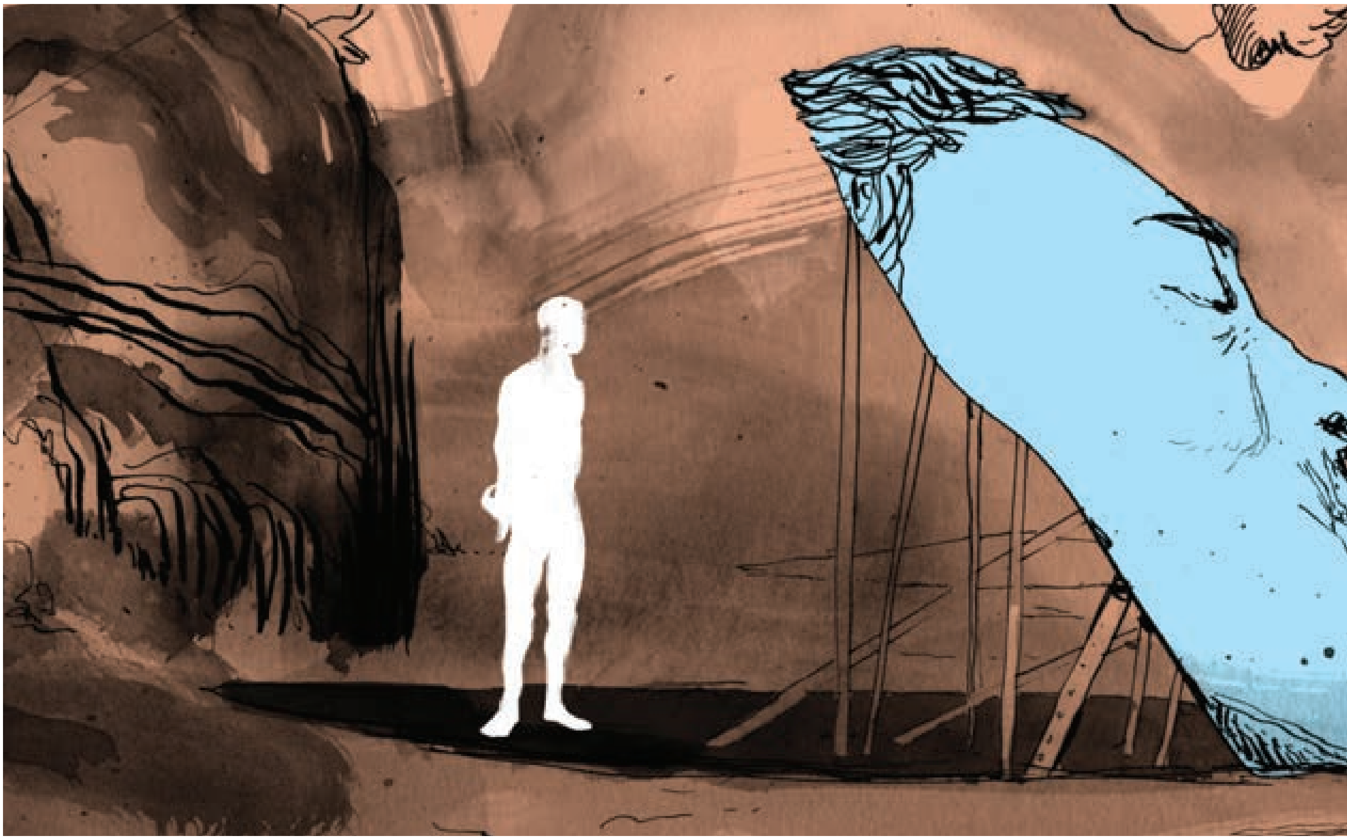


ILLUSTRATION BY IGNACIO SERRANO

**WHEN ADRIAN OWEN,** a neuroscientist at the University of Western Ontario, asked Scott Routley to imagine playing a game of tennis, any acknowledgement would have been surprising. After all, Routely had been completely unresponsive for the 12 years since his severe traumatic brain injury. He was thought to be in a vegetative state: complete unawareness of self or environment. But, as Owen watched Routley's brain inside a functional magnetic resonance imaging (fMRI) scanner, he saw a region of the motor cortex called the supplementary motor area—thought to play a role in movement—light up with activity. When he told Routely to relax, the activity ceased. And when he asked Routley to imagine walking around his house, he saw clear activity in the parahippocampal gyrus—a region of the brain that plays an important role in the encoding and recognition of spatial environment.

After dozens of repetitions of these mental imagery tasks, Owen was sure that Routley was conscious. Then Owen went a step further: He asked Routley to answer yes-or-no questions by directing his imagination. Imagining playing tennis stood for "yes," and walking around his house for "no." Routely was able to correctly identify himself ("Is your name Scott"—"yes"; "Is your name Mike"—"no"), his location ("Are you in a hospital?"—"yes"; "Are you in a supermarket?"—"no"), the current year ("Is it 1999?—"no"; "Is it 2012?"—"yes"), and the name of his personal care worker, whom he had only met after his accident. He also answered that he was not in pain, and that he enjoyed watching hockey on TV. Routley, it turned out, was not in a vegetative state. In fact, he and patients like him required a new classification, which later researchers would call cognitive

motor dissociation (CMD).

One question that Owen didn't ask Routley was if he wanted to die. It's easy to imagine how Routley's life might not be worth living. He might be in pain, for example, or unable to do the things that he wanted to do in life, or be mourning the loss of his relationships. On the other hand, people who sustain debilitating injuries often report a level of well-being that approximates that of healthy people. Even patients in a locked-in state—total paralysis with the exception of eye-movement—have reported that they are happy with their lives.

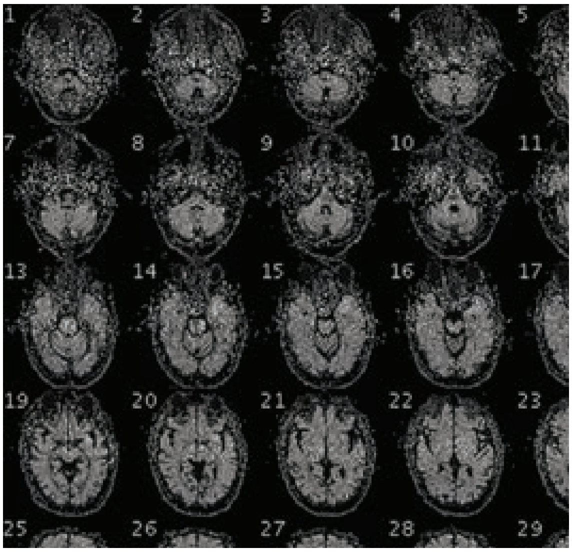
As it stands, our appraisal of the subjective states of nonresponsive patients is almost entirely guesswork—and our guesses are often lethal. Thirty-two percent of patients with severe brain injury die in hospitals, and 70 percent of these do so as a result of life-sustaining treatment being withdrawn, often within a few days of their injury, and long before their prognosis is certain.[1] In many cases, the decision is made by families and physicians trying to avoid the worst-case scenario, in which the patient remains permanently unconscious. But this means giving up any chance of a good recovery. And some of these patients are actually conscious.

For truly vegetative patients, it does seem clear that life is not worth living. They no longer have the capacity to experience any aspect of life, positive or negative. They are not benefited by continued treatment, and would not be harmed by having it withdrawn. These patients should be allowed to die. But CMD patients can, in principle, have positive experiences, including pleasure. They can still do things they enjoy, like watching hockey on TV, or even going to the movies.

Another patient, Jeff Tremblay, was incorrectly diagnosed as being in a vegetative state for over a decade before researchers realized, again using fMRI, that he was conscious. Instead of asking him to imagine performing certain tasks, neuroscientist Lorina Naci showed him a short Alfred Hitchcock film. We might not realize it while lying on the couch or sitting in a theater, but following the twists and turns of a film's plot is a cognitively demanding experience. It requires us to integrate visual and auditory information with our existing knowledge of the world. We need to focus our attention and ignore distractors. We need to interpret behavior and language to know what the characters are thinking.

It also turns out that different people will exhibit similar brain activity in response to engaging stimuli like movies, suggesting a similar conscious experience. Owen and Naci had previously detected a characteristic

We have built a tool to reach patients who we thought had been lost forever.




**SEARCHING FOR CONSCIOUSNESS**
A series of fMRI images from a single patient.

pattern of brain activity in healthy participants that was closely synchronized to the plot of the Hitchcock film.[2] When Naci and her team showed Tremblay the film inside an fMRI scanner, they saw this same pattern of complex mental response.

The ability to distinguish CMD from vegetative patients could save lives worth living. A little less than a fifth of patients who are behaviorally non-responsive at the bedside are CMD rather than vegetative.[3,4] Many are removed from life support on the mistaken assumption that they are vegetative. If we had a reliable method to distinguish CMD from vegetative patients, along the lines of the functional neuroimaging performed by Owen and Naci, this would represent a great advance in the care of this class of patient. But it would also only mark the beginning of the story.

**SUPPOSE ROUTLEY WAS ASKED** whether he wanted to die, and answered "yes." What would be the appropriate response? It isn't clear if a CMD patient retains the kind of sophisticated cognitive capacities necessary to make an important medical decision. How can we tell if they truly understand what the question means? What would be their reasons for answering yes or no? Would they really mean it?

Decision-making capacity must be judged relative to the decision at hand: A patient might have the capacity to choose what clothes to wear, but not whether or not to take their medication. Generally speaking, the more serious the potential consequences, the greater the capacity required to make the decision. To ensure that a CMD patient had the capacity to make a decision about ending their life, they would need to consistently exhibit full decision-making capacity.

Assessing decision-making capacity requires an evaluation of a patient's ability to understand, appreciate, reason about, and communicate a decision ("Why did you choose option *X*, and not option *Y*?"). This is not currently possible using fMRI. CMD patients who have used mental imagery to communicate required approximately 60 minutes to answer five yes-or-no questions, after which time they became exhausted. Moreover, the range of responses available to CMD patients is too narrow to respond to open-ended questions.

Perhaps the decision-making capacity of CMD patients could be assessed, if the means of communicating with them improved. For example, patients could be instructed to attend to a number between one and five while ignoring the others, to choose from a range of responses. This could add a level of detail to communication and contribute to capacity assessment for some kinds of decisions. Selective attention tasks similar to this have been performed with CMD patients using fMRI, but have not been used for communication. But that would probably not be enough to determine if a CMD patient had the capacity to make a life-or-death decision. And, we would still need to be concerned about potential mental disorders, or how emotional factors could be influencing decision-making.

For these reasons, asking CMD patients if they want to die is a non-starter for the foreseeable future. The value of functional neuroimaging applied to CMD patients lies in what it can tell us about their well-being. Improvements in communication could greatly enhance their lives, and provide insight into their experience. It could help others to care for them better, and make their lives worth living by unlocking their voices.

The possibility of distinguishing CMD from vegetative patients is another exciting application of new technology, and it raises a second set of ethical questions, to do with cost. According to the Centre for Health Economics at the University of York, 95 percent of vegetative patients are cared for in long-term care facilities (with the other 5 percent cared for at home), at a cost of £90,000 (approximately $119,000) per patient, per year.[5] The life expectancy for a young adult vegetative patient one year after injury is roughly 10.5 years, meaning their lifetime cost of care would be roughly $1,250,000.

If functional neuroimaging develops to the point where it can be used to reliably distinguish patients who retain consciousness (including CMD patients) from those who will remain in a vegetative state permanently, it could spare us the enormous expense of keeping alive patients who have no hope of benefiting from extra years of life. These funds could then be used to greater effect elsewhere in the medical system. If early detection of consciousness can be linked to recovery, functional neuroimaging could also help doctors and families in making the difficult decision to treat a patient with a severe brain injury, or allow them to die.

Currently, fMRI is not a part of standard care for patients with severe brain injury. fMRI is mostly used in a research context, and the $2 million price tag for a new MRI scanner is prohibitive for many smaller hospitals. However, once a machine is in place, the cost for an fMRI scan is only around $500. If life-sustaining treatment were withheld or withdrawn from two permanently vegetative patients, the cost savings would pay for the purchase of an MRI scanner. Electroencephalography (EEG) offers an even more cost-effective and portable option, and has also been used to detect consciousness in behaviourally non-responsive patients.

Given these options, it is hard to argue that we do not have an ethical obligation to apply some kind of functional neuroimaging—either fMRI or EEG—to every patient before they are diagnosed as being in a vegetative state. We have built a tool to reach patients who we thought had been lost forever. We've given them a voice; now we have to listen.

MACKENZIE GRAHAM is a research fellow studying practical ethics at the University of Oxford.

## REFERENCES

1. Turgeon, A.F., *et al.* Mortality associated with withdrawal of life-sustaining therapy for patients with severe traumatic brain injury: A Canadian multicentre cohort study. *Canadian Medical Association Journal* **183**, 1581-1588 (2011).

2. Naci, L., Cusack, R., Anello, M., & Owen, A.M. A common neural code for similar conscious experiences in different individuals. *Proceedings of the National Academy of Sciences* **11**, 14277014282 (2014).

3. Monti, M.M., *et al.* Willful modulation of brain activity in disorders of consciousness. *New England Journal of Medicine* **362**, 579-598 (2010).

4. Cruse, D., *et al.* Bedside detection of awareness in the vegetative state: a cohort study. *The Lancet* **378**, 2088-2094 (2011).

5. Formby, A., Cookson, R., & Halliday, S. Cost analysis of the legal declaratory relief requirement for withdrawing clinically assisted nutrition and hydration (CANH) from patients in the permanent vegetative state (PVS) in England and Wales. Centre for Health Economics, The University of York (2015).

ILLUSTRATION BY **BRIAN STAUFFER**

# The Selfish Dataome

*Does the data we produce serve us, or vice versa?*

BY CALEB SCHARF

**YOU'VE HEARD THE ARGUMENT BEFORE:** Genes are the permanent aristocracy of evolution, looking after themselves as fleshy hosts come and go. That's the thesis of a book that's been christened the most influential science book of all time: Richard Dawkins' *The Selfish Gene*.

But we humans actually generate far more actionable information than is encoded in all of our combined genetic material, and we carry much of it into the future. The data outside of our biological selves—call it the dataome—could actually represent the grander scaffolding for complex life. The dataome may provide a universally recognizable signature of the slippery characteristic we call intelligence, and it might even teach us a thing or two about ourselves.

It is also something that has a considerable energetic burden. That burden challenges us to ask if we are manufacturing and protecting our dataome for our benefit alone, or, like the selfish gene, because the data makes us do this because that's what ensures *its* propagation into the future.

Take, for instance, William Shakespeare.

**SHAKESPEARE DIED** on April 23, 1616, and his body was buried two days later in Holy Trinity Church in Stratford-Upon-Avon. His now-famous epitaph carries a curse to anyone who dares "move my bones." And as far as we know, in the past 400 years, no one has risked incurring Will's undead wrath.

But he has most certainly lived on beyond the grave. At the time of his death Shakespeare had written a total of 37 plays, among other works. Those 37 plays contain a total of 835,997 words. In the centuries that have come after his corporeal life an estimated 2 to 4 billion physical copies of his plays and writings have been produced. All of those copies have been composed of hundreds of billions of sheets of paper acting as vessels for more than a quadrillion ink-rich letters.

Across time these billions of volumes have been physically lifted and transported, dropped and picked up, held by hand, or hoisted onto bookshelves. Each individual motion has involved a small expenditure

JULIA TIM / SHUTTERSTOCK

of energy, maybe a few Joules. But that has added up across the centuries. It's possible that altogether the simple act of human arms raising and lowering copies of Shakespeare's writings has expended well over 4 trillion Joules of energy. That's equivalent to combusting several hundred thousand kilograms of coal.

Additional energy has been utilized every time a human has read some of those 835,997 words and had their neurons fire. Or spoken them to a rapt audience, or spent tens of millions of dollars to make a film of them, or turned on a TV to watch one of the plays performed, or driven to a Shakespeare festival. Or for that matter bought a tacky bust of "the immortal bard" and hauled it onto a mantelpiece. Add in the energy expenditure of the manufacture of paper and books, and their transport, and the numbers only grow and grow.

It may be impossible to fully gauge the energetic burden that William Shakespeare unwittingly dumped on the human species, but it is substantial. Of course, we can easily forgive him. He wrote some good stuff. But there is also a sense in which the data of Shakespeare has become its own living part of the dataome, propagating itself into the future and compelling all of us to support it, just as is happening right now in this sentence.

**SHAKESPEARE, TO BE FAIR,** contributed barely a drop to a vast ocean of data that is both ethereal yet actually extremely tangible in its effects upon us. This is both the glory and millstone of *Homo sapiens*.

We have been pumping out persistent data since our first oral exchange of a good story and our first experimental handprint on a cave wall. Neither of those things were explicitly encoded in our DNA, yet they could readily outlive the individual who created them. Indeed, data like these have outlived generation after generation of humans.

But as time has gone by our production of data has accelerated. Today, by some accounts, our species generates about 2.5 quintillion bytes of data a day. That's more than a billion billion bytes for each planetary rotation. And that rate of output is still growing. While lots of that data is a mixture of fleeting records—from Google searches to air traffic control—more and more ends up persisting in the environment. Pet videos, GIFs, political diatribes, troll responses, as well as

JOHN TAYLOR / WIKIPEDIA

**TO BE, OR TO BECOME DATA** The bard has become a living part of the human dataome.

# Our dataome is both an advantage to us humans, and a burden.

medical records, scientific data, business documents, emails, tweets, photo albums, all wind up as semi-permanent electrical blips in doped silicon or magnetic dots on hard drives.

This data production and storage takes a lot of energy to maintain, from the moment someone's hands scrabble for rare-earth elements in the soil, to the electricity that sustains it all. There's a reason that a large company like Apple builds its own data server farms, and looks for ways to optimize the power generation that these air-conditioned, electron-pushing factories demand, whether it's building massive solar farms in Nevada or utilizing hydroelectricity in Oregon.

Even Shakespeare's medium—traditional paper—is still an energy-hungry beast. In 2006 it was estimated that United States paper production gulped down about 2,400 trillion BTUs (about 4 million trillion trillion trillion Joules) to churn out 99.5 million tons of pulp and paper products. That amounts to some 28,000 Joules of energy used per gram of final material—before any data is even printed on it. Or to put it another way, this is equivalent to roughly 5 grams of high-quality coal being burnt per page of paper.

Why are we doing this? Why are we expending ever increasing amounts of effort to maintain the data we, and our machines, generate? This behavior may represent far more than we at first think.

On the face of things, it seems pretty obvious that our capacity to carry so much data with us through time is a critical part of our success at spreading across the planet. We can continually build on our knowledge and experience in a way that no other species seemingly does. Our dataome provides us with a massive evolutionary advantage.

But it's clearly not free. We may be trapped in a bigger Darwinian reality where we are in effect now serving as a supporting organelle for our own dataome.

This is an unsettling framework for looking at ourselves. But it has parallels in other parts of the natural world. Our microbiome, of tens of trillions of

**IN PERSPECTIVE** The human genome fits on about two CDs. The human species produces about 20,000 CDs worth of data a second.

single-celled organisms, is perpetuated not so much by us as individuals, but by generations of us carrying this biological information through time. Yet we could also flip this around and conceptualize the situation as the microbiome carrying us through time. The microbiome exists in us because we're a good environment. But that's a symbiotic relationship. The microbes have to do things a certain way, have to work at supporting their human carrying systems. A human represents an energetic burden as much as an evolutionary advantage to microbes. Similarly, our dataome is both an advantage to us humans, and a burden.

The question is, is our symbiosis still healthy? The present-day energetic burden of the dataome seems like it could be at a maximum level in the history of our species. It doesn't necessarily follow that we're experiencing a correspondingly large benefit. We might do well to examine whether there is an optimal state for the dataome, a balance between the evolutionary advantages it confers on its species and the burden it represents.

The proliferation of data of seemingly very low utility (that I might grumpily describe as cat pictures and selfies) could actually be a sign of worrying dysfunction in our dataome. In other words, undifferentiated and exponential growth of low-value data suggests that data can get cancer. In which case we'd do well to take this quite seriously as a human health issue—especially if treatment reduces our global energy burden, and therefore our impact on the planetary environment.

Improving the utility of our data, purging it of energy-wasting junk might not be popular, but could perhaps be incentivized. Either through data credit schemes akin to domestic solar power feeding back to the grid, or making the loss of data a positive feature. What you might call a Snapchat approach.

In that case, the human-dataome symbiosis might become the only example in nature of a symbiotic relationship that is *consciously* managed by one party. What the long-term evolutionary robustness of that would be is hard to say.

But more optimistically; if the dataome is indeed an integral and integrated part of our evolutionary path then perhaps by mining it we can learn more about not just ourselves and our health, but the nature of life and intelligence in general. Precisely how we interrogate the dataome is a wide-open question. There may be emergent structure within it that we simply haven't recognized, and we will need to develop measures and metrics to examine it properly. Existing tools like network theory or computational genomics might help.

The potential gains of such an analysis could be enormous. If the dataome is a real thing then it represents a missing piece of our puzzle; of the function and evolution of a sentient species. We'd do well to at least take a look. As Shakespeare once said : "The web of our life is of a mingled yarn, good and ill together."

CALEB SCHARF is an astrophysicist, the Director of Astrobiology at Columbia University in New York, and a founder of yhousenyc.org, an institute that studies human and machine consciousness. His latest book is *The Zoomable Universe: An Epic Tour Through Cosmic Scale, from Almost Everything to Nearly Nothing*.

# She Rewrote the Moon's Origin Story

*A giant impact put Earth in a hot vaporized state, explains Sarah Stewart. Then it gave birth.*

**BY BRIAN GALLAGHER**

**SARAH STEWART IS LIVING** her ideal life—and it just got sweeter. The University of California, Davis planetary physicist won a MacArthur Foundation Fellowship in October of 2018, famously and unofficially known as the "genius grant," for her work on the origin of Earth's moon, upending a decades-old theory. She's been awarded $625,000.

"It's an amazing concept to just say, 'We're going to give you the opportunity to do something, and we're not going to tell you anything about what to do.' That's very unusual and freeing," she told *Nautilus*, referring to the grant program. She was particularly thrilled by the recognition the award represents. The foundation speaks to several dozen of a candidate's peers as a part of its vetting process. "What I really feel is appreciation for my colleagues," she said. "That really touches me."

*Nautilus* spoke to Stewart during World Space Week in 2018, the theme of which was "Space Unites the World." It compelled her to pen a poem, using the theme as a title. *Nautilus* asked Stewart about that, as well as how her laboratory experiments, which replicate the pressures and temperatures of planetary collisions, informed her model of the moon's birth.

**How can space bring us together?**

This World Space Week is happening at a time where the world seems to be highlighting divisions. And so I wrote what I wrote as a response to that. Space exploration and discovery of things that are surprising and new is a way to bring everyone together, and enjoy the profound beauty of nature. And I would like us to spend more time talking about the things that bring us together.

**Like the moon. Give us a brief history of its origin theories.**

2019 is the 50th anniversary of the Apollo moon landing. The rock samples that the Apollo missions brought back basically threw out every previous idea for the origin of the moon. Before the Apollo results were in, a Russian astronomer named Viktor Safronov had been

PHOTO COLLAGE BY FRANCESCO IZZO

developing models of how planets grow. He found that they grow into these sub- or proto-planet-size bodies that would then collide. A couple of different groups then independently proposed that a giant impact made a disc around the Earth that the moon accreted from. Over the past 50 years, that model became quantitative, predictive. Simulations showed that the moon should be made primarily out of the object that struck the proto-Earth. But the Apollo mission found that the moon is practically a twin of the Earth, particularly its mantle, in major elements and in isotopic ratios: The different weight elements are like fingerprints, present in the same abundances. Every single small asteroid and planet in the solar system has a different fingerprint, except the Earth and the moon. So the giant impact hypothesis was wrong. It's a lesson in how science works—the giant impact hypothesis hung on for so long because there was no alternative model that hadn't already been disproven.

**How is your proposal for the moon's birth different?**
We changed the giant impact. And by changing it we specifically removed one of the original constraints. The original giant impact was proposed to set the length of day of the Earth, because angular momentum—the rotational equivalent of linear momentum—is a physical quantity that is conserved: If we go backward in time, the moon comes closer to the Earth. At the time the moon grew, the Earth would have been spinning with a five-hour day. So all of the giant impact models were tuned to give us a five-hour day for the Earth right after the giant impact. What we did was say, "Well, what if there were a way to change the angular momentum after the moon formed?" That would have to be through a dynamical interaction with the sun. What that means is that we could start the Earth spinning much faster—we were exploring models where the Earth had a two- to three-hour day after the giant impact.

**What did a faster-spinning Earth do to your models?**
The surprising new thing is that when the Earth is hot, vaporized, and spinning quickly, it isn't a planet anymore. There's a boundary beyond which all of the Earth material cannot physically stay in an object that rotates altogether—we call that the co-rotation limit. A body that exceeds the co-rotation limit forms a new object that we named a synestia, a Greek-derived word that is meant to represent a connected structure. A synestia is a different object than a planet plus a disc. It has different internal dynamics. In this hot vaporized state, the hot gas in the disc can't fall onto the planet, because the planet has an atmosphere that's pushing that gas out. What ends up happening is that the rock vapor that forms a synestia cools by radiating to space, forms magma rain in the outer parts of the synestia, and that magma rain accretes to form the moon within the rock vapor that later cools to become the Earth.

**How did the idea of a synestia come about?**
In 2012, Matija Ćuk and I published a paper that was a high-spin model for the origin of the moon. We changed the impact event, but we didn't realize that after the impact, things were completely different. It just wasn't anything we ever extracted from the simulations. It wasn't until two years later when my student Simon Lock and I were looking at different plots, plots we had never made before out of the same simulations, that we realized that we had been interpreting what happened next incorrectly. There was a bonafide eureka moment where we're sitting together talking about how the disc would evolve around the Earth after the impact, and realizing that it wasn't a standard disc. These synestias have probably been sitting in people's computer systems for quite some time without anyone ever actually identifying them as something different.

**Was the size of the synestia beyond the moon's current orbit?**
It could have been bigger. Exactly how big it was depends on the energy of the event and how fast it was spinning. We don't have precise constraints on that to make the moon because a range of synestias could make the moon.

**How long was the Earth in a synestia state?**
The synestia was very large, but it didn't last very long. Because rock vapor is very hot, and where we are in the solar system is far enough away from the sun that our mean temperature is cooler than rock vapor, the synestia cooled very quickly. So it could last 1,000 years or so before looking like a normal planet again. Exactly

# The surprising new thing is that when the Earth is hot, vaporized, and spinning quickly, it isn't a planet anymore.

SARAH STEWART

how long it lasts depends on what else is happening in the solar system around the Earth. In order to be a long lived object it would need to be very close to the star.

**What was the size of the object that struck proto-Earth?**
We can't tell, because a variety of mass ratios, impact angles, impact velocities can make a synestia that has enough mass and angular momentum in it to make our moon. I don't know that we will ever know for sure exactly what hit us. There may be ways for us to constrain the possibilities. One way to do that is to look deep in the Earth for clues about how large the event could have been. There are chemical tracers from the deep mantle that indicate that the Earth wasn't completely melted and mixed, even by the moon-forming event. Those reach the surface through what are called ocean island basalts, sometimes called mantle plumes, from near the core-mantle boundary, up through the whole mantle to the surface. It could be that that could be used as a constraint on being too big. Because the Earth and the moon are very similar in the mantles of the two bodies, that can be used to determine what is too small of an event. That would give us a range that can probably be satisfied by a number of different impact configurations.

**How much energy does it take to form a synestia?**
Giant impacts are tremendously energetic events. The energy of the event, in terms of the kinetic energy of the impact, is released over hours. The power involved is similar to the power, or luminosity, of the sun. We really cannot think of the Earth as looking anything like the Earth when you've just dumped the energy of the sun into this planet.

**How common are synestias?**
We actually think that synestias should happen quite frequently during rocky planet formation. We haven't looked at the gas giant planets. There are some different physics that happen with those. But for growing rocky bodies like the Earth, we attempted to estimate the statistics of how often there should be synestias. And for Earth-mass bodies anywhere in the universe probably, the body is a synestia at least once while it's growing. The likelihood of making a synestia goes up as the bodies become larger. Super-Earths also should have been a synestia at some point.

**You say that all of the pressures and temperatures reached during planet formation are now accessible in the laboratory. First, give us a sense of the magnitude of those pressures and temperatures, and then tell us how accessing them in labs is possible.**
The center of the Earth is at several thousand degrees, and has hundreds of gigapascals of pressure—about 3 million times more pressure than the surface. Jupiter's center is even hotter. The center-of-Jupiter pressures can be reached temporarily during a giant impact, as the bodies are colliding together. A giant impact and the center of Jupiter are about the limits of the pressures and temperatures reached during planet formation: so tens of thousands of degrees, and a million times the pressure of the Earth.

To replicate that, we need to dump energy into our rock or mineral very quickly in order to generate a shockwave that reaches these amplitudes in pressure and temperature. We use major minerals in the Earth, or rocky planets—so we've studied iron, quartz, forsterite, enstatite, and different alloy compositions of those. Other people have studied the hydrogen helium mixture for Jupiter, and ices for Uranus and Neptune.

In my lab we have light gas guns, essentially cannons. And, using compressed hydrogen, we can launch a metal flyer plate—literally a thin disk—to almost 8 kilometers per second. We can reach the core pressures in the Earth, but I can't reach the range of giant impacts or the center of Jupiter in my lab. But the Sandia Z machine, which is a big capacitor that launches metal plates using a magnetic force, can reach 40

> The target simply gets turned to dust after being vaporized and then cooling again. They're very destructive experiments.

kilometers per second. And with the National Ignition Facility laser at Lawrence Livermore National Lab, we can reach the pressures at the center of Jupiter.

**What happens to the flyer plates when they're shot?**
The target simply gets turned to dust after being vaporized and then cooling again. They're very destructive experiments. You have to make real time measurements—of the wave itself and how fast it's traveling—within tens of nanoseconds. That we can translate to pressure. My group has spent a lot of time developing ways to measure temperature, and to find phase boundaries. The work that led to the origin of the moon was specifically studying what it takes to vaporize Earth materials, and to determine the boiling points of rocks. We needed to know when it would be vaporized in order to calculate when something would become a synestia.

**How do you use your experimental results?**
What runs in our code is a simplified version of a planet. With our experiments we can simulate a simplified planet to infer the more complicated chemical system. Once we've determined the pressure-temperature of the average system, you can ask more detailed questions about the multi-component chemistry of a real planet. In the moon paper that was published this year, there are two big sections. One that does the simplified modeling of the giant impact—it gives us the pressure-temperature range in the synestia. Then another that looks at the chemistry of the system that starts at these high pressures and temperatures and cools, but now using a more realistic model for the Earth.

**What was it like to get a call from the MacArthur Foundation?**
It did come out of the blue. They called me in my office, and I answered the phone. There were three people on the other end, and they said they were from the MacArthur Foundation. I knew what it was, and I stopped listening, because it was such a nice surprise. To me it probably is just unreal at the moment, meaning it will probably take some time to really sink in.

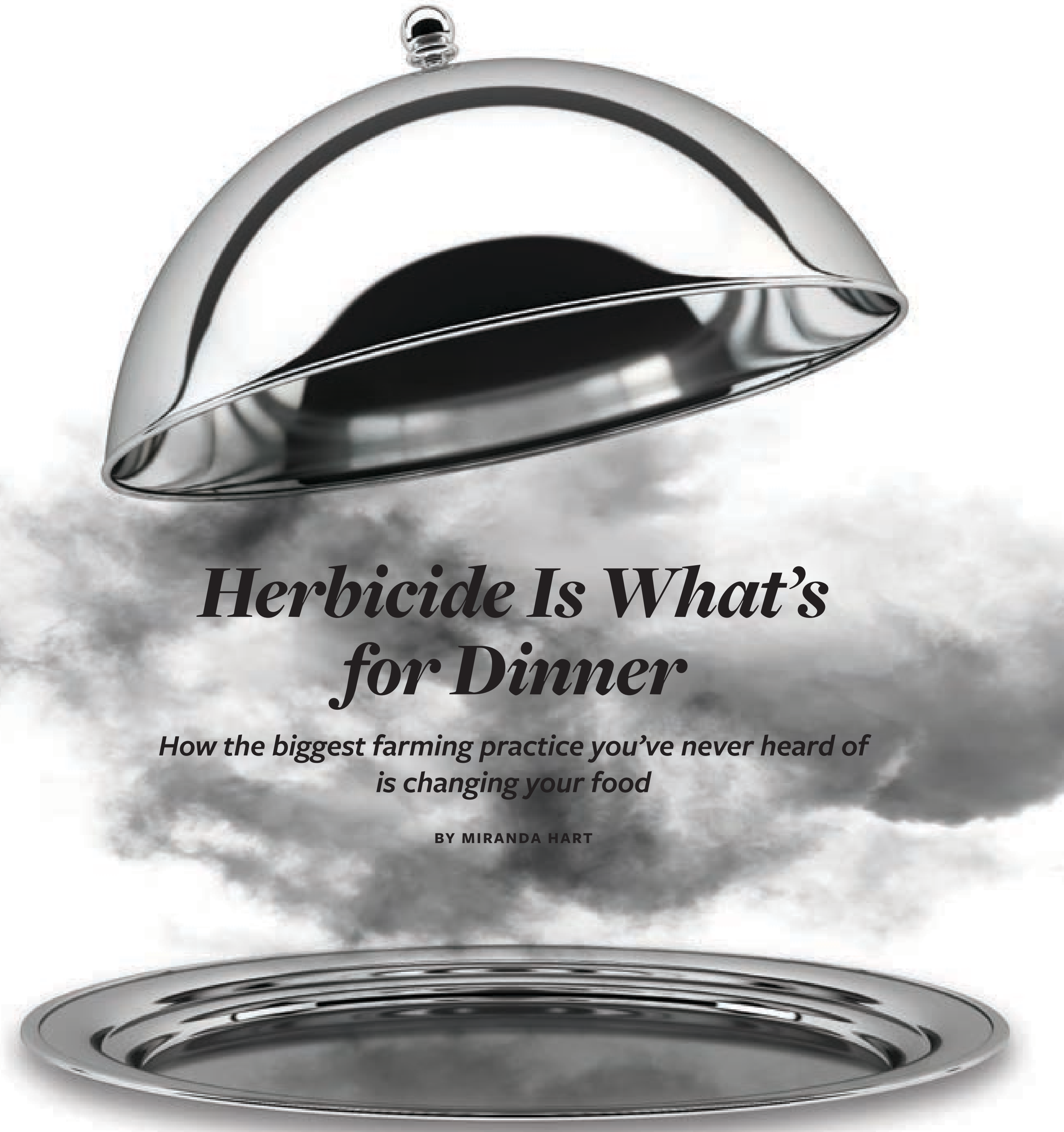
**How did you come to study planetary physics?**
I had enjoyed science fiction, not thinking I was going to be a scientist. But while I was in high school I had phenomenal math and physics teachers. That really grabbed my interest, so when I went to college I wanted to be a physics major. I quickly learned that the astronomers very much welcomed undergraduate researchers because the work was very accessible to someone with undergraduate skills. I met amazing scientists, and that sparked a whole career.

**What would you be doing if you weren't a scientist?**
That's hard. Because it has been my ideal for a very long time. In college I did a lot of theater. More theater than homework. The best theatrical experience I had was directing *Sweeney Todd*. It was absolutely amazing. So I did watch with some envy as some of my friends pursued a theatrical life. That is something that you can be wistful about, except that that would have been a hard path.

**NASA is celebrating its 60th anniversary. What does that mean to you as a scientist studying space?**
It feels like we've learned so much over 60 years, because we've had our first visits to everything in the solar system now. But at the same time, we're completely surprised every time we arrive at a new object. So in some ways we're still in the youthful period in planetary science, where we're trying to work out basic knowledge. That's a very exciting time. We're still on a very big growth curve.

---

**BRIAN GALLAGHER** is the editor of Facts So Romantic, the *Nautilus* blog.



# *Herbicide Is What's for Dinner*

***How the biggest farming practice you've never heard of is changing your food***

BY MIRANDA HART

**DRIVING DOWN A GRID ROAD** in central Saskatchewan, a machine that looks like a giant insect approaches me in a cloud of dust. The cab, hanging 8 feet above the road, is suspended by tires at least 6 feet tall, with wing-like appendages folded along each side. Should I drive around it or under it?

It is harvest season, and the high-clearance sprayer is on its way to desiccate a field. Desiccation may be the most widespread farming practice you've never heard of. Farmers desiccate by applying herbicide to their crops; this kills all the plants at the same time, making them uniformly dry and easier to cut. In essence, desiccation speeds up plant withering. Before desiccation, crops would have to dry out naturally at the end of the season. Today, there are examples of desiccation being applied to every type of major crop in Canada, the United States, and the United Kingdom. Chances are that most of what you ate today was harvested using a desiccant, but you'd never know.

Mike Shewchuk jumps down from his swather as I pull into his farmyard. He is a young farmer whose blond brush cut and robust stride would not have been out of place 50 years ago. Along with his dad, uncles, and brother, he farms 12,000 acres an hour outside of Saskatoon, Saskatchewan. They recently received a century farm award, for having continuously farmed the land since the early 1900s.

He is in the middle of a cut, and asks if I would mind riding with him as we talk. I climb up beside him on a small fold-down seat.

Swathers are giant lawn mowers farmers use to cut crops. The cut plants are left to dry on the ground before combining. It can be tricky knowing when to cut. If you start too early, you'll get seeds that are too green, too small, or some combination of both, leading to lower yield and less profit. But if you wait too long, seeds could shatter during the harvesting process (like canola), or start to germinate (like wheat) if a lot of rain falls on a mature crop.

Swathing is quickly going out of fashion, as more farmers desiccate to ripen their crops. One of the big agro-chemical companies even has a marketing campaign with the hashtag #selltheswather, encouraging farmers to desiccate and ditch swathing altogether. I asked Mike why he hadn't sold his swather yet.

He laughs. "We're not desiccating canola, and canola is paying the bills right now."

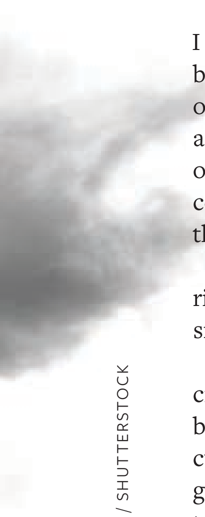
For many farmers, that is changing. Until recently, farmers did not desiccate canola because it "shattered" the seedpods, shedding the seeds in soil. But breeders have been busy: In 2017, five new varieties of shatter-resistant canola were released in Canada. That will make desiccation viable for Canada's most common crop, and accelerate a trend that began around 10 years ago, when desiccation started to become popular.

Not coincidentally, it was also around then that herbicide use spiked. When you sit down to eat dinner tonight, there will probably be desiccant in your food.

**THERE ARE THOUSANDS OF WAYS** to kill a weed. You can starve it, bleach it, mess with its proteins. You can feed it fake hormones. You can force it to make acid so that it disintegrates from within. There are more than 400 licensed weed killers, or herbicides, in Ontario alone. And we love to use them. Canadians used more than 58,000 tons in 2014, compared with only 21,000 tons in 1994. Our landscape, and our crops, have never been so saturated.

Our thirst for herbicides is partly due to GMOs like Roundup Ready corn, soy, and canola. These herbicide-tolerant crops came on the market in the late 1990s, and changed the farming landscape by making it possible to control weeds by using herbicides on crops still in the field.

Herbicide resistance explains part of the increase in herbicide use around the world over the past decades. If you blast a weed with herbicide, eventually its cells become resistant. Farmers are left with fields of weeds they can't kill. This is what happens in people, with antibiotic resistant bugs. Faced with resistant weeds, farmers double down, spraying even more and using multiple herbicides. But desiccation accounts for a significant part of the growth in herbicide use. It's impossible to say precisely how much, because stats are tracked for herbicide use by crop—not by usage type.



BULATNIKOV; WARAT42 / SHUTTERSTOCK

In theory, anything that kills a plant can desiccate a crop, but farmers can only use herbicides that are licensed as desiccants. In practice, there are only a few that are regularly used.

Glyphosate, sold under the trade name Roundup, is the most commonly used herbicide in the world. The active ingredient, glycophosate, is increasingly used in herbicides marketed and sold as desiccants. In 1974, global use of glyphosate was 3,200 tons per year. It is expected to reach 1 million tons per year by 2020.[1] In the U.S., the rate of growth has been accelerating. Americans used almost five times more glyphosate between 1995 and 2004 than during the preceding decade. That number increased to over a billion kilograms used between 2005 and 2014.[2]

Glyphosate works by interrupting protein synthesis in plants, rendering them unable to photosynthesize. It is also considered relatively safe for humans. But in 2015 the World Health Organization (WHO) declared it a possible carcinogen, on the basis of an independent survey of the scientific literature. Outrage from governments and industry around the world fueled a re-analysis by the Food and Agriculture Organization of the United Nations and WHO, which concluded in 2016 that it was "unlikely to pose a carcinogenic risk to humans from exposure through diet."

Industry, and farmers, breathed a sigh of relief. The reports analyzed, however, did not consider the increase in exposure to glyphosate via desiccation. This practice has dramatically increased the dissemination of glyphosate into the environment, and into us.

I asked Sherri Roberts, a crop specialist with the Ministry of Agriculture in Saskatchewan, whether she thought desiccation was safe. She was reluctant to make the call, but said she wished it was not so commonly used. "The timing's really tight," she said. "If you don't get it just right, that herbicide ends up in the grain." If farmers apply a non-contact herbicide (like glyphosate) too early, it will be taken up by the growing plant and end up inside the seed. Non-contact herbicides are taken up by the living plant and incorporated into still growing tissues, while contact herbicides kill the tissues they touch.

A 2015 study by the Canadian Food Inspection Agency found glyphosate in 30 percent of 3,200 food products.[3] Similar studies have found glyphosate exceeding maximum residue limits (or MRLs) in Cheerios, beer, and wine.[4,5] MRLs are the allowable concentration of herbicides on food crops. Health Canada and the Environmental Protection Agency (EPA) come up

**THE FUTURE** A fleet of combines harvests a field of desiccated peas on the Shewchuk farm near Saskatoon. The uniform senescence of the crop has made it dry, causing the combines to kick up chaff and dust as they work.

We can't prove that there is any health cost to the practice. But neither can we say there isn't a cost.

with MRLs by feeding rats or dogs herbicide until an effect is observed. The figures are important for trade: If countries have different MRLs, shipments can be rejected. In 2011, the European Union rejected a shipment of Canadian lentils because MRLs were 40 times the E.U. limit. Alternatively, countries can use MRLs to negotiate a lower price, or raise their MRLs in response to industry pressure.

According to the EPA, between 1993 and 2015, glyphosate MRLs increased by 100 percent to 1,000 percent in the U.S., depending on the crop. Desiccation has changed the game: Because we are using more herbicides, herbicide residues and MRLs have also gone up. Countries can use MRLs as a bartering tool to negotiate lower prices, and will raise their MRLs in response to pressure. Monsanto and other manufacturers of glyphosate have requested increases in MRLs, and been granted many of them.[2]

Current MRLs for glyphosate range from 0.2 parts per million to more than 300 ppm, depending on the crop. Between 1993 and 2015, the U.S. EPA glyphosate tolerance levels have increased by a factor of 50 for corn, and 2,000 for alfalfa.[2]

As MRLs rise, some industry groups are starting to avoid desiccated crops. Stuart Smyth, an agricultural economist at the University of Saskatchewan, tells me that certain oat millers are no longer accepting desiccated oats. "They say it's because they don't mill as well," he says, "but there's not a single study showing this."

The millers might be worried about more than oat milling properties. General Mills, producer of Nature Valley granola bars, was recently sued by a group disputing their claim to be 100 percent natural. Because oats are commonly desiccated before harvest, the grains contain glyphosate residues. The case was dismissed in July of 2018, because the judge ruled that the glyphosate residues satisfied EPA standards.

**AT FIRST, I DOUBT** that I'll be able to tell which of Shewchuk's fields had been desiccated. But the shriveled, brown peas are in stark relief to the green fields around them. Even if the surrounding crops hadn't been green, the sprayer tracks, squashing a path through the dead plants, are a dead giveaway.

As we drive along, the pale green, almost rubbery stems of canola are left denuded on the bare soil, while brown seedpods collect in neat windrows behind us.

After the canola, we stop by a field of wheat. It is mostly yellow, but there is still a tinge of green in places, and the occasional deep green weed, which is the real clue that it hasn't been desiccated. We enter the field, pushing aside the prickly, barbed awns. He slides some grains off a head and hulls them in his palm.

"We'll probably spray it this week; could have sprayed earlier, " Shewchuk decides, chewing on some berries.

Why spray—why spend the extra fuel and herbicide—if the crop is ready to go?

"Insurance. When we spray [with a dessicant] we can harvest within 10 days."

Given that he has roughly one month to get the crops off the field, I'm starting to see that it might be impossible to do any other way. The farm is so big that its fields are never ready to cut at the same time. It's not the big machines that allow Shewchuk to farm such a massive operation—it's the herbicide.

"Farms these days are huge," Chris Willenborg, a farmer and an academic at the University of Saskatchewan, tells me. "A large farm is 30,000 acres." I can't visualize the scope of a farm that big. It could have different soil types, different climates even. It could be hard, even impossible, to have good weather long enough to harvest it all. "In my 'farmer' hat, desiccation

MIRANDA HART

**THE PAST** Mike Shewchuk in a field of canola that's almost ready to swath. This variety of canola is vulnerable to pod shattering if harvested too late, and so isn't a good candidate for dessication, but that might change as new dessicants are developed.

makes sense because it's efficient," he adds.

There are economic reasons, too, for desiccation. There hasn't been a new herbicide in 25 years because they're so expensive to develop. If herbicide sales have topped out, why not encourage pre-harvest spraying, and sell twice the product? In business circles, this is called increasing "use patterns." Willenborg tells me that farmers are being enticed to desiccate by herbicide manufacturers. Reporters for industry standards, like *The Western Producer*, a bible for Canadian farmers, frequently run editorials about proper desiccation protocols.

The question is: How much is too much?

"In my 'researcher hat', I'd say we already apply too much herbicide," Willenborg says. "Some weeds are good—you don't want to get rid of all weeds. What would the seed predators eat?" Willenborg sees the cropping system as an ecosystem whose health relies on things like weeds and insects.

Then there's the question of gut health.

**DESICCANTS KILL** more than plants. Herbicides like glyphosate also kill bacteria. You could just as easily call them "antibiotics." Our gut bacteria are sensitive to antibiotics, which is why we should avoid eating herbicides. When our microbes are healthy, our immune system is stable. But when microbes are disturbed, diseases like obesity, Alzheimer's, or celiac disease can result.

Long-term exposure to antibiotics results in lasting shifts in gut microbiota. Cattle are fed low-dose antibiotics in feedlots—not to stave off disease, but because it makes them gain weight more easily than an antibiotic-free cow. It changes their gut microbes so that they grow fat on less food. A 2018 study showed that glyphosate exposure changed the composition of honeybee gut microbes, which could make the bees more susceptible to colony collapse.[6]

Herbicides are particularly dangerous for gut microbes because they're poorly absorbed by the gut. Low absorption means that gut bacteria are subjected to prolonged contact with the herbicide as it passes through the digestive system. Ironically, poor absorption is part of the reason that herbicides are deemed safe enough to put on our food.

"We don't actually know what happens when gut microbes are exposed to herbicides," Deanna Gibson tells me. She studies the interaction between diet, gut microbes, and disease at the University of British Columbia, Okanagan. Her lab is a hive of researchers from around the world homogenizing frozen poop samples and mice guts. "It's shocking to me that the chemicals we feed to lab mice to disrupt gut function are actually common herbicides—like glyphosate," Gibson says. "How are we not talking about this as a society?"

Part of the answer is that neither Health Canada nor the U.S. EPA consider herbicides as antibiotics. This means that their safety assessments don't consider effects on human gut microbes. There have been no explicit tests of the effect of desiccation on our microbiome. The only studies that exist consider rats, cattle, bees, and turtles—because it is unethical to test the effects of toxins on humans.

Plus, there is other stuff in herbicides that is dangerous for both animals and microbes. Commercial herbicides are cocktails of chemicals that include herbicidal agents and chemicals that improve their delivery. These "adjuvants" include petroleum byproducts, neurotoxins, and endocrine disruptors. Adjuvants help the herbicidal penetrate the thick, waxy layer that surrounds plant cells, making them good for breaching bacterial cell walls, too. But adjuvants are not subjected to the same regulation as herbicides, and are considered "inert" without much evidence. Desiccation means adjuvants are being applied to edible crops in large quantities (as opposed to weeds, their original target). Their toxicity has not been studied.

So what can we do? To begin, we need to clearly determine how much glyphosate the human population is exposed to. My lab has started to do this—but it's not easy. How much glyphosate are we exposed to? We can estimate residues in foods, but what about in the water table? Indirect exposure through agricultural and forestry use? Then we need to begin the difficult task of evaluating that risk, through animal models and correlational studies in humans. This will not be easy, or fast.

**DESICCATION MAKES IT POSSIBLE** to cultivate massive tracts of farmland and feed billions of people profitably. Based on the evidence we have so far, we can't prove that there is any health cost to the practice. But neither can we say there isn't a cost—and there are many reasons to think there might be one.

On my way home from Shewchuk's farm, I stopped by a desiccated pea field. It was a clear afternoon, but the air was heavy with dust, casting an orange glow on the field. Four combines, each as big as a small building, were kicking up dirt and chaff from the peas while two enormous semi-trailers waited to receive the seeds. At least a dozen hawks circled overhead, waiting for the rodents that were now exposed on the bare ground. I knew agriculture had changed, but I couldn't have imagined this scene so divorced from the mom and pop farms of my childhood. The scene was from some dystopia. I was reminded of a famous quote by Alanis Obomsawin: "When the last tree is cut, the last fish is caught, and the last river is polluted ... you will realize, too late, that wealth is not in bank accounts and that you can't eat money."

But what if we can't eat our own food, either?

**MIRANDA HART** is a microbial ecologist and professor at the University of British Columbia, Okanagan.

## REFERENCES

1. Landrigan, P.J. & Belpoggi, F. The need for independent research on the health effects of glyphosate-based herbicides. *Environmental Health* **17**, 51 (2018).

2. Benbrook, C.M. Trends in glyphosate herbicide use in the United States and globally. *Environmental Sciences Europe* **28**, 3 (2016).

3. Canadian Food Inspection Agency. Safeguarding with Science: Glyphosate Testing in 2015-2016.

4. CBC News Staff. Nearly a third of food samples in CFIA testing contain glyphosate residues. www.cbc.ca (2017).

5. Copley, C. German beer purity in question after environment group finds weed-killer traces. *Reuters* (2016).

6. Motta, E.V.S., Raymann, K., & Moran, N.A. Glyphosate perturbs the gut microbiota of honey bees. *Proceedings of the National Academy of Sciences* **115**, 10305-10310 (2018).

# Does Scrabble Need to Be Fixed?

*An experiment in controlling how much of Scrabble is luck*

**BY KEVIN MCELWEE**

Y**OU CAN FIND** Lynda Woods Cleary playing Scrabble every Tuesday at a Panera in Princeton, NJ. Cleary, a 68-year-old retired financial consultant, has been playing every week for 20 years since founding the Princeton Scrabble Club in 1998. When I asked her if she's ever disappointed to draw certain tiles, she looked surprised, even hurt. "Oh no," she said with an Alabama twang. "I want each and every one."

It's a sweet sentiment, but according to a 2014 statistical program written by Joshua Lewis, then a Ph.D. candidate at the University of California, San Diego, it isn't a sensible one. His study showed that there are "lucky" tiles in Scrabble: A "Q" is harder to place on a board than a "Z," and yet both are worth 10 points. Therefore, it's luckier to draw a "Z" than a "Q." Lewis argued that the traditional values associated with each letter diminish the role of skill in the game, and recommended changing them to make Scrabble scores more indicative of skill.

The suggestion was picked up by the BBC, the *Huffington Post*, and *TIME*, among others. As you can imagine, traditionalists like Cleary were dismissive of Lewis' suggestion. Some of them were passionately opposed. John Chew, then the co-president of the North American Scrabble Players Association, titled a two-part, 2,600-word diatribe in response to Lewis' suggestion "Catastrophic Outrage."

Recently, I conducted my own tests to see if Lewis' values really make Scrabble more fair. In short, Lewis was wrong. His values don't reduce the element of luck in Scrabble. The tests also show, however, that traditional tile scoring isn't more fair than random tile values. If we want to make Scrabble scoring more indicative of skill, we've been looking at the wrong part of the game for years.

**THE PROFESSIONAL SCRABBLE WORLD** is well aware of how important luck is to the game. "The community mostly agrees it's around 15 percent luck," said John Williams, the former head of the National Scrabble Association. He mentions the same number in his book

PIXABAY


Z
~~10~~ 6

*Word Nerd*. "But some people say it's more like 20 percent. Somewhere in that range." Lewis' hypothesis is that the degree of luck can be tuned by changing the point values of tiles.

The creator of Scrabble, Alfred Butts, first determined the values by hand in the 1930s by studying letter frequency, including of articles published on the front page of *The New York Times*. Lewis calculated new tile values, reasoning that after 80 years, with new words added to the dictionary, Scrabble could use an update. He wrote a program that used multiple metrics, considering a letter's frequency in the dictionary and the typical word length, to calculate the difficulty of placing it. His results recommended, for example, that "Q" remain at 10 points, but that "Z" drop to 6.

In theory, the slimmer the average difference in score over many games between two identical opponents, the less luck is inherent in a game. This fact can be used to test whether Lewis' new tile values actually reduced the role of luck, and increased the role of skill, in Scrabble scores. I set up a Scrabble AI program called Quackle to play against itself with various tile values. The program was developed by competitive Scrabble players at the Massachusetts Institute of Technology and is commonly used in the professional Scrabble community to train. Williams' estimate turns out to be pretty accurate. Thousands of self-play Scrabble games revealed that the traditional tile values produce an average difference of approximately 18 percent in final scores between two identical players. But Lewis' suggested values not only fail to reduce this difference, they actually cause a small (but statistically significant) *increase*: from 18 to 19 percent.

Scrabble's complexity makes any clear-cut answer inherently difficult.

PUERI / WIKIMEDIA

Why did the amount of luck in Scrabble stay approximately the same even after shifting to Lewis' tile values? The tests don't give a definitive answer to this question: Scrabble's complexity makes any clear-cut answer inherently difficult. But some Scrabble enthusiasts think it's because of players' adaptive strategy. "You learn how to use [your tiles] even if you have a rack with five vowels on it," Cleary explains. "That's what you do." Stefan Fatsis, author of *Word Freak* and expert-rated Scrabbler, was one of the first to point out that Lewis' findings, though interesting, misinterpreted how a typical Scrabble player plays. He was unsurprised by what my Quackle experiment showed. "It doesn't matter what values you give me," he said. "I'm going to work with what I have and make the best of it." In other words, players recognize the difference between the nominal point value of a tile and its real value, and strategize around that. It is part of the game.

If that's true, we should be able to assign quasi-random values to Scrabble tiles, and still have the same results. Naturally if "Q" was worth 500 points and the rest of the tiles worth 1 point, then Scrabble would

| | Traditional values | Lewis's values | Random-ish values | Tiles equal to 50 |
|---|---|---|---|---|
| Percent Differences in Scores | 18.24 ± 0.3% | 19.20 ± 0.3% | 17.889 ± 0.7% | 14.64 ± 1.3% |
| When Bingos are Equal | 11.32 ± 0.4% | 11.12 ± 0.4% | 12.92 ± 1.0% | 13.00 ± 1.6% |
| When Bingoes are Unequal | 18.24 ± 0.3% | 19.20 ± 0.3% | 19.55 ± 0.8% | 16.31 ± 1.9% |
| Sample Size | 7759 | 9546 | 1529 | 299 |

become purely a game of luck, but after assigning random tile values between 1 and 10 ( "A" equal to 5, for example, and "Q" equal to 1) with a similar standard deviation and average to the traditional tiles, we get the same 18 percent different, on average.

So is there not much luck to a game of Scrabble? There is—but it has to do with a completely different part of the game.

**A SCRABBLE BINGO HAPPENS** when one player plays all seven tiles in one turn, earning an extra 50 points.

Most Scrabble amateurs don't need to worry about bingos bringing an unfair element of luck into their game. Most of us go tens of matches without witnessing a single bingo appear on the board. For professional Scrabblers, however, bingos are a lot more common, and they may be more about luck than skill. In the Quackle tests, only in 1 of 4 games do both players get an equal opportunity to play bingos. Lewis' values may have slightly increased the role luck plays simply because they had a lower average value (2.74) than traditional tiles (3.22). It's harder for a player with one fewer bingo to catch up if tiles are simply worth less.

If we devalue the bingo by setting all tiles equal to 50, the average percent difference falls to 14 percent. Furthermore, when players earn an equal number of bingos, the percent differences in scores for all different kinds of tile distributions—the traditional values, Lewis' values, all tiles equal to 50, even random values—are roughly equal.

Therefore, Scrabble would be more indicative of skill if we remove bingo altogether, or devalue the bingo by proportionally increasing all tile values. But after making all our "fixes," we would no longer be playing Scrabble.

Some, like Cleary, won't be interested in that change: "I like the tiles just the way they are."

KEVIN MCELWEE is a software engineer based in Washington, D.C. As a freelance journalist, his articles have appeared in the *Columbia Journalism Review* and *Discovery*, Princeton University's research magazine. In 2017, he reported from Moscow for The GroundTruth Project.

# CULTURAL PROGRAMS OF THE NATIONAL ACADEMY OF SCIENCES

Phillip K. Smith III, *Lucid Stead: Focused Views – View 4*, 2013-2019, archival pigment print, 44 x 30.5 inches

## From Lucid Stead

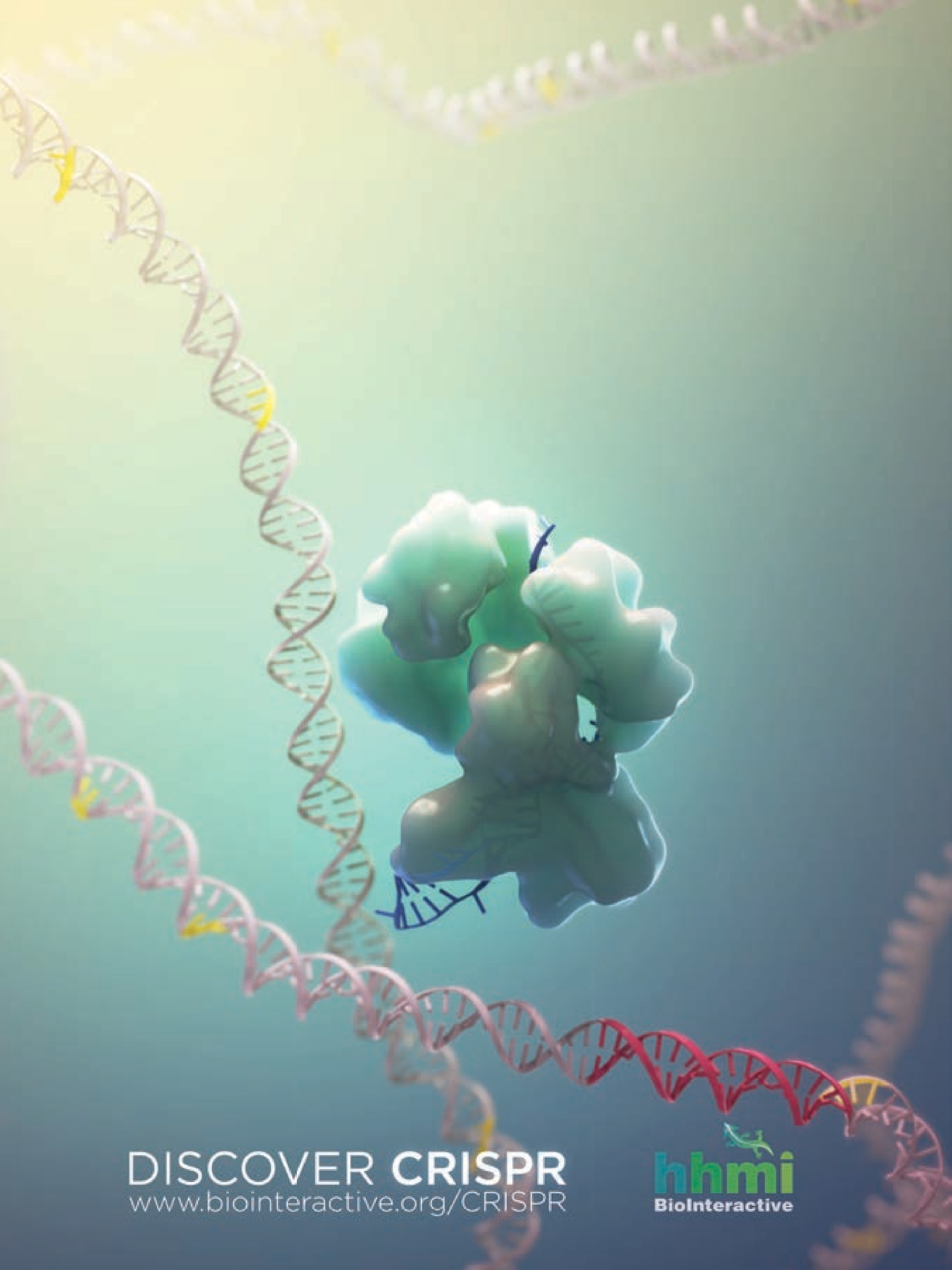
Prints and Works by Phillip K. Smith III

March 18, 2019 - September 13, 2019

2101 Constitution Ave., N.W., Washington, D.C.
Upstairs Gallery. Open weekdays 9-5. Free.
Photo ID required.

FOR MORE INFORMATION, VISIT WWW.CPNAS.ORG.

@CPNAS


DISCOVER CRISPR
www.biointeractive.org/CRISPR
hhmi
BioInteractive

# 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


ESO
Road to the stars
A unique opportunity to conduct part of your PhD research at the European Southern Observatory
#ESOJOBS
eso.org/studentship
ESO Headquarters, Garching near Munich, Germany
ESO Vitacura, Santiago, Chile
Application deadline: 31 May and 15 November, each year

# Issue Index


**25**

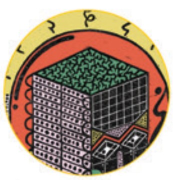
**2019**
A NEW MOON THEORY
WHAT TREES TALK ABOUT
HERBICIDES FOR DINNER

**24**

**2018**
**56** PERSPECTIVE
**57** COMMUNITIES
**58** SELF

**23**

**NOV/DEC 2017**
**54** THE UNSPOKEN
**55** TRUST



**22**

**SEPT/OCT 2017**
**52** THE HIVE
**53** MONSTERS

**21**

**JULY/AUG 2017**
**50** EMERGENCE
**51** LIMITS

**20**

**MAY/JUNE 2017**
**48** CHAOS
**49** THE ABSURD

**19**

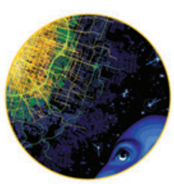
**MAR/APR 2017**
**46** BALANCE
**47** CONSCIOUSNESS

**18**

**JAN/FEB 2017**
**44** LUCK
**45** POWER

**17**

**NOV/DEC 2016**
**42** FAKES
**43** HEROES



**16**

**SEP/OCT 2016**
**40** LEARNING
**41** SELECTION

**15**

**JULY/AUG 2016**
**38** NOISE
**39** SPORT

**14**

**MAY/JUNE 2016**
**36** AGING
**37** CURRENTS

**13**

**MAR/APR 2016**
**34** ADAPTATION
**35** BOUNDARIES

*Science Connected.*

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

**12**

**JAN/FEB 2016**

**32** SPACE
**33** ATTRACTION

**11**

**NOV/DEC 2015**

**30** IDENTITY
**31** STRESS

**10**

**SEP/OCT 2015**

**28** 2050
**29** SCALING

**09**

**JULY/AUG 2015**

**25** WATER
**26** COLOR
**27** DARK MATTER

**08**

**MAY/JUNE 2015**

**22** SLOW
**23** DOMINOES
**24** ERROR

**07**

**MAR/APR 2015**

**19** ILLUSIONS
**20** CREATIVITY
**21** INFORMATION

**06**

**WINTER 2015**

**16** NOTHINGNESS
**17** BIG BANGS
**18** GENIUS

**05**

**FALL 2014**

**13** SYMMETRY
**14** MUTATION
**15** TURBULENCE

**04**

**SUMMER 2014**

**10** MERGERS & ACQUISITIONS
**11** LIGHT
**12** FEEDBACK

**03**

**SPRING 2014**

**07** WASTE
**08** HOME
**09** TIME

**02**

**WINTER 2014**

**04** THE UNLIKELY
**05** FAME
**06** SECRET CODES

**01**

**FALL 2013**

**01** HUMAN UNIQUENESS
**02** UNCERTAINTY
**03** IN TRANSIT

**SUBSCRIPTIONS**
Address subscription and address changes to:
*Nautilus*
25 Broadway, 9th Floor
New York, NY 10004;
phone: 212-221-3870;
email: order@nautil.us
Visit subscribe.nautil.us for more information.

**POSTMASTER**
Send address changes to:
*Nautilus*
25 Broadway, 9th Floor
New York, NY 10004

# Philip Glass

*The composer reflects on the subjectivity of time and music*

INTERVIEW BY FREDERICKA FOSTER

### SPACE AND TIME

There are many strange things about music and time. When I'm on a tour with the dance company we work in a different-size theater every night. The first thing the dance company does when we arrive is to measure the stage. They have to reset the dance to fit that stage. So you also have to reset the time of the music: In a larger theater, you must play slower. In a smaller theater, you have to play faster. The relation of time and space in music is dynamic. I have a range of speed in mind. If the players don't pay attention to that, it will look really funny. You can see the stage fill up with dancers because they are playing at the wrong speed.

### FIRE OF CREATIVITY

Sometimes when I sit down to write a new symphony, I say, "Wait, I did that already," and then I throw it away. I'm suspicious of pieces that sound like something I did before. It's the easy way out. I change as much as I can. I'm playing a piece at Carnegie Hall that I haven't played in 49 years. I have to rehearse it and I find I am playing it differently than I played it initially. The 31-year-old Philip who played that piece is gone. If that Philip had been able to hear the piece as I do today, I think it would have freaked him out. The challenge of any artist is to keep the fire of creativity alive. What we mostly do, we get good at doing something, and we keep doing it, and don't change much at all. I found that my engine of change was working with new people and the new ideas they brought to the conversation. Also, I have a mantra: "I am never happier than when I don't know what I am doing."

### ENGINE OF CHANGE

How do I continue to change? What is the engine of change? It can be a lot of things. It's like keeping the ball in the air. I have boys who are 14 and 16. They look at me and see a guy who is 80, and I look at them and see myself as a 16-year-old. I had a strange conversation with one of them. At the end of the summer, I asked, "How was the summer?" Marlowe said, "It was fine daddy, but it went by so fast." When I was a kid at camp, the summers seemed to go on forever. What if both of us were right? Is time passing by faster now than it was 65 years ago? What if time is actually speeding up? If everything is changing at the same speed, there is no way to measure it. The summer of 1947 went by very slowly for me, and this summer flew by for both Marlowe and me. What I suggest is these are not subjective but objective experiences. It's also a little terrifying. What if 1,000 years from now, a life span felt like it was only a few days?

ILLUSTRATION BY FRANCESCO IZZO