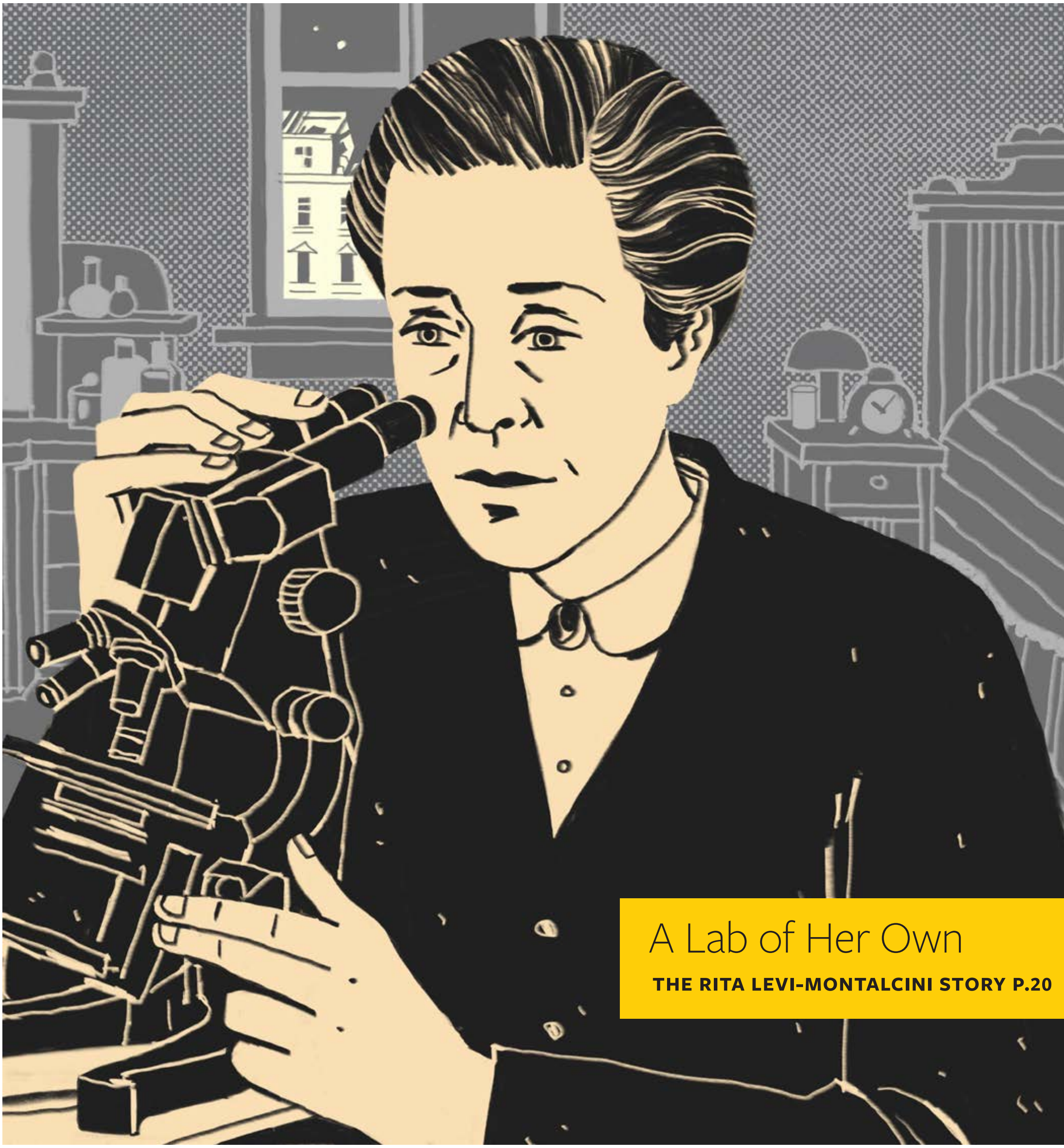
NAUTILUS

LOVE IS RATIONAL
Psychology according to Steven Pinker

YES, IT IS ROCKET SCIENCE
SpaceX gives NASA a boost

TOILET GREEN
Recycling human poop into fertilizer



A Lab of Her Own

THE RITA LEVI-MONTALCINI STORY P.20

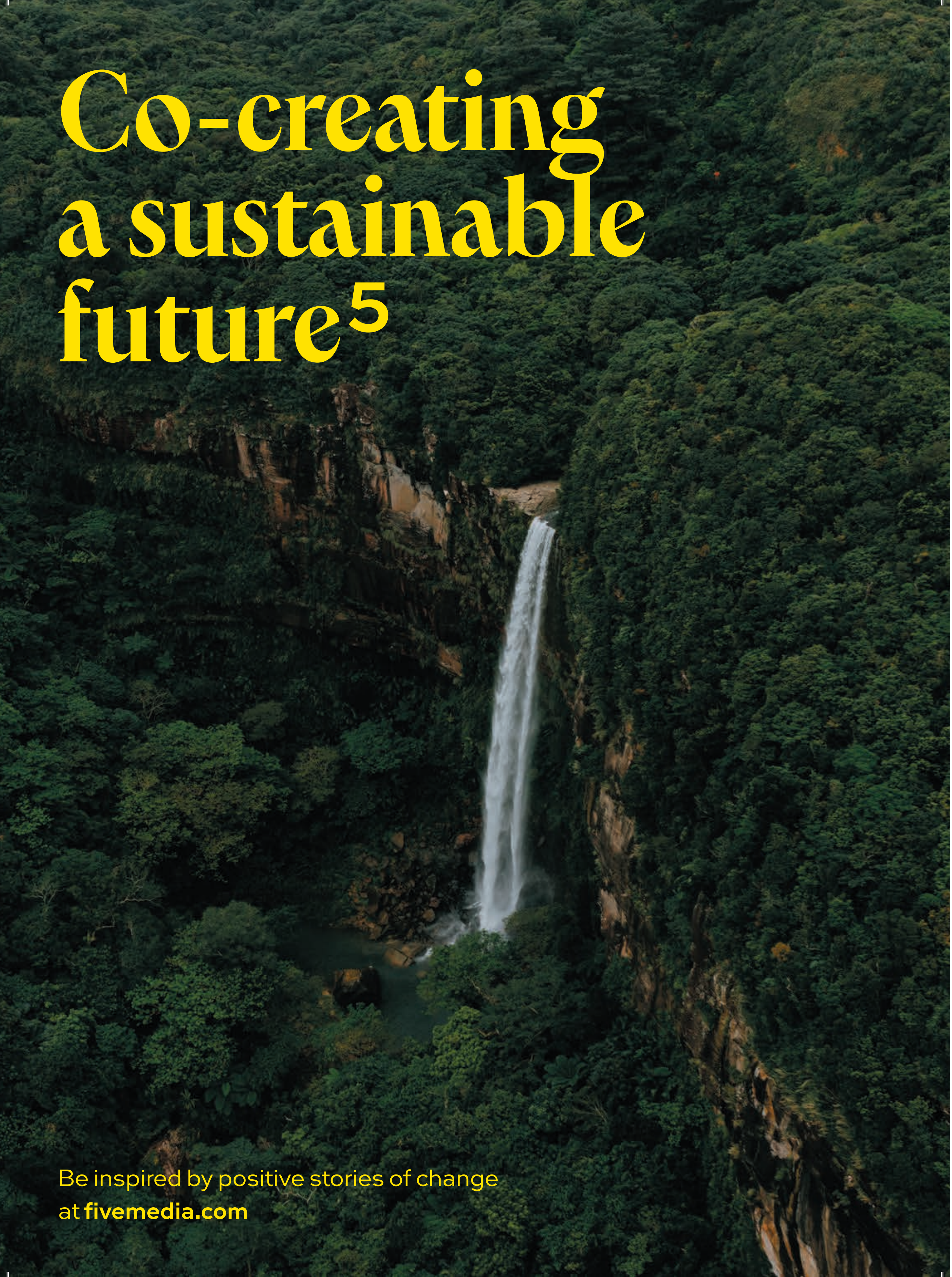
ISSUE 41 Science Connected **NAUTIL.US**


JOIN
THE
OCEAN
KNOWLEDGE
REVOLUTION
2021 2030 United Nations Decade of Ocean Science for Sustainable Development
The UN Ocean Decade is calling for innovative knowledge-based solutions and ideas to create the Ocean We Want.
Submissions open until 31 January 2022.
Scan for more information
Or visit oceandecade.org
Credit: Shaun Wolfe / Ocean Image Bank

ISSUE 41

Contents

COVER Jorge Colombo


Co-creating
a sustainable
future5
Be inspired by positive stories of change
at **fivemedia.com**

Features

NAUTILUS

Published by:

NAUTILUS *Next*

Emotional Primates

BY KEVIN BERGER

SCIENCE IS BEAUTIFUL and moving," a reader wrote after reading our article, "The Beloved Mesolithic Girl," published in this issue, when it first appeared online. Those might be the most satisfying five words I have read about our magazine. We created *Nautilus* to show that science is beautiful and moving.

Our reader is referring to anthropologist Jamie Hodgkins story on being part of an archaeological team that uncovered a burial site of a baby girl in a cave in Italy from 10,000 years ago, the most ancient burial site of a child currently documented in the European archaeological record. Based on the findings, including bone fragments and beads, Hodgkins recreated a scene in the cave. "The girl's mother and father, accompanied by their community, took her tiny body to a marble cave, just upslope from the river," she writes. "The baby was wrapped in a garment decorated with over 60 pierced shell beads and three pendants. The pendants looked huge next to the tiny infant, but she was worth it. She had been a part of their group."

