

NAUTILUS

HIGH TIMES

Weed farming goes organic

BETWEEN TWO WORLDS

A physicist retreats from reality

WE ARE HYBRIDS

The tangled tree of human evolution



Last of an Ancient Sea Creature

THE DEEP IMPACT OF GLOBAL WARMING P.20

An aerial photograph of a person in a blue and white kayak on a body of water. The water is surrounded by dense, brown, leafy vegetation, possibly seaweed or submerged plants, creating a textured, almost abstract background. The kayaker is positioned in the center of the frame, moving towards the bottom.

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NAUTILUS *Next*

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Resilience

BY KEVIN BERGER

THERE'S A MELANCHOLIC CAST to our cover story, "Twilight of the Nautilus." Peter Ward, a paleontologist and marine biologist at the University of Washington, is a leading expert on the sea creature with the beautiful spiral shell. To bring readers up to date on the state of the ancient mollusk—it hasn't changed for 100 million years—Ward relates his personal experiences as a scuba diver, tracking the nautilus, and explains how ocean conditions have changed in the past four decades.

In Ward's vivid descriptions, the ocean is a much lonelier place than it once was. So many of the sharks that once hunted the nautilus have themselves been hunted to near extinction by humans. Warm water, depleted of oxygen, has drained color from kaleidoscopic coral reefs.

I asked Ward, given he was an objective scientist, schooled to collect, analyze, and publish data on ocean conditions and species numbers, if diving in a barren sea affected him emotionally. Given his big personality, I wasn't surprised by his outburst. "Who says I'm objective! I'll tell you, when you go to these places, you are as subjective as can be. It's emotional, it hurts. You see this and know what's going on—overfishing and climate change—and objectivity is really hard to have."

Science is a rigorous process, performed best by keeping personal feelings in check and politics at bay. To pull back the curtain on the mechanics of nature, scientists work with diligence and humility. They are subjectively driven toward objective results. In the end, facts are facts, no matter how we might like them to be otherwise.

But science is done by people and people stuff can't be avoided; it's always part of the process—for worse, but most often, it seems, for better. This theme runs through this issue of *Nautilus*.

In "Life Always Wins. Follow Me," plant biologist Stefano Mancuso relays a chance encounter in Hiroshima that deepens his appreciation for nature's resilience. Astrophysicist Sarafina El-Badry Nance, meanwhile, writes about her struggles in college against sexist students and professors. "I would fall asleep to night terrors and wake up sweating, their words circling in my head and feeding my vultures of anxiety," she writes. Physicist Subodh Patil tells a similarly moving story about running afoul of immigration after 9/11 and being barred from returning to Brown University. Home in India, he buried himself in work and produced a breakthrough in string theory.

For Ward, doing good science has solidified his personal convictions. With recent DNA techniques, he and his fellow scientists can pinpoint where nautilus and giant clams, whose shells are increasingly in demand, are being pirated. "We don't need little seashells for trinkets and cheap jewelry. We don't need it," Ward says. "I want to finish my career to stop the seashell trade."

What unites these scientists and their stories in this issue, is that their personal experiences made them better scientists. Without the struggles, Nance writes, "I wouldn't have grown resilient. I wouldn't have pushed the boundaries of what I can do and learned so much about the magic of our universe."



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Readers Respond

Comments and letters about stories from print issue 38.

“THE PLANETS WITH THE GIANT DIAMONDS INSIDE”

Fascinating; a mission looks really worthwhile and will probably have all those unexpected bonuses. I suspect that the moons will be full of surprises.

—James Salmon

“THE ENGLISH PROFESSOR WHO FORESAW MODERN NEUROSCIENCE”

It's fascinating that an English critic from the 1920s had a thought process that was, and still is, in alignment with what we know about cognition today. Such a lovely evolution from the accepted “behaviorism” of his time, to the less popular “mental imagery.” A truly inspiring article indeed.

—Dalia Samaan

“SCIENCE ISN'T HERE FOR YOUR MOMMY SHAMING”

While many “mommy-shamers” may be motivated by good intentions for the child, I suggest that many are just the types of people who like to tell others what they're doing wrong, thereby satisfying their desire for authority. Usually they have no other authority, so every bit of new “knowledge” they come across elevates their sense of authority and they feel compelled to show it immediately.

—Marek Klemes

All sad, but true. Shaming is ubiquitous in our modern consumer culture, in part because shaming works to motivate behavior. The behavior that is being motivated is attention-capture, which is the driving engine of both old-fashioned materialism and the new social media-ism. It is not just mommy-shaming, although that is particularly egregious because our social constructs are highly demanding of the mother role. Body-shaming is perhaps even more ubiquitous and obnoxious, but marketers, attention-grabbers, trolls, and even do-gooders can and will shame anything and everything if there are eyeballs to be captured. Of course, this all helps the platforms which feed the frenzy be extremely profitable. We might want to do something about this.

—George Gantz

“THE BOTANIST WHO DEFIED STALIN”

The story of Vavilov is a profound example of how ignorance works to shape knowledge as much as science does, but in the opposite direction. Which will prevail? Given that most people have only the slightest familiarity with any science, but a robust belief in their own judgement, it should be clear.

—brian



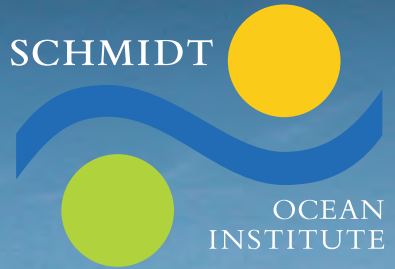
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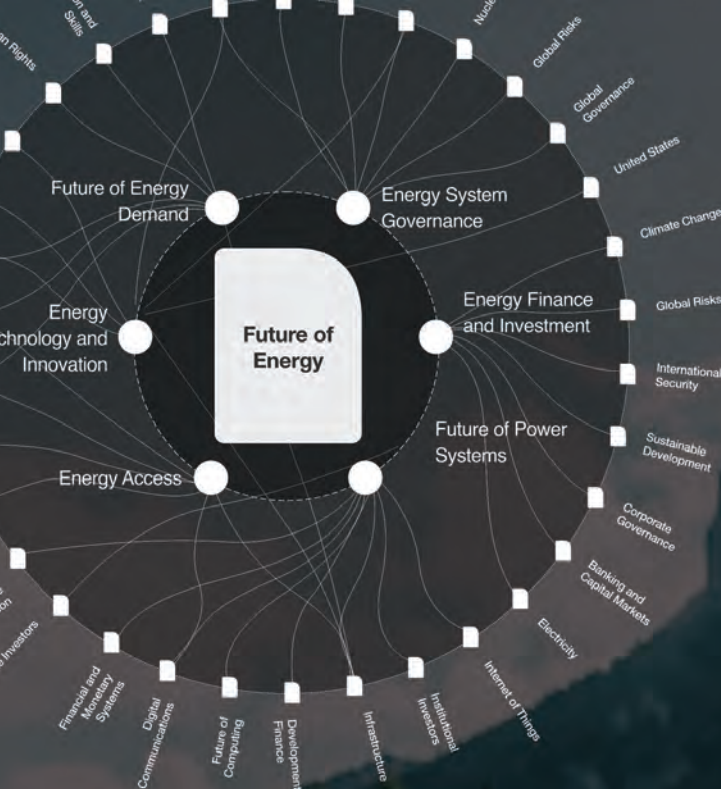
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Nile dam talks stall again amid Egyptian-Ethiopian dispute



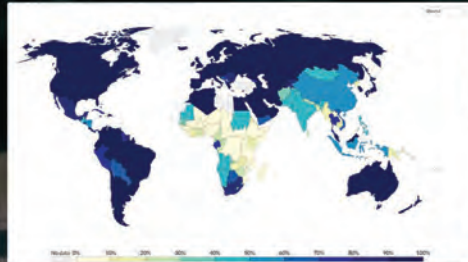
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Dr Helen Czerski
Presenter, Ocean Matters

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Preludes

PSYCHOLOGY

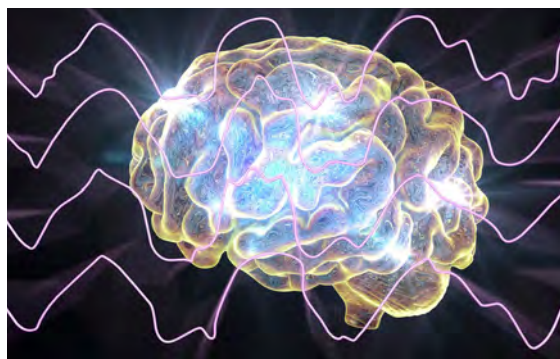
What Your Sleeping Brain Does

DURING THE 2021 OLYMPICS, I've been rooting for Kelleigh Ryan, who is on the women's foil team. She's from Ottawa, where I live. Whenever she scored a point, she'd emit a victory scream, probably feeling a rush of pleasure. Watching her on television, I did, too.

Getting better at something involves emotion. When we do well, we have good feelings—pride, pleasure, excitement—and these emotions help reinforce whatever behaviors we just engaged in. Similarly, the pain of failure makes recent behaviors less likely in the future. This is conditioning, and we've all experienced it—when we're awake. But what about when we sleep?

Sleep reinforces memories. We know this because after half an hour of sleep, people can remember things better than when they spend half an hour doing something else, like watching TV. Studies of rats show that their brains rehearse running through mazes while they sleep, in a process known as sleep replay. Memory's function is to store information that will be useful. Because of this, our mind prioritizes remembering some things over others. Studies have shown, for example, that it's easier to remember things that are useful for survival. Might sleep similarly focus on things that are particularly good or bad for us, like food and dangerous animals, and ignore things that are irrelevant to our well-being, like the exact shape of a cloud?

A recent study by the University of Geneva's Virginie Sterpenich and colleagues tried to find out. They had subjects play two computer games, which were designed to be engaging and to use two very different brain areas. One game involved picking a target face out of a set of 18, and the other game involved navigating through a 3-D maze. The face game players use areas of the brain specializing in recognizing faces—the fusiform and occipital face areas. The maze game players use the parahippocampal place areas, gray



matter regions that compute scene recognition and memory. The subjects did both of these tasks while Sterpenich and her team scanned their brains using both an electroencephalogram (EEG), which measures electrical activity over time, and functional magnetic resonance imaging (fMRI), which provides information about what parts of the brain are active by measuring the amount of blood flow happening all over the brain.

What the subjects didn't know is that the games were rigged. The players only won one of the games, but thought that their winning and losing was a result of their performance. If our brains are more likely to rehearse things they are rewarded for, then, when sleeping, they should rehearse the game they won more often than the game they lost. After the games were over, the participants went to sleep in a brain scanner. The researchers used an AI trained on the EEG and fMRI data to recognize which game was being played while awake, to decode the sleeping players' brain scans and see if they were thinking about one game or the other during sleep. (Once the AI learns how to identify a task in somebody who is awake—when scientists know what task they're doing—they can apply it to the brain activity observed during sleep and see which task the players' brain scans most resembles.)

It turned out that, yes, the participants' brains revealed they were doing a kind of “neural replay” of the game they had been manipulated to win. The

KATERYNA KON / SHUTTERSTOCK

reward you felt after “winning” the face game made a neural replay of it more likely to arise in your sleep. Not only did the detector identify this, but the brain areas associated with the rewarded games were preferentially active.

This suggests that our minds are rehearsing things during sleep and that they preferentially feature things that are good for us over experiences that don’t matter to us. Does this have anything to do with dreaming? Well, none of the participants entered rapid-eye movement (REM) sleep, which is when most dreams happen, during their time in the sleep lab. The neural replay happened only during slow-wave sleep, when dreams tend to be infrequent, dull, and go unremembered. The participants might not even have been aware of the rehearsal their brains were engaged in.

Other evidence suggests that dreaming during REM sleep tends to be more negative—bad dreams are more common than good ones. This leads to the interesting

Might sleep focus on things that are particularly good or bad for us?

idea that positive experiences are rehearsed during non-REM sleep, and negative ones are rehearsed during REM sleep.

I can’t help but think that Kelleigh’s victory scream enhanced her pleasure at scoring her points. It’s interesting to think that it made her more likely to rehearse fencing that night, when her adrenaline calmed down and she was ready to sleep. She got beaten in the quarter final, by Larisa Korobeynikova, from Russia. She didn’t medal, but tonight her brain might be preparing for the next challenge.

—Jim Davies

TECHNOLOGY

Reports of a Baleful Internet Are Greatly Exaggerated

IT’S NOW FASHIONABLE, when something has you mildly obsessed, to say that it is “living rent-free in your head.” Well, in my case, that something is an earworm—Bo Burnham’s catchy, creepy, poignantly acidic song “Welcome to the Internet.”

I can’t be alone. The song has been viewed on YouTube and Spotify more than 54 million times. The Internet’s near-utopian promise of speedily disseminating knowledge has, for Burnham, revealed itself to be a cartoonishly bad deal. We’re not enlightened as a result of this; we’re addicted, distracted, and motivated, much of the time, by the wrong things.

To get this out of my system, I thought I’d talk about the song—and its portrayal of the Internet as something pervasive and enticing that messes with our cognition—with a scientist. Doctoral student Lorenzo Cecutti had just published an article in *Nature Human Behavior*, the title of which aroused my curiosity: “Technology may change cognition without necessarily harming it.”

Cecutti was a great guide into the nuance of how the online world interfaces with our offline minds. “I have to be always mindful to draw a line between how digital technology usually affects things like our well-being, versus how it actually impacts our cognition,” he told me.

What studies show that the bad cognitive effects arising from digital technology are only short term?

One paper that we thought about was from 2011, called “Google Effects on Memory: Cognitive Consequences of Having Information at Our Fingertips.” One of the central theories in that paper is about transactional memory, which is an idea that doesn’t necessarily involve technology. It looks at how people share information, and how sometimes we rely on others to be the information receptacle. We can, in that way, extend our cognition, extend our memory.

One of the interesting things is that it’s likely their entire sample had used search engines, or Google, before they came into the lab for the experiment. The researchers gave participants trivia statements to type



and remember and told them that the computer would delete, or save, their typed statements. The researchers also explicitly asked them—or did not ask them, depending on the group—to remember the statements. Participants who thought the computer had deleted, versus saved, the statements recalled more statements, regardless of whether they were explicitly asked to remember them or not. So lacking, versus having, access to information stored on a computer increased deliberate and spontaneous remembering of the information.

This suggests that we use technology as a source of transactive memory, meaning that when we intend to retain this information internally, we can. So, it's possible that when technology is present, yes, we can make use of it, but when technology is not there, then we have no choice—we have to rely on our naked brains, so to speak.

Has the ability to offload tasks to digital devices made our lives easier and better?

It's made our *cognitive* lives easier, better. One way is simplifying. We rely on notification settings to remember calendar appointments. Not having to do this frees up capacity. It also enables us to do tasks that normally would be beyond our limits mathematically or computationally. Complicated equations can be very challenging to work with, but computers are very good at doing that. Of course, they cannot provide all of the solutions. They cannot think for us, or interpret and present findings for us.

Computers cannot think for us, or interpret and present findings for us.

Is there any good evidence that using digital technology worsens cognition in the long term?

Not really. A lot of the literature on digital technology and cognition are correlational studies looking at the effect of multitasking. A lot of the studies on long-term effects are coming out now. We talk about one, "The Negative Effect of Smartphone Use on Academic Performance May Be Overestimated: Evidence From a 2-Year Panel Study."

In that study, the researchers find the effects of using smartphones during classes are negatively affecting their grades. But, when they control for more stable characteristics—things like student impulsivity, socioeconomic status, class size, course difficulty—these effects aren't significant. So the longitudinal evidence does seem to point toward smartphones not affecting us in the long run. I wouldn't say this is definitive evidence. More studies need to be done. But saying that digital technology definitely negatively affects our cognition may be too premature.

—Brian Gallagher

ANIMALS

Life at the Edge of Impossible

YOU MAY HAVE ridden out the pandemic in compact living quarters without, say, much natural light or air conditioning. Perhaps you lived with roommates or family in an atmosphere that, as time wore on, grew increasingly toxic.

Things could be worse! You could be a member of the *Alviniconcha* species—specifically, a small, spike-studded snail who thrives in an environment inhospitable to most aquatic life; mere meters from deep-sea hydrothermal

Your chef-roommate, who happens to live in your respiratory system, also decides where you hang your hat.

vents that constantly spew toxic chemicals into the water. Think you have limited natural light? Try living nearly 10,000 feet below the surface of the ocean, where complete darkness envelops you 24 hours a day, under pressure so intense all the air pockets in your body would instantly collapse.

And forget Seamless. Forget *food*—at least the kind you ingest with your mouth. Your survival hinges on bacteria living in your gills (you have gills!) in a symbiotic relationship that provides you with energy, via a process called chemosynthesis. It's like photosynthesis, but chemosynthesis is driven by chemical reactions instead of light. As there's no sunlight and minimal oxygen present, the bacteria that dwell within *Alviniconcha* use hydrogen and sulfur molecules to produce sugars and other macronutrients that the animals then use as food. "There's very little food so deep in the ocean," says Corinna Breusing, postdoctoral researcher at the University of Rhode Island. "Having your own food-producing machine is much better than waiting for it to fall to you." While chemosynthesis is common around hydrothermal vents, it can occur in places outside of vents, such as in cold seeps and whale falls and even salt marshes: anyplace the proper mélange of inorganic compounds is brewing.

The researchers studied *Alviniconcha* living at the bottom of the Lau Basin, in the southwestern Pacific Ocean, and found that the type of bacterial symbiont determined where their particular host species could live. "The symbionts have different metabolic capacities and adaptations, so we think that the symbionts influence the distribution of the animal," Breusing says, adding that snails with *Campylobacteria* dominated at vents with higher concentrations of sulfide and



hydrogen, while those with *Gammaproteobacteria* were able to thrive at sites with lower concentrations of sulfide and hydrogen. Meaning: Your chef-roommate, who happens to live in your respiratory system, also decides where you hang your hat (so to speak).

When *Alviniconcha* are free-wheeling larvae, they still have digestive tracts and mostly feed on plankton. At some stage in early development, Breusing says, the snails take up bacteria from the environment in a process called horizontal transmission. "We don't know a lot about the exact infection process, but they probably invade the gill cells of the animal," she says. Once the snails become sessile, they lose the ability to digest food and the bacteria swing into action. Having a live-in roommate might be a drag, but there are upsides to it, too.

Part of what makes this research so remarkable is how logistically challenging it is, says Breusing. To study these snails, you need both a research vessel and a robot to collect the snails, and then the experiments need to be done under terrific atmospheric pressure. In order to mimic the extreme conditions on the margins of these hydrothermal vents, the researchers collected *Alviniconcha* during a 2016 expedition aboard Schmidt Ocean Institute's R/V Falkor using a remotely operated vehicle. After bringing the *Alviniconcha* to the surface, they put them in high-pressure tanks, where the team let the animals acclimate for a day or so before studying them.

Most hydrothermal vent-dwelling animals, such the aforementioned snails and deep-sea anemones, as well

as some species of mussels and tube worms, depend on bacteria that they pick up from the environment, but there is a species of deep-sea clam that passes their symbiont down from mother to offspring, like a fancy set of dinner plates. (This is rare in the marine world, Breusing says.) In the case of the deep-sea clams, where the symbiont is inherited, the symbiont cannot thrive outside the host and dies with it. But if a symbiont is taken up from the environment, it can be released back into the environment after its host dies, ready to help feed a brand-new host.

Alviniconcha might not pack the same visual punch as much marine life does much closer to the surface, but their very existence points to the origins of life on Earth. Before oxygen was free and plentiful, microbial life had to work with inorganic compounds like methane and ammonia, which over millennia dissolved into the seas. Much is still murky about how these little snails co-evolved with the bacteria that enable them to survive, but these fascinating ecosystems indicate that our education about life at the margins is just getting started.

—Adrienne Day

MATH

Why You May Have More Friends Than Your Friends Do

THERE'S A RUDE CHARM to the title, "Why Your Friends Have More Friends Than You." It's catchy, like the title of an antagonistic explainer: Here are the causes of your lack-luster social life. It sounds more like an op-ed than an academic paper. But in fact, "Why Your Friends Have More Friends Than You" is a 1991 paper from Scott Feld published in the *American Journal of Sociology*. It now has some claim to fame for introducing into popular culture the so-called "friendship paradox," which researchers have used to detect the early onset of contagious outbreaks and design effective vaccination strategies. New research, published in the *Journal of Complex Networks*, suggests the paradox is more nuanced than Feld figured it to be.

The paradox stems from our poor intuitions about networks and averages. If you were to guess how many friends you have, compared to the number of friends your friends have, how would you fare? You may say it's your friends that have more friends than you, if you're feeling modest. But it's also the case that some of those friends who have more friends than you also have friends who have more friends than them, and so on. The friendship paradox says that this is true for everyone—on average, everyone has friends with more friends than they have.

How is that possible? The paradox goes beyond friendship. It holds true any time you have a network of objects where any two of them are either connected



or not connected. Mathematicians call the objects "nodes," the connections "edges," and the whole network a "graph." Two nodes are "neighbors" if they are connected by an edge, and the number of neighbors of a node is called its "degree." You can define a sort of "net popularity" of a node by taking its degree and subtracting the average degree of its neighbors. For example, if I am friends with Annika, Bing Wen, Carolina, and Daud, and Annika has (including me) three friends, Bing Wen has five friends, Carolina has seven friends, and Daud has five friends, then my net popularity is:

$$4 - (3+5+7+5)/4 = -1.$$

It is a mathematical fact that if you average over all of the net popularities in a network, then that average

The friendship paradox is true mathematically, but very often has no practical consequence.

will be negative: Your friends have more friends than you do. You are more likely to be Carolina's friend than Annika's, exactly because Carolina has more friends. If someone has lots of friends, one of them is more likely to be you. In his paper, Feld suggested that this might be psychologically significant. People, when they wonder how many friends they ought to have, could be looking at the number of friends their friends have as a point of comparison, which will almost always leave them feeling inadequate.

But in a new paper, a trio of researchers from the Santa Fe Institute and the University of Michigan, who study physics and networks, show that the truth of the friendship paradox isn't as gloomy as it might seem. There are some networks where the friendship paradox doesn't meaningfully manifest at all. The authors—George Cantwell, Alec Kirkley, and Mark Newman—confirmed this by comparing their mathematical results against over 30 real-world networks, including among jazz musicians, collaborating scientists, drug users, and dolphins. So, if you were ever bummed out in the way Feld suggested, cheer up—the reality is much more complicated than the headline. You might be more popular than one single number makes it seem.

Statisticians have long understood that there are different ways to compute the “average” of something, with different advantages and disadvantages. The method I described above—add up all of the values and divide by the number—is more technically known as the “mean.” One disadvantage of the mean is that it is particularly sensitive to extra values. This is often referred to as the Bill Gates effect: If 10 middle-class people are sitting in a bar and Bill Gates walks in, the average income in the bar jumps from five to nine digits. This jump doesn't really show the real-world experience of the bar-goers, however. (Except they get to brag that they had a drink with Bill Gates.)

Similarly, Cantwell and his colleagues give the example of 1,000 people who are all friends with each other

except two—call them Avital and Boris. Those two are friends with everyone else but not with each other. That means that 998 people will have 999 friends each, and 2 people will have 998 friends each. For most people, the net popularity will be:

$$999 - (999 + 999 + \dots + 999 + 998 + 998)/999 \approx .002$$

But for Avital and Boris, the net popularity will be:

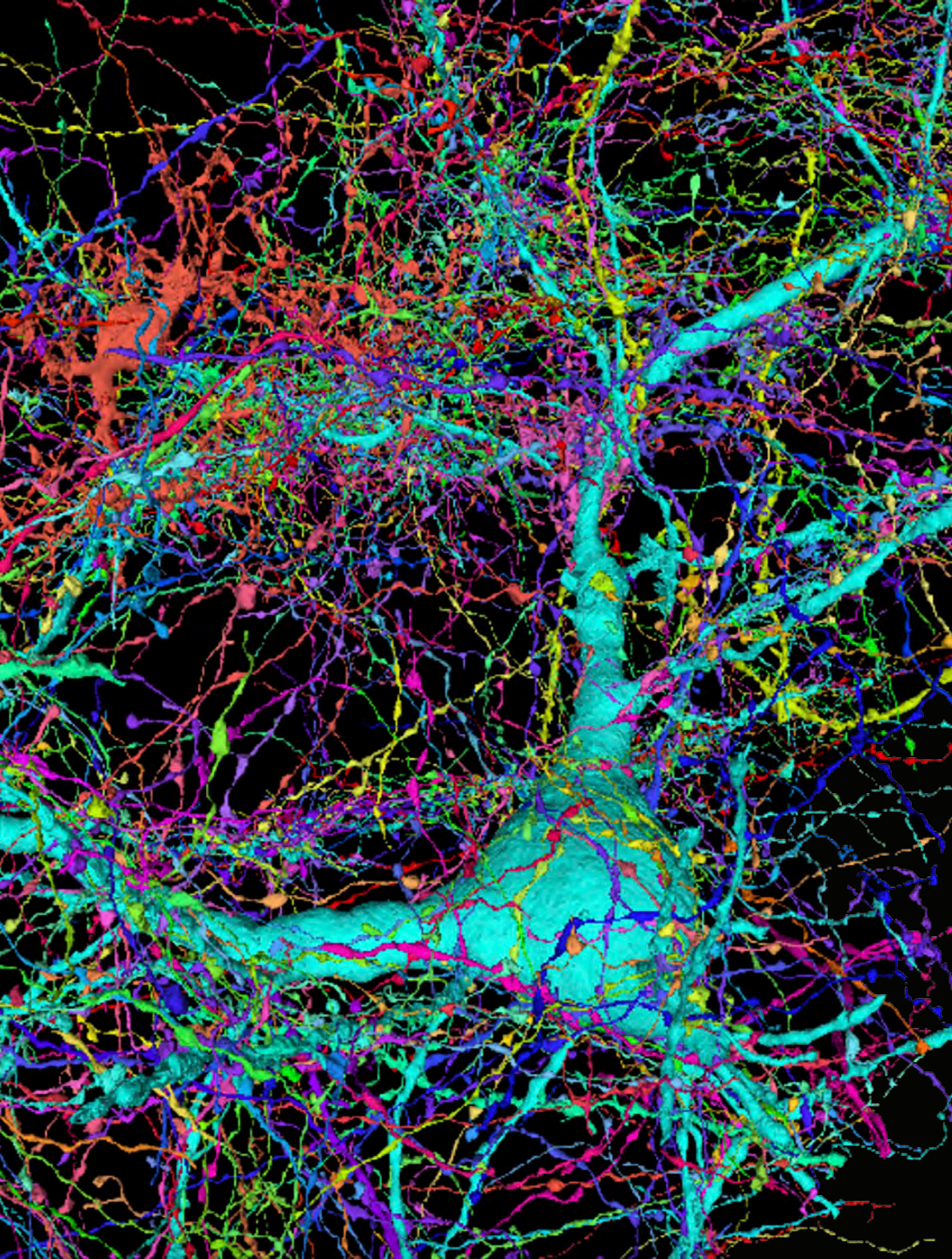
$$998 - (999 + 999 + \dots + 999 + 999 + 998)/999 \approx -0.999$$

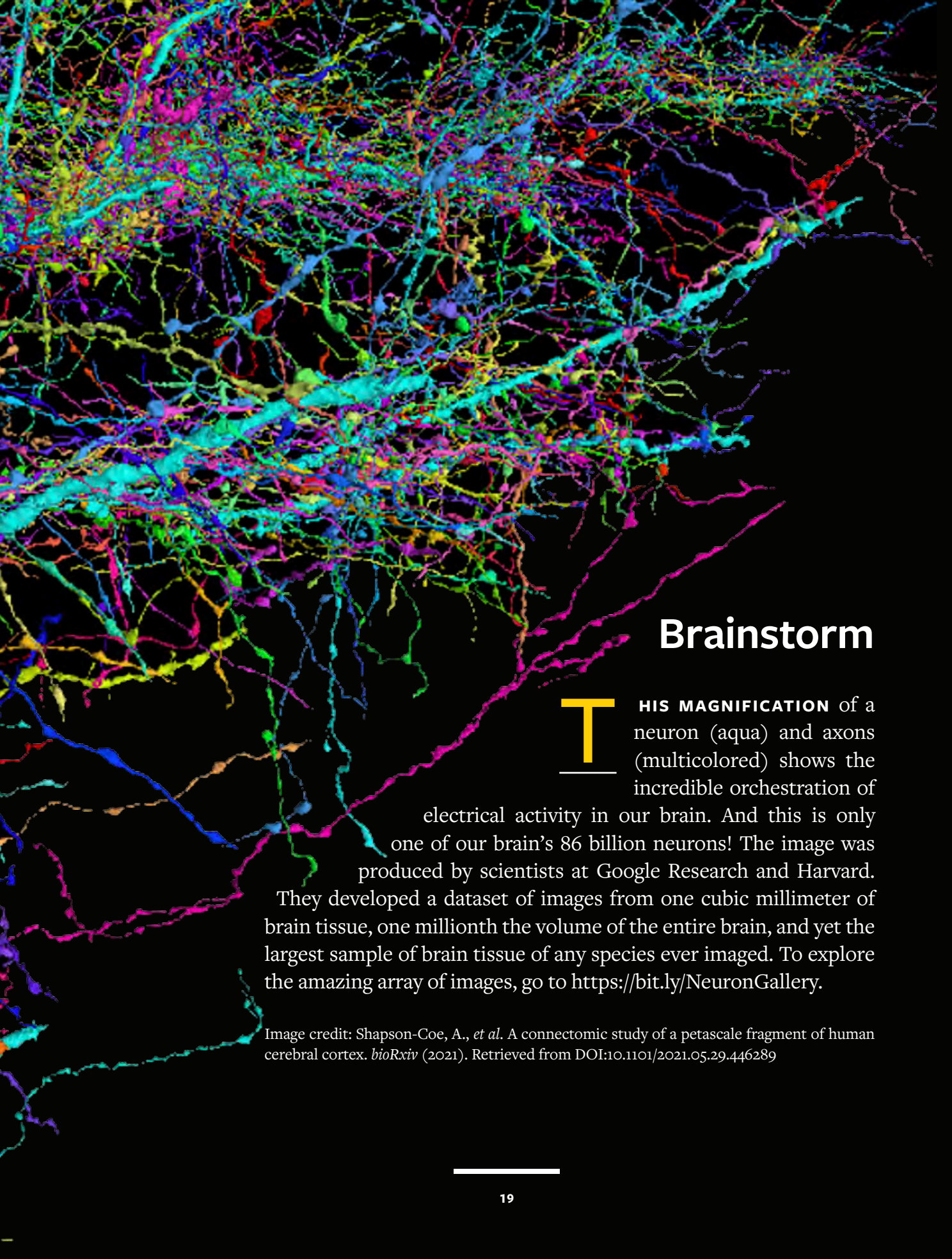
Due to the Bill Gates effect, the average net-popularity of the entire friend network will be pulled negative by Avital and Boris, despite everyone else in that network actually being more popular, on average, than their friends.

The simplest way to choose a network at random is to pick a probability, say 25 percent, and give every two nodes an edge 25 percent of the time and no edge 75 percent of the time. This is called a Poisson random graph. Cantwell and his colleagues show that, although the mean net popularity of such a graph will usually be around -1, confirming the mathematical friendship paradox, in fact, a large fraction of the nodes will have positive net-popularity. As the average number of neighbors of a node gets large, the fraction of nodes with positive net-popularity gets closer and closer to 50 percent. For these graphs, as they say, “no meaningful ‘friendship paradox’ applies.”

So now we have a paradox of paradoxes; the friendship paradox is true mathematically, but very often has no practical consequence due to the Bill Gates effect. What should you do if you are worried about your popularity? Relax. Despite what Facebook tells us, it's the quality of friendships that count, not the quantity, and certainly not your average popularity. Enjoy your time with whatever friends you have. And if you see Bill Gates, tell him to call me.

—Joshua Holden





Brainstorm

T HIS MAGNIFICATION of a neuron (aqua) and axons (multicolored) shows the incredible orchestration of

electrical activity in our brain. And this is only one of our brain's 86 billion neurons! The image was produced by scientists at Google Research and Harvard.

They developed a dataset of images from one cubic millimeter of brain tissue, one millionth the volume of the entire brain, and yet the largest sample of brain tissue of any species ever imaged. To explore the amazing array of images, go to <https://bit.ly/NeuronGallery>.

Image credit: Shapson-Coe, A., *et al.* A connectomic study of a petascale fragment of human cerebral cortex. *bioRxiv* (2021). Retrieved from DOI:10.1101/2021.05.29.446289



Twilight of the Nautilus

*What the scientist who has studied the iconic sea creature
for 45 years now sees*

BY PETER WARD

PETER WARD



W

E WERE ALL VERY TIRED. My crew and I had been tracking nautilus off tiny Ndrova Island in Papua New Guinea for close to a week. Every day we spent 16 hours on small dugout canoes and then got eight hours of fitful sleep on the deck of a Melanesian sea craft. Rice and fresh tuna for breakfast, lunch, or dinner. In the open boats, the sun, the wind, the rain, the dark, all seemed to merge. Time melted in fatigue.

I was most struck by the absence of sharks. In 1984, we were repeatedly chased from the water. Not now.

A week before, we had fitted the nautilus with acoustic transmitters that gave their position and depth. To track them, we had to stay within a kilometer as they bumped through a muddy habitat near the ocean bottom and climbed up the coral reefs lining the small islands here. We sat above them in small boats and canoes, dangling hydrophones over the side to pick up the faint acoustic signals.

It was 2015 and we were tracking the two different kinds of nautilus—Nautilus and its descendent, Allonautilus—found here and virtually nowhere else on Earth. Both varieties were going extinct from overfishing and changing ocean conditions. We wanted to know how they were managing to survive. Could they cross large bodies of water to find sufficient food?

In 1984, I had done this same kind of work, in exactly this place, but with inferior equipment. Now, 31 years later, my memory jangled. Major changes had occurred. Back then the water was blessedly cool as it rose up reef walls from deep ocean zones. To dive was to escape the heat of this place, a geographic hot spot athwart the equator. Now the rising water, deficient in oxygen and nutrients, was a warm death to the reefs it once sustained.

I was most struck by the absence of sharks. In 1984, we were repeatedly chased from the water. On one occasion, my dive buddy slammed his large camera against the head of an especially aggressive black tip as we scrambled over the transom and into our boat. Not so in 2015. We dived every day for two weeks. We never saw a single shark. Not even a tiny, white-tipped reef shark. I knew where they were. Or at least where their fins were. Hanging in the Thailand, Cambodia, Hong Kong, and mainland Chinese stores by the tens of thousands, waiting to become soup.

Our transmitters, miracles of miniature electronics that looked like AA batteries (albeit \$1,000 each; pretty pricey for AA's!), picked up the nautilus as they swam above the bottom of the ocean. Each second, they sent us their position, their depth, and the temperature of the water they were in. They didn't descend below 800 meters because at that depth the ocean pressure would cause their shells to implode. Our tracking showed they followed the ocean bottom contour toward shallower water, where there was more food, but also more danger. Their predators, sharks and large fish, are visual hunters, so the nautilus were safer in the darker, deeper depths. At least they once were.

In 2015, our research brought me a revelation that my colleagues in marine biology and paleontology and I are still sorting out today. Although the nautilus doesn't face as many predators, whose own hunter, humans, have reduced their numbers, the buoyant, deep-sea organism with the beautiful spiral shell faces a bigger problem. The water temperature in the ocean layer, defined as the Mesophotic Zone, through which the nautilus travels, is growing so warm that it's destroying the life of all the organisms that thrive there.

"Canary in the coal mine" has become a hoary environmental saw. But it's still a useful one. Canaries are more sensitive than humans to increases in carbon dioxide and methane, when combined with lowered oxygen. It was wise for early miners to use the birds to detect when gas accumulations in mines rose to levels that would kill them. The nautilus is the prototypical animal in the Mesophotic Zone. Its survival now foretells the fate of the oceans' ecological health.

THE MESOPHOTIC ZONE ranges from 100 meters to 500 meters deep, where light, when it penetrates to the bottom, is a dim twilight, even at noon. The animals in this twilight zone share many characteristics, but among the most important is slow growth, leading to extended adolescence, low fecundity once maturity is attained, and long lifespans.

Because light is so low, the animals, the bony fish, sharks, and many kinds of mobile invertebrates, largely eschew bright color displays. To find food they largely use chemoreception—like a dog hunting for that elusive kibble on a dark floor at night, they can pinpoint food by smell—rather than vision. They all live life in the slow lane, using techniques to jealously guard their energy, given food is often scarce. This is the case with nautilus and another bellwether species, the coelacanth. The coelacanth is a giant



CAPTAIN NAUTILUS Author Peter Ward holds an Allonautilus aboard an outrigger off Ndrova Island in Papua New Guinea. Ward has been tracking and studying the cephalopod for more than 40 years.

blue fish with lobe fins that are a “missing link” to the limbs of the first amphibians, and ultimately our limbs, making the coelacanths our own deep ancestors. But coelacanths still exist, at the depths and sometimes the same localities of nautilus, true snapshots of bygone geological eras.

The two animals have come down to us from impossibly long ago. Both first appeared in the fossil record in their present guises about 100 million years ago. (The very first nautiloids appeared 500 million years ago, and the first coelacanth-like fish almost 400 million years ago, based on well dated fossils of each.) Recent studies using oxygen isotopes of their skeletons, and technique that yields temperature of skeletal growth, reveal the nautilus and coelacanth first evolved when they were shallow-water species. But sometime around 60 million years ago, their species migrated down into the Mesophotic Zone, while the fossil record tells us that all those that stayed in the more flourishing shallows went extinct.

GREGORY BARORD

In deep water, both species can live for a very long time, at least a century. A key to their longevity is they evolved to live at extremely low metabolic rates. Nautiluses can bump across the ocean bottoms with almost no energetic effort, using their 90 tentacles to chemically search for that perhaps once-a-month windfall of a dead fish falling down the reef cliff onto their muddy habitat. But their genius is their buoyant shell. They expend virtually no energy in searching for food. Their body plan involves one of the greatest evolutionary trade-offs of all time. Swimming takes energy. Breathing takes energy. For the nautilus, the energy expended for swimming also allows for respiration. The coelacanth has perfected life in the slow lane in a different way. Almost uniquely among animals, their normal position is head down, tail up, perfectly vertical and still. So here we have a 100-million-year-old fish, bright blue, 6 feet long, standing on its head and rarely feeding, like a deep-water Zen master.

In the past, both species largely subsisted on the food from above, from animals that lived in shallow waters. Plankton and organic-rich sediments tumbled down the long stony walls of coral reefs. The greatest treasures were bodies of animals that sank to the bottom, to be fought over by the animals adapted to search for meat. Neither the nautilus nor coelacanth appear to be predators of live animals. They exploit a scavenging lifestyle instead, the great jackals of the sea.

Coral reefs are the palaces of the Mesophotic Zone. They hum with life. Trying to count the number of different species visible on a thriving reef is like trying to count the stars in the sky. A more accurate analogy may be plants in a rainforest, as reefs harbor so many kinds of life.

Reefs are often and not inaccurately described as “superorganisms.” They are immense, composed of millions of organic parts, and function as conduits taking sunlight and turning it into both plant and animal flesh. The tiny animals making up a coral colony can only

Hope: An Interview with Peter Ward

In “The Twilight of the Nautilus,” you present a bleak, or maybe I should say, melancholic, prognosis for the ancient cephalopod, for the ocean. Give us some hope.

The nautilus is not dead yet. The greatest sense of hope is the fact that the United States government has hooked up with a bunch of countries with which we don’t always see eye-to-eye. In India, Palau, and two or three other Pacific countries, people in governments recognize the importance of conservation. Palau had industry for a long time where they let dive boats catch the nautilus, bring them up, photograph them, and let them go. The problem is when you bring them up into warm water that can kill them. The international body, CITES [the Convention on International Trade in Endangered Species of Wild Fauna and Flora] has really shut down the nastiest stuff.

The positive thing going forward is I’m starting to study giant clams, the Tridacna. Terrible harvests are taking place. It’s just so tragic. Elephant ivory has been used for trinkets and baubles and little carvings. People are killing elephants for nonsense, for jewelry, just like they killed the nautilus for jewelry. Not long ago, officials in the Philippines seized \$25 million of giant clams, big ones, the biggest ones, the 100-year-old clams. And these pirates must’ve been scouring the Philippines for years, bringing these up. They had a little remote beach and they had tons of clams that were going to be picked up, put in shipping containers, and sent off for carving to replace the missing ivory. We’ve been successful shutting down the elephant ivory trade so there needs to be a replacement.

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Continued from page 25

What's being done to stop the clam trade?

I hooked up with a guy instrumental in stopping the ivory trade. He succeeded in extracting DNA from an ivory tusk. He can tell you where that elephant came from. We're now doing those same techniques to nautilus shells. We'll be able to tell who's pirating nautilus, where they came from. We're now doing the same with the giant clam trade. I want to finish my career by stopping the seashell trade. You don't need little seashells. You don't need the nautilus. You don't need giant clams. You don't need that stuff. Don't do it.

—Kevin Berger

exist by keeping a greenhouse full of tiny, photosynthesizing algae deep within its transparent flesh. That goes for the different types of reefs, including barrier reefs, atolls, lagoon reefs, and shallow fringing reefs. They all have anatomical parts that evolved to acquire energy, grow, and for as long as possible, stave off death.

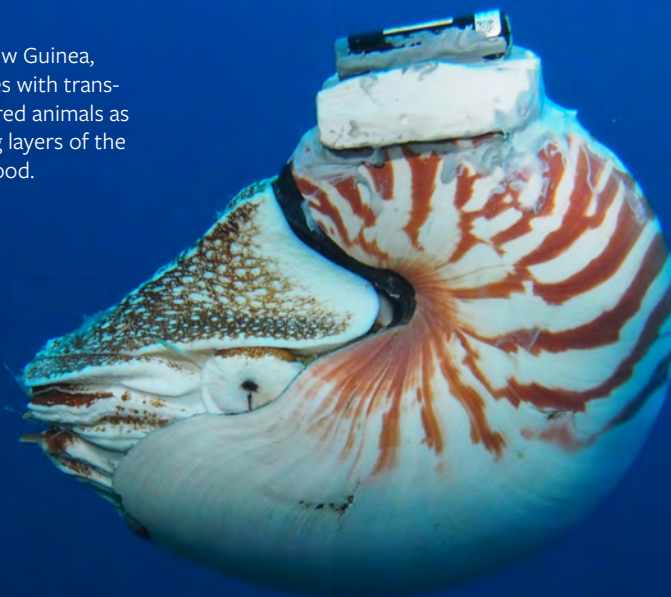
And they have staved off death for more than 500 million years. If we could enter a souped-up time machine and hire a local airplane to photograph reefs during the geological periods Ordovician, Devonian, Permian, Triassic, and Cretaceous, each of which experienced a mass extinction of organisms, we would find the majestic reefs relatively unchanged.

Reefs' resilience is aided by vertical walls. The walls have specific shapes at specific places, on a transect from deep to shallow water. In fact, of all underwater environments, the vertical, stony walls that mark the deep-water edges of coral reefs are among the most sublime, colorful, and ancient of Earth's biologically produced habitats.

The deep water in front of coral reefs is normally cold and nutrient-rich. Because cold water contains more oxygen than warmer water, this nutrient- and oxygen-rich resource is as necessary for the life and growth of reef tracts as fresh water and fertilizer are to a garden. What's more, the perpetual winds of the coral-living latitudes push ocean water in unvarying directions. This causes the deep, cold water to rise into the warmer, often oxygen-deprived surface waters where corals most actively grow. This process is called upwelling and results in the richest fisheries in the world. Along with nourishing coral, it allows for the rich sardine and herring fisheries of western South America, western South Africa, western North Africa, and California.



FINDING NAUTILUS In New Guinea, Peter Ward outfitted nautilus with transmitters to follow the endangered animals as they bobbed through warming layers of the ocean in search of sufficient food.



Here we have a 100-million-year-old fish, 6 feet long, standing on its head and rarely feeding, like a deep-water Zen master.

IN LESS THAN A CENTURY, climate change has upended conditions that have sustained life in the Mesophotic Zone for millions of years. Global warming, generated by human activity, has penetrated surface water and caused the water in front of reefs to become lethally warm and anoxic. Our work showed that the same species I studied at this place in 1984 were living and growing in water temperatures 3 to 5 centigrade cooler than now.

One of nature's greatest symbiotic partnerships is between coral and a tiny organism called zooxanthellae. Zooxanthellae adsorb the coral's respired carbon dioxide and phosphatic wastes and are in turn protected from predation in the open sea. The corals get a different benefit. Zooxanthellae allow the coral to build gigantic, hard skeletons. But when the oxygen-deprived warm water hits the zooxanthellae, they feel poisoned, and their reaction is to flee. When the zooxanthellae escape their coral hosts, they leave the once colorful coral animal transparent, so that the white calcareous skeleton of the coral is now visible. We call this coral bleaching.

It is not only the shallow reef being killed by the increasing upwelling of giant "blobs" of the warm water. The entire ecosystem of animals and plants in the once oxygen-rich environments of the Mesophotic Zone is encountering death by poison.

During our work in that hot equatorial visit in 2015, we brought back tiny slivers of nautilus shells for analysis in giant mass spectrometers. Long gone are the days when we would collect and kill for science. For the past

TWILIGHT ZONE Peter Ward on a dive off the coast of Ndrova Island, just north of Papua New Guinea, the only region on Earth home to the Allonautilus (his left hand) and Nautilus (right hand).



In less than a century, climate change has upended conditions that have sustained life in the Mesophotic Zone for millions of years.

decade, we've returned all the nautilus we caught to the sea. The bits of their shell edges gave us sad evidence of the warming of the Mesophotic Zone.

More than 80 years ago, the great Chicago chemist Harold Urey discovered the temperature of skeletons in many kinds of invertebrates, including the nautilus, can be determined with mass spectrometry. The instrument measures the fractionation of molecules; in this case, the isotopic composition of oxygen in seawater baked into the nautilus shell. The readings told us the fractionation, a function of temperature, represented significant warming between 1984 and 2015 in the nautilus habitats off Ndrova Island. That suggested the nautilus was moving toward deeper, cooler waters. But depth exacts its own lethal penalty. Higher pressure slows their growth, and slow growth of juveniles has been a death sentence for them.

We had been put down remote video systems that allowed us to make estimates of population numbers. Nautilus and Allonautilus are so efficient in finding

GREGORY BARORD

the meat in deep-water crab traps, the preferred mode of capture by illegal shell traders, that they have been easy to catch. Traders have reported up to 50 nautilus on a particularly good haul. That's led to the assumption that there are millions of these archaic animals crisscrossing the deeps in front of coral reefs. But our estimates are that there might be 10 nautilus per square kilometer where there is no nautilus trapping, and maybe 1 per kilometer in the Philippines and Indonesia, sites of the most virulent trapping. A square kilometer of ocean bottom is a very large area. That so few nautilus live in that area, even in the best of circumstances, represents a life on the edge.

Perhaps if Nautilus and Allonautilus only had to survive the warming depths, they would do as they have always done—eke by. If they were only fished by those who can sell a single, freshly killed Allonautilus for \$1,000—a sum more than the annual income in the area where they are found—perhaps there would be a world in a thousand years with this iconic animal. But the nautilus and coelacanth are being rapidly killed simply for food by fishing communities in the tropics, whose livelihoods are slowly being destroyed by climate change and overfishing. Like so much in our warming world, the delicate balance of the Mesophotic Zone, and the ancient animals in it, are being crushed by the human thumb of extinction. ☹️

If the Nautilus only had to survive the warming depths, they would do as they have done for millions of years—eke by.

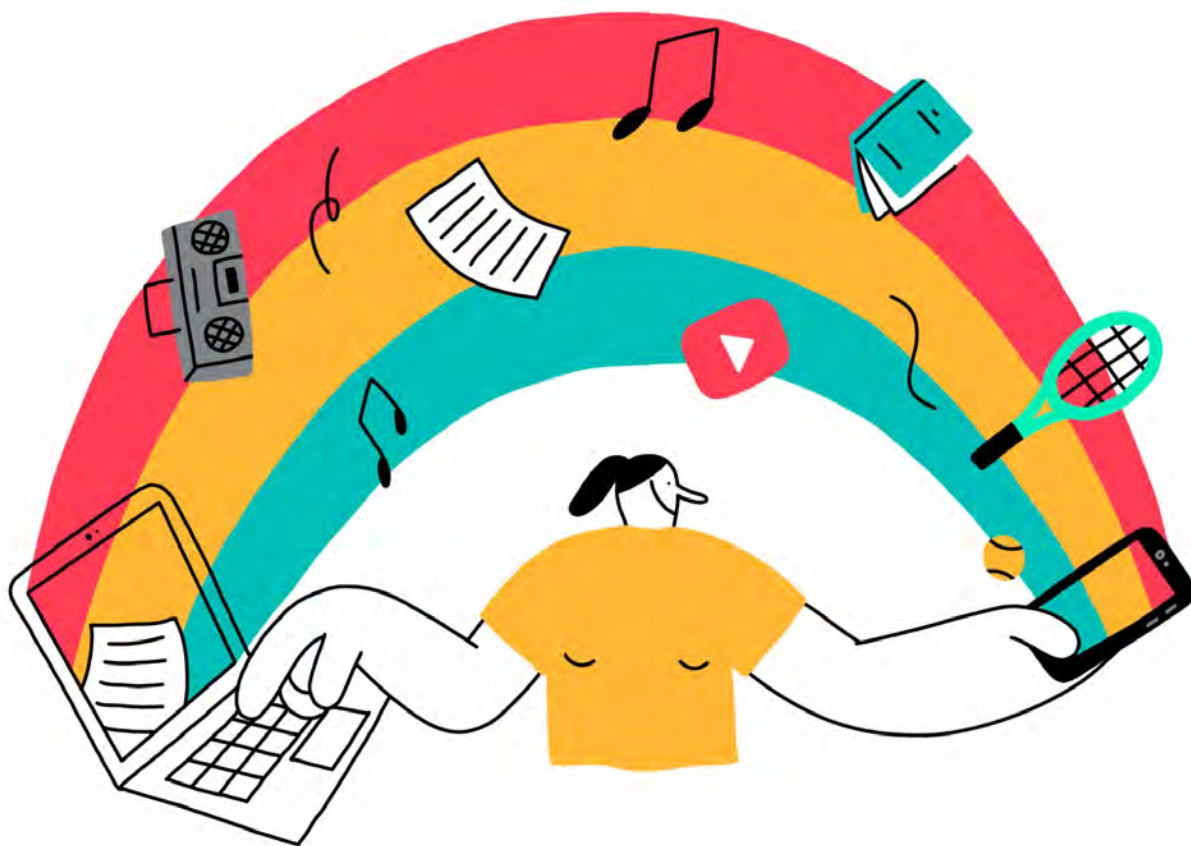
PETER WARD is a professor of biology and Earth and space sciences at the University of Washington. He began field research on living nautilus in 1975 at age 25. He continues this work today.

ADDITIONAL READING

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The Incredible Fig

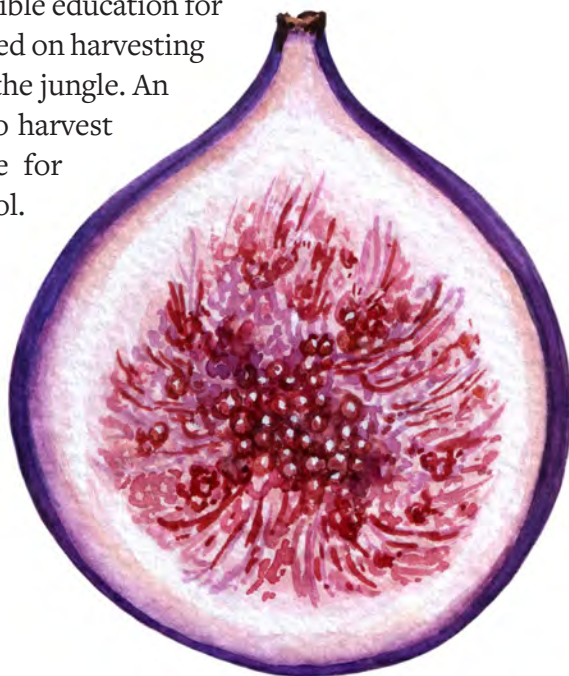
*The fig is an ecological marvel.
Although you may never want to eat one again.*

BY MEG LOWMAN





ONE OF MY FAVORITE walkways in the world spans a beautiful fig in the village of Falealupo on the island of Savai'i, Samoa, formerly Western Samoa. My colleague the ethnobotanist Paul Cox invited me to visit this island in 1994 at a critical juncture in its history. The 16 tribal chiefs were at a crossroads. The Western Samoan government required villages to build cement schools because their former palm-thatch construction could not withstand the frequent monsoons. But the cost of a school was over \$50,000, and Savai'i did not have a cash economy. Samoans are incredibly supportive of their children and wanted the best possible education for them, but their livelihood was based on harvesting fish from the sea and fruits from the jungle. An Asian logging company offered to harvest the island's timber in exchange for enough funds to build a new school. The chiefs were uneasy because their entire existence over many generations relied on the forest, and even their ancestors were part of this ecosystem, returning to Earth as flying foxes in the canopy.



If figs disappeared in the Amazon, the entire ecosystem could collapse.

I flew to Samoa with two construction engineers to discuss the notion of a walkway. I was honored to be included in a ceremony with all 16 tribal chiefs, where they sang, drank their sacred kava, and discussed the options of logging versus ecotourism with regard to the fate of their island trees. After more than five hours, they unanimously agreed to take out a loan and build this newfangled idea called a treetop walk. They had never heard of ecotourism before but decided to trust the concept our team had proposed: that visitors would pay to explore the island's eighth continent. Today, a platform circles the island's largest fig, connecting to a bridge that spans to the local school. Within two years, the debt for the new school was repaid by ecotourism, not logging. As a thank-you, the senior chief anointed me "Mati," which means "fig," and presented me with a sacred kava stick, now a favorite treasure. I have always admired and loved figs, but in this case, one emergent Samoan fig literally saved the trees of an entire island.

Theophrastus, an ancient Greek philosopher who studied plants (circa 300 B.C.), is credited as the founder of botany, and the first person to describe fig species. He focused on *Ficus carica*, an important edible fig, and was unaware that hundreds of others existed, each with its own life story. He did learn about one particularly important banyan (*Ficus benghalensis*) from the stories of one of his contemporaries, the conqueror Alexander the Great, who claimed that 10,000 soldiers sheltered under one fig, with all its pillar roots forming

an enormous leafy umbrella. Much later, in the early 20th century, the English botanist E.J.H. Corner specialized in *Ficus*, and described hundreds of them. One of Corner's unique legacies was training four monkeys to fetch fig fruits in the canopy, so he could describe new species without climbing himself. He affectionately called them his "botanical monkeys." Within six months, they collected the fruits of 350 species, far more than a human climber could.

A member of the diverse mulberry family (Moraceae), the Latin genus *Ficus* includes approximately 800 species of deciduous or evergreen trees, some of which are cauliflorous (meaning they flower and fruit along their main trunk instead of at the ends of branches), plus a few shrubs and vines. An estimated 150 figs inhabit the New World (Americas), and over 600 species in the Old World tropics (India, Asia, and Australia). Most are edible and germinate in the conventional way, starting life as a seedling and growing upward. Any fig that begins life as an epiphyte is called a banyan, technically part of the subgenus *Urostigma*, and includes the well-known strangler figs. In my global exploits as a field botanist, I found that stranglers occupy the most extraordinary lifestyle of any trees on the planet, bar none! The name itself conjures up the antics of James Bond or some Sherlock Holmes murder mystery, but the actual life history of this species engenders shock and awe. During his exploration, Alfred Russel Wallace called stranglers "the most extraordinary trees of the forest."

A wasp dies inside a fig after pollination. Anyone who eats figs is consuming wasp biomass.

My first exposure to the incredible strangler figs came when I climbed them in Australia, most notably the iconic emergent *Ficus watkinsiana*, named for George Watkins, the former president of the Pharmaceutical Society of Queensland and plant collector. He was an Englishman who came to Queensland in the 1800s and trained as a pharmacist. He pursued natural history in his spare time and participated in numerous expeditions. In 1891, F.M. Bailey named a fig species after him. It was called Watkins' fig, nipple fig (due to the fruit structure), or green-leaved Moreton Bay fig. Its fruits are rounded, purple-black, and have distinct "nipple" structures, although the word "fruit" is deceptive because figs are anatomically not really fruits but a cluster of hundreds of flowers enclosed in a smooth skin. Like other fig species, the trees have male and female flowers on one plant, known as monoecious, from the Greek word for "one house." *F. watkinsiana* leaves are tough, waxy, and entire, although a few fig species have lobes. Another famous Australian banyan is the curtain fig outside Atherton, Queensland, which occupies close to an acre of ground with all its aerial roots, though it's not nearly as vast as Alexander the Great's historical tree.

Different from most tree seeds that germinate on the forest floor, which is relatively dark and inhospitable to a delicate seedling, stranglers start life at the top with plenty of sunlight. When a figbird ingests fig fruits, it defecates the seeds onto an upper branch. This unique beginning means stranglers literally start life

as an epiphyte with adequate light, eventually sending down roots to absorb water and nutrients below. The limiting factor for a strangler seed tends to be moisture, so germination is most successful on rotting or decaying bits of branches. My fellow "arbornaut" (who explores tree canopies) Tim Laman of *National Geographic* studied the germination of one strangler fig (*Ficus stupenda*) in Asia. He placed its fruits in the canopy to determine ideal conditions for downward growth and found they grew best in moist, decaying branches or wet bark crevices. Tim also documented the many animals that disperse figs, including hornbills, gibbons, orangutans, and flying foxes.

Once a strangler is established in the crown, a lattice-work of downward-growing stems thickens with time and often surrounds the host, sometimes creating a hollow center if the host has soft wood and subsequently rots inside. In some cases, strong-wooded host species survive and live in tandem with the strangler, so both trees are intertwined as a massive duo. Although stranglers, or banyans, often constrict their host,





A PERFECT STRANGLER In her global exploits as a field botanist, Meg Lowman has found that strangler fig trees “occupy the most extraordinary lifestyle of any trees on the planet, bar none!”

they also sustain thousands of other creatures in the ecosystem. It seems astounding that other species have not evolved this adaptation to outcompete for light, space, and water by starting at the top. Seedlings that germinate on the forest floor must wait patiently, sometimes decades, for a treefall to create a light gap, plus have the good fortune of not being trampled, eaten, or buried during their precarious juvenile phase. Some figs eventually form buttresses, which are aboveground prop roots that stabilize their shallow-rooted shapes; they would otherwise be prone to fall during monsoons.

Mature *Ficus* (including banyans) produce thousands of fruits, an important food source in tropical food webs. Fertile figs, like the ones we eat, are distinct because of their unique fleshy, hollow receptacle with an inner surface laced with tiny flowers or fruitlets. All species have tiny male and female flowers that develop

on the inside wall of a syconium, which eventually becomes a fruit. A tiny female wasp of the Agaonidae family enters a hole in the top of the syconium and passes through a tunnel lined with downward-facing scales that only allow one-way travel. The wasp finds two types of female flowers inside: stalked, short-styled flowers and long-styled flowers that are not stalked. While she pollinates the flowers, the wasp also lays her eggs and then dies. After a few weeks, her offspring hatch, and wingless males mate with winged females, then chew an exit tunnel that allows the females to fly to another fig and repeat the process. The females pick up pollen from recently matured male flowers as they exit. Some botanists originally thought all 800 species required a specific pollinator wasp, but more recent molecular analyses reveal that 119 fig species shared multiple pollinator wasp species. When a wasp dies

inside the fig after pollination, enzymes (called ficain) break down the carcass; consequently, anyone who eats figs is also consuming wasp biomass. When scientists at the National University of Singapore experimentally exposed fig wasps to warmer temperatures, their lifespan significantly shortened. This suggests climate change could jeopardize *Ficus* pollination success, if wasps don't have enough time to find their specific fruits. As always, it is difficult to extrapolate from the laboratory to the forest.

As with most complex interactions, additional players in the fig-wasp interactions are parasitic wasps, some of which also lay eggs inside figs, which prevents the beneficial pollinator wasps from entering. Even worse, some parasitic wasps inject their eggs through the fig's surface without even boring a pathway inside, and their offspring feed on the pollinator wasp larvae. Hundreds of wasps function as pollinators, and each *Ficus* species is known to host up to 35 species of non-pollinating wasps, making their crowns a hotspot of biodiversity. In addition to wasps, over 1,200 recorded species of birds, insects, bats, and mammals, including humans, eat the fruits, making *Ficus* a true keystone species for the biodiversity of many tropical forests. In the Amazon, ornithologist John Terborgh wrote that if figs disappeared, the entire ecosystem could collapse. Biologist Dan Kissling correlated the number of fig species in sub-Saharan Africa with the abundance of fruit-eating bird species, and concluded figs were the keystone resource.

Figs have many uses for humans as well as for insects, birds, and animals. Their milky latex contains medicinal properties, and in the Amazon, villagers administer a teaspoon to cure stomach parasites in children. According to indigenous people in French Guiana, Colombia, and Brazil, the same sticky latex can cure cuts, fractures, and abscesses. In Nepal, *Ficus benghalensis* leaves, bark, and roots are used to treat more than 20 ailments; this useful banyan is also used in India to treat a wide variety of disorders ranging from tooth decay to hemorrhoids, diabetes, and constipation. At one time, figs were grown for rubber latex in India and parts of Africa. Probably the most famous fig is *F. religiosa*, or the Bo tree, native to India and Southeast Asia, thought to be the canopy under which Buddha received enlightenment. This is one of several species

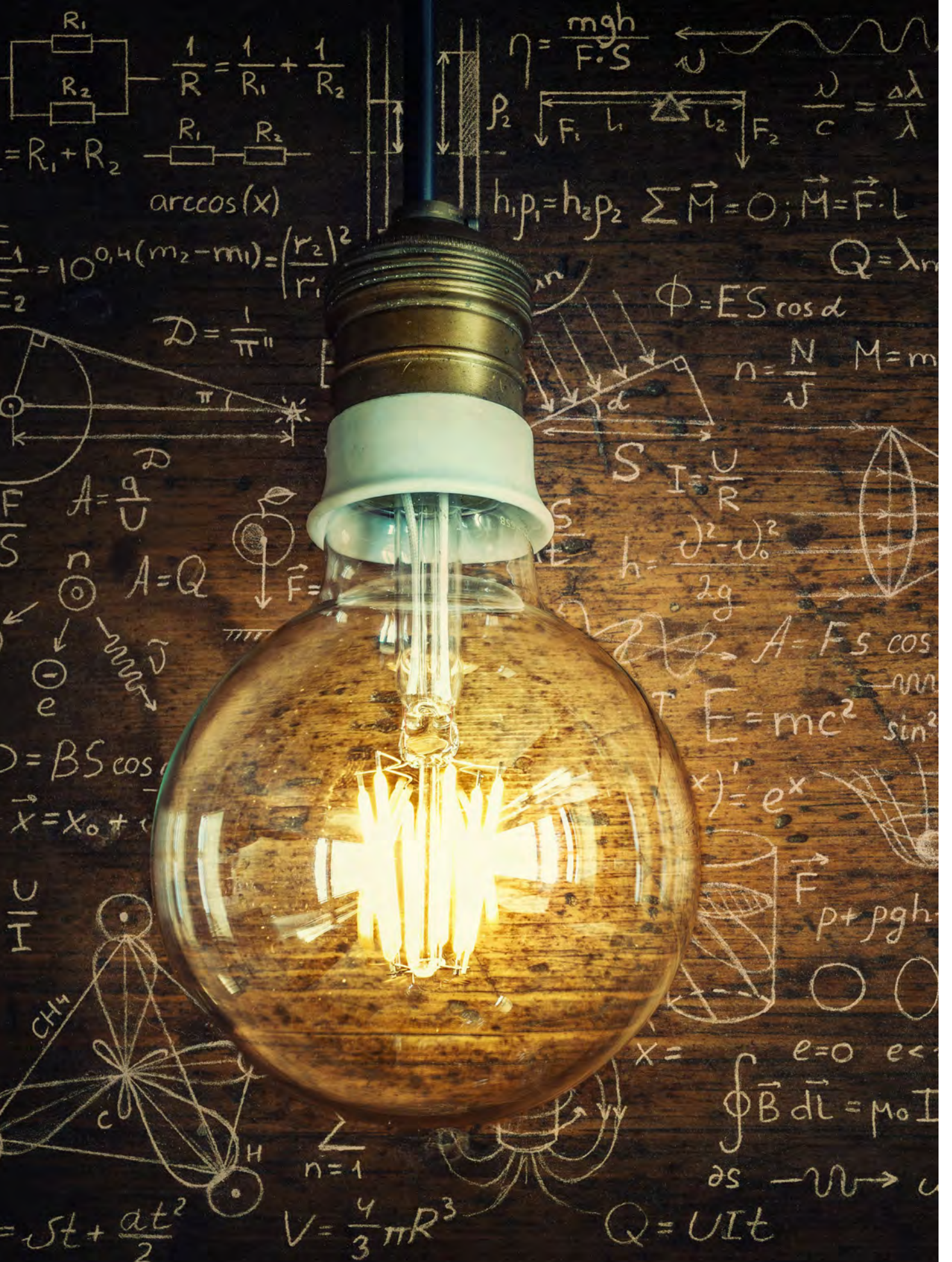
that in India and Asia dominates the center of many rural villages as an important spiritual gathering site.

Embarking on a new role as grandmother this decade, I have decided to use my Samoan nickname of Mati instead of Grandma; I will tell my grandchildren about all the wonderful figs I have encountered. Maybe someday I'll whisk them off to the island of Savai'i in Samoa to see an incredibly special walkway in an emergent fig or to climb a few favorite stranglers in Australia. ☺

MEG LOWMAN, Ph.D., aka "CanopyMeg," is an American biologist, educator, ecologist, writer, editor, and public speaker. She is the executive director of the TREE Foundation and a professor at the National University of Singapore, Arizona State University, and Universiti Sains Malaysia. Nicknamed the "real-life Lorax" by *National Geographic* and "Einstein of the treetops" by *The Wall Street Journal*, Lowman pioneered the science of canopy ecology. Her motto is "no child left indoors." She travels extensively for research, outreach, and speaking engagements for audiences large and small.

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How I Escaped My Troubles Through Science

My life in theoretical physics took a fateful turn after 9/11

BY SUBODH PATIL

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Occasionally, when Ammu listened to songs that she loved on the radio, something stirred inside her. A liquid ache spread under her skin, and she walked out of the world like a witch, to a better, happier place ...

—Arundhati Roy, *The God of Small Things*

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W

E’VE ALL FELT the need. To just drop whatever loads we’re bearing, retreating to some private realm where our worldly concerns fade into oblivion. Freed from responsibilities, anxieties, hurts, and other miscellaneous burdens, if only transiently.

My earliest recollection of the urge must’ve been when I was around 5. My mother was colorfully scolding me the way Indian mothers do, for something I probably did but nevertheless felt unjustly prosecuted for. Turning to the sky beyond the window of our apartment building, I remember becoming consumed by what it would be like to be the letter R. Just being the letter R. Where I could exist wherever it was that letters existed, in solid form, bathed in saturated white light, finding solace in the emptiness, where feelings didn’t exist.

After a sleepless night in an orange jumpsuit in a maximum-security immigration-detention facility, I was taken back to the airport.

The urge to retreat from reality can take on a compulsive nature for some, whether it's into the worlds in video games, literature, or some other obsession. For others, the choice instead is to palliate reality through alcohol or other assorted fixes. Although I'm no stranger to any of these, the most soothing flight from the mundane I've come to seek comfort in over the years has been the retreat into my work. The *real* stuff of my work that is, not the worldly responsibilities that go along with it. Although I do take great pride in the latter, nothing comes close to providing me the solace, sometimes even deliverance, as some of my flights into the corner realms of theoretical physics. I recognize the solipsism and selfishness in this, but also the act of self-preservation that it represents.

Perhaps the seeds were planted in a somewhat difficult childhood and adolescence growing up in Hong Kong and onto a young adulthood, struggling to navigate the different worlds I had to straddle as a many-time immigrant. Perhaps it was perpetuated by the need to seek refuge whenever something about the world would confuse or frighten me. Although I didn't know it at the time, my reflexive retreats into abstract realms was the nursery in which my individuality was fostered as a teenager. It wasn't just that my parents would leave me alone when I was hunched over a desk, scribbling on scraps of paper or buried in a book; that nursery was an invisible and formidable shield against any of their expectations that conflicted with the personhood I was beginning to assert. A struggle for the self that many immigrant children have to confront in some way.

But there was another edge to it. Like many of my fellow travelers, what drew me to the worlds of theoretical physics was also seeded in my earliest existential doubts, and the struggle to come to terms with the answers the people around me seemed to content themselves with.

I WILL NEVER FORGET my first real bout with a question. I was a few years into grad school at Brown University, and just beginning to find my legs as a researcher. My first two papers had just come out, and I had just moved in with my girlfriend at the time in New Haven, commuting to Providence for my weekly meetings with my advisor. In a matter of days, the ground beneath my feet fell out from under me.

In the drawn out aftermath of 9/11, immigration problems entirely of my own making resulted in my being denied entry to the United States after a visit to Mumbai, to which my folks had moved back. I was ruled inadmissible over a run-in with the law many years before, when I was a teenager. It didn't result in any charges, but did manage to linger on a computer somewhere. After a sleepless night in an orange jumpsuit in a maximum-security immigration-detention facility, I was taken back to the airport where I was told by Customs and Border Patrol agents that I'd probably never see these shores again. I did. But only after six of the longest months of my life, spent in a daze of uncertainty and anxiety over whether I'd ever be able to go back to my former existence. During this limbo, I frequented the Tata Institute for Fundamental Research in Mumbai, where my advisor had arranged a precious

desk for me so that I could keep working. It was home to a vibrant community of string theorists who warily welcomed me. I was thrust into an intellectual hot-house of blackboard discussions, and seminars that would always go way over the allotted time that helped me momentarily forget why I was there.

Several of the researchers at the Tata Institute were working on what seemed like impossibly simple transcriptions of string theory known as matrix models. As the name suggests, matrix models encode the complicated dynamics of objects within string theory into the dynamics of two-by-two arrays of numbers, or matrices, familiar to anyone who's ever taken a linear algebra class. People were beginning to notice structures arising within matrix models that made them wonder if it could really be a description of M-theory, the supposed parent theory from which all string theories descend.

I was hooked. I started devouring papers on the subject, many of which I could barely understand. I also had the nerve to find minor gaps in certain derivations that just didn't sit right with me. The researchers I spoke to brushed them off as inconsequential, but I just couldn't let go of the doubts.

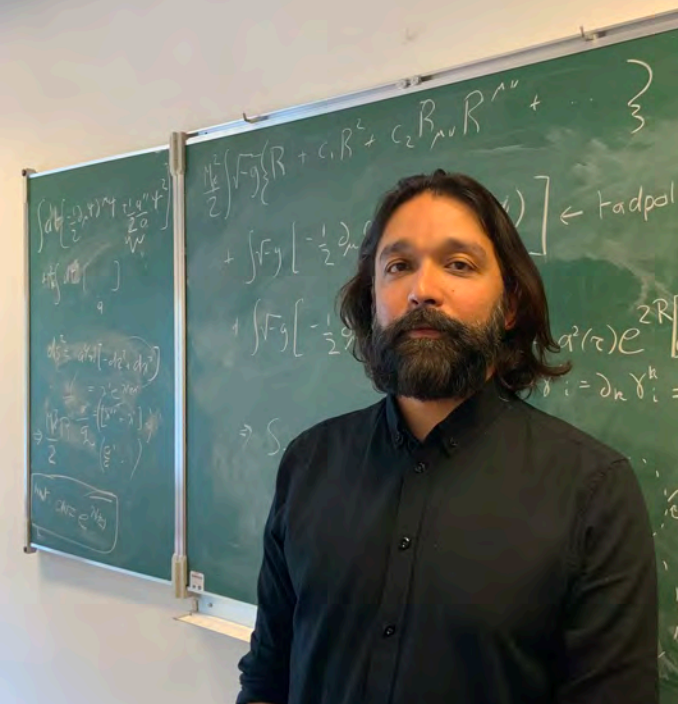
There are different types of infinity. The most familiar perhaps, is one you can count your way toward. One, two, three, and so on, to countable infinity, denoted somewhat biblically as $\aleph_0$, or aleph-zero. The other should also be familiar, but slightly more abstract: *uncountable* infinity, or $\aleph_1$. It represents the number of real numbers between zero and one. That these infinities are not the same was proved in the late 19th century by Georg Cantor in a manner so simple, you could sketch it out to your friends on a bar napkin. It's one of the most beautiful and profound results in all of mathematics, one that I would rederive for myself multiple times over the years and still scarcely believe. (In fact, many of Cantor's contemporaries didn't believe it, either. He died alone and in penury in a sanatorium, the result of a steady decline in health after years of ridicule and professional humiliation.)

The thing about matrices is that they can also have a very large number of entries, even up to countable infinity. These so-called infinite-dimensional matrices have a very different algebra from finite-dimensional ones. The thing about certain matrix models is that their finite-dimensional versions are supposed to be

Without the ability to scribble anything in the margins, I'd while away the commutes manipulating symbols the best I could in my mind.

taken only as approximations to the underlying dynamics they're trying to capture, becoming exact only in the infinite-dimensional limit. I thought about this for weeks. Weeks where crippling anxiety had reduced me to a displaced and disjointed shadow of my former self.

In the searing heat, I would commute almost two hours each way, from the Tata Institute to my parents' apartment in the far northern suburbs. Mumbai commuter trains are not for the faint-hearted. Riders cram themselves into carriages running at thrice their capacity, in a self-organized human jigsaw that would sometimes find you dangling outside the permanently open doors of carriage, where at least you could breathe freely. Collective suffering, however artificially induced, unfailingly brings out the best in people. The unspoken kindness and indifference with which people would elbow past each other, occasionally trampling on each other's feet on their way in and out of the train, is a lesson in letting go I update myself with every time I'm back in Mumbai.



THE HIGH OF DISCOVERY “It’s a rush that never gets old, no matter how niche or subtle the result, no matter how few people end up caring about it, let alone citing your paper,” writes Subodh Patil (above), about cracking a scientific problem. “To me, it’s the real stuff of being a physicist. Of being alive.”

I’d always be reading physics papers on these long commutes. One arm wedged against my body, holding a paper at head height, the other, finding some form of grip to maintain a precarious balance as the carriage swayed back and forth, my center of gravity now in a collective with other bodies packed tightly against mine. Without the ability to scribble anything in the margins, I’d while away the commutes manipulating symbols the best I could in my mind.

On one such journey, I came to with a pounding sensation in my head, which was now wedged between my knees. A fellow commuter was holding out a bottle of water for me, another was handing me back the crumpled paper I was reading. I don’t remember how I got there, but the evidence suggested I had passed out and was shepherded to the nearest seat. Taking advantage of the predicament, I assured everyone I was okay, and remained slouched over for the rest of my commute, crying silently into my duffle bag.

I’ve come to appreciate that you form personal relationships with some of the problems you end up working on.

Not knowing what else to do, I would lose myself for hours on end over the following days in the algebra of matrices, of strings ending on membranes, of the mathematics of infinity. No flashes of insight, no grand epiphanies, just slow and steady deliberation over subtle details. The dull aches that had characterized my inner state for months up till then transiently tempered. Finding uncomplicated pleasures in the purity and simplicity of the abstractions in front of me. I had slowly come to realize that there was a straightforward way to map the multiplication of infinite-dimensional matrices into the calculus of continuous functions. I saw that, in fact, my earlier doubts were founded. I had cracked an opening to an extension of a particular matrix model that hadn’t been noticed before.

I called it a *central extension*, which was familiar terminology from other infinite-dimensional algebras seen in string theory. It was then that I finally felt a gush of joy, as after all that steady deliberation, new solutions that hadn’t been noticed before starting falling out naturally. They had the geometry of cylinders, and warped planes. *Fuzzy* cylinders and *fuzzy* planes, whose geometry is quantum rather than continuum. It’s a rush that never gets old, no matter how niche or subtle the result, no matter how few people end up caring about it, let alone citing your paper. To me, it’s the real stuff of being a physicist. Of being alive.

A few months later, I received a new visa to return to the U.S. with a waiver for the inadmissibility that kept me out many months earlier. I felt incredibly lucky, blessed, and privileged, given what my lawyer had conveyed to me would be the likeliest outcome. I wrote up my results in what was to become my first

and only purely theoretical paper on string theory, dryly thanking all the folks who made my life bearable over the course of it in the acknowledgements. What I really wanted to say to them was thank you for keeping me sane. Thank you for helping me through the worst of all of this by paving the way for the flights of imagination that turned into this paper.

I've come to appreciate that you form personal relationships with some of the problems you end up working on. You're never quite the same person after having encountered them, and they'll always remain in you somewhere long after. Over the years, I've learned to become better at picking them, but it hasn't always worked out. Some have induced an obsession so unhealthy, that I've been unable to work on anything else for over a year, even if it was looking like the task I had set for myself was an impossible task.

Now that I'm at a station in my professional life where I'm kept up at night by concerns that go far beyond myself, such indulgent bouts are fewer and further between. But they still come and go, and it's the only thing that still, selfishly, feels like the real thing. What could have ended up as a crippling dysfunction in any other incarnation turned out to be my survival kit, not just in life, but in my chosen craft. A sort of existential protest perhaps that from time to time, I will escape, therefore I am. ☺

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On the days that the radio played Ammu's songs, everyone was a little wary of her. They sensed somehow that she lived in the penumbral shadows between two worlds, just beyond the grasp of their power.

”

SUBODH PATIL is an assistant professor at the Lorentz Institute for Theoretical Physics at Leiden University. He tweets on occasion at @_subodhpatil.

Plants Feel Pain and Might Even See

It's time to retire the hierarchical classification of living things

BY PETER WOHLLEBEN







IN 2018, A GERMAN NEWSPAPER asked me if I would be interested in having a conversation with the philosopher Emanuele Coccia, who had just written a book about plants, *Die Wurzeln der Welt* (published in English as *The Life of Plants*). I was happy to say yes.

The German title of Coccia's book translates as "The Roots of the World," and the book really does cover this. It upends our view of the living world, putting plants at the top of the hierarchy with humans down at the bottom. I had been giving a great deal of thought to this myself. Ranking the natural world and scoring species according to their importance or their superiority seemed to me outdated. It distorts our view of nature and makes all the other species around us seem more primitive and somehow unfinished. For some time now, I have not been comfortable with viewing humans as the crown of creation, separating animals into higher and lower life-forms, and treating plants as something on the side, definitively banished to a lower level.

And so I found the conversation with Coccia most refreshing when he visited our Forest Academy. A small bearded man, Coccia turned up in a blue suit and blue

checkered tie, completely inappropriate attire for the outdoors, even though we had agreed that we would take a walk in the forest together. Although he is from Italy and now teaches in France and writes in French, he also speaks fluent German because at one time he studied and worked in Freiburg.

After our first cup of coffee, we were soon deep into our main topic: trees and plants in general. Coccia argued that our biological classifications are not grounded in science. They are strongly influenced by theology and are dominated by two ideas: the supremacy of the human race and the world as a place humans must bend to their will. And then there is our centuries-old compulsion to categorize everything. When you combine these concepts, you get a ranking system that puts humankind at the top, animals in the middle, and plants way down at the bottom.

I listened, fascinated by what he had to say. Here was a man of my own heart. I would prefer it, I told Coccia, if science categorized species one beside the other. That would still allow an order, a system of sorting, without imposing any kind of a hierarchy. He immediately agreed. He reiterated his belief that the ordering system we have today is not scientific but rather influenced by cultural, historical, and religious values. For Coccia, the hard boundary between the plant and animal world does not exist. He believes plants can experience sensations and even reflect on them. And he is not the only one who thinks this.

František Baluška is also very good at making inconceivable connections. Baluška, a plant cell biologist at the University of Bonn, has for some time now been of the opinion that plants are intelligent—after all, they can process information and make decisions. But do plants have consciousness? That takes the discussion to a whole different level. If we could prove that plants have consciousness, we would have to radically change the way we interact with them, because we'd find ourselves facing the same kinds of issues that we face with factory farming in conventional agriculture.

Baluška, together with colleagues from around the world, including Stefano Mancuso from the University of Florence, has come a little closer to answering the question about plant consciousness. Baluška and his colleagues sedated plants that feature moving parts, such as Venus flytraps. These plants catch their prey in a trap that snaps shut as soon as insects touch trigger hairs on the inner side of their double-lobed leaves. The two sides of the leaf fold together in a flash, capturing the insect between them, and the plant then digests its prey. The anesthetics the scientists used, which included some that are used on people, deactivated electric activity in the plants so that the traps no longer reacted when they were touched. Sedated peas showed similar changes in behavior. Their tendrils, which usually move in all directions as they slowly feel their way through their surroundings to find supporting structures to grow on, stopped searching and started to spiral on the spot. After the plants broke the narcotics down, they resumed their normal behavior.

Did the plants wake up as we do when we come to after a general anesthetic? This is the critical question, because in order to wake up, you need one thing above

“Survival of the fittest” doesn’t mean the strongest prevails. Rather, it’s about being able to thrive in an environment and reproduce successfully.





VENUS RISING After Venus flytraps, in an experiment, were given an anesthetic, which prevented them from snapping their traps shut, they “woke up” and went back to catching flies. Is that a sign of consciousness? asks author Peter Wohlleben.

all others: consciousness. And it was exactly this question that a reporter from *The New York Times* posed to Baluška. I really liked his answer: “No one can answer this because you cannot ask [the plants].”

I EXCITEDLY IMAGINED what Baluška’s kind of plant research would look like: well-equipped laboratories with plants all over the place monitored by elaborate apparatuses finally giving up their secrets. That was something I absolutely had to see. On a sunny afternoon in 2018, I parked my car in front of his institute. I took a musty-smelling elevator to the fourth floor. Then (according to the email I received from Baluška), I was to turn right when I stepped out of the elevator and take a flight of wooden stairs up to his office. The corridor straight in front of the elevator door led to neat, uniformly gray rooms of the kind you expect to see in universities. The wooden staircase to the right led to an out-of-the-way corner in the huge building complex. Up there, on a tiny landing, Baluška greeted me with his strong Slovakian accent.

He led me into the conference room and we sat side by side at a huge round table. I was eager to hear what

he had to say. After all, I had cited his research in my book *The Hidden Life of Trees* and repeatedly mentioned his groundbreaking research when I attended events. His results sounded so fantastic that I sometimes wondered if I had interpreted them correctly when I translated them into everyday language for the general public. Baluška immediately put my fears to rest.

One of the first things we talked about was how plants feel pain. Fellow foresters roll their eyes when I talk about spruce feeling pain when they are attacked by bark beetles. “Of course a plant, trees can feel pain,” the professor answered when I asked him about it. “Every life form must be able to do that in order to react appropriately.” He explained that there is evidence for this at the molecular level. Like animals, plants produce substances that suppress pain. He doesn’t see why that would be necessary if there was no pain.

Baluška was ready with other quite different discoveries. There’s a vine that grows in South America that adapts to the form of the tree or bush it is climbing on. Its leaves look just like the leaves on the host plant. You might think this is chemically controlled. In that case, the vine might be detecting scent compounds from

Forests need foresters? Trees have existed for more than 300 million years, modern humans for 300,000.

the bush and changing the shape of its leaves in a way that was genetically predetermined. Three different leaf shapes had been observed. Then a researcher came up with the idea of creating an artificial plant with plastic leaves and relocating our botanical chameleon to its new home. What happened next was amazing. The vine imitated the artificial leaves, just as it had imitated the leaves in nature. For Baluška this is clear proof that the vine can see. How else could it get information about a shape it had never encountered before? In this case, the usual suspects—chemical messages released by the host plant or electric signals between both plants—were absent. He went further. In his opinion, it is conceivable that all plants might be able to see.

Up until then, the only thing I knew was that trees can differentiate between light and dark. Sleep behavior has been researched in birches and oaks, and beeches can measure day length—all of this requires light receptors that transmit signals to the trees and spur the whole organism into action. This is far removed, though, from vision in the sense of being able to recognize shapes and colors. And now this: plants which register precisely that and change their behavior accordingly. I found that astonishing.

Baluška directed me to research being done on the cuticle or outer layer of leaves. On most plants, this layer is completely transparent, which makes no sense if all the leaves are doing is collecting light to manufacture sugar. In that case, these outer cells should be equipped with green chloroplasts, the organs used for photosynthesis—after all, this is where the most

sunlight falls. Logically, less light is harvested in layers farther from the surface. And yet the cuticle is transparent, which seems wasteful. Not only that. In several plants, the cuticle is constructed in the shape of a lens, which means that it focuses light, making the cuticle functionally similar to the lens in our eye. It doesn't seem logical to me to focus light if photosynthesis is the only goal, because the cuticle could simply let the sun's rays through. Focusing light doesn't increase how much light falls on a leaf. The same amount of light is simply more concentrated or, more specifically, focused more intensely to the back of the cell.

Leaves that function like eyes? There's an idea that takes some getting used to, particularly as a tree regularly discards its "eyes" in the autumn when its leaves fall off. Does that make leaves disposable eyes? In a certain sense, yes. A working life of six months (under European climate conditions) is relatively long in comparison with some animals. Flies, for example, use their eyes for little more than a month simply because that's how long they live. And mayflies, which live for barely a day after metamorphosing from a larva into a flying insect, use their visual apparatus for less than 24 hours—and yet the eyes they have are real.

There's another thing with trees. The cells in the leaves, once they are formed, last for the whole growing season, which means they are relatively long lived. In contrast, our eyes are in a constant state of partial rejuvenation: The cells in the outer cornea, for instance, are completely replaced every seven days.

He went further. In his opinion, it is conceivable that all plants might be able to see.

YOU WOULD THINK that plants experiencing pain and now the hypothesis that they might even be able to see would put the whole scientific community into a state of high excitement. The reaction, however, was muted. I had assumed that plant neurobiology was an up-and-coming scientific field. Baluška shook his head. He was practically the only one still studying the topic in depth. And that means this branch of science could disappear and be forgotten for a second time. The first time it disappeared was back in Darwin's day.

Darwin had studied plant roots and even back then he postulated that the tips might function like the brains of simple animals. Roots containing "tiny brains?" The hard boundary between animal and plant could have fallen in his time. Could have. The research was put on hold for a hundred years and then suffered another blow from which it has not recovered to this day. The blow came in the form of a well-intentioned book by Peter Tompkins and Christopher Bird entitled *The Secret Life of Plants*, published in 1973. It was based on experiments that were not reproducible and definitely strayed from science into the mystic.

There was, however, another problem, Baluška explained. All the research on nerves, the brain, and phenomena such as pain had originally been done on people. All the important biological terminology, therefore, was already taken. This meant it would not be scientifically correct to transfer the definitions to plants that exhibited very similar structures and processes. And so, neurobiology was reserved for animals, which is why a similar periodical for plant research is called *Plant Signaling & Behavior* and not *Plant Neuroscience*. I immediately thought that philosophy and biology should be more closely connected, because Coccia's thoughts on the subject matched those of Baluška.

The path to greater harmony between all life forms is long and turns on perspective and scientific clarity. For example, the more I think about the differences between conventional forestry and the original ecosystems of the forest, the more I conclude that the differences rest on a big misunderstanding. Conventional foresters believe that they are protecting ecosystems and through their stewardship are imitating or at most speeding up natural processes. However,

the understanding of these ecosystems is grounded in a different philosophy about natural processes, in short in a different definition of evolution. This definition goes back to Darwin and his colleagues, who coined the phrase “survival of the fittest.” However, that doesn’t mean every life form fights every other life form and the strongest prevails. Rather, it’s more about being able to thrive in an environment and reproduce successfully. That is a completely different interpretation of “survival of the fittest” and means, for example, that social communities can also be very successful in nature.

Trees and wolves—and especially our own species—prove how successful social communities can be. A more accurate rendering of the phrase would be “survival of the most well adapted” (“fittest” in the sense of being the best fit rather than the strongest), which means survival of the species that manage best in the environment in which they find themselves. If that were not the case, evolution would mean that ever stronger and therefore perhaps also more aggressive species would be the ones that survived. If you read the phrase as the strong species surviving best, you would expect earlier species to have been underdeveloped, whereas in reality they were well adapted to the conditions that prevailed at the time. But because nature is always in flux, continents wander, and climate changes, the appearance and disappearance of species is not evolution in the sense of improvement but simply in the sense of adapting to new environmental conditions.

I, for one, used to interpret the phrase completely differently and thought that species were constantly improving until we finally got to us. And so, according to this outdated understanding, the logical conclusion was that humans stood at the pinnacle of creation. From a scientific point of view, however, this conclusion is incorrect. Its current meaning can only be explained from a cultural and religious perspective. And when we get to trees, we have got the wrong end of the stick completely, just like many foresters.

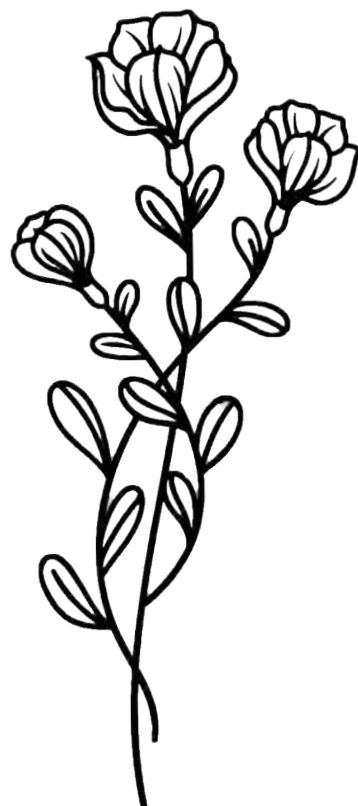
Foresters believe that trees not only of different species but also of the same species fight each other for light, water, and food. In managed forests, foresters get involved in what they think is the fight that plays out in undisturbed forests. You could say they see themselves as the referees. In Germany, I have often heard them say that the native forests could not

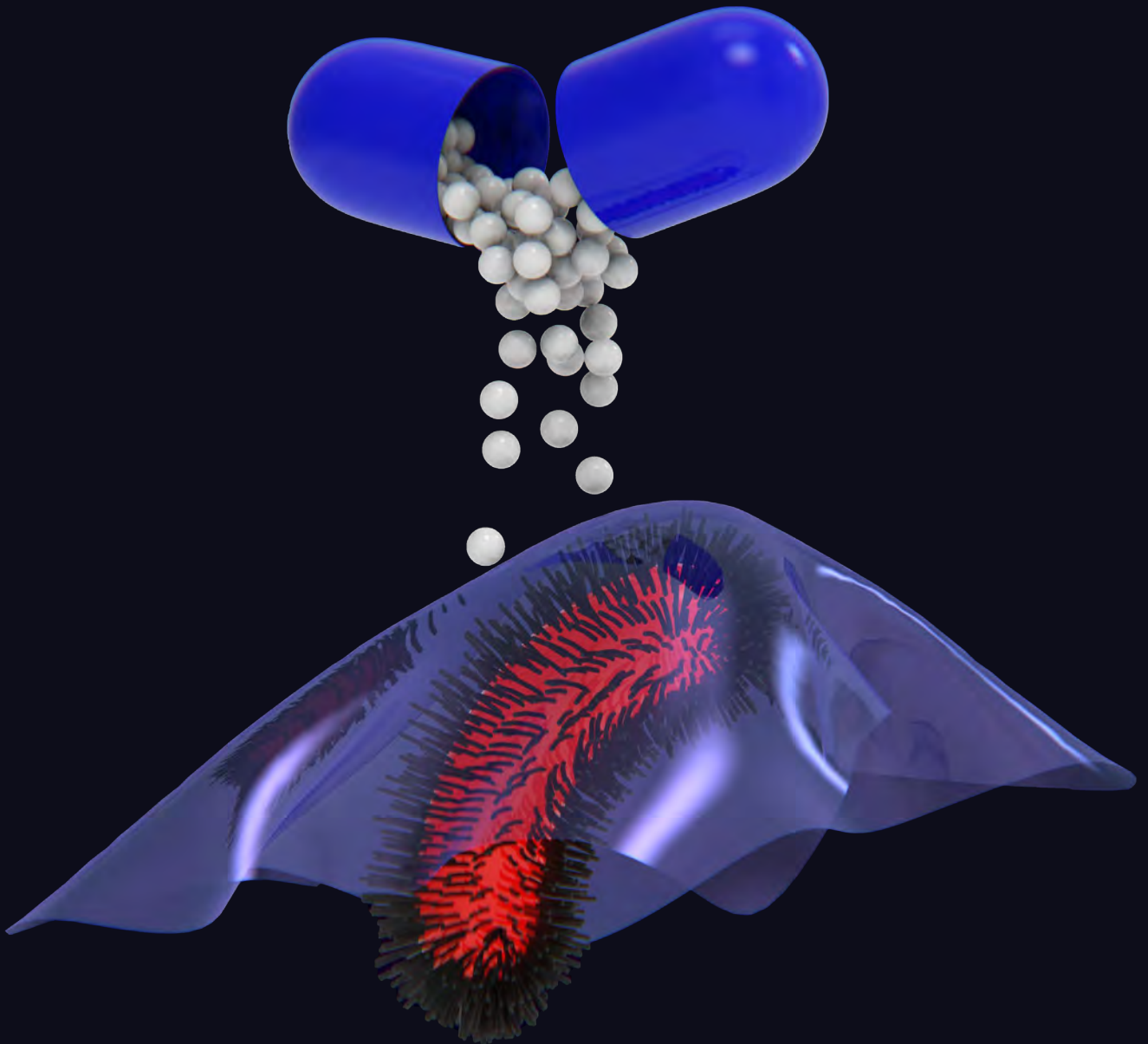
survive without foresters. And yet, trees have existed for more than 300 million years, modern humans for 300,000, and the profession of forestry for just 300. For most of the time, trees have managed very well without human referees—in no small part because they have not been fighting.

And here I return to Coccia. He thinks it is a great shame that for the past 100 years we’ve seen nature as a huge war zone in which everyone is fighting everyone else. But, according to Coccia, nature is not a war zone. On the contrary, it is characterized by solidarity. To that thought, I have nothing to add. ☺

PETER WOHLLEBEN is the author of numerous books, including the *New York Times* bestseller *The Hidden Life of Trees*, and its follow-ups, *The Inner Life of Animals* and *The Secret Wisdom of Nature*. He is also the author of books for children, including *Can You Hear the Trees Talking?* and *Peter and the Tree Children*. When he’s not writing, Wohlleben manages a sustainable forest and runs a forest academy near Germany’s Eifel Mountains.

Excerpted and adapted from *The Heartbeat of Trees: Embracing Our Ancient Bond With Forests and Nature*, by Peter Wohlleben, available now from Greystone Books. Excerpted by permission of the publisher.





How to Outwit Evolution

We can defeat superbugs by staying one step ahead of them

BY LINA ZELDOVICH

THERE'S A SILENT EPIDEMIC slowly brewing around the globe. It hasn't claimed as many lives as COVID-19, but if it gets out of control, it will likely prove even deadlier. It's caused not by a single virus, but by a number of different bacterial species that have been slowly evolving defenses against our once potent antibiotics. Think of it as a sea slowly swelling with superbugs.

Currently, someone in America dies from an antibiotic-resistant bacteria or fungi every 15 minutes, adding up to 35,000 annual deaths. Globally, the United Nations reports that a mind-boggling 700,000 people a year die from infections antibiotics can no longer fight. The report warns that this number could reach 10 million by 2050 if we don't find alternative therapies against our bacterial enemies.

How did we arrive at this existential threat to humanity? Whether we like it or not, that's evolution in progress. In the 20th century, we invented powerful antibiotics that destroyed bacterial cells before they destroyed us. In response, the bugs evolved too. They learned to produce chemicals that deflect our antibiotics, so they can continue multiplying. We thought we could outpace bacterial evolution with our pharmaceutical prowess, but the germs beat us, bolstering their defenses. We can't fight evolution.

Or can we?

We thought we could outpace bacterial evolution with our pharmaceutical prowess. But the germs beat us.

David McCandlish, who studies evolution and population genetics at Cold Spring Harbor Laboratory, thinks we can predict it. A computational biologist, McCandlish uses mathematical and statistical techniques to study living organisms, with a goal of building predictive models of how they may evolve. McCandlish believes that using the knowledge of genetic and biological mechanisms of how bacteria develop resistance can help us foretell what they might do in the future, in response to our meds. “If there’s a microorganism that we have a drug against, an antibiotic, or antimicrobial, we want to predict the specific sequence of mutations by which it will evolve antibiotic resistance,” McCandlish says. “So yes, we want to be able to predict evolution.”

McCandlish’s approach draws on the concept of the so-called adaptive landscapes—an idea that looks at organisms’ evolution as peaks and valleys. The adaptive landscapes model views evolution as a hill-climbing

process in which the populations with winning genetic traits—or highest genetic fitness—would rise up to the peaks, while those with inferior genetics would remain in the valleys between the peaks. Pictorially, these adaptive landscapes, sometimes called fitness landscapes, look like mountain ranges. In these charts, the horizontal axis depicts the organism’s one or several genes and the vertical one depicts that organism’s genetic fitness. The better-fit populations that were lucky to get “the good” mutations climb to peaks. Those that got “the bad” mutations that weigh them down end up in the valleys.

When it comes to bacterial species that are pathogenic to humans, those that climb to the peaks are bad news for us, particularly if that ascent is due to their drug-resistance abilities. If one were to depict some of the deadliest superbugs using adaptive landscapes, the much-dreaded Methicillin-resistant *Staphylococcus aureus* or MRSA, which claims close to 20,000 lives a

year in the United States, would likely be on one of the peaks. So would be the multidrug-resistant tuberculosis, which kills 230,000 worldwide. We'd much rather prefer to see them languishing in the valleys.

How can adaptive landscapes help us predict how the next potential superbug may evolve? To answer that question, scientists first need to understand the cellular, molecular, and genetic forces that drive antibiotic resistance in bacteria. They must also understand how we arrived at this now-looming post-antibiotic era, which, on the grand evolutionary scale, was here in a hurry.

WHEN ALEXANDER FLEMING first discovered penicillin in 1928, which led to the creation of the first antibiotic that became widely used in the 1940s and after, humans got an evolutionary advantage over bacteria. We could easily and efficiently kill many bacterial species before they wreaked havoc on our organs, tissues, and bodies. But in the years that followed, we might've been a little too overzealous with our antibacterial armor and we used it too much. Doctors prescribed antibiotics to patients when they weren't necessary. Cleaning product manufacturers put antimicrobial compounds into soaps and dishwashing liquid. Industrial farmers mixed antibiotics into the animals' fodder, not only because it helped fight infections but also because it made them fatter, which was viewed as a positive side effect.

Consequently, a certain amount of antibiotics washed out or escaped into sewage, trickling into water and soil, where vast populations of bacteria lived. As a result, millions of them died, except for some mutants who survived because they were lucky to have a slightly different assortment of genes that enabled them to develop special cellular defenses. Because the less fortunate bacteria were dead, these lucky mutants went on growing, replicating and passing on the antibiotic-resistant genes.

"That's what happens when you put a stressor on a bacterial population, such as an antibiotic," says Parjit Kaur, professor of molecular genetics and biochemistry at Georgia State University, whose recent paper examines microbial drug resistance mechanisms. "There may be a random mutant that can now withstand that antibiotic, or there can be a spontaneous mutation.

And then the resistant bacteria became the dominant population."

Antibiotics are essentially poisons for bacteria. Once antibiotic molecules enter bacterial cells, they either damage or break the cell, or interfere with the cell's replication. In either case, the bacterial population eventually dies out. To survive, the bugs must either eject the antibiotic molecules or demolish them, before they destroy the cell.

Different bacteria species fight antibiotics differently, explains Kaur. Some mutate their genes to produce specific efflux proteins that "escort" the trespassing antibiotic molecules out as soon as they enter the cell. That may sound like a sophisticated defense, but it's not a novel concept. Organisms rely on the so-called transport proteins to bring substances in and out of cells. Typically, these transfer proteins usher in nutrients and spew out waste substances. Some germs simply evolved their genes to generate new transport proteins that ferret out the poisonous antibiotic molecules. "Antibiotics are toxic substances and these specialized proteins pump them right out," Kaur says. And they go on living and replicating.

Other types of bacteria have double cell membranes—an inner and an outer layer. The space in between the two is called the periplasm, and that's where these germs stage their antibiotic defense. These bacteria produce antibiotic-cleaving enzymes that work as molecular scissors, which are released into and kept inside the periplasmic space. Once antibiotics enter, these enzymes shred them into a heap of molecular debris. The enzyme mechanism isn't superbly novel either. Bacteria use enzymes as part of their cellular "housekeeping" to cut other substances, Kaur explains, so it's possible that some housekeeping enzymes were recruited and developed into "antibiotic warriors."

Bacteria can also acquire antibiotic resistance genes from each other, and they have multiple ways of doing it. Under certain conditions, some can pick up these genes from the dead bacteria whose DNA had been dumped in the environment. Others can acquire such genes from a virus that penetrates microbial cells but doesn't kill them—instead it might bring along some genetic material beneficial for bacteria. Lastly, the bugs can "trade" their genes. Two bacteria can sidle next to each other, open their cell walls and exchange their

genetic material. Think of it as MRSA snuggling next to an ordinary Staph, whispering, “Psst! I finally figured out how to kick this annoying methicillin bomb. Come close and I’ll share my secret.” And then they both can climb to the peaks.

MODERN GENETIC TOOLS offer scientists the ability to experiment with cells’ genetic mutations and see what evolutionary advantages or drawbacks they may produce.

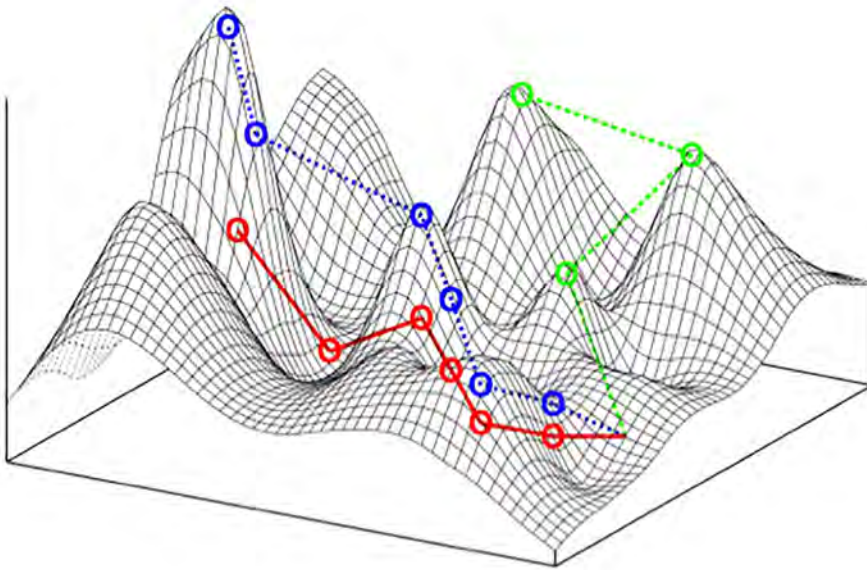
“You take a bug and put in a bunch of genetic variants and see how fast they will grow,” explains McCandlish. “You take a protein of interest, make lots of different mutations in it, then stick these mutated sequences into cells and try to grow these cells. If that sequence works well, the cells will grow and increase in numbers. And if the sequence doesn’t work, the cells limp along and maybe divide once and then die.”

Scientists can identify the growth rates of each of these variants and what effects the mutations had on cells’ growth. They can then determine whether any of

these mutations conferred evolutionary advantages. Some mutations may completely wipe out the population while others may imbue it with superpowers. A great advantage of this approach is that it’s versatile—the same concept can be used to predict evolution of any cells—not only microbial, but also tumors.

Scientists are already experimenting with such combos or mutational sequences, as they call them. McCandlish cites one recent study in which researchers inserted a variety of mutational sequences into yeast cells and measured their growth rates. The yeast cells with the most mutations proved to be the sickest, he notes, but it doesn’t have to be so—an occasional combo may prove just as deadly. By noting which mutational sequences give an organism a superb advantage, you can predict which ones will grow and take hold.

McCandlish’s predictive algorithms rely on such studies for data and learning. The more information these algorithms can learn—particularly about pathogenic organisms like bacteria or fungi—the more precise and meaningful their forecasting would be. The



CLIMB TO SUCCESS The concept of adaptive landscapes looks at organisms’ evolution as peaks and valleys. Here, the horizontal axis depicts the organism’s one or several genes and the vertical one depicts that organism’s genetic fitness. The populations that were lucky enough to get “the good” mutations climb to peaks. Those that got “the bad” mutations end up in the valleys.

Scientists are learning to predict the cellular and genetic forces that drive antibiotic resistance in bacteria.

yeast was a good playground, but one can do similar experiments for how drug resistance will evolve in bacteria, and see which mutational sequences would enable the bugs to fight antibiotics better.

“Let’s say we have developed a new antibiotic,” McCandlish says. “Now we want to be able to predict how would that enzyme that previously evolved to degrade the last generation of antibiotics, change to degrade new ones? Or maybe it won’t.” Knowing which genes might produce the resistance enzymes or proteins can let pharmaceutical companies stay one step ahead of the bugs.

Having accurate resistance forecasts might ease the pressure of developing new antibiotics. The model might predict that bacteria A can develop resistance to antibiotic X, and later to antibiotic Y, and later antibiotic Z. But the last two rounds of adaptation to Y and Z might weaken the pathogen’s defenses against antibiotic X or disable them altogether. That means a specific germ will now be once again susceptible to antibiotic X, and no new ones would have to be developed to fight it.

Accurate forecasts could allow medics to control or foster the evolution of cells—those of pathogenic microbes or cancer. If we understand how a particular cell evolves on its fitness landscape, we can design drug treatment strategies. “If we know that one specific drug will push bacterial population to evolve resistance by one or the other of these peaks, then maybe by applying the second drug we can choose which way it evolves,” McCandlish says. “Or we can try to push the bugs to evolve to a peak where we know we have a second drug that crushes that peak. It would be like setting a trap.”

While those drug traps may not be available in your neighborhood pharmacist tomorrow, overall prediction models might help us get a leg up in the evolutionary race against microbes to avoid the dreadful 10 million deaths by 2050. Once the models are working, they would restore our evolutionary advantage over pathogens. Superbugs will keep climbing the evolutionary peaks. But we will be there waiting for them—with our antibiotic armor at the ready. 🧐

LINA ZELDOVICH grew up in a family of Russian scientists, listening to bedtime stories about volcanoes, black holes, and intrepid explorers. She has written for *The New York Times*, *Scientific American*, *Reader’s Digest*, and *Audubon Magazine*, among other publications, and won four awards for covering the science of poop. Her book, *The Other Dark Matter: The Science and Business of Turning Waste into Wealth*, will be released in October 2021 by Chicago University Press. You can find her at LinaZeldovich.com and [@LinaZeldovich](https://twitter.com/LinaZeldovich).

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Life Always Wins. Follow Me

A botanist is introduced to escapees from the atomic bomb in Hiroshima

BY STEFANO MANCUSO

JAPANESE CUISINE is so varied and refined that it's hard to happen upon something unpleasant to the palate. My personal procedure in Japan is to take a seat at the counter and start pointing, completely at random, to a series of dishes chosen on the basis of how much I like the characters with which they are represented. Normally, they turn out to be small dishes, with small servings, that in no time start crowding the counter space allotted to me, turning it into a little work of art. That's the moment I like best: You feel the rush that comes with gambling, but without the risk, except the negligible one of a truly unsavory dish. Then comes the pleasure of discovery: What am I eating? What are the ingredients? How was it prepared?

MARMORE / SHUTTERSTOCK

During one of these blind dinners in Kitakyushu, I happened onto a mysterious dish that defied all my efforts to figure it out. It was a sort of whitish little pouch about the size of a ravioli, lightly fried and filled with a creamy substance tasting of fish. The flavor was delicious and so, having finished the first serving, I promptly ordered a second, so as to study it in depth. It reminded me of something from Italian cooking but I couldn't put my finger on it. I puzzled over it for a while but nothing came of it. I even tried to talk to the waiter about it, but in Japan hardly anyone speaks anything but Japanese. Disconsolate, I was ready to ingest the second serving, leaving my queries unanswered, when something totally unexpected happened—one of those things that make me love going out to eat by myself in Japan.

An elderly man, sitting next to me at the counter, addressed me. That in itself is crazy. Never in all my years of visiting the Land of the Rising Sun had anyone spoken to me without being spoken to first. I had always been the one to start a dialogue. But that's not all: He spoke to me in perfect, elegant Italian that hit a bump just for a second, right at the start of our conversation, when, embarrassed, he couldn't find the right words to tell me, without scaring me, what I was eating.

"You see, dear sir, we give great importance to the reproduction of life," he began, leaving me a bit disoriented. "Even though our culture is often noted in the West for its aggressive connotations, in reality there is a strong component of panpsychism [that's the word he used] in our civilization."

I reassured him, for reasons of courtesy, that this aggressive connotation of Japan belonged more to the past than to the present. The look on my face, however, must have remained puzzled. What did panpsychism have to do with what I was eating? He tried again.

"As a consequence of the presence of the divinity in everything, we tend by tradition to consume every single part of animals."

Now we seemed to be getting closer. And so?

"So, that dish that you are consuming, which by the way is called shirako and is without a doubt among my favorites, too, is produced from the male germinal line of various marine species."

"The male germinal line? You mean ..."

"Yes, what do you call it in Italian?"

"Sperm."

"Exactly."

So that's what it reminded me of: milt, an exquisite Sicilian specialty with the sperm sacs of tuna or ricciola (greater amberjack), the male equivalent of bottarga or roe. The fact that in Italy people eat the same not-so-noble parts of fish (I believe for reasons much more material than those associated with panpsychism) reassured my new dinner companion.

We introduced ourselves; he was a retired diplomat. During his career, he had served his country as consul in Italy for many years, and he had learned the language. We went on to talk for a long time and with great pleasure until, just before saying goodbye, he asked me, "I imagine, Professor, that you have already had occasion to visit our Hibakujumoku," and left

the question floating in the air between us for a few seconds. I answered that I had never heard of them and that I was sorry about that. Whatever the Hibakujumoku might have been, it is not polite in Japan to say you don't know about something without excusing yourself. The consul was very struck by this knowledge gap of mine.

"But you are concerned with plants! You simply must meet them."

He said exactly that, "meet them," so I thought he was referring to a group of people who in some way were concerned with plants. But his next words shattered my supposition.

"The Hibakujumoku are our escapees from the atomic bomb. A living hymn to the force of life."

I knew that in Japan survivors of the bomb attacks in Hiroshima and Nagasaki held a fundamental position as witnesses to those atrocities. But I couldn't understand the reason he was so insistent that I should meet them. The mystery did not last long.

"They are not people, but trees exposed to the atomic bomb. In Japan, everyone knows them and respects them. Personally, I love them. You should know them, too. I am going to allow myself to make a proposal. Hiroshima is not more than two hours from here by train. If you like, I can accompany you there in the next few days to meet them. Please tell me if you would like to do that. Since my wife died, my days are mostly free of commitments."

I thanked him intensely and accepted his offer with pleasure.

Two days later, each of us armed with his own bento, as befits two friends on an outing, we met early in the morning in front of the train station in Kokura, ready for our trip to Hiroshima. In a little over an hour and a half, we arrived at the station in Hiroshima, and 10 minutes later we were standing before my first Hibakujumoku.

The consul had led me through a magnificent garden—whose name I unfortunately don't remember—to "meet" three trees that had survived the bomb. I remember them very well: a ginkgo (*Ginkgo biloba*), a Japanese black pine (*Pinus thunbergii*), and a muku (*Aphananthe aspera*), three very common trees in any classical Japanese garden. The ginkgo was conspicuously bent in the direction of the city center, the black pine had a considerable scar on its trunk, but all in all, they were in good shape. Normal trees by all appearances, if it hadn't been for the evident feeling of respect and, I would say, affection that they inspired in the people who were there to "meet them."

A genteel elderly couple (probably husband and wife) had taken a seat on two portable chairs in front of the ginkgo and were engaged in a long conversation with the tree. A young boy gave it a quick hug before continuing on his walk. Everyone who passed by the trees seemed to know them well, and many people, from kids to old folk, bowed deeply before them. On each Hibakujumoku hung a yellow sign, the only characteristic that distinguished them from the other trees. I asked the consul what it said.

The consul was struck by my knowledge gap. “But you are concerned with plants! You simply must meet them.”

“I’ll try to translate it for you. It says more or less that we are standing before a tree that suffered an atomic bomb attack. Then it gives the vegetable species and finally the distance from ground zero,” he explained, pointing toward the river. “The explosion happened down there, where the river forks, exactly 4,494 feet from here.”

That day I visited a lot of Hibakujumoku, making my way closer and closer to the place where, for the first time, an atomic ordnance was used against a defenseless population. I remember another magnificent ginkgo inside the enclosure of the Hosenbo Temple at 3,700 feet. A camphor tree (*Cinnamomum camphora*) inside the quadrilateral of the Hiroshima Castle, at 3,674 feet. A Kurogane holly tree (*Ilex rotunda*) also inside the castle grounds at 2,985 feet. A marvelous peony (*Paeonia suffruticosa*) in the temple of Honkyoji at 2,920 feet.

As we moved in closer to the center of the disaster, the Hibakujumoku began to thin out. At 8:15 in the morning on Aug. 6, 1945, the ground temperature in the place where we now were had risen above 7,200 degrees Fahrenheit; very probably it went as high as 10,800 degrees Fahrenheit. The consul had just taken me to see the shadow (literally) impressed on the stairway of the Sumitomo Banking Corporation, left by the vaporization of Mrs. Mitsuno Ochi, age 42 at the time, caught unawares by the explosion as she was waiting for the bank to open. No hope that anything could have survived all that destruction. I voiced this thought to the consul, who responded, smiling, “Man of little faith. Life always wins! Follow me.”

We went around the corner and found ourselves once again along the Honkawa River. The “atomic bomb dome,” the only building left standing and preserved as a peace museum, which by convention marks ground zero, was there in front of me, at less than 1,300 feet from where we were, and there, too, right in front of us on the riverbank stood the champion of the Hibakujumoku, a weeping willow (*Salix babylonica*) reborn from its roots left alive underground. Its yellow sign indicated a distance of 1,214 feet from ground zero.

He looked me straight in the eye and said, “Talk about the Hibakujumoku, make them known.”

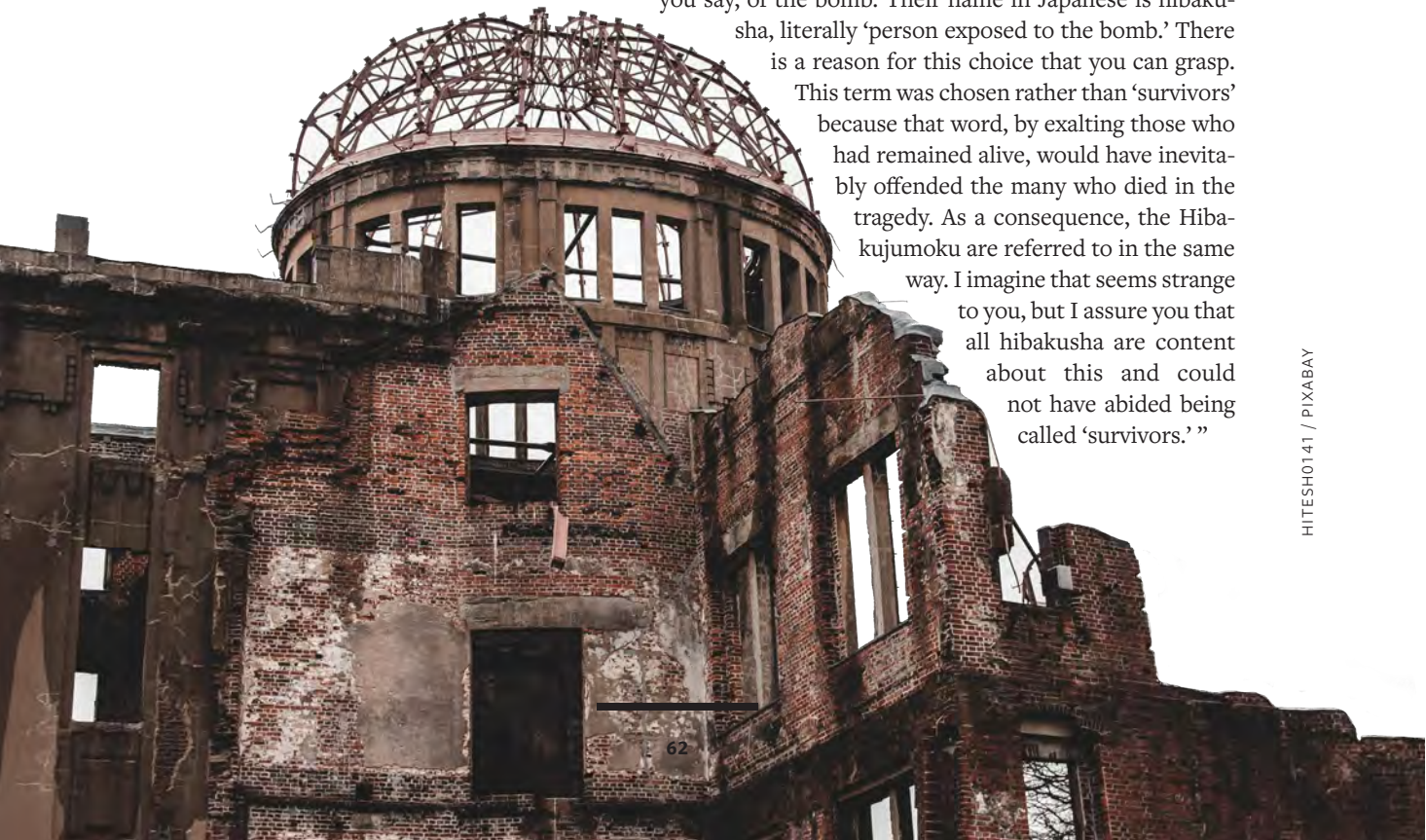
On the way back home to Kitakyushu that evening, the consul invited me to dinner at an inn he knew. I gladly accepted. It was a very pleasant evening and we drank a lot, as often happens among friends in Japan. As we spoke about our “encounters” in Hiroshima, something left me puzzled. Each time the consul spoke of the Hibakujumoku, he defined them as “trees that had suffered an atomic explosion,” and this long circumlocution sounded funny and strangely discordant with his otherwise perfect proficiency in Italian.

So I dared to venture, “Excuse me, consul, why do you keep saying that the Hibakujumoku are “trees that have suffered an atomic explosion”? Wouldn’t it be simpler to use a word like “survivors”?

Here is his explanation: “The question is more complicated than it seems, dear Professor. It all starts with the name given to the survivors, as you say, of the bomb. Their name in Japanese is hibaku-

sha, literally ‘person exposed to the bomb.’ There is a reason for this choice that you can grasp.

This term was chosen rather than ‘survivors’ because that word, by exalting those who had remained alive, would have inevitably offended the many who died in the tragedy. As a consequence, the Hibakujumoku are referred to in the same way. I imagine that seems strange to you, but I assure you that all hibakusha are content about this and could not have abided being called ‘survivors.’ ”



I suggested the Italian word *reduci*, or “veterans.” He didn’t know it and he liked it very much. “Thank you so much for teaching me that word. It sounds very good. Let’s toast to our veteran friends.”

After leaving the restaurant, I insisted on accompanying him home. No one would have guessed it from looking at him, but the consul was well over 80 years old, and he had had a lot to drink. In any event, he agreed, and I accompanied him on the short walk to his home. We said goodbye. Breaking every Japanese rule, by virtue of his many years spent in Italy, the consul hugged me. He looked me straight in the eye and said, “Talk about the Hibakujumoku, make them known. And come back to visit them again.”

He paused, trying to decide. “I have to tell you. I, too, am a hibakusha. I was seven years old when the bomb did away with my whole family and everyone else in the world I knew. I was saved because the classroom in the elementary school where I was studying was protected by a curtain of trees. I and four of my classmates are the only veterans from that school. We were 120 children.”

He thought about that for a second, smiled at me one last time, and, turning to pass through the door to his home, thanked me again for my company. ☺

STEFANO MANCUSO is one of the world’s leading authorities in the field of plant neurobiology, which explores signaling and communication at all levels of biological organization. He is a professor at the University of Florence and has published more than 250 scientific papers in international journals. His previous books include *The Revolutionary Genius of Plants: A New Understanding of Plant Intelligence and Behavior* and *Brilliant Green: The Surprising History and Science of Plant Intelligence*. Translated by Gregory Conti.

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What's Fueling Today's Extreme Fires

A geophysicist breaks down the elements of wildfires

BY DAN FALK



STOCKPEXEL / SHUTTERSTOCK

A **S I WRITE THIS** at the end of July, 79 wildfires are burning across 12 states in the United States. In Oregon, a mammoth fire has engulfed some 400,000 acres—an area half the size of Rhode Island—and destroyed hundreds of buildings and vehicles, including more than 160 homes. Smoke from wildfires in the western half of the continent has darkened skies over cities in the east, including Toronto, where I am. People in Boston, New York, and Washington D.C. are struggling with hazy, smoke-filled skies.

The recent rash of news stories about wildfires has implied wildfires are getting more frequent and burning more intensely, fueled by climate change. Janice Coen is a project scientist at the National Center for Atmospheric Research in Boulder, Colorado. She has devoted her career to studying wildfires and the complex relationships among those fires, weather systems, and the atmosphere. She uses infrared imagery and computer models to try to predict where such fires will ignite and how they evolve over time, and the connections between wildfires and climate.

In an interview over Zoom, Coen tells me climate change plays a significant role in wildfires. However, she says, “It’s not as obvious as ‘the world’s getting hotter’ or ‘the world’s getting drier.’ ” The geophysics of wildfires is complex, but Coen relishes the challenge of explaining them. She says her research center is “trying to teach me to give the media soundbites of 30 seconds.” But, she adds with a laugh, her answers “are more like Thanksgiving dinners!”

And nourishing ones at that. As we discuss “fire whirls,” how fires create their own weather system, prescribed burns, and our warming world, Coen brings the science alive with authority and clarity.

Winds spreading a fire are entirely generated by the fire. We've measured them at 100 mph.

Are wildfires becoming more extreme or frequent? Or both?

There's a lot of year-to-year variability. Some years have been above average in terms of area burned, while others have been lower. We generally don't report on that, right? It's not a headline story. But trends can last for several decades at a time. It's important to remember that even if you were to look at average global temperature, it could go up for 50 years, and that doesn't mean humans are influencing the climate. Or could stay the same for 50 years, and that doesn't mean we're not. There's a lot of natural variability, and humans are adding to that.

At the very least, it often seems like the world is burning.

Pretty much all of us who haven't yet retired have only lived in this period where temperatures overall are warming. That does have an overall effect on wildfires, though the effect on individual fires can be different. For example, we've seen the jet stream shifting north, so there's a dynamic effect. California has been seeing more Diablo winds, Santa Ana winds. That's when you have a high pressure in the Great Basin over Nevada,

pushing air down offshore, creating these strong winds over the Sierras and the coastal ranges. But as the jet stream shifts north, the predictions are we won't see as many of them in the future. Also, when we talk about wildfires, it's very much a power law distribution. Only a few percent of ignitions ever get above 100 hectares, and those few fires account for more than 85 percent of the area burned. So we're really talking about a few extreme events.

Do we know what's triggering these extreme events?

They tend to fall on one end of that spectrum, either from wind-driven events where there are strong winds pushing the fire downslope, or the other end of the spectrum, where it's hot and dry, but the winds are weak and perhaps blowing onshore. If you get an ignition at a fortuitous place, like at the base of a canyon, it can start to burn and release energy, creating a plume of rising, buoyant air above it, that draws air into its space, fanning the flames and pushing the fire forward, creating a stronger plume. This internal dynamic feedback loop can make the fire run very quickly uphill. So those tend to be the two extremes.

Persistent fires have the potential to create regional climate disturbances that affect not only your weather, but also the food you eat.

When we look at these extreme events, they're often—I hate the term—"a perfect storm" of underlying susceptibility to fire. That could be a persistent dry period, with a locally appropriate weather pattern that could spread fires. Last year, the entire Southwest had a high vapor pressure deficit, and then a fortuitous ignition. In the northeast corner of California, fires are often driven by the outflow from thunderstorms.

But when we look in the weather history, we can identify what these patterns are. They have similar features in Colorado, where I live. Our big events historically have been when we have an unseasonal downslope wind event, so we have winds coming from the northwest across the Rockies, and you get some interesting gravity wave dynamics that drive winds down the east slope at 90 to 100 miles per hour. We usually get them in November and December because of the weather patterns, but when we get them in July, that overlaps with fire season, when the fields are susceptible. And with an ignition, either from lightning or humans, we've got these catastrophic fires.

I recently read about the phenomenon "pyrocumulonimbus," or "pyroCb." What is that?

When a fire is burning through vegetation, it releases heat and water vapor—water in the form of a gas—into the air above it, and that makes it more buoyant than the air outside, so it rises and creates this "fire flow." If that's sufficiently moist and the fire is strong enough, it will lift it to the point where it expands and cools, causing the water vapor in the air to condense into a cloud over the fire. That's a pyrocumulus.

If it's a sufficiently strong fire, it can drive it deeper [upward] into the atmosphere, forming ice particles. It can even rise into the stratosphere, like some of the British Columbia fires in recent years, producing deep cumulus, way up past where jet airplanes fly, creating these smoke plumes that go up to where the air is moving very quickly toward the east. It has the potential to create plumes that produce smoke that descends somewhere on the East Coast.

Those are problematic in the long term because when you create this cloud and you produce particles, it can turn into precipitation, which fall and evaporate, creating a gust front, which can change the wind direction; the fire can suddenly turn toward the firefighters. Those have been associated with a number of fatalities, including the Yarnell Hill Fire in Arizona in 2013.

What does it mean for a fire to create its own weather system?

Although this comes up when we're discussing extreme weather, fire affects the atmosphere even with a simple, small grass fire. For example, if you start a fire from uniform fuels, in a straight line, with a uniform wind pushing it forward, it won't go forward in a straight line, but instead it'll bow into an elliptical shape. And that's because of the nature of convection; it's more comfortable if it collapses to a column than if it rises in a line. So it's a really basic aspect of fire behavior.

But that term also comes up when we're talking about more extreme events, where the wind is pushing the plume faster than the fire can keep up. In these big plume-driven events, we've measured winds at over 100 miles per hour, within the fire. The winds spreading the fire are entirely generated by the fire. We call them "fire-induced winds." And those can be ten times stronger, or more, than the winds in the fire's environment. They can rip trees out of the ground; they can snap large trees.

Tell us about "fire tornadoes" or "firenadoes."

They're also called "fire whirls." I've been able to model some of them, like one in the Carr Fire outside Redding, California, a few years ago. It was a giant fire whirl with winds over 100 miles per hour. It formed when winds that were coming from the west over the coastal range

came down into Redding, which is at the top of the Sacramento Valley, and intersected with winds coming north up the valley, creating a shear zone where winds were coming from different directions. As the fire ran across it, the shear zone tilted that vorticity up into the vertical to create a long-lasting, very strong fire whirl, which spread for several minutes through town, causing immense destruction. So that would be another phenomenon that is created entirely by the winds generated by the fire.

Can you predict where or when some of those exotic phenomena, like the fire-whirls, are likely to happen?

We're able to predict many of these fire phenomena, like the fire whirls. Sometimes you get a pair of these rotating columns that tilt forward at the leading edge of the fire, and where those come together, they can accelerate the fire between them, or slow it down. When helicopters go over a ridge, sometimes they experience a sudden downdraft, where they drop 100 feet or so, which is very dangerous because they're not very high to begin with. Those sudden descents are produced by the fire winds, and those we can capture in our models. It's complicated, and it requires special expertise, but it is possible to do all these amazing things—predict changes in wind direction and how events will unfold. I think within the next 10 years, we ought to be able to predict where fire whirls are likely to form.

Let's get back to the connection between these extreme wildfire events and global climate change. What else can you say about that?

Whenever there's a giant fire, people either say, "Oh, it was fuel accumulation," or, "Oh, it was climate change." But it's this alignment of factors, some of which change over much slower periods than others. When we take it apart and look at those slower-changing factors, we see certain aspects are affected by climate, like canopy moisture: Tree canopies are affected by slow-changing things like drought and insects; seasonal changes. There are certain fires which they can affect, and others where they would have a minimal impact. Attributing fire behavior to climate varies a lot from fire to fire.

We have to look at how weather patterns are changing over time. When my colleague [Andreas Prein] looked at the historical record of downslope wind



FIRE FIGHTERS Scientists who analyze fires constitute a "very strange field," says Janice Coen (above). "In atmospheric science, a lot of us have similar backgrounds. But a lot of people are foresters, and that's not physics, it's ecology. They see the world and try to look for cause and effect, and it kind of confuses them when you talk about computational fluid dynamics models. I get a call every week from somebody modeling fires with machine learning. There's so many things coming together."

events, he found an increase over the past 50 years. That means if you're in Vancouver or Washington or Oregon, you might see more of those downslope wind events. And if that overlaps with a dry period—we also have to think about weather, particularly the dryness—if those summers extend longer into the fall and overlap these wind events, then we might see more extreme fires, like we saw last year in Oregon and Washington. It's really complicated how these different scales come together and produce extreme fires in different areas. It's not as obvious as "the world's getting hotter" or "the world's getting drier."

COURTESY OF JANICE COEN

I've also read there can be cooling that occurs when smoke from the fire starts to block out sunlight. Is that significant?

Yes. The smoke from the fires can trail out for very long distances. I remember during the Hayman Fire [in Colorado] in 2002, we had a very deep smoke plume that went up into the atmosphere, one of those generated by a wind event, so there were strong winds drawing the smoke plume across eastern Colorado. And under the smoke plume, the temperature had gone down 10 degrees Fahrenheit, so it was much cooler under it; and that, no doubt, affected the weather. So it can become a dominant regional weather factor.

During the 2018 wildfires in British Columbia there was such a persistent smoke plume that people claimed to have detected a reduction in crop generation under it, because of the decrease in solar radiation. So persistent deep fires have the potential to create regional climate disturbances that affect not only your weather, but also the food you eat.

How important are prescribed fires—fires set intentionally, in a controlled manner—as a strategy for mitigating the potential damage from wildfires?

Prescribed fires are used to reduce fuel in ecosystems where fire is a natural disturbance, and it's a good thing. We need to learn to look out the window and see a smoke plume and say, "That's a good fire; it's doing good things for the landscape." Certain fires we don't like because they impact our cities, and our communities, and the wildlands. But many of these fires serve a good purpose. But there are risks associated with them. Here in Colorado, we had a prescribed fire that escaped control. That's not unusual, but it killed people, and that sets back the use of that tool, making land managers resort to other tools that are perhaps more clumsy and less effective, like mechanical thinning.

People want to use it more, but I think it's overstated as a solution. The 2018 Camp Fire in Paradise, California, was the most destructive fire in having killed at least 85 people. In that case, the fire was re-running through previous fire scars because local weather patterns had made it a really windy spot. The Camp Fire, in its early period, ran through mostly grass. That was a previous fire scar. So we can't attribute every catastrophic fire to not having done a lot of thinning.

We're drowning in new tools, each of which has promised to be innovative and solve the fire problem.

As a scientist, you want to learn as much as you can about these complex systems; but obviously there's also work for the policymakers and politicians. What sort of interplay between scientists and policymakers should be happening to mitigate the harm caused by these fires?

In our federal government, there are a variety of agencies that have a stake in it, but no one really controls fire. There's been a lot of activity in the private sector in terms of bringing new tools and trying new things. But now we're drowning in new tools, each of which has promised to be innovative and solve the fire problem. There's a lot of money flying around, and it's a very interesting, chaotic time. It seems to me it's obviously a weather problem and a physics problem—but a lot of the policies are made using antiquated models. With the tools we have, we should be able to make better predictions about, for example, prescribed fires. Many people will say the problem isn't a lack of technology, but that it comes down to other factors, like policy and regulation. And the culture of politics is much more challenging than the technology. ☺

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This NFT Painting Is a Work of Art

Machines are the new descendants of Picasso

BY ARTHUR I. MILLER



ON MARCH 11, 2021, the auction house Christie's sold a work by an American graphic designer, Michael Winkelmann, a.k.a. Beeple, for a colossal \$69 million, making it the third most expensive work ever sold by a living artist. The work,

Everydays: The First 5000 Days, is a nonfungible token, or NFT. It's a computer file that cannot be exchanged, copied, or destroyed, which gives the purchaser proof of authenticity. It lives online in a virtual space—an immaterial space—in a blockchain, a secure digital public ledger. The file is a mint copy, an original, like the *Mona Lisa* that hangs in the Louvre. It's also a work of art.

Everydays exemplifies a new generation of digital art that uses computers in adventurous ways and is pushing boundaries, just as artists from Da Vinci to Picasso to Rothko have always done. Even more exciting is AI art, generated by machines with just a little prompting by humans. It's exciting because AI art may one day show us how machines see the world.

For 5,000 days straight—nearly 15 years—Beeple created images, sometimes by hand, sometimes digitally, and posted them online. He then made a vast collage of his work on a jpg. The individual tiles are colorful and highly imaginative. Some are dystopian sci-fi images, some abstract, some crude sketches, others political or satirical. What I find endlessly fascinating is the incredible variety and detail of the images. It's fascinating to zoom in on tiles. There are scatological images, people rollerblading among giant juice bottles, disturbing otherworldly images of astronauts, some nightmarish, some surreal, all colorful and inventive. The whole contents of a weird imagination are there to be seen.

Like all original works of art, *Everydays* has a subject, theme, and a point of view. Beeple's images express his take on current events. He resents accumulation of wealth by the few, is critical of America's political turbulence, and delves into what's new on Twitter.

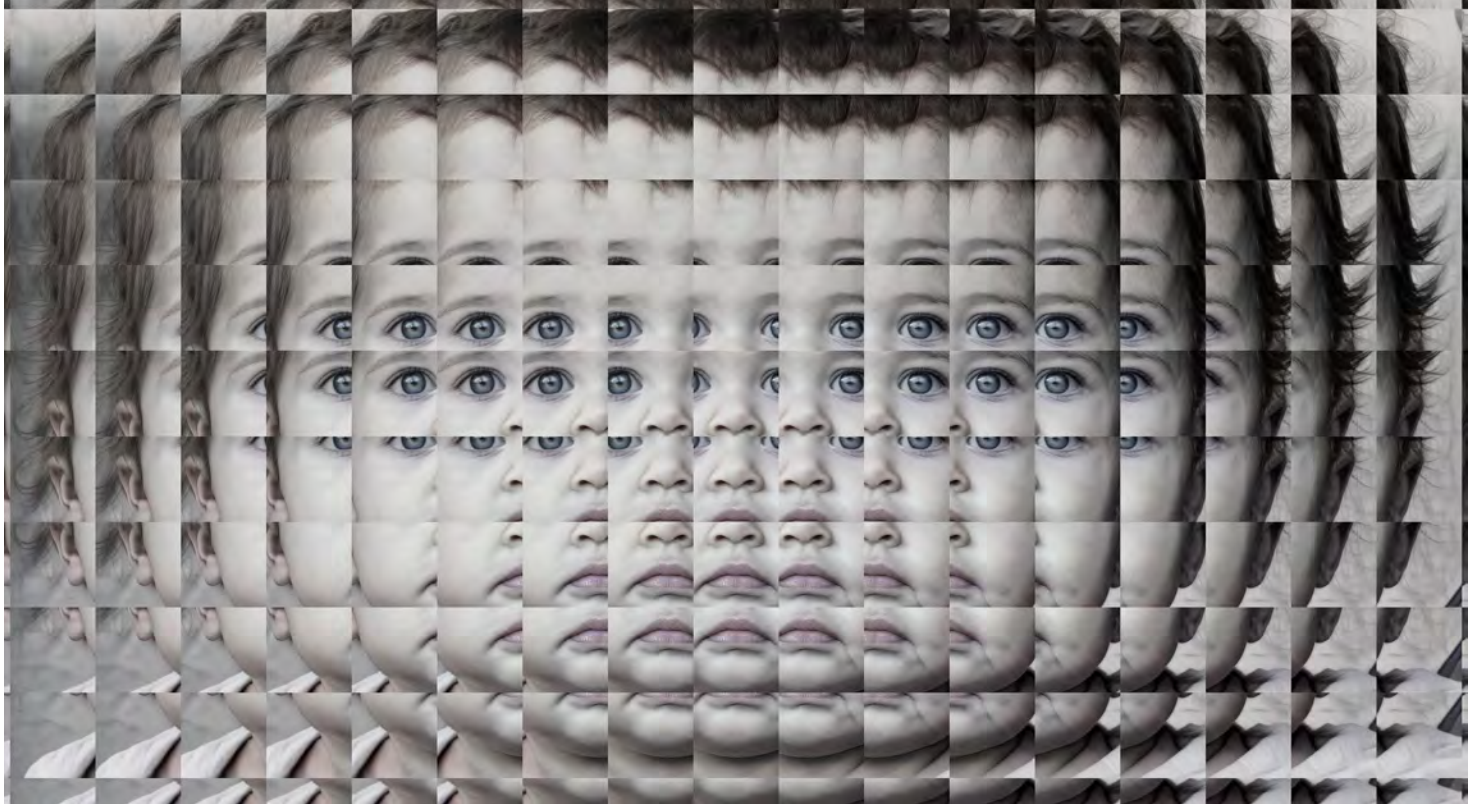
Another element of art is the aesthetic of a work, which sets it apart from other works and is what makes it original. Cubist art had its own aesthetic—the reduction of forms to geometry—and so does *Everydays*, a

The point is not whether we can distinguish AI-created music from human music but whether machines will be able to create music of their own, music we cannot imagine.

sort of sci-fi, comic book, surreal aesthetic. *Everydays* can also be compared to Hieronymus Bosch's otherworldly paintings, which must have seemed utterly shocking in their day.

Artists before Beeple had turned their works into NFTs but Beeple was the first to transform a checkerboard of 5,000 images into a single NFT, which tickled the fancy of Christie's, no less. But for all the talent and creativity of digital artists like Beeple, it's AI art, which is creating images never imagined before, that brings into focus the differences, or, more to the point, the lack of differences, between us and machines.

Beeple's art is generated by digital software packages such as Adobe Photoshop that allow artists to manipulate images, rather like manipulating a paintbrush. AI



MITOSIS In a still from a video loop, created by Mario Klingemann, faces belong to no one in our world. We could say the computer generating the artwork is imagining, constructing an inner world of its own.

art, on the other hand, is created by algorithms, the set of instructions that you program into the machine to tell it what to do. With AI art, it's the machine that manipulates the paintbrush.

Chief among artists who employ artificial intelligence in their creations is Mario Klingemann. Klingemann uses an artificial neural network, a machine whose architecture resembles the way the human brain is wired. On this he runs a GAN (Generative Adversarial Network), made up of a generator and a discriminator network. Data, often digital images, are coded into a GAN. The generator then creates images from, essentially, nothing—data noise—and then passes them to the discriminator network. The network assesses whether each image is real or not.

Klingemann's discriminator network is trained on thousands of faces harvested from the web. At first the generator creates formless blobs that are rejected by the discriminator. Soon the generator is no longer generating images from nothing, but from the rejected

images, which begin to form its database, its memory. These are faces that belong to no one in our world. We could say that the generator network is imagining, beginning to construct an inner world of its own. In this way Klingemann created *Mitosis*, meaning the moment when the embryo begins to form.

Mitosis is a two-minute video loop made up of over 750,000 faces continually being generated by a GAN. The ever-changing face in *Mitosis* symbolizes how AI is becoming an integral part of our daily life, changing us in subtle ways that are noticeable only in hindsight. The effect is akin to Cubist art, where the viewer sees a scene from many different perspectives, one at a time. Besides the eye-catching checkerboard array, it reflects the Cubist aesthetic. While Beeple's work is static, a checkerboard of tiny squares, Klingemann's is endlessly moving and changing before our eyes. Far from cartoon-like, it has the gravity of a black and white photograph. These are images created not by the human artist but by the machine.

AI ART LIKE KLINGEMANN'S shows that machines can imagine what we cannot imagine and see what we cannot see. This is especially evident in artificial neural networks that run the DeepDream algorithm invented by Alexander Mordvintsev initially to probe the machine's "hidden layers" of neurons to glean a better understanding of how they work. Basically, DeepDream overinterprets an image, which gives a sense of how individual neurons contribute to it.

Suppose we take an artificial neural network running DeepDream and trained on ImageNet, a huge database of 14 million images. We feed in a jpg of Van Gogh's *Starry Night*, then stop analysis part-way through. Will the machine see a fuzzy image of Van Gogh's painting? No. What it produces changes every time, but it might come out with something like the one below—the world as seen through the eyes of a machine. We could not have imagined such images before DeepDream created them.



STARRY NIGHT This image, below one of Vincent van Gogh's most renowned paintings, shows how an artificial neural network "sees" the Dutch master's *Starry Night*. Haunting, isn't it?

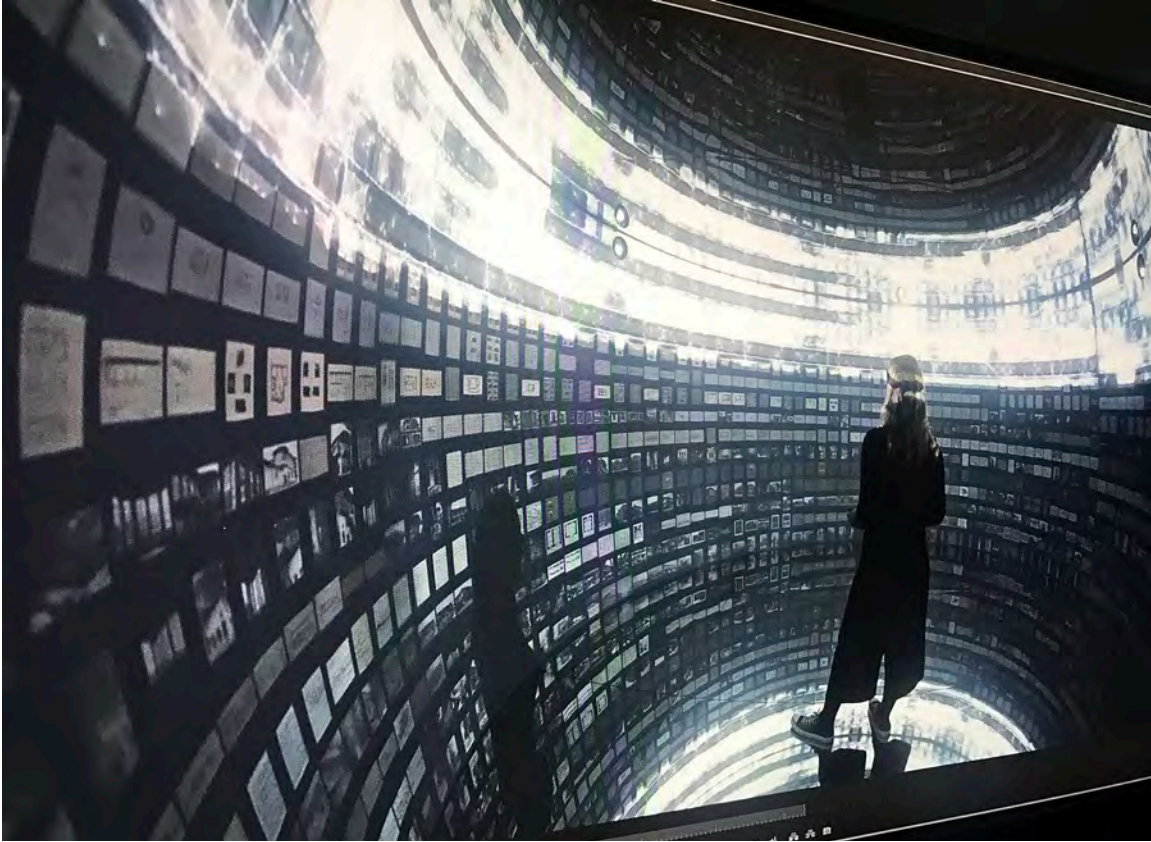
Next to make a splash will be art created entirely by machines with humans nowhere in the picture.

DeepDream's works have been included in many exhibitions including the Gray Area show of 2016, which was the first to reveal the esoteric world of artificial intelligence to the public. They are totally new, have no link with art of the past, and have a style all their own, a unique aesthetic. We can recognize a DeepDream work just as we recognize a Rembrandt or a Monet. They also push the boundaries of conventional art in that they have no specific subject matter. They are the world as seen by an alien being, a machine, like the images created by machines running GANs. This is what I find so exciting with DeepDream. You never know what to expect and whatever emerges is nothing you could have imagined.

Another fascinating example of computer-generated art is Refik Anadol's work. It's a stunning example of the potential of machines to dream, to create a new world of extraordinary and beautiful images. Anadol, a media artist, took 1.7 million documents relating to Turkey, from the late 19th century to the present, from

a Turkish art institution and online library called SALT Galata, and encoded them all in numbers. *Archive Dreaming* is an immersive media installation. Viewers stand in a cylindrical room and the images are projected onto the walls and onto them.

When the installation is dormant, a GAN comes into play, using a discriminator network trained on these 1.7 million documents. The generator network begins generating images which soon start to look much like the real ones but are documents that have never existed. Viewers are surrounded by a whirl of images in which it's impossible to distinguish real from unreal. These images are new representations of the original subjects and texts, which are designated as art, so the images too are art. To me the interactive aspect is especially intriguing. The audience becomes part of it, with others seeing views of the work as it moves over the contours of your body. As in Borges's "The Library of Babel," on a library generated by 22 letters of the alphabet, plus punctuation marks, there is literally an infinity of images.



ARCHIVE DREAMING This still is from an immersive installation by media artist Refik Anadol. He took 1.7 million documents relating to Turkey, from the late 19th century to the present, and encoded them all in numbers.

THE IMAGES GENERATED by DeepDream and GAN demonstrate how art and technology are fusing in the 21st century. For the moment, human artists program the machines. But it is the machines themselves that do the creating, going beyond the parameters set up by their human programmers.

Can AI art really be called art? Few question whether AI-created music is music. Some AI researchers, for instance, have trained artificial neural networks on hundreds of scores by Bach. Having learned the rules of baroque music, the machines come up with more of the same. It's a long way from Bach because at present machines are rather limited and have neither emotions nor the memory of scores by Bach's predecessors, as

Bach did. But asked to pick which of two pieces is Bach and which by a machine, only about 50 percent of the listeners will make the right choice.

But it's a pointless exercise. The point is not whether we can distinguish AI-created music from human music but whether machines will be able to create music of their own, music which at present we cannot imagine. There are already machines, such as nSynth, capable of producing musical sounds we've never heard before, and which musicians can use to create music.

But how can a machine made up of wires and transistors, created and programmed by human beings, be considered creative? While Mozart's father taught him the rules of composition, we don't attribute the

REFIK ANADOL

son's music to the father. Similarly, there's no need to attribute the music or art a machine creates to its programmer. As for human creativity, we ourselves are an amalgam of bones, muscles, arteries, and veins. And we are clearly creative.

What's so different about the components of a machine? Like us, machines have a memory and can respond to the world around them and are built to adapt as they learn and think. When you feed pixels, text, or musical notes into an artificial neural network, they are all encoded and stored in the machine's memory as numbers. We can imagine sculpting with words or musical notes or transforming Picasso's *Les Femmes d'Alger* into a symphony.

This goes for us too. We too are machines. At one level we are biological machines made up of muscles, bones, arteries, and veins; at a deeper level, chemical machines; and at the deepest level, neutrons, protons, gluons, and the rest of the elementary particles. In theory, the dynamics of these elementary particles can be calculated using the equations of quantum physics, which when encoded for computers become numbers. It's numbers all the way down.

Next to make a splash will be art created entirely by machines with humans nowhere in the picture. AI art is already developing akin to the way in which human art has developed through the millennia. By doing so, AI art is opening our own minds, causing us to reflect on ourselves, what we're made of, who we are. The next step will be when we merge with machines. 🌀

ARTHUR I. MILLER is a scientist, historian, and author, and Emeritus Professor of the History and Philosophy of Science at University College London. His most recent book is *The Artist in the Machine: The World of AI-Powered Creativity*.

My Personal Quest to Study Supernovae on Mars

Overcoming sexist naysayers and self-doubt in astrophysics

BY SARAFINA EL-BADRY NANCE

WALKED OUT OF THE AIRLOCK onto the blood-red Martian surface. My mind was crystal clear and laser focused. There was no room for panic or anxiety as I surveyed the landscape and remembered the job ahead. I had conditioned my body to instinctively complete the tasks at hand.

1. Triple check that the life support in my backpack is functioning and I can feel the stream of air tickling my face. My life depends on that trickle of air.
2. Triple check that the airlock pressure matches the Martian ambient atmospheric pressure of 6 millibars before exiting the Hab, our home, so I don't blow it up into oblivion.
3. Communicate with HABCOM, my colleagues remaining in the Hab, to tell them that the airlock is secure. With everything checked, it was finally time to ...
4. Walk on Mars.



In reality, I was at an altitude of 8,200 feet on Mauna Loa, one of the world's largest volcanoes, on the Big Island of Hawaii, completing an analog astronaut mission. I am a Ph.D. candidate in astrophysics at UC Berkeley and Lawrence Berkeley National Lab, where I research supernovae and computational cosmology. I study exploding stars, tracing them from birth to death, to learn more about their physics and how they might reveal untold secrets of the universe. Ultimately, my goal is to be an astronaut and study the traces of exploded stars in the rocks on the real Mars.

This summer I was selected for an Analog Astronaut Mission in collaboration with NASA Goddard and the International Moonbase Alliance, as a field test to replicate living as an astronaut. Currently, these missions focus on Mars and the moon, though there is some interest to expand them to sites like the Jovian moon Europa. It was a dream come true to be selected for a Mars analog mission—and a stepping stone to one day becoming an astronaut and getting to do the real thing.

I felt a rush of shock and accomplishment when I walked on “Mars.” I’ve devoted my life to reaching for the stars, ultimately with the goal of conducting astrophysics research on another planet. I was struck by the moment of realization that I’ve now accomplished a big goal of mine—alongside the reminder that I still have so much more to explore.

I’D KNOWN I WANTED to devote my life to exploring the night sky since I was 5 years old. I used to spend my nights stargazing with my dad, my best friend, and he’d point to shooting stars as we spent hours under the wide Texas sky. On the way home from school each day, my mom dialed our Volkswagen radio to NPR just in time for Star Date, a short radio segment introducing daily cosmic phenomena. I would rest my head against the suede of our car door and let my eyes droop, allowing the ethereal music to lull me into calm as I pictured glowing stars dancing across my eyelids.



MISSION ACCOMPLISHED

Sarafina El-Badry Nance posing after being selected for HI-SEAS.

I'd known I wanted to devote my life to exploring the night sky since I was 5 years old.

As I grew older, my passion for the stars only grew greater and greater. As my parent's marriage crumbled and my anxiety took form, I sought out the night sky on long midnight walks. I channeled my anxiety by becoming a workaholic, a perfectionist. My hard work was praised by my parents, coaches, and teachers, and I let it fuel me, becoming the singular force that drove me forward. If I got anything less than an A+ I would

crumble, allowing my anxiety, and perhaps something deeper, darker, to take hold. The thoughts that consumed me, "I'm stupid, I'm not worth anything, I'm a failure," became the constant buzz that rippled through me whenever I would take breaks. I became an insomniac, avoiding sleep at all costs, to keep the clawing terror at bay.

Aside from work, the only reprieve from my anxiety was the night sky. On my midnight walks, I would often lie down in the grass and stare unblinkingly up at the canvas of stars above. The longer I looked, the more I would see, and the never-ending abyss was *comforting*. It wrapped around me like a warm blanket, reminding me of

how small we are in the grand expanse of the universe. There are other worlds orbiting their home suns, making up the fabric of billions of galaxies in a forgotten corner of our universe. Up there, my successes and failures mean nothing. There is nothing but that unending abyss, peering down at us, at me, and waiting ... waiting for us to explore.

Despite my love for the cosmos, I struggled in math and physics. During my introductory algebra class, the school Dean went so far as to tell my parents that "girls just aren't cut out for this sort of thing." When I took Algebra II a few years later, my teacher, a 60-something white man, looked out at my class and bluntly told us that the only people who would ever succeed in a quantitative field were the four boys sitting next to me. My friends and I looked at each other, eyes gleaming in hurt, and our dreams flashed across our eyes: me, astrophysicist; Alia and Lillian, doctors; Sibel, bioengineer.

One summer, I attended a science camp out in middle-of-nowhere Texas. I spent two weeks gallivanting through the underbrush and swimming across a deep blue lake, savoring the reprieve from my parents and school. I learned how to identify damselflies and take soil samples, what to do when we spotted a brown recluse and how to not bang my head against the ceiling when I'd rise from the towering bunk beds. But the thing I looked forward to most was the final night of camp, when an astronomer was to visit and let us peer through his telescope. I counted down the days in my little blue notebook, a diagonal stripe for each completed day.

On that final night, I rushed out to meet the astronomer. My hands were shaking in excitement when I introduced myself, throwing glances toward the immense black telescope behind him. But the excitement wasn't reciprocated, and when I bashfully confessed that I want to grow up and be an astronomer, he looked me directly in the eyes and said, without missing a beat, "No, you don't. This isn't for you." I paused, sure I misheard, but he just kept staring at me, making no effort to hide the derision warping his smile and damning his gaze.

I was never entirely sure what I did to garner such judgment. As the years passed and I entered college as a physics and astronomy double major, the vitriol and gatekeeping only increased. Whether it was my brown skin or Egyptian curls, or simply the fact that I was often the only girl in classes of a hundred boys, I always felt out of place. Faculty and classmates alike reminded me—often—that I don't fit in.

It wasn't just the sexist jokes ("Who'd you have to fuck to get into this class?") or the blatant disregard when male professors ignored my questions and pretended that I didn't exist. It was the internal dialogue, as I absorbed all of the judgments and condemnations, that was most toxic. I would fall asleep to night terrors and wake up sweating, their words circling in my head and feeding my vultures of anxiety. I got seriously ill:

When I bashfully confessed that I want to grow up and be an astronomer, he said, without missing a beat, "No, you don't. This isn't for you."

first, pneumonia, then a particularly bad strain of the flu, my body physically rebelling against the stress I was putting it through.

But I refused to quit. I might not be a natural-born physicist—I struggled, a lot, to wade through the foreign equations in front of me—but I *loved* astronomy. I spent my first summer in college at the McDonald Observatory, where I led talks on the sun and the stars, explaining how astronomers conduct research and teaching the intricacies of research telescopes. I loved communicating my love for the stars, loved sharing my passion

for the cosmos. For I believed—and still do—that some of the most fundamental questions that humans can ask are written in the stars: Are we alone? How did the universe begin? How will it end?



INTREPID EXPLORER Sarafina El-Badry Nance using the SciAps Laser Induced Breakdown Spectrometer (LIBS) while on "Mars" to analyze the elemental abundances of volcanic rocks.



STARDUST An image of the Tycho Supernova remnant SN 1572, showing the expanding shells of gas and dust.

I will remain steadfast, asking questions and pushing the boundaries of what we know, what we can achieve, for a chance at a better world.

So I endured. After five long years of physics classes and sexist jokes, I graduated with honors in physics and astronomy. To my utter surprise, I was nominated by the faculty to give the commencement speech for

the University of Texas' College of Natural Sciences. In my speech, I spoke candidly about the pain—and the importance—of failure. For without struggling through—and sometimes failing—various physics assignments, I wouldn't have grown resilient. I wouldn't have pushed the boundaries of what I can do and learned so much about the magic of our universe. Some part of me was grateful for that failure.

I also discussed the importance of communication. How as scientists, I believe it is our moral imperative to share the magic of what we learn with the world. Too often, scientists sequester themselves to the apex of the Ivory Tower, content with looking down on those who have not joined them. Looking back, I believe this is the beginning of my science communication career, though I did not know it at the time. It is also the most important message I shared that day, and one I refer back to often.

X-RAY: NASA / CXC / RUTGERS / K. ERIKSEN ET AL.; OPTICAL: DSS

*Without struggling through—
and sometimes failing—
various physics assignments, I
wouldn't have grown resilient.*

I FELL IN LOVE with supernovae when I learned that our universe is not static; in fact, it is expanding. And shockingly, that expansion is accelerating with time. The very concept that our universe is constantly changing, growing ever outward propelled by some invisible force, hooked me. To this day, I get chills whenever I think of it. Some astronomers use supernovae to probe the fabric of dark energy, to try and determine exactly how fast the universe is expanding and how it changes with time. This is my passion, the question that keeps me up at night as I cast my gaze upward to the stars.

I took my passion for exploding stars to HI-SEAS, where I analyzed the composition of volcanic rocks to learn more about the formation of the early solar system and, perhaps, identify the supernova responsible. But research was only a portion of the analog astronaut experience. My crew of five and I went on EVAs, wore full spacesuits every time we left the Hab, rationed food and water, experienced a Martian time delay of 20 minutes for communications, and essentially simulated as much as possible of what life on Mars might be. We could not shower or call friends and family. We ate freeze-dried food and monitored all water intake, for we were limited to 100 gallons for two weeks. We stuck to a rigorous schedule: breakfast and mission debriefing in the morning, followed by an EVA or research in the Hab, lunch, EVA, research, and exercise in the afternoon, dinner, and mission reports. By the time we fell asleep, we were utterly drained. And I loved it.

There is something glorious about fulfilling a dream. During our first night EVA, I stayed still under the Milky Way, looking up at the glittering stars through my helmet, and took a deep breath. I proved to myself that I can do hard things. That despite the hardships and struggles, the contempt and the gatekeeping, I made it.

It was not without scars. I still feel like an imposter, still feel that I have to constantly achieve to prove that I deserve to be here. I often question my intelligence and my worth. I battle with anxiety and go to therapy weekly.

But thoughts I dared myself to dream, the ones I cast upward to the stars on those long midnight walks, carry me forward. They are the dreams that sing me to sleep and wake me with joy. It is because of them that I know in a far deep part of myself that I will never stop exploring. I will remain steadfast, asking questions and pushing the boundaries of what we know, what we can achieve, for a chance at a better world.

For a glimpse into the unknown.

To endeavor to understand and explore the universe, just as I work to untangle the universe within myself. ☺

SARAFINA EL-BADRY NANCE is an astrophysicist, analog astronaut, science communicator, author of *Little Leonardo's Fascinating World of Astronomy* (2021) and *Starstruck* (forthcoming 2023), and a fervent women's health advocate. Sarafina currently lives in Berkeley with her partner and their dog, Comet. You can find her on Twitter and Instagram at @starstrickenSF.



Who Said Science and Art Were Two Cultures?

Revisiting C.P. Snow's infamous thesis

BY KEVIN BERGER

AGSANDREW / SHUTTERSTOCK



ON A MAY EVENING in 1959, C.P. Snow, a popular novelist and former research scientist, gave a lecture before a gathering of dons and students at the University of Cambridge, his alma mater. He called his talk “The Two Cultures and the Scientific Revolution.” Snow declared that a gulf of mutual incomprehension divided literary intellectuals and scientists.

“The non-scientists have a rooted impression that the scientists are shallowly optimistic, unaware of man’s condition,” Snow said. “On the other hand, the scientists believe that the literary intellectuals are totally lacking in foresight, peculiarly unconcerned with their brother men, in a deep sense anti-intellectual, anxious to restrict both art and thought to the existential moment.”

Snow didn’t expect much of his talk. “I thought I might be listened to in some restricted circles,” he said. “Then the effect would soon die down.” It didn’t. Snow tapped a cultural fault line that continues to rumble to this day. In his 2018 book, *Enlightenment Now*, cognitive psychologist Steven Pinker wrote that “Snow’s argument seems prescient.” The “disdain for reason, science, humanism and progress has a long pedigree in elite intellectual and artistic culture.”

Yes, in bygone cultures, the disdain for science snaked through the tenebrous salons of art. “We murder to dissect,” Wordsworth lamented in his poem, “The Tables Turned.” In popular culture today, the image of the cold scalpel of science slicing through the heart of human sanctity remains indelible. In some circles they ask, “Who does Dr. Frankenstein think he is, creating vaccines that do who-knows-what in our bodies?”

But in the art scene today, science is a regular. Novels are written about geneticists. Operas composed about physicists. Paintings

created by computer scientists. Although artists may frame science in a critical light, it’s becoming hard to ignore the view that art and science, and the states of consciousness they represent, stream from one culture not two.

Which was what Snow was driving at all along. In an essay about Snow’s life and culture, published on the 50th anniversary edition of “The Two Cultures,” Stefan Collini, a professor of Intellectual History and English Literature at the University of Cambridge, wrote that Snow exaggerated the gap through a personal lens. His great divide stemmed from his love of science and hatred of literary pretension.

Growing up in industrial England in the 1930s, Snow “saw science as the great hope in a world driven into the economic depression and another world war by traditional elites,” Collini wrote. Snow loved H.G. Wells and was turned off by critics who disdained the author of *The War of the Worlds*. The “young Snow developed an antipathy to ‘literary intellectuals,’ especially to what he identified as their snobbish and nostalgic social attitudes, which was never to leave him,” Collini wrote.

Whatever psychological gremlin gave birth to Snow’s split vision of science and the humanities, the novelist and scientist saw them as equals. He went on to lecture that colleges could close the gap between the sciences and humanities. Curriculums should require classes in both. Educational culture shouldn’t prize one discipline over the other.

Artist Francoise Gilot was asked what she had in common with Jonas Salk. She responded, “The drive to get into an equation with the unknown.”



“With good fortune,” Snow wrote, “we can educate a large proportion of our better minds so that they are not ignorant of imaginative experience, both in the arts and in science ...” I guess we should

be generous and ignore Snow’s phrase, “our better minds,” as if “our worst minds” are not worthy of being educated about the bridge between science and the humanities. The mindset of the 1950s Cambridge don has its limitations.

The “imaginative experience,” though, is an astute phrase. It represents the place in the human mind where science and art meet. In 1970, the painter Francoise Gilot, who lived with Picasso for 10 years, married Jonas Salk, pioneer of the polio vaccine. When the artist was asked what she had in common with the scientist, she responded, “We were compatible mainly because, even though we were in different fields, we had that same intrinsic drive, the drive to get into an equation with the unknown. The spirit of discovery allows one to get something known out of the unknown. That’s what he had. That’s what I loved best in him.”

It’s true that artists strive to create works that encourage subjective responses while scientists strive to create explanations that remove them. But their drives are powered by the same current. “Both science and art are creativity and imagination and execution,” Kirk Johnson, a paleontologist and illustrator, and director of the Smithsonian National Museum of Natural History, said. “You come up with new ideas and you test those ideas, and you execute them.”

Like a scientist, Beethoven formulated a hypothesis that a symphony could be written about the grand philosophical concept that life was a Promethean struggle against fate. The composer wanted “to convey something ferocious, inescapable: a force of nature, a relentless drumming of fate,” wrote Jan Swafford in his 2014 biography, *Beethoven: Anguish and Triumph*. Beethoven experimented with musical passages, borrowing some from previous drafts, until the right design, based on four simple notes, began to take shape. It was rigorous work to create and sustain the right tension, wrote Swafford, “one of the hardest things to do in music that has to be worked out over months and sometimes years, penned one note at a time.”

The Beethoven Fifth Symphony of science was the discovery of the molecular structure of DNA, worked out over years, penned one atom at a time. It too had four building blocks: A, G, T, C, the da-da-da-dum of organic molecules, the nucleotides. The scientists had to figure out the structure of DNA to determine how it functioned, how it shaped an organism’s traits and passed them to future generations. The scientists were as obsessed as Beethoven in their pursuit. But they weren’t writing a symphony. They could leave no room for interpretations that weren’t supported by the laws of physics and biology.

None of the DNA scientists was more scrupulous than Rosalind Franklin, the chemist who was a master of X-ray crystallography, a method of identifying the atoms that define a

molecule. After she helped identify the double helix shape of DNA (sadly unacknowledged by the Nobel committee), Franklin analyzed viruses. In *The Art of Fiction*, Henry James advised writers, “Try to be one of the people on whom nothing is lost.” That was Franklin. In her 1975 biography, *Rosalind Franklin and DNA*, Anne Sayre quotes Aaron Klug, one of Franklin’s coworkers. “She noticed everything,” Klug said. “The fact that she produced the best specimens ... wasn’t due to chance, or simple mechanical skills. It’s an art, doing this, it’s a matter of the pains she took, the way she nursed it, the keeping track of things, the noticing. That’s how discoveries are made.”

WHILE SCIENTISTS AND ARTISTS share a creative drive, Snow’s cultural radar was keen. History passed on the sense the twain didn’t meet between the cold reason of science and messy passions of art. Plato told us Socrates wanted to boot the poets and storytellers from the city because they dared to boast that wicked men could be happy. That was no way to mold the moral virtues of a serious republic. Wicked passions must be buried. The ancient Greek philosopher’s decree became gospel. A dualist nature was born.

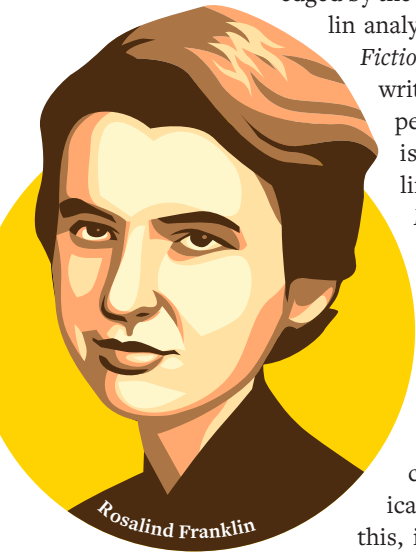
In the 17th century, Descartes applied another layer of concrete. We think therefore we are. The bulwarks of knowledge crumble on humans’ changeable feelings. But as science marched on, it chiseled away the bedrock of dualism. By the 20th century, neuroscientists like Antonio Damasio, through biological experiments, showed Descartes was in error. Knowledge and reason can’t be separated from our feelings. Brain activity ineluctably

The Beethoven Fifth Symphony of science was the discovery of the molecular structure of DNA.

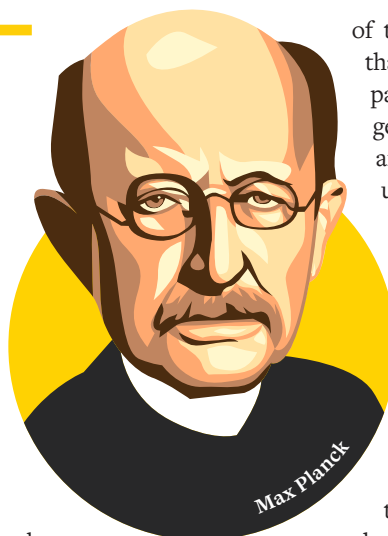
mixes-and-matches knowledge and reason with inputs from our senses, always colored by our memories. And by the way, Mr. Descartes, that doesn’t make knowledge less solid. “The fact that feelings motivate knowledge and reason do not make the knowledge and reason any less truthful or valid,” Damasio said. “Feelings are simply a call to action.”

Dreamers in science and the arts heed the same call. In his 2017 biography, *Leonardo da Vinci*, Walter Isaacson wrote that the Renaissance man’s science, his explorations of engineering, anatomy, geology, and botany, were not separate endeavors from his art, his painting, and sculpture. “Together they served his driving passion, which was nothing less than knowing everything there was to know about the world, including how we fit into it,” Isaacson wrote.

The same could be said, though seldom is, about the Romantic poets. British writer Richard Holmes, a biographer of Coleridge, is also the author of *The Age of Wonder*, about science in the Romantic era, and *Falling Upwards*, about the history and science of ballooning.



“As a scientist, one of the worst things you could do is forget your humanity.”



One of the reasons Holmes wrote those two books, he told me, was to step back in history to correct the “modern notion of two cultures, that arts and humanities can’t speak to scientists, and vice versa.”

Holmes explained that Romantic poets and writers, including Keats, Byron, and the Shelleys—Percy Blythe and Mary—read deeply in science, incorporating the latest theories in astronomy, evolution, and physics into their poems and novels. Likewise, 19th-century astronomer William Herschel, chemist Humphry Davy, and Michael Faraday, whose discoveries in electromagnetism revolutionized physics and modern society—he created the first electric motor—knew the poets and musicians of the time, “and were fascinated and inspired by them,” Holmes said.

Davy, who first isolated sodium and potassium, and was a pioneer in electrochemistry, learned a great deal from his friend Coleridge, the dark heart of Romanticism, and author of “The Rime of the Ancient Mariner.” “They had a very interesting exchange on the idea of pain,” Holmes said. “What is the function of pain, particularly in animal life? What is it doing? Why was it put there? They would frame it in terms of why did God put pain into this system? It was a kind of metaphysical discussion, but it bears on Davy’s actual experiments. One

of the things Davy found is that nitrous oxide suspended pain. He writes a paper suggesting its use as anesthesia, and tragically it’s not taken up for 40 years. So this is the scientist talking to the artist, and the artist saying back to him, ‘Think of this in larger terms, direct your science this way.’”

Walter Murch is a modern-day Renaissance man. The film editor and sound designer of the *Godfather* trilogy, *Apocalypse Now* and *The English Patient*,

has read deeply in the history of science. He told me about a theory by 20th-century Hungarian physicist Karoly Simonyi. It went like this. “Breakthroughs in art break up the hardpan of the soil and fertilize it, add compost to the mix, and then the fruit of science, the plant of science, can find its roots,” Murch said. “The turn of the 20th century brought the development of motion pictures, which is basically the quantization of movement, breaking movement down into discrete frame movements. About 10 years later, along comes Max Planck and gives us the theory of the quantum. That’s around the same time that films began to be edited and put together to tell a coherent story out of parts that are not shot in sequence. So those two things, quantum mechanics and the development of motion pictures, work together.”

Is Simonyi’s theory accurate? Did cultural movements in art fertilize scientific breakthroughs? It’s an intriguing correlation, perhaps not much more. But it underscores the point that one culture, not two, inspires scientists and artists in their times.

In interviews, scientists invariably say the arts, especially movies, were and remain an inspiration to them. Being transported out

Romantic poets and writers incorporated the latest theories in astronomy, evolution, and physics into their poems and novels.

of your critical mind is important, said Caleb Scharf, director of the Columbia Astrobiology Center at Columbia University, and author, most recently, of *The Ascent of Information*. “As a scientist, one of the worst things you could do is to forget your humanity, forget the elements of being human that have nothing to do with being analytic or able to invent things,” Scharf said. “There’s an element of humanity that’s uncontrolled but incredibly creative. I like to taste that creativity.”

Scharf got that taste at an early age. He was raised in a rural English village. Both of his parents were art historians. “They instilled in me the notion there are many different ways to explore the universe around you,” Scharf says. “There are the ways they used—studying human interaction with the arts—but they also taught me science was a way to explore the universe. So I got a lot of my fascination for science from these humanities parents.”

To be human is to be biased, Scharf said. Recognizing that was the first step to overcoming bias. “If scientists don’t retain a sense of humanity, a sense of connection to being human, it’s detrimental to their work,” he said. “We’re all blinkered. We’re all inevitably biased by so many things in our culture and our own personal makeup. Even the most hard-nosed, analytic scientist is not immune to that. It will skew the way they look at nature, it will skew the way they explore problems. My principle in science is an open mind. Always question and never shut off any avenue.”

It’s great advice for artists, too. When artists venture down the avenues of science, they discover interconnections they may have never imagined—among people and the environment, among organisms, among elementary particles. But the final point about the harmony between science and the arts may be the most obvious one. The fallout of science without humanity is Hiroshima. When scientists are engaged with the humanities in a shared culture, the benefits to all of us are clear. ☺

KEVIN BERGER is the editor of *Nautilus*.

This article is adapted from the author’s “Why Do So Many Scientists Want to Be Filmmakers?” which appeared in *Nautilus* in 2018.



The Ecology of Good Weed

How one small farmer is creating a buzz with organic pot

BY MADISON MARGOLIN

IN HIGH SCHOOL, DANIEL STEIN built a solar-powered car and drove it across the country. “I got to see the possibility of doing something with my own hands and seeing the success of taking action for what you believe in,” he says, some 30 years later. It’s a slow winter day on the farm as a bearded Stein prepares seeds for the planting season. Soon he will be donning a straw hat, a clean shave, and a T-shirt, most likely swag from his or neighboring farms, as he works the land.

Today Stein and his wife Taylor Thornton operate an award-winning homestead called Briceland Forest Farm. The couple and their two young sons live in southern Humboldt—one of a triad of counties, alongside Mendocino and Trinity, that comprise the Emerald Triangle. This Northern California sprawl of coast, cliffs, and woods is world famous for its cannabis.

Unlike many of the first hippie farmers, Stein relies on ecological science.

Indeed, cannabis is Stein's main cash crop, enabling him to diversify Briceland's output, growing a variety of vegetables for local restaurants and farmers' markets. The farm is grounded in the values of "regenerative farming"—"no till," "living soil"—which lay the foundation for Stein's mission: to remediate the Earth and sustainably grow food, medicine, and a good high.

Like many in the Triangle, Stein is a second-generation farmer, tending a 5,000-square-foot plot inherited from his parents—hippies who bought the land for cheap in the 1970s during the "Back to the Land" movement. Young people from cities like New York, such as Stein's parents, trekked out west to live off the grid, in harmony with nature. To support themselves, they "guerrilla-grew" cannabis in the shadows of the backcountry, hidden in clandestine corners among the forest, mountains, and mist.

Like his parents, Stein has rejected a life and career in the confines of institutions, with their bureaucracies and environmental sins. "The status quo is comfortable with taking more than giving, using fossil fuels and being extractive, rather than being regenerative and finding creative methods to live," he says.

Unlike many of the first hippie farmers, though, Stein has managed to sustain his farm by relying on ecological science—and endless hard work. When he says he lives in harmony with nature, he's not talking so much about metaphysics but sound ecological principles that propel his business and preserve the land.

The most obvious break with the first Back-to-the-Landers who went to pot is that Stein grows marijuana legally. Times of course have changed over the past 25 years, with California having legalized medical marijuana in 1996 and then "adult use" (recreational) in 2016. Cannabis is a key component of the ecosystem that allows his entire farm to flourish. In an irony, though, that the flower children could never imagine, growing legal pot has tangled Stein in the red tape he has spent his life avoiding. The regulations that come with selling cannabis from sustainable farms like his constitute the most invasive species in his life. He's working on a solution.

BRICELAND FOREST FARM is nestled beneath sky-scraping redwoods and off a hilly road near the town of Redway, population 1,225. The farm abounds with perennials. Its grounds are full of carrots, beets, potatoes, lettuce, tomatoes, cucumbers, zucchinis, eggplants, corn, peppers, melons, shishito peppers, arugula, radishes, and cilantro—not to mention varieties of cannabis. "About everything you can imagine in a farmers' market, we do in small amounts," Stein says.

The farm, with its regenerative methods, is certified organic. Andrew Smith, chief scientist at the Rodale Institute, a nonprofit which created the term "regenerative organic," explains that soil health is at the heart of the regenerative movement. The healthier the soil, the greater its capacity for carbon sequestration, and



FRUITS OF THEIR LABOR

Taylor Thornton, who operates Briceland Forest Farm with husband Daniel Stein, enjoying some of their award-winning cannabis.

the greater the farm's biodiversity, the healthier soil. Regenerative farming "benefits human health, as well, by eliminating the use of chemicals like fertilizers and pesticides," Smith says.

A key component of the practice is not tilling the soil. Untilled soil, Stein explains, retains nutrients important to plants' growth. It also sequesters carbon, helping reduce the release of carbon dioxide, the main global warming gas, into the atmosphere. Traditionally, and especially in industrial agriculture, farmers prepare the soil by tilling it with a tractor. Tilling churns the surface of the soil, aerates it, and allows it to be mixed with plant material or fertilizer for the next planting.

"For the first few years of tilling, you get good returns on your soil and your crops grow great," Stein says. "But what you're doing is pulverizing diversity within the soil, killing earthworms, fungi, and a lot of the microfauna, and making a soil that's primarily bacterial dominant. And bacterial-dominant soil is a threat to soil diversity."

Without tilling, Stein says, "You end up with a more resilient system, which creates healthier plants and a longer term, more sustainable soil." Untilled soil, he explains, is "like a sponge," noting its capacity to hold

water and nutrients, which renders them more available to the plants. A no-till system also finds its own balance of fungi, earthworms, microbes, beneficial nematodes, and other flora and fauna beneath the surface of the earth. This method allows farmers to leave plant roots in the ground, even after harvest.

"The plants take atmospheric carbon and create a carbon structure of roots within the soil," Stein says. "When you cut the plant and it dies, there's all that carbon from the atmosphere that's now deep in the soil profile and becomes stable soil carbon."

In the 10 years since founding Briceland, Stein says he's increased his soil's stable carbon by about 4 to 5 percent; on less than an acre, he's been able to sequester more carbon every year than what a car driving across the country and back would produce and put into the atmosphere. "It doesn't make us carbon neutral," he says, "but it's a good-hearted attempt."

SOIL HEALTH is the foundational element of a regenerative farm. It's also helped Stein produce a bounty of quality cannabis and highs, and win the area's top cannabis award, the Emerald Cup, in 2017, for cultivation practices that "go beyond sustainability in that they heal, improve, and remediate."



THE HAPPY FARMER “Growing and selling veggies isn’t the most profitable business or the most glamorous,” Daniel Stein says. “But it is fulfilling in a way none of the many other jobs I have done in my life have been.”

A key method of maintaining soil health is “cover cropping,” or growing plants not necessarily meant to be eaten or sold. Along with his vegetable crops and cannabis, Stein plants grasses and legumes, including oats, beans, and peas. The fast-growing grasses create additional nutrients in the soil. To aid the process, Stein coats the grasses and legumes with layers of fresh compost, wood chips, manure, and straw.

Along with cover cropping, Stein creates fungal beds and swales (meant to absorb surface runoff back into the soil); this allows vegetation to pull nutrients (that would otherwise pollute the environment) from water as it flows off the property. On his farm, he uses stored winter rainwater, which in Humboldt yields about 80 inches. During the growing season in spring and summer, there is almost no rain, so he draws from a water catchment pond, where he stores it from the wet through dry season.

Stein’s regenerative methods feed both the soil and the quality of his pot. To nourish his cannabis plants,

he explains, he must make the right moves throughout the seasons. During harvest in early October, Stein cuts the cannabis plants, leaving the roots in the ground, and puts a layer of compost on the beds; he then seeds the cover crop into the compost, without removing mulch from the previous year.

Cover crops photosynthesize throughout the winter, bringing up more nutrients from the soil to make them available for the upcoming cannabis planting season in the spring. Once the spring comes along, Stein crimps the cover crop down with flattening boards, then covers it with more compost to start decomposing—facilitating the best possible environment in which to plant the cannabis.

Tina Gordon of Moon Made Farms, another regenerative cannabis farm in Humboldt County, explains that “companion planting,” which may include nettles or comfrey, is another key tenet. “When there’s diversity, you’re feeding the soil,” she says. “We also use the plants right next to the cannabis to make teas that

COURTESY OF BRICELAND FOREST FARM

HEAD START Workers at Briceland Forest Farm prepping beds for cannabis. They crimped the cover crop and then added minerals before spreading compost, alfalfa, and straw over them. Bacteria and fungi will break down the cover crop and the mulch layers as earthworms come up and carry minerals and nutrients to lower levels, and the roots of the cover crop will die back and decompose into stable soil carbon.

we then feed back to the cannabis.” Gordon also plants flower gardens that attract bees to the cultivation site. “The more flowers, the more bees, the more bees the healthier, more robust the crops,” she says.

Throughout the growing season, Stein feeds his cannabis with “fermented plant juice.” He creates the juice by taking plants called “dynamic accumulators,” like horsetail or nettle, that are good at absorbing certain nutrients and minerals, and soaking them in water with a bit of added sugar. “With regenerative practices, you’re creating a balanced ecosystem in the soil,” Stein explains. “You’re giving the plant all that it could possibly want so that it gets to express itself to its fullest, without ever being in want of the proper nutrients and minerals.” A plant’s relationship with soil biology and the plants around it creates a web of mutual support, he adds. “To me, that pure expression of the plant creates a better product, and because of the complexity of the plant life, I know that all the minerals, nutrients, vitamins, and enzymes are available within our soil.”

Stein says his growing methods allow him to design a specific type of high. He implements certain techniques to bring out the plant’s terpenes, or aromatic compounds, which give the plant its flavor and influence the quality of the high. During the late stages of

Growing legal pot has tangled Stein in the red tape he has spent his life avoiding.

flowering, the amount and type of stress that a plant endures—such as watering or companion planting—will impact how it expresses its terpenes. “I like having chamomile or yarrow around them to help produce essential oils and terpenes,” Stein says. One of his strains, “Cuddle Bud,” is named for producing a high that’s “sweet, physical, warm, and loving,” he says.





Stein's strain, "Cuddle Bud," produces a high that's "sweet, physical, warm, and loving."

STEIN IS A PROLIFIC POSTER on Facebook. "I love what we do," he wrote in July. "Growing and selling veggies isn't the most profitable business or the most glamorous. It is really physically demanding, and the hours seem to never end, but it is fulfilling in a way none of the many other jobs I have done in my life have been. Being outside, working with natural cycles and soil is great. It is endlessly challenging in good and hard ways and always changing."

There is, though, one challenge that bedevils Stein, and that is selling his pot. It's a major challenge because cannabis amounts to most of Briceland Forest Farm's income. For one thing, it's expensive to grow pot. Annual fees amount to more than \$20,000 a year, he says, and that's just for "a very small family producer—just us and one helper doing the whole operation, including the veggies." There's a cultivation tax that costs \$150 for every pound produced, and it doesn't matter how much that pound is sold for (even if it only sells for \$150). "Taxes are not based on our profits, but are a flat tax across the board," Stein says.

The biggest legal hassle of selling cannabis, according to Stein, is the California state law mandating multiple middlemen, including distributors, lab testers, and dispensaries. Stein sells his veggies directly to consumers through farmer's markets and community-supported agriculture subscription services. But each time his cannabis changes hands, each intermediary step takes about 20 percent off the profit. It's the "cumbersomeness of the laws," he says, which makes selling weed on the legal, regulated market so difficult. "It doesn't matter if you grow 10 acres or 10 square feet," Stein says. "The greater percentage of your profits go to bureaucratic necessities, without much of a reward system for exemplary practices or motivation to stay small and focused on boutique craft cannabis."

COURTESY OF BRICELAND FOREST FARM

HIGHER AND HIGHER Daniel Stein on his regenerative farm, inspecting his very healthy cannabis. If only selling and distributing his crop could be as satisfying as growing it.

Essentially, the legal pot market penalizes organic farmers. Due to the California Environmental Air Quality Act, cannabis is considered a “product” rather than a “crop,” explains Kristin Nevedal, board chair and co-founder of the International Cannabis Farmers Association. The idea behind the designation is to keep outdoor cannabis production from impacting the surrounding environment—even if that impact is positive, as in the case of regenerative agriculture. The law incentivizes cannabis farmers to cultivate in a closed environment, like a greenhouse or indoor facility, though it’s nearly impossible to implement regenerative practices in an enclosed system. Regulations also mandate that farmers provide a map of their cultivation activities and have everything approved. So those who implement crop rotation practices may need to apply for a license modification every year. Indoor cultivation sites also qualify for exemptions that outdoor sites don’t.

“The law in California has been structured around big business and has often approached cannabis as an industrial product and catered to large grows or indoor grows,” Stein says. Big growers can get their per unit cost down, he explains, while small farmers like him, who prioritize land practices, still have to go through all the same legal processes and pay the same fees. He notes that at least the regulations mandate third-party testing for toxic herbicides and pesticides.

But in September 2020, California passed a law that is changing the fortunes of organic pot growers. The law establishes “appellations of origin” for cannabis that’s grown in certain geographic areas of the state. Weed grown within a certain terroir, such as in Mendocino County, can receive a special designation, reminiscent of the terroirs used in the wine industry, such as Bourdeaux in Southern France and Napa in Northern California.

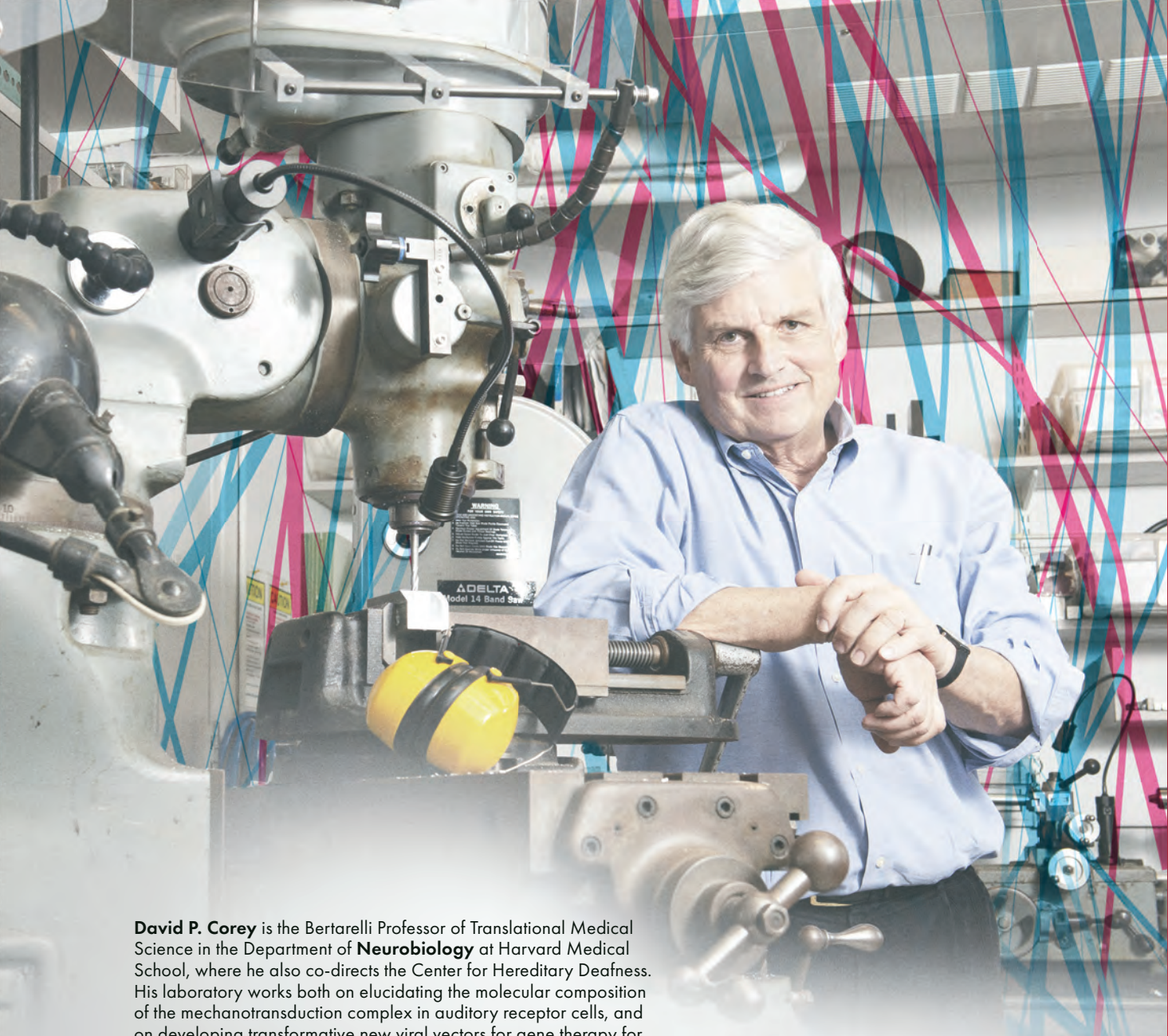
“There’s this idea that there are lots of factors that go into a product that are of the place where it is



grown,” he says. “You can feel, taste, and experience it in the cannabis.” Soil types, growing practices, and other markers link multiple farms in an area and give consumers a sense of where the cannabis comes from. “Having this experience where you can create something of a place and share it with people who can learn to recognize those differences on their own—I’m glad we’re laying down the tracks now, so later on we can use that as a tool for communication with our customers,” Stein says.

Stein is proud to have revived and sustained the land he inherited from his parents. His regenerative approach to farming has allowed his family’s environmental values to live on. “Small farmers are less likely to exploit land, people, and situations to make money,” says Stein. “It’s all right in front of us, we want to see it cared for.” ☺

MADISON MARGOLIN is a New York/California-based journalist covering cannabis, psychedelics, and Jewish culture. She is the co-founder of the Jewish Psychedelic Summit and *DoubleBlind* magazine, where she works as an editor. Her writing has appeared in *Rolling Stone*, *Playboy*, *Vice*, and *Tablet*.



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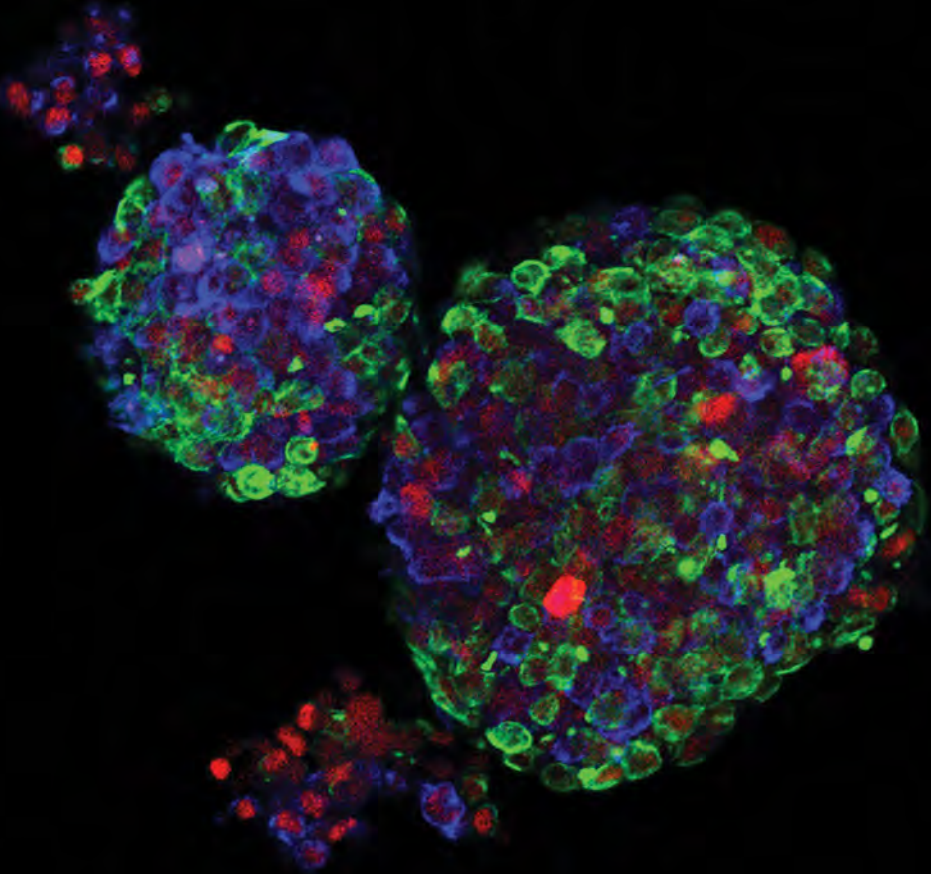
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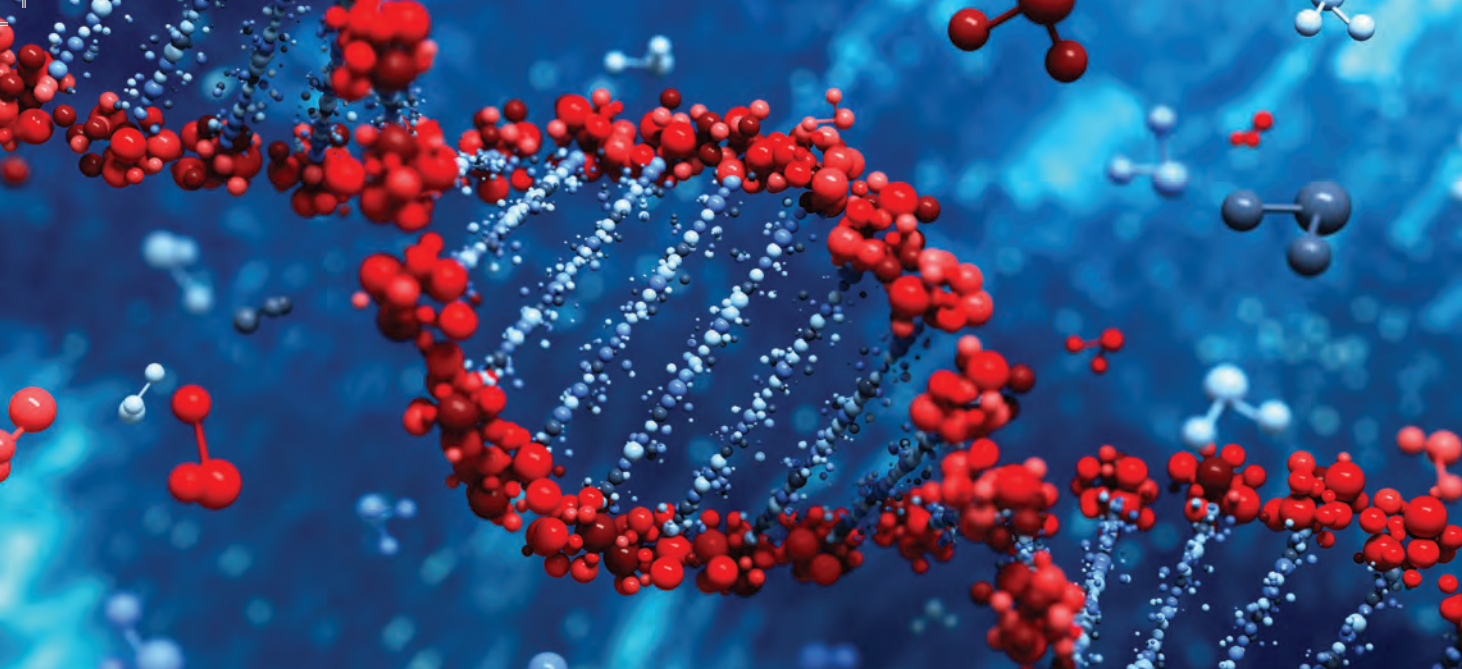


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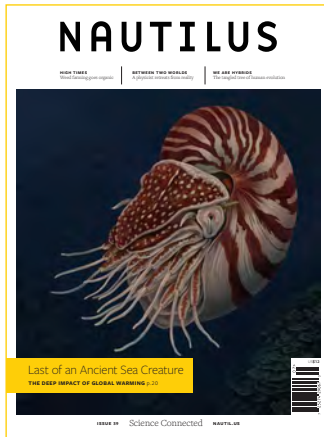


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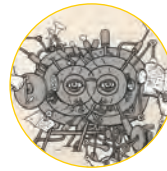
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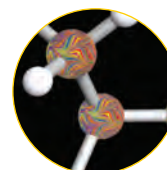
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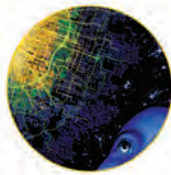
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Todd Disotell

The biological anthropologist on why humans are one mixed-up ape

INTERVIEW BY PHIL JAEKL

OUR VIRAL ORIGIN

About 10 percent of our genome has a viral origin. Some of these viruses are ancient. They go all the way back to vertebrates. Some are more recent. This viral DNA complicates the tree of life because some viruses can pick up strands of DNA from other organisms. Then, when they infect other organisms, their descendants will have snippets of DNA from another branch of the tree of life. That's pretty cool. You've brought branches of the tree of life together in a single organism. If you look at the branches of life, it's not one clean tree. Instead of a bifurcating tree, I refer to human evolution as being more like a short, chubby bush with many branches.

OUR INCESTUOUS ANCESTORS

In the last few hundred thousand years, multiple species of hominins existed and interbred with each other. In Africa, it looks like there were two or three archaic introgressions—basically hybridization between two populations or species—in the last 50,000 to 100,000 years, and it looks like it was the same in India. I think there are up to seven or eight archaic introgressions into the human genome in different populations. I like to joke that the Middle Pleistocene was a lot like Middle Earth where you had Dwarves and Elves and Orcs; all these different creatures cohabiting the planet.

OUR MESSY GENOME

There's about 1 percent difference between our genes and a chimpanzee's. And about 15 percent of a chimp's genome is closely related to gorillas. That means if we go back 7

or 8 million years ago—before humans, chimps, and gorillas split—you would have had a huge and variable population of apes. When apes begin to diverge, they would have still been able to interbreed with each other because they wouldn't have been a separate species yet. When you look at our genome, you see this messiness from the ancestral variation. So the evolutionary tree is neither a clean thing within modern humans nor within human origins. New fossils are being discovered all the time. But it seems for every 5- to 7-million-year-old fossil we find, somebody says, "It's human!" It could be. It could be chimp. It could be gorilla. I think it's just bias showing. Everyone wants their fossil to be the "oldest human fossil."

OUR BRAINS AREN'T THAT UNIQUE

Our brain is the most different thing from our relatives because it's so enlarged. There are definitely a few unique genes but not really many. Humans have extra copies of some genes that aren't found in other primates. Most genes related to our brain development are found in other primates, but we may have more copies of them, or the expression and regulation of them might be different. We now know, with the discovery of several new African hominids like *Homo naledi* and *Australopithecus sediba*, that some other species of humans developed smaller brains and smaller body size, and that makes sense because the brain is full of incredibly energy-expensive tissue. If you can survive in some area with a smaller brain it would be advantageous compared to these big present lugs who have to fill it full of calories! ☺



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