Along with detailing the fascinating archaeological methods of uncovering and preserving the site, Hodgkins tells readers that she was a new mother at the time and was moved as it became clear she was holding the remains of an infant. The scientists named her Neve after the river valley where the site was located. "Though I assume my emotions over the death of Neve are not as strong as the grief her group must have felt, I cried and grieved over Neve's remains, especially as I sat recovering the tiny tubes of her hand bones," Hodgkins writes.

Hodgkins' admission echoes the sentiments shared with me earlier this year by paleoanthropologist Jeremy DeSilva. When his twins were young and he was away on a dig in Ethiopia, analyzing the tiny foot bones of a human ancestor, DeSilva said, "it was hard to not to think about my kids." He added, "Science is the most objective thing we've ever come up with. But it's done by emotional primates."

This issue's cover story is also written by a scientist about a personal discovery. Bob Goldstein, a professor of biology at the University of North Carolina at Chapel Hill, had long been fascinated by the research done by Rita Levi-Montalcini about how the animal nervous system, especially the complex nervous system of the human animal, branched out from an embryo. Some books had noted Levi-Montalcini, during World War II, was forced to work in her childhood home, an apartment in Turin. That alone was an intriguing fact, but what exactly had Levi-Montalcini discovered in her bedroom? As you will read in "A Lab of Her Own," Goldstein learned, to his admiration, the bold and independent Levi-Montalcini made breakthrough discoveries, with bombs raining down on her and the surrounding city.

"A Lab of Her Own" and "The Beloved Mesolithic Girl" humanize science. They show us the practice of science, and its discoveries, can indeed be a source of happiness, sorrow, beauty, and pain. They remind us that in the world of science, we are all in this together.


SCHMIDT
OCEAN
INSTITUTE
OUR PLANET'S OCEAN
UNDERSTOOD THROUGH
TECHNOLOGICAL ADVANCEMENT,
INTELLIGENT OBSERVATION
AND OPEN SHARING OF INFORMATION
schmidtocean.org

Readers Respond

Comments and letters about stories from print issue 40.

“HOW THE CORONAVIRUS STAYS ONE STEP AHEAD OF US”

The information in this article should be shared with every human on the planet. Humanity is truly interconnected—and the COVID-19 pandemic makes this abundantly clear. Collectively, we can substantially improve the global outcome. Vaccination needs to be foremost in our collective efforts. Masks, distancing, quarantines, and contact tracing are also essential tools in minimizing infections and mutations. Scientific research must also be a continuing priority. If we fail the situation may yet get worse. This is a test of whether global civilization can respond and adapt appropriately to a global threat. I hope so.

—*George Gantz*

Top summary. Very clearly written. The case for world-wide vaccination could not be more obvious.

—*Michael Williams*

“WHY THESE CHILDREN FELL INTO ENDLESS SLEEP”

The girls and their family have been deeply traumatized. Why does anyone need further explanation? The need to define some biological or psychological syndrome are just ways of avoiding the awful truth. While we continue to assume that all beings must process and respond to experiences in the same way we are simply exacerbating the trauma

—*Tim Hall*

“ONE OF THE MOST EGREGIOUS RIPOFFS IN THE HISTORY OF SCIENCE”

Unfortunate lessons from all of this is to not share data with other scientists until you have had a chance to analyze it and publicly present the results, to lock up your data, and to not discuss ideas with other scientists without witnesses. Anyway, I am delighted Rosalind Franklin is finally getting the recognition she disserves.

—*Douglas Furtek*

I am related to Rosalind through my mother’s English family, so this is of great interest. I did meet Watson once and mentioned my relationship. He hurried away. But revenge, even posthumous, is sweet—there is a now a Rosalind Franklin School of Medicine and Science, as well as a planned Rosalind Franklin Mars rover (launch in late 2022). Also in honor of that, our Roomba is called Rosie.

—*Richard Levenson*

“IAN AND THE LIMITS OF RATIONALITY”

All this boils down to is that there’s no reason to believe in reason, but that’s frankly the same as anything else. All we know is that reason seems to work, because all those processes that don’t work aren’t rational.

—*James Kim*

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

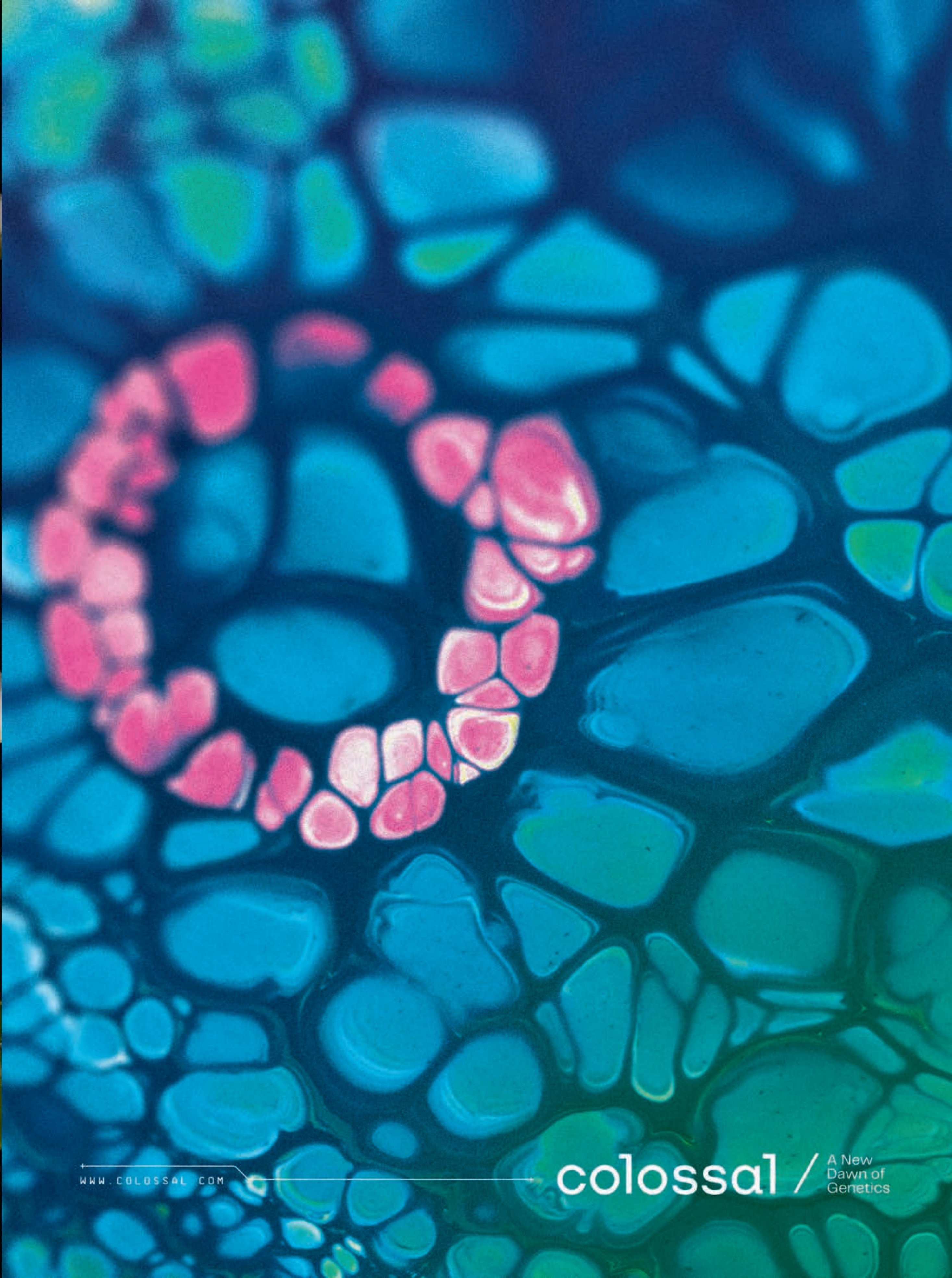
CONTACT

360 W 36th Street, 7S
New York, NY 10018

info@nautil.us

subscriptions
Visit subscribe.nautil.us


WORLD SENSORIUM / CONSERVANCY
worldsensorium.com
@worldsensorium


WWW.COLOSSAL.COM
colossal
A New Dawn of Genetics

Preludes

ANIMALS

He Did Right by Animals. And Didn't Take Bull from Anyone.

WELL INTO THE 1980S, doctors would perform open-heart surgery on infants without giving them pain-relieving drugs. This is hard to believe: By the standards of contemporary medicine, not to mention common sense, the practice is akin to torture. Yet then-conventional wisdom held that babies did not feel pain, at least not in any meaningful way. Their brains and nervous systems were considered undeveloped. And regardless of what they felt, they wouldn't remember it.

One can read about this in *Science and Ethics*, written in 2006 by Bernard Rollin, an iconoclastic philosopher who died in November at age 78. When I read of his passing, I recalled a conversation we had several years ago. Rollin, who devoted much of his life to speaking for the voiceless, was still enraged at what happened to those babies. He might have made the point that knowledge changes, sometimes profoundly, and that one era's objective truth may be revealed, by the light of another era, as a fallacy held together by thoughtless habit. The exact word he used was "mindfuck."

Our own conversation was prompted by an ongoing research project on so-called fistulated cows, into whose sides holes are cut that give scientists and veterinarians access to the contents of their stomachs. Often they don't receive pain relief. From there we went on to talk about animal husbandry, vet schools, and the cowboys and ranchers he had come—improbably, but Rollin delighted in defying stereotypes—to admire.

I was shocked to learn that cows having portholes cut into their stomachs don't routinely receive analgesia.

For a long time they didn't use any anesthesia, either. They used what the vets savagely called brutocaine: brute force. To be fair, there are vets who will insist

on using post-surgery analgesia for procedures like dehorning, castration, and so forth.

Post-procedural analgesics are routine in human medicine. It would be malpractice if someone didn't give you analgesics unless you requested otherwise. Yet for 40 years they did open-heart surgery in newborn babies without analgesia. It was based on some bullshit anatomy from 19th-century Germany that said infants didn't feel pain. The nurses said, "Bullshit."

I got involved in it with the American Pain Society and blasted the shit out of them. That's me. I don't care. I've made a lot of enemies in my lifetime—and if I hadn't made enemies, I wouldn't have accomplished what I did.

Such as?

I made the federal law that you have to use an analgesic if you hurt an animal. It went out under the name of Bob Dole, which you wouldn't expect. I said, "Dole, what's your interest in this?" He said, "It doesn't win me votes in Kansas—but it's the right thing to do." So it passed.

When I started teaching veterinary ethics in the vet school, I had some students come and tell me, "We start surgery in a couple weeks. It's a three-week block." I said, "Cool." They said, "Not cool. They give us a dog from the pound and we have to do nine procedures in three weeks." I said, "What do they use to control the pain?" They said, "We don't think they use anything."

I could tolerate being a range cow because they live in the conditions for which they are evolved.

I went over there. It was a scene out of Hieronymus Bosch. Animals whining and crying. I went over to the Dean and read them the riot act. In those days I could bench 500 pounds and I'm an angry New Yorker. We got them stopped. Nine procedures on the same animal. It's inconceivable, isn't it?

Earlier you told me, "I was a big radical when I suggested that cows be given pain relief." Are you talking about animals in serious pain?

Yes we are. They cut the tails of cows off with garden shears. The reason being that milkers don't want to be painted with shit—so they lop them off. By the way, the tail is an extension of the spine. It's not like cutting a nail. And one of the things people don't know is that cows use their tails to communicate with each other.

In many cases tail docking isn't even done by a vet. Not that it matters—brutality is brutality. There's been a campaign against tail docking. My position is that if you don't want to be plastered with shit, don't be a milker. We went after it in Colorado. We put so much pressure on the dairy industry that to belong to their association you couldn't be docking tails. But it took 20 years, because that's how they are.

People are beyond belief. When I was fighting with the American Pain Society about anesthesia for babies, their guy said to me, "Weren't you circumcised? Do you remember it?" I said, "No, I don't." He said, "Then it doesn't matter." I said, "That's a stupid position. Follow them through life." And—lo and behold—people who got open-heart surgery without anesthesia had a far greater tendency to develop chronic pain later in life.

Can animal production be done in a good way?

Sure. We did it for 10,000 years. It was called good husbandry. As it says in the Bible, you take the animals, put them in an optimal environment, feed them when there's famine, water them when there's drought, give them what help in birthing that you can give. If the animal is hurt, you hurt. This was a big deal for the Church. There were lots of sermons on husbandry. God is to us as we are to the animals.

My position is that you do what's right by the animals. And if the meat costs more, tough shit. Don't eat meat. Chicken, when I was a kid, was the luxury item. And now chicken is the cheapest meat of all. Why? Because we produce billions of them who are freaks. Turkeys can't even breed naturally. We built them into something with so large a breast that they can't copulate.

Sometimes it seems to me that farmed animals, even those raised and slaughtered in "humane" ways, live in something close to hell. We'd never subject our pets—much less ourselves—to such a life.

It depends on which animals you're talking about. I could tolerate being a range cow because they live in the conditions for which they are evolved. Those range cows have a life that is pretty much dictated by their biological and psychological nature. Their telos. That's very different from how pigs are treated. A cow on a ranch is not that different in its life from what it was 100 or 200 years ago.

There's a statute in front of the agricultural building at Colorado State University called *20% Chance of Flurries*. It shows a cowboy surrounded by snow, the wind blowing his duster, and across his saddlehorn is a four-week-old calf. He's gone out to retrieve the calf. I've been there. I've been in those conditions to retrieve a calf. And God forbid the horse throws you or goes lame. You're in deep shit.

Have you been in a blizzard in the West? We're 40 miles from Cheyenne, Wyoming, and damn near every year you get these ground blizzards, snow driven by wind, and people pull off the highway and can't see anything and make the mistake of getting out of their car. They can't find their car again. Imagine going out on a horse in that. Yet that's husbandry. That's why the statue is up. Ask any of my rancher friends whether they'd go out to retrieve a calf and they look at you like you're crazy. They'd say, "Of course."

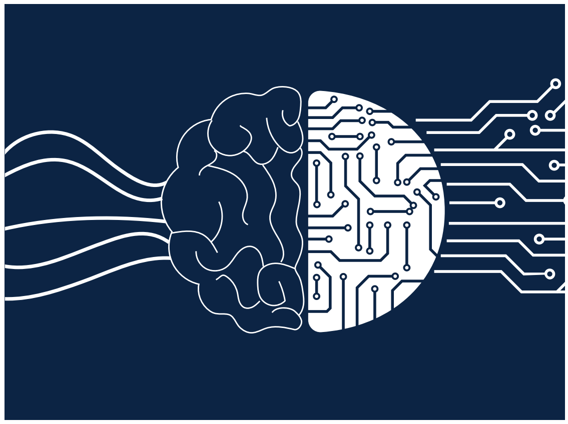
—*Brandon Keim*

ARTIFICIAL INTELLIGENCE

Why AI Lags Behind the Human Brain

RECENT ADVANCES HAVE MADE deep neural networks the leading paradigm of artificial intelligence. One of the great things about deep neural networks is that, given a large number of examples, they can learn how to act. This means we can get software to learn to do things that even their programmers don't know how to do. The more complicated the task is, the more powerful the neural net has to be.

Although inspired by brain architecture, research on neural nets usually doesn't have anything to do with actual neurons. But in a recent analysis, neuroscientist David Beniaguev and his team found out just how powerful a deep neural net would need to be to replicate the behavior of a *single neuron*: really, really powerful.



PSPN / SHUTTERSTOCK

With artificial neural nets, rather than directly programming in the rules of thought, the programmer instead makes a system that can learn from input data. It's called a neural network because its architecture is inspired by neurons in brains—although the "units" in an artificial neural network are far simpler than biological neurons.

An artificial neural network is exposed to thousands, sometimes hundreds of thousands, of examples. Every time it experiences a new example, it subtly changes the links between the units to produce a better output. You might train a neural network to determine if a picture is of a child or an adult. Over time, the program learns how to do it well.

Notoriously, however, even when we have a working neural network, the explanation for *how* it does what it does is unknown and requires further study and analysis: What we end up with are numeric "weights" between thousands of units, which are difficult to look at and derive general principles from. Traditional ("shallow") neural networks had only three layers (one input, one hidden, and one output). In the past decade, more hidden layers have been effectively used, which is why they are called "deep" neural networks that do "deep learning."

This makes artificial neural networks particularly useful for situations where we don't understand what thinking would be involved to do the task. The network learns for itself from examples, and we don't need to know how we would have programmed it in a traditional way.

So how did Beniaguev and his team use neural nets to understand biological neurons better? Previous neuroscience has come up with partial differential equations to describe neural behavior, and the team used these equations to calculate what the neurons would do when given thousands of randomly generated possible inputs. Then they used these inputs and outputs to train deep neural nets. Their question was: How complex would the deep learning neural net have to be to model what the equations produced?

One way to estimate the complexity of a neural net architecture is to look at how many layers are used—deep nets are called "deep" because they have more than one hidden layer. Another measure of complexity is the number of units in each hidden layer.

It turns out that modeling some neurons doesn't require deep networks at all. One kind of neuron is the "integrate-and-fire." All this neuron does is add up its excitatory input, subtract the inhibitory input, and then fire if the amount is greater than some threshold. The researchers were able to model this with a traditional "shallow" neural net (a single hidden layer with only one unit!).

Think of many of the brain's 10 billion neurons as being deep networks themselves.

Things were different when they tried to model a more complex kind of neuron found in the cerebral cortex. What they found was that these individual neurons are much more complex than we'd previously thought: Artificial networks (the temporal-convolutional type) needed a full *seven* layers, each with 128 units, to successfully simulate these pyramidal neurons.

Deeper investigation suggests that these neurons don't simply fire or not fire given their immediate input. Rather, they integrate input over tens of milliseconds. The dendrites (the input structures of neurons) seem to be doing significant processing by themselves, using information about space (where the input came in) as well as time (when each input arrived). Each neuron is, as the authors put it, a "sophisticated computational unit," all by itself.

In fact, rather than thinking that the brain works like a deep learning network, it might be more accurate to think of many of the brain's 10 billion neurons as being deep networks, with five to eight layers in each one. If true, this would mean that the brain's computational capabilities are much greater than we'd thought, and that simulating the brain at a biological level will involve staggeringly large computational resources.

—Jim Davies

ENVIRONMENT

Trillions of Bacteria Are Screaming with Light

ON A CALM and cloudless night far out to sea, gazing toward the heavens, you'd expect to see the sky glowing with stars, offsetting the impenetrable black of the deep ocean.

But one night 167 years ago, in waters off the coast of Java, Indonesia, things were far from normal. According to an account by Captain W.E. Kingman, it was as if sky and sea had traded places. "There was scarce a cloud in the heavens, yet the sky ... appeared as black as if a storm was raging," noted the captain in his logbook. "The whole appearance of the ocean was like a plain covered with snow." To his apparent horror, the seas looked as if they were glowing.

Tales of seas that glow have popped up alongside mermaids and dragons in nautical lore throughout the ages. While these creatures of fiction appear in many different guises, the appearance of glowing seas is remarkably consistent. In the past decade or so, with an assist from historical record, scientists have discovered that these milky seas, though quite rare, do indeed exist. The challenge is exactly how to find them.

One clue came to light with the help of sophisticated satellite imagery. Steven D. Miller, now a research

ILYA SVIRIDENKO / SHUTTERSTOCK

scientist at Colorado State University, stumbled across an account of milky seas in the northwestern Indian Ocean. On Jan. 25, 1995, British merchant vessel the SS Lima was sailing 150 nautical miles east of the Somalian coast and found itself surrounded by light:

> … a whitish glow was observed on the horizon and, after 15 minutes of steaming, the ship was completely surrounded by a sea of milky-white color with a fairly uniform luminescence. The bioluminescence appeared to cover the entire sea area, from horizon to horizon … and it appeared as though the ship was sailing over a field of snow or gliding over the clouds.

By pairing maritime lore with cutting-edge science, Miller's team found their first milky sea, albeit years after the fact. Now the challenge was to detect them evolving, to study them in real time. Gathering over 200 accounts of milky seas, they discovered that they were most common in the northwest Indian Ocean and Indonesian waters, between January and March. Then, the team looked for them with satellites equipped with an instrument called the Day/Night Band—a spaceborne low-light imager capable of sensing light roughly 10,000 times fainter than reflected moonlight.

The "aha" moment came while flipping through these new images. Searching from 2012 to 2021, the team discovered 12 events that matched their strict criteria for milky seas: approximately one every eight months.

But what caused the sea to glow in the first place?

Scientists believe milky seas are caused by the "screams" of trillions of bacteria called *Vibrio harveyi*. In the oceans, many species scream with light instead of sound. Fear is the most common "scream" trigger—a quick bright flash to scare off an attacker, much the way we might scream when startled or under threat. But sometimes creatures scream for attention.

Scientists believe milky seas are caused by the "screams" of trillions of bacteria.

Vibrio harveyi bacteria "scream" to be eaten. They can live adrift in seawater, but also feel right at home in the guts of fish. Normally these bacteria light up only when they're living on clumps of dying and decaying algae—biological debris that scientists informally call marine snow—and only when they're clustered in large numbers. When they're packed together tightly enough on these clumps, they begin to glow in a kind of community effort to be collectively consumed. In fact, this is why dead fish sometimes glow.

When a single bacterium floats alone in the ocean, lighting up would be a waste of energy. Its light would be so small it would essentially be invisible. But bacteria have a way of synchronizing their illumination via a process called quorum sensing. Each bacterium releases a small amount of a chemical signal into the surrounding water. As the population of bacteria increases, the signal grows stronger, until eventually all surrounding bacteria sense it. The beat drops, the concert starts, and glowing bacteria light up the night ocean.

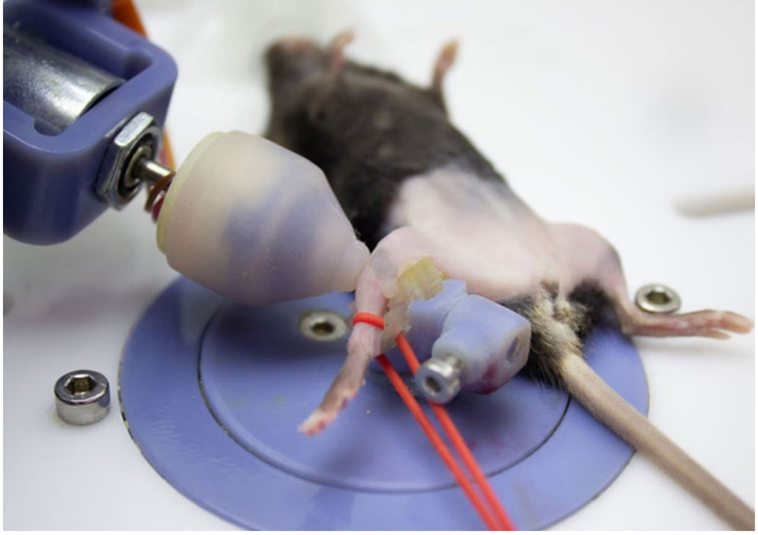
—Rebecca R. Helm

HEALTH

When Massage May Be the Best Medicine

IF YOU'RE AN ATHLETE—even a very occasional one—odds are you've dealt with a muscle injury at some point. After all, muscle injuries account for 10 to 55 percent of sports traumas. Often they're just a nuisance—say, a minor strain that takes you a couple days to get back on your feet. But severely injured muscles, such as muscles that have been torn, frequently require treatment involving medication and invasive surgeries, and recovery can take a long time.

However, recent research suggests that something as simple as massaging the injury site can speed up healing. A study recently published in *Science Translational Medicine* found that massage therapy can directly improve the regeneration of severely injured muscles. Not only that, but the benefits from "mechanotherapy"—the scientific term for massage—may be comparable to the more invasive pharmaceutical and surgical interventions.



MOUSE MASSEUSE Seo and her collaborators designed a custom massage gun for mice. Here, the robotic actuator is positioned toward the mouse limb, which is held in the soft material-covered limb-holder. Mice with severe leg injuries received two 5-minute massage sessions daily for two weeks.

COURTESY OF BO RI SEO

The study was led by Bo Ri Seo of Harvard's Wyss Institute for Biologically Inspired Engineering and John A. Paulson School of Engineering and Applied Sciences (SEAS). Seo and her collaborators designed a custom massage gun for mice. Every day for two weeks, mice with severe leg injuries received two 5-minute massage sessions targeting the injured tissues. The researchers found that the treated mice's legs had fewer damaged muscle fibers than mice who did not receive the massage therapy. The treated mice also had larger muscle fibers at the injury site. In other words, the massage therapy was helping the mouse muscles to heal both faster and stronger. What was less clear, however, was how.

Typically after an injury, the first immune cells to arrive are neutrophils, a type of white blood cell. The neutrophils kill and remove damaged tissues and then leave the injury site so other immune cells can continue the healing process. With severe injuries, however, neutrophils will sometimes overstay their welcome. And if neutrophils stick around for too long, they can start attacking healthy tissues as well.

Seo and her team found that by the third day of the study, the massage-treated muscle had far fewer neutrophils than the untreated muscle. And, when neutrophils were present for a prolonged period of time, they inhibited muscle stem cells from differentiating into new muscle fibers. In other words, the earlier the neutrophils departed, the faster the new muscle could develop.

So, massage therapy helps to clear out the neutrophils. How? By literally squeezing them out of the injured tissue, like juice out of an orange. It's the same mechanism that allows mechanotherapy to squeeze toxins out of tissues, another benefit of massage. The big discovery here is that physical compression can actually impact the way the immune system works in the body.

In addition to treating torn muscles, Seo thinks that massage therapy could treat a wide range of ailments, from peripheral artery disease to inflammatory myopathy. Her team has already found that mechanotherapy yields results that are comparable with stem cell surgery and VEGF-based therapy—and that's a big deal, according to Seo. Massage therapy is of course much less invasive than surgery, as well as less technically complex, which translates to lower risk and more predictable outcomes.

Much more needs to be studied before these applications could be possible. For instance, studies on mice don't always translate to humans. Seo's team has already designed a model that can scale the effective force range to be used on larger animals.

Another consideration: Muscle injuries are often accompanied with other issues, such as bleeding, fractures, or tendon tears. "Different types of trauma might mean that the same principles wouldn't apply," said Tammy Martin, an orthopedic surgeon at Brigham and Women's Hospital.

However, she thinks the research addresses a question that athletes, among others, would love to see answered. "As we learn more about our bodies, and how they work and heal, factors like this will be important to help us understand how best to navigate injury," she said.

Perhaps someday soon massage therapy will be thought of as not just a treat for our weary and damaged muscles, but a practical option for healing them.

—Anna Gibbs

Fantastic Beasts Brought to Life by the Wind

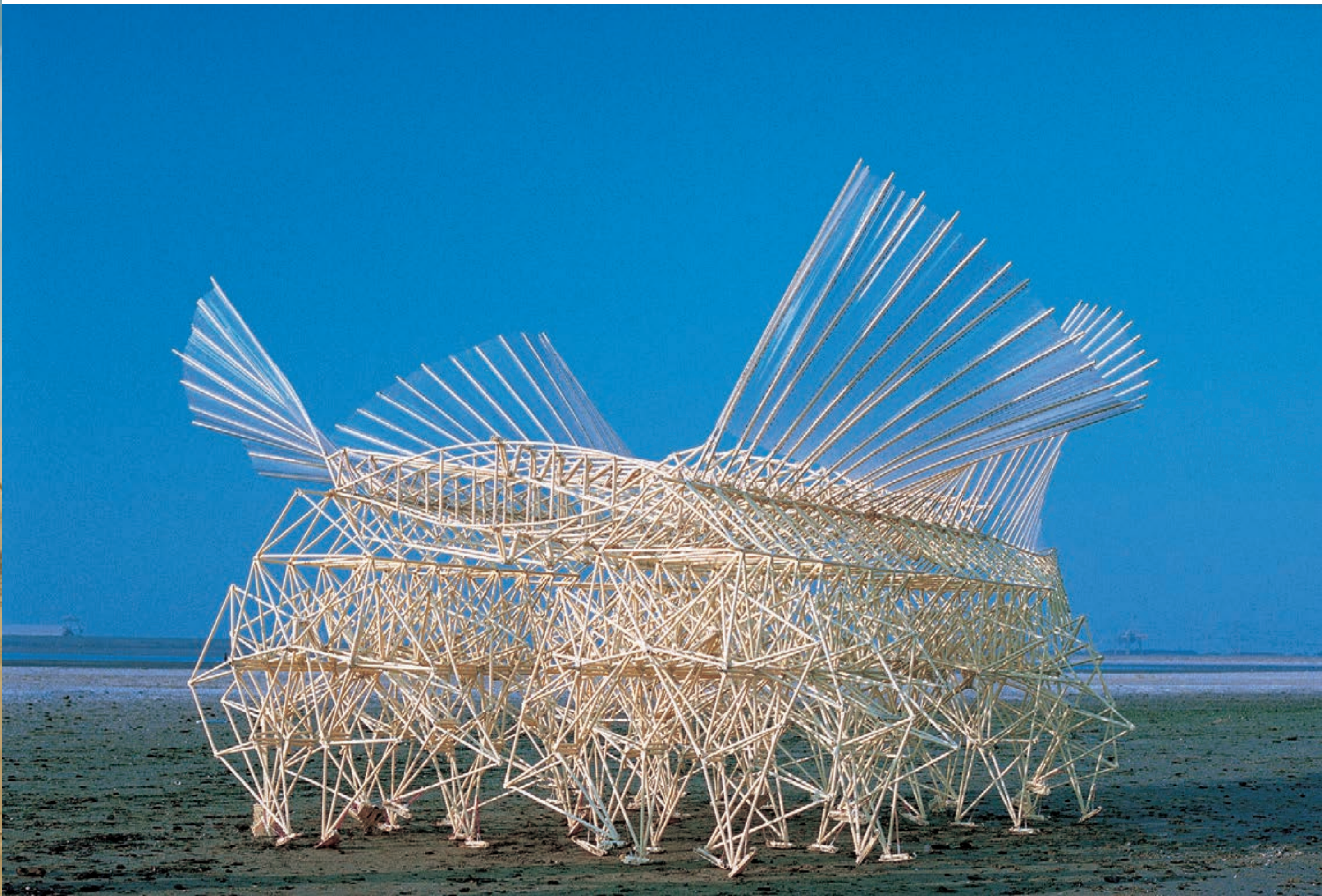
Many of us hit the beach to enjoy some sunshine or catch a wave. But for Dutch artist Theo Jansen it's all about the wind. Jansen's been working with this limitless natural resource for 30 years to create a fabulous array of giant beach creatures—brought to life by the wind. With every gust, his wondrous seaside sculptures become more lifelike, ambling along the coast like creatures in their own right.

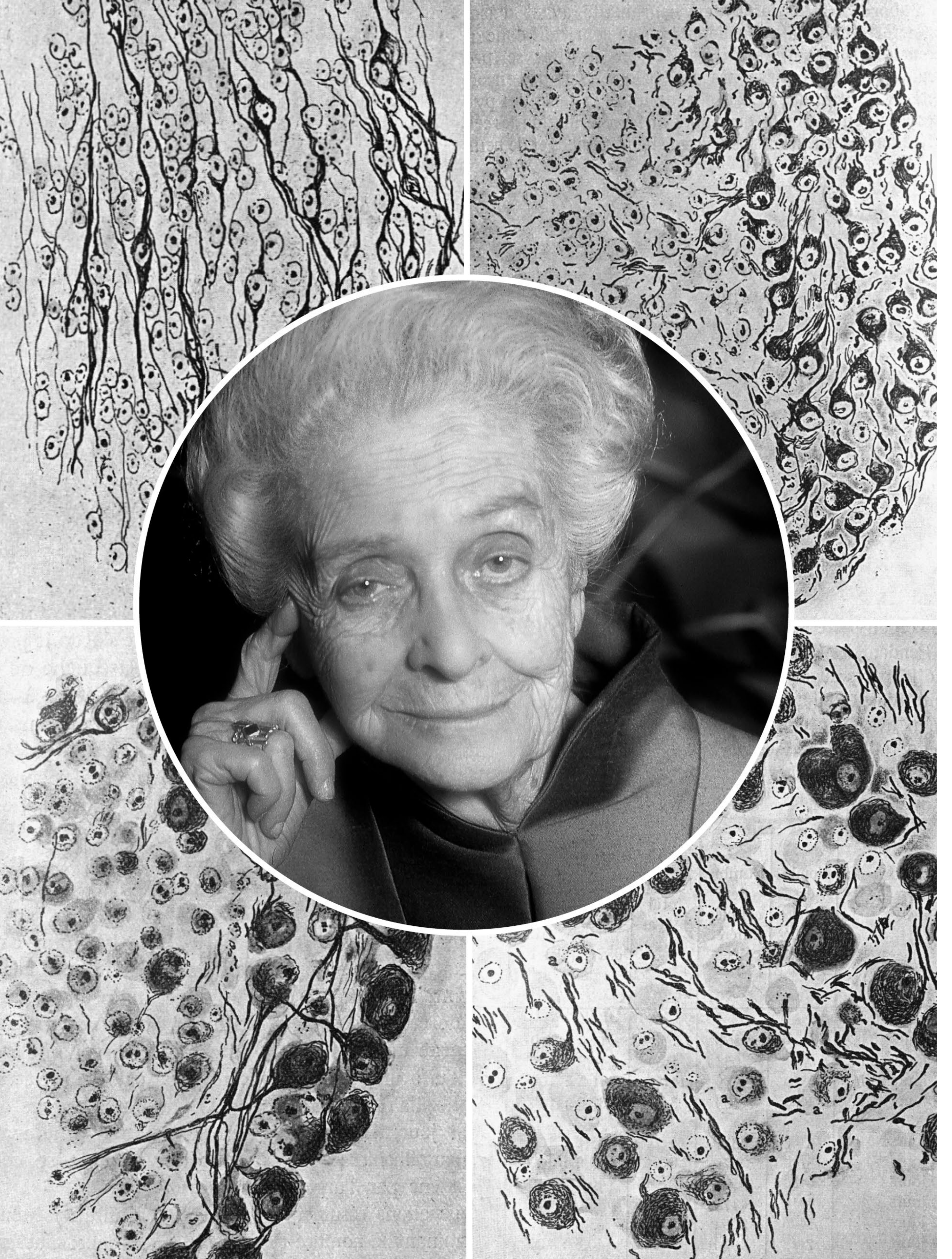
They come in the most imaginative shapes and rely on intricate engineering. Some have sail-like wings and seem to dance across the sands, others scuttle along like enormous centipedes. One of them can even fly. Made of PVC pipes, their skeletal white forms and spiky silhouettes are like relics of a bygone geological era. Yet, watching these beasts make their way across the beach it somehow feels as if they belong here.

Jansen started designing them in the 1990s after reading about rising sea levels threatening the low-lying Netherlands—a country famous for the fact that one third of it is below sea level. He had a dream of creating a herd of wind-powered coastal sentinels, perpetually piling sand high onto the dunes to keep the water at bay.

—Anne-Marie Hoeve

To learn more about Theo Jansen's Strandbeests, visit www.strandbeest.com.





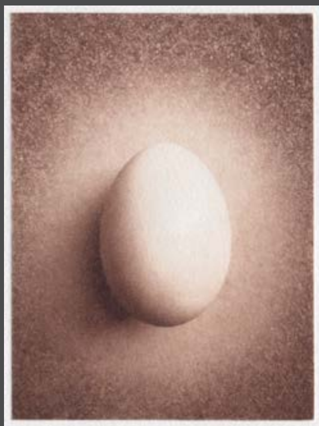
COLLAGE: TASNUVA ELAHI; PHOTO BY AP IMAGES; TRACINGS OF NERVE CELLS BY RITA LEVI-MONTALCINI, MADE IN HER HOME LAB.

A Lab of Her Own

Sheltered in her bedroom during WWII, Rita Levi-Mantalcini discovered how the nervous system is wired

BY BOB GOLDSTEIN

ON A COLD, DRY TUESDAY in December, 1940, Rita Levi-Montalcini rode a train from the station near her home in Turin, Italy, for 80 miles to Milan to buy a microscope. Milan had not seen bombings for months. On her return to the Turin train station, two police officers stopped her and demanded to see inside the cake-sized box that she was carrying. With wartime food rationing, panettone cakes were only available illegally. The officers found her new microscope instead. They let her go. Just a week after her trip, British bombers hit Milan.



The Author's Home Experiment

I wondered where Rita Levi-Montalcini would have found a steady source of fertilized chicken eggs in Turin during World War II. A colleague of mine who studies chicken embryos told me most of the eggs for sale at the time were probably fertilized because even now most eggs from farmer's markets are fertilized. Farmers often leave a rooster with their hens to protect the hens from predators, and many of the eggs end up fertilized as a result. The fertilized eggs only develop if they're kept warm. I was skeptical. Sometimes I buy eggs from our local farmer's market, and I've never noticed a tiny embryo inside. Maybe I hadn't looked carefully enough. I went to my local farmer's market on a rainy Saturday morning and bought a dozen eggs. At home, I opened a few eggs, dropped a little blue dye onto the surface of each yolk and looked under my microscope. Sure enough, I could see a tiny disk of cells on the yolk in some of the eggs. I kept a few eggs warm and humid for a few days, until the tiny "f" shape formed—the shape of the embryo that Levi-Montalcini would have seen in her bedroom lab. I can see now how it was possible for her to find a steady source of developing embryos.

—Bob Goldstein

Levi-Montalcini was a 31-year-old scientist who had been working at the University of Turin. Despite her father's disapproval, she had trained in medicine, inspired by seeing a nanny succumb to cancer. In 1938, the Italian dictator Mussolini banned Jews from positions in universities. Levi-Montalcini was not raised in the Jewish religion, but her Jewish ancestry would have been evident from her surname. Mussolini's ban had pushed Levi-Montalcini to leave Italy for Belgium in 1939, where she did research using fertilized chicken eggs as a source of material for her research topic: the developing nervous systems of vertebrate embryos. Levi-Montalcini also spent time with her older sister Nina, whose family was in Belgium as well. Rita wrote home to her mother of an "infinite desire to embrace you again," but research at the university in Turin would have been impossible had she returned home. Her passion for research alternated with her frustration with challenges. When Hitler invaded Poland in September, launching war, her worst frustrations were realized. The "whole world was in danger," Levi-Montalcini later wrote. In December 1939, she returned to Italy.

Levi-Montalcini moved in with her mother, her twin sister Paola, who was an artist, and her architect brother Gino, in her childhood home. The apartment, in the center of Turin, was large, with 10 rooms, including a bedroom for each family member and a common living room. Some of the rooms faced into the apartment building's common courtyard. There was little for Levi-Montalcini and her family to do outside of the apartment; Mussolini's laws restricted Jews from most jobs and schools and threatened to confiscate Jewish-owned property. A fascist manifesto asserted that Jews do not belong to the Italian race, and declared, contrary to popular sentiment in Italy, "It is time that Italians proclaim themselves genuinely racist." In June 1940, Mussolini joined Hitler by declaring war on France and Great Britain, and Britain responded with nighttime aerial bombings of Italy through summer and fall, focused on Turin and other industrial cities. The city was dark each night as a blackout was enforced across Italy. No lights were permitted to be visible from homes or shops.

PHOTOGRAVURE BY BOB GOLDSTEIN

I sought to walk in Rita Levi-Montalcini's footsteps to build a clearer sense of what life was like for her.

Levi-Montalcini responded to the tumult by transforming her bedroom into her own research lab. The bedroom was long and narrow, and opposite its entrance was a window, which overlooked the courtyard. In front of the window, she placed a table for opening eggs and a simple microscope for operating on the embryos. Near her bed she placed the more elaborate microscope that she carried from Milan, a new model with two eyepieces so she could look into it with both eyes. It was equipped with a camera, and a device with mirrors that would allow her to see both microscopic detail and her own hand next to the microscope at the same time, so she could trace on paper the tiny nerve cells that she viewed. The bed was against one of the long walls, and at the opposite wall she put shelves, on which sat a heater for melting wax, and an egg incubator that her brother built with a thermostat and a fan. She could embed embryos in the melted wax which, once hardened, she would cut into paper-thin slivers, so that she could view nerve cells in the slices in the microscope from Milan. The experiments "absorbed her completely," she later recalled, satisfying a childhood dream to explore unknown places, in this case the "jungle" of the nervous system.

Today, few people—even very few scientists—know what it was that Levi-Montalcini uncovered in her bedroom lab in Turin. Textbooks cite her courage but rarely her wartime discoveries, which are usually credited to others. Levi-Montalcini earned a Nobel Prize for scientific accomplishments that she made after the war. But when she died in 2012, at age 103, she left behind only a little writing about her experiences during the war, along with some rarely read technical articles from the time, published in Italian and French.

I had read Levi-Montalcini's autobiography, *In Praise of Imperfection*, but it divulged little about her research during the war or about what she experienced at the time. I found her research articles from the time and began to translate them to English, to pore through the details of her discoveries. In 2018, on a work trip to nearby Switzerland, I contacted Levi-Montalcini's closest living relative—her niece Piera Levi-Montalcini—who agreed to meet with me and talk. I sought to walk in Rita Levi-Montalcini's footsteps in Italy to build a clearer sense of what life was like for her when she was making discoveries in the midst of a war.

As I reconstructed her experiences, her research articles from the war revealed to me that the experiments from her bedroom were more pivotal than I'd expected based on textbooks. Levi-Montalcini's wartime experiments asked something fundamental. How do our billions of nerve cells wire up so precisely inside our bodies? Her bedroom discoveries charted a new course for humankind's understanding of how our nerves connect, allowing us to walk and see and feel.

WHEN YOU WERE AN EMBRYO, nerve cells shaped like long, thin wires snaked throughout your body, connecting your brain and spinal cord to many targets—to the muscles that each nerve cell will control, for example. Imagine your body as a house under construction, but where the wires grow themselves out from the central circuit box, winding through the walls, and connecting to each outlet, appliance, and light bulb. A human body is more complex than a house, so you'll need to imagine a house with not dozens of wires, but billions. How can each wire locate each target, making accurate connections in your body—billions of accurate connections—and all while your tiny fetal body is growing and changing shape? Getting wires to connect to all these targets is a formidable task. And miswiring can lead to paralysis. There are birth defects in which babies are born permanently unable to smile, or to walk, because certain nerve cells fail to connect to targets.

TAKE SHELTER
Author Bob Goldstein traces the steps that Rita Levi-Montalcini and her family took during WWII in Turin, Italy. As bombs fell, they fled into the cellar beneath their apartment building. Levi-Montalcini often brought her microscope and precious glass slides with her.

FLORIAN JUG

Levi-Montalcini had a lifelong obsession with understanding how our nervous system develops. And, in the summer of 1940, she had what she called her "conversion." She was reading an article by Viktor Hamburger, a German working in the United States exploring how nerve cells develop. She read the article as she sat on the floor of an open train car moving slowly through the countryside, enjoying a backdrop of yellowing corn plants and bright red poppies.

Hamburger's article described his experiments aimed at understanding how nerve cells connect accurately. Hamburger's goal in the experiments was to remove some targets—the muscles that some nerve cells would wire up to the brain—to learn whether nerve cells grow differently if deprived of targets. He did his work in chicken eggs—nerves in chicken embryos develop much as they do in humans, and using eggs ensured a plentiful source of material for his experiments.

Hamburger described carefully cutting a window in an eggshell at a stage when the chick embryo inside was only about the size and shape of a typed letter "f," but translucent and nearly invisible on the surface of the yolk. Near the middle of the "f" were two bumps that would normally grow to become wings, at least in fertilized chicken eggs that are not eaten. Hamburger used a glass needle under a microscope to remove one bump—the wing bud on the right side. And about five days after the operation, he examined nine eggs to see the effect of depriving the nerve cells of their targets. He saw that in each egg, the normal wing bud on the left side had grown to a few millimeters long, and nerve cells had grown out to it as expected. But on the right side, where he had removed the wing bud, the nerve cells were missing.

Hamburger surmised that in the absence of targets, the nerve cells had never formed. He speculated that normally, the target muscles must somehow send a signal that can induce other cells to become nerve cells, or perhaps cause young nerve cells to divide, making more nerve cells. In the article he noted a long line of earlier researchers whose experiments or observations of birth defects—in humans or animals—revealed that the number of nerve cells would match roughly the number of targets. Loss of a limb would result in fewer nerve cells found nearby. And increasing the target population would result in more nerve cells nearby. Hamburger's interpretation suggested a simple solution to how this match was made: Each muscle somehow turns other cells nearby into nerve cells, guaranteeing that a population of nerve cells would be available locally to connect to each muscle.

Levi-Montalcini was struck by the clarity of Hamburger's writing. By this stage she had trained in Turin with the famous neurobiologist Giuseppe Levi (who only coincidentally shared a surname with her), worked in Belgian labs, and published nine scientific articles reporting new discoveries. She had worked with chick embryos, with mice, and with microsurgery, and she had observed detailed nerve and muscle anatomy. She was an experienced researcher who was well equipped to take some next steps to understand how nerve cells make accurate connections to their targets.

After the aerial bombings began in 1940, Levi-Montalcini could work all day in her bedroom lab. At night, when sirens announced incoming warplanes, Levi-Montalcini and her family would hurry out of their apartment, down a set of stairs, and then across the courtyard to another set of stairs that led to cellars. Levi-Montalcini would bring her microscope and precious glass slides with her. Families would wait for hours in the cellars and hope they would not be buried in rubble.

Today very few scientists know what it was that Levi-Montalcini uncovered in her bedroom lab in Turin.

Levi-Montalcini must have left the apartment frequently to buy chicken eggs for the experiments, at times likely walking among bomb rubble. She repeated the experiment that Hamburger had described, removing a tiny limb bud from each chicken embryo and examining the effect on nerve cells later. Hamburger had used a glass needle to cut out the tiny limb bud; in place of a glass needle, Levi-Montalcini used an ordinary sewing needle that she had sharpened. But Levi-Montalcini also decided to do something new: To see how the embryos developed, she examined the results of the operation each day after removing the limb bud. This required embedding one embryo in wax each day, then slicing the wax, observing the slices on glass slides under the microscope, and counting thousands of nerve cells. Her patience with the experiments would allow her to see how development proceeded little by little after removing a limb bud—like watching a movie made from individual frames—instead of seeing only a single moment in time as others had before her. She also used a silver stain and a blue dye to see the nerve cells more clearly than before, allowing her to distinguish young nerve cells from fully formed ones. And she used a red dye that could highlight dividing cells. She recorded counts of thousands of nerve cells nearly every day from 2 to 19 days after removing a limb bud.

Levi-Montalcini responded to the tumult by transforming her bedroom into her own research lab.

In August, 1941, Levi-Montalcini's mentor Giuseppe Levi joined her and began to assist with her experiments. Levi had moved to Belgium too and had been working alone in an empty Belgian institute for a year after the Germans invaded. He arrived thin and pale after a difficult trip across Germany. Levi-Montalcini's bedroom lab became a meeting place where Levi's friends and former students would visit and talk about the events in the news.

IN THE CHICKEN EMBRYOS, Levi-Montalcini saw what Hamburger had seen about five days after the operation: There were fewer nerve cells on the side of the embryo where the limb bud had been removed. But following this day-by-day revealed to Levi-Montalcini something unexpected.

For the first two days after removing a limb bud, the areas where nerve cells would form looked surprisingly similar on both sides of the embryo. Nerve cells did not fail to form—they were forming in the thousands on both the normal side and the operated side. On the third day after the operation, nerve cells continued to form: Levi-Montalcini saw dividing cells on both sides. Young nerve cells had accumulated as well as more fully formed ones. Only then did she begin to notice slightly fewer of the fully formed nerve cells on the operated side. Peering in the tiny wax slices at embryos on each successive day made clear that nerve cells continued to form after removing a limb bud. But then soon after forming and extending out toward targets, the nerve cells that were deprived of targets would disappear. Only nerve cells that contacted nearby targets, like in the skin along the back, remained.

How were the nerve cells disappearing? In her bedroom lab, Levi-Montalcini saw something that other scientists had not predicted. The nerve cells deprived of targets appeared to be dying after reaching toward targets in vain. In the areas where nerve cells were disappearing, Levi-Montalcini could see signs of nerve cell death—she reported abnormally "conglutinated" masses of nerve cell fibers, and a shrunken nucleus in many of the cells. Dying nerve cells had been described in animal embryos before by others, but what Levi-Montalcini saw was the first sign that nerve cells would die specifically when they lacked targets. Imagine removing a light bulb from a house under construction, and watching as wires snaked through the walls, reaching everywhere—but then shriveling up specifically where they failed to find the missing bulb.

Levi-Montalcini sent the results for publication in a scientific journal in Belgium—Jewish scientists were barred from publishing in Italian journals. In the article, published in French in 1942, she and Levi reported the discovery: Nerve cells that were deprived of targets formed normally, but then disappeared. Near the end of the article was a promise to better document how exactly the cells were disappearing: "We propose to do this in a more detailed presentation and with more documented results." But British bombings of Turin intensified that fall. In hindsight, there was no guarantee that Levi-Montalcini or her bedroom lab would have survived to fulfill her promise.

Levi-Montalcini continued to observe her sectioned embryos, in essence replaying the film of nerve cells disappearing but looking more closely at the details of the disappearance. After documenting for herself what she saw, she prepared an article in

THE STREET WHERE SHE LIVED A destroyed apartment building, in 1942, in Turin, Italy, where Rita Levi-Montalcini lived during WWII. On some nights during the war, nearly 200 planes flew over the city, dropping hundreds of tons of bombs.

Italian for a Vatican journal, again evading the ban on publishing in Italian journals. As the earlier article had promised, this one was indeed packed with detail—descriptions of a microscopic world of nerve cells in the throes of death before they vanished near where their targets had been removed. Granules organized in neat stripes had disappeared from the insides of dying cells, and the shrinking nucleus of each dying cell had material that was abnormally organized inside, surrounded at times by only "a thin and pale cytoplasmic veil." Levi-Montalcini described the details of death in all sorts of nerve cells that are common to chicken or human embryos, from nerve cells that convey to our brains what our extremities feel, to others that allow our toes to move. The research article had 45 pages of detail, including seven pages of photographs and drawings. If there was some doubt left after the earlier paper that nerve cells deprived of targets would die, this next article had settled it.

These two articles charted a new course for understanding how our nervous system is shaped. Cell death sculpts our nervous system: Our brain becomes wired to our body so precisely in large part because those nerve cells that fail to find targets simply die.

In October, 1942, the nighttime bombings of Turin resumed after a seven-month lull. One Thursday night, sirens started near 9 p.m. and sounded for more than three hours, as bombs fell from British planes heading southeast to a coastal city. The next night, the sirens

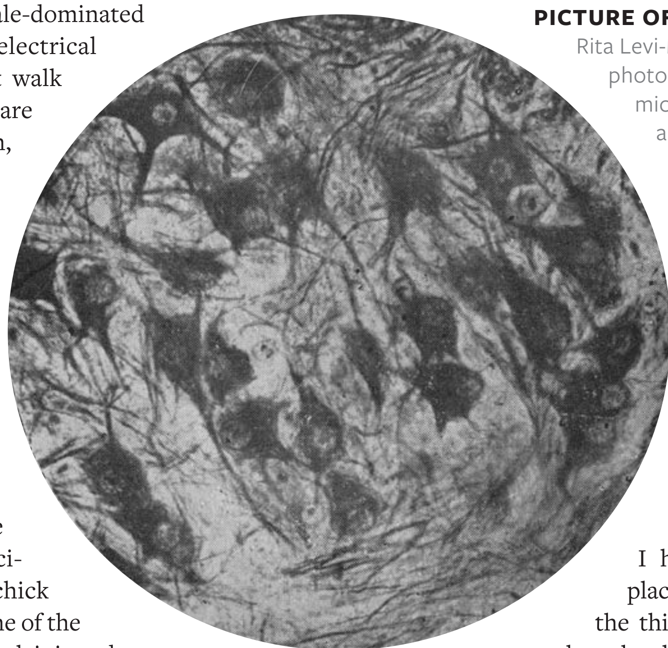
Textbooks nearly always credit what Levi-Montalcini discovered during the war to other scientists.

started just after 10 p.m., sounding for more than two hours. The bombings intensified in November. On some nights, nearly 200 planes flew over Turin, dropping hundreds of tons of bombs. Bombs and devices to start fires hit industrial sites, homes, theaters, and hospitals. Hundreds of Turin residents were killed. A Turin resident described in his diary seeing in the mornings the "astonished, amazed faces of the people who wander the streets" surveying the damage from the night before. The strategy of hiding in cellars was abandoned for many citizens of Turin, as they began to evacuate the city en masse. Levi-Montalcini and her family moved to a family farmhouse in the countryside, near the town of Asti.

IT WAS A BRIGHT SATURDAY in April, 2018, when I arrived in Turin. I made my way to a boulevard shaded by horse chestnut trees vying for height and grandeur with ornate, five-story apartments. I admired the carvings on the 12-foot-tall wooden doors. This was Rita Levi-Montalcini's apartment building. I pushed on the doors, but they were locked. Behind them was the courtyard that was Levi-Montalcini's view from her window. A woman with her son walked out of the front of the building. After some hesitation, she let me walk back in with them. I passed through a short, covered walkway to the grassy courtyard, which was surrounded by five floors of windows and doors and narrow balconies. The woman had met Levi-Montalcini before, "many times," she said with a smile. She was Levi-Montalcini's grand-niece—the daughter of Piera. In a café behind the apartment, I found stairs that led to the cellars where families would hide during the bombings. The cellars were apparently unchanged since the war. I walked on dry dirt and scattered rocks along a narrow passageway of roughly mortared brick walls and old wooden doors, each with a hand-painted number and a small window of metal mesh.

The next day, I drove to Asti, an hour away. I checked into a hotel and walked through town past medieval churches and busy outdoor cafes. On the following day, Gino Montalcini—a cousin of Piera's who now owns the farmhouse where Levi-Montalcini and her family went in 1942—took me in his car out of the center of town, to the top of a nearby ridge where the house sits. I met Piera, and Gino's wife, Anna.

Piera, who was Rita's frequent travel companion late in Rita's life, bore some resemblance to the Rita I'd seen in photos. They shared an upswept, styled volume of white hair. Piera also shared some of the unconcerned confidence that Levi-Montalcini had while working in a male-dominated field. Piera was an electrical engineer. "If you just walk your own way and you are brave enough—I mean, reckless enough—they look at you as if you were an alien, so they stay away from you," Piera said with a smile. When she was choosing a career path in the 1960s, Piera visited Rita, who at the time had a lab in Rome. She recalled Levi-Montalcini's thin hands, the chick embryos, and seeing one of the needles that Levi-Montalcini used, "They appear enormous when viewed through the microscope!"



PICTURE OF NERVES

Rita Levi-Montalcini took this photo of nerve cells under a microscope she bought on a dangerous trip to Milan during the war. She also illustrated the nerve cells. Her illustrations surround the portrait of her at the beginning of this article.

Behind the house sat a green lawn shaded by a row of linden trees. From the lawn I could see the town below, and the tracks on which the trains came from Turin. Asti was not a frequent target for bombings when Levi-Montalcini was there, but sirens announced British warplane flyovers. A mid-July 1943 nighttime bombing in town probably would have been visible from the house.

I walked to a high spot on a corner of the property, and Gino Montalcini pointed along a path toward a neighbor's house where Levi-Montalcini stayed when the farmhouse was filled with the extended family. Levi-Montalcini would have walked to the farmhouse each morning along the path, past grape vines, a few cows, goats and sheep, and some chickens. She relocated her microscope and the other lab equipment from Turin in front of a window in a corner of the dining room. Here she worked through the fall of 1943, when it became unsafe.

We went inside and sat down in the dining room. We were just an arm's length from where Levi-Montalcini would have sat at her microscope. Piera told us, "I think of all the things we often did together. I have memories of the places we've been together, the things she would tell me about her life. When she was traveling with me, she knew that I would listen if she wanted to talk, and that if she didn't feel like talking, she just didn't have to." Piera smiled and recalled that Rita would tell her, " 'You've always been my best travel companion.' Because I didn't bother her, basically."

I asked Piera how she thought that Levi-Montalcini could have maintained her focus on research in the midst of a war, studying cell death while in real danger of her own death. She said that Levi-Montalcini "kept working to survive, to cope with that weird life of people who didn't exist. Because they had been erased everywhere."

Piera recently discovered the letters that Rita and her sister Nina had sent home from Belgium in 1939 soon after the war had begun, while they had waited for visas to return home. The letters elaborate on how Rita maintained her focus on research as a war began around her, describing the escape from despair that her research offered as the war began. Rita wrote, "I am amazed at the complete possibility of escaping to the present, diving into the marvelous charms of nerve conduction." Nina added in the margins that her younger sister Rita, "here reading next to me ... is so well ... she is so animated for her studies."

RITA LEVI-MONTALCINI

BACK HOME, IN MY LAB at the University of North Carolina at Chapel Hill, I searched for any signs in Levi-Montalcini's wartime research articles that the experiments took place in a bedroom. As was typical in scientific articles, the writing focused tightly on the experiments and their results. Levi-Montalcini didn't mention her home, or the sewing needle that she had used for microsurgery. I could find only one cryptic clue, in the 1942 article, that the site of the work might have been atypical. Every other scientific article in the 1942 volume included the name of the institute where the work was performed. "University of Brussels, Laboratory of Embryology of the Faculty of Medicine." "University of Liege, Laboratory of Histology." Levi-Montalcini's article listed just one word for the address, "Turin." No institute. I wondered if scientists reading the article in 1942 might have noticed the peculiar omission.

Viktor Hamburger saw the 1942 article after the war ended. Levi-Montalcini's results confirmed to Hamburger what he had seen earlier—that targets could affect how many nerve cells would be nearby. But they also showed that Hamburger's speculations about how this worked were wrong. He invited her to come to the United States to continue the experiments in his lab at Washington University in St. Louis. There, Levi-Montalcini discovered that even in normal, unoperated embryos, many nerve cells die where they lack targets—for example in the areas where no limbs form. And the nerve cells that would die in normal embryos could be rescued—they would survive if targets were added nearby, confirming that even in normal development, many nerve cells form but die because they lack targets. Hamburger was clear about his own limited role in this work. He contributed his thoughts and his enthusiasm for Levi-Montalcini's results, but, as he reported later, "the experiments and observations on the slides were done by Dr. Levi-Montalcini." And he accepted that the results proved him wrong. "It was a regressive process rather than a progressive process as I had guessed, wrongly," he reported in an interview. Levi-Montalcini recalled later what she called one of Hamburger's finest traits, his "whole-hearted joy over fortunate turns in a colleague's or pupil's research."

In the warm evenings of summer 1948, Levi-Montalcini would share dinner with Hamburger and his

STILL STANDING This apartment building, where Rita Levi-Montalcini grew up, and worked during the war, stands tall to this day, showing off its grandeur.

FLORIAN JUG

> I asked how Levi-Montalcini maintained her focus during war. Her niece said she "kept working to survive."

aged father, and then sit at a table under the porch in St. Louis as they wrote an article describing the results. Levi-Montalcini had published more than 20 research articles by this time, but none in English. That summer, she wrote of her pleasure of re-experiencing the clear thinking in Hamburger's writing years earlier. Just a mile from where they met in the evenings of summer, 1948, Levi-Montalcini now has a star on the sidewalk in the St. Louis Walk of Fame, along with Chuck Berry, Stan Musial, Maya Angelou, and others.

Levi-Montalcini's experiments in the 1940s revealed that our brain and spinal cord manage to make connections all over our body because our embryonic bodies become densely filled with an excess of nerve cells—about a twofold excess, scientists now estimate. Those nerve cells that make accurate connections are afforded the privilege of survival. The rest die. The process seems remarkably inefficient, but it is remarkably robust: Birth defects where connections are not made are rare. Even if you were born with an extra body part, it would almost certainly become wired up to your brain. Indeed, people born with an extra finger or toe can generally attest to this: Their brains can move the extra part, and feel using it. And vertebrate animals of all different sizes and shapes no doubt have nervous systems that fit their bodies in large part because of this process. Levi-Montalcini's bedroom discoveries were the turning point in humankind's understanding that our nervous system is minutely shaped by death. Cell death is not alone in shaping the nervous system—later scientists discovered that other processes make important contributions as well. And cell death has more complex roles than had been revealed by the end of the 1940s. But Levi-Montalcini's experiments established a fundamental finding about how our nervous system is shaped.

SAFE HAVEN When bombing intensified in Turin, Rita Levi-Montalcini fled to her family's farmhouse in Asti, Italy, where, today, a row of trees shade a walking path.

FLORIAN JUG

NEARLY EVERY TEXTBOOK TODAY on the development of the nervous system has a chapter on cell death's prominent role in wiring our bodies. Some of them note Levi-Montalcini's courage for doing experiments in a homemade lab during the war. What she discovered in the war, though, is today nearly always credited to other scientists. One book credits a scientist working in the 1930s, who did not report on cell death at all. Others credit Hamburger. Some cite Levi-Montalcini only for guessing that nerve cells lacking targets might die, crediting Hamburger and Levi-Montalcini working together in 1949 to first show it definitively—years after Levi-Montalcini had shown it in the articles she wrote from her bedroom lab. It perhaps did not help that Hamburger and Levi-Montalcini themselves had muddied the history of the discoveries over the years. They each lived beyond their 100th birthdays, and both made statements about their roles at times, particularly late in their lives, that did not precisely match the published record.

I contacted scientists who wrote the textbooks to ensure I had my facts straight. Dale Purves, author of the book *Body and Brain*, told me that he had never read Levi-Montalcini's wartime research articles. Dan Sanes, who co-wrote the textbook *Development of the Nervous System*, said the same. Lynne Bianchi, Bill Harris, David Price—none of the textbook writers I reached had read the articles. I find it hard to place blame, really. English has become the international language of science in recent decades, even at international conferences, and the wartime articles were published in Italian and French. My translations benefitted from Google Translate, which improved after the textbooks were first written. And textbooks cover a lot of ground—thousands of research papers. "You know there's only so many hours," Price explained, adding an invitation to correct the record. "I'd love to get it right in my head. And then in the book."

I offered to share the translations of Levi-Montalcini's wartime papers with the writers. And based on the translations, it was clear to me that among a muddied record was a detailed historical article by another scientist, Maxwell Cowan, who had read each of the papers and who had the facts straight. I shared that article as well. Some of the writers reached back to say they were already drafting corrections for the next edition of their textbook. Their responses reminded me of Hamburger's enthusiasm about Levi-Montalcini disproving his own hypotheses. When new facts came to light, he accepted them. Purves, who knew Hamburger, said about Levi-Montalcini's wartime science, "These were remarkable times, and she was a remarkably resilient person."

From the time Levi-Montalcini arrived at Washington University, she continued to build on her research during the war: how target tissues like muscles talk to nerve cells, enabling the survival of only those nerve cells that find targets. That led to her co-discovery with Stanley Cohen of Nerve Growth Factor—a molecule that nerve cells take up from target tissues and that enables the nerve cells to survive. Nerve Growth Factor was the first of several growth factors discovered by scientists, and these factors are now known to have critical roles in nervous system wiring and also in cancer. In 1986, Levi-Montalcini and Cohen were awarded the Nobel Prize in Physiology or Medicine for their discovery of growth factors.

Throughout her life, Levi-Montalcini denied that she had experienced discrimination as a woman in science. Her colleagues, though, recall her fiercely defending her own role in her discoveries. After the Nobel Prize, she established a foundation to provide scholarships to African women, and she was made a Senator for Life in the Italian Parliament in 2001. Fifty years after her 1942 article reporting experiments from the bedroom in Turin, she reflected on how she managed to focus on her research in the midst of a war, "when all the values I cherished were being crushed." She wrote, "The answer may be found in the well-known refusal of human beings to accept reality at its face value, whether it be the fate of an individual, of a country, or of the whole of human society. Without this built-in defense mechanism, life would be unbearable."

BOB GOLDSTEIN heads a biology research lab at the University of North Carolina at Chapel Hill.

The Beloved Mesolithic Girl

As a new mother, an anthropologist makes a moving discovery at an infant's burial site

BY JAMIE HODGKINS

T**EN THOUSAND YEARS AGO,** a mother clutched her growing belly. A month earlier, the pregnancy had become difficult—something was wrong. The mother's stress was the baby's stress too, and the baby was due to be born in a few weeks.

DOMINIQUE MEYER, DANYLO DROHOBYTSKY, FALKO KUESTER, THE CULTURAL HERITAGE ENGINEERING INITIATIVE (CHEI) TEAM, AND THE QUALCOMM INSTITUTE AND JACOBS SCHOOL OF ENGINEERING AT THE UNIVERSITY OF CALIFORNIA, SAN DIEGO.

THE CAVE A digitally reconstructed image of the Arma Veirana cave with the burial seen just below the surface. Bones in the the top right corner are from Neve's hands.

The mother rested by the Neva River as it flowed down the mountains on its way to the sea. She lived in the Ligurian region of northwest Italy. People in her community went about their daily lives, gathering seeds and nuts, butchering mountain goats, and preparing meals. Some members tanned hides and prepared clothing, adding shell beads and pendants for decoration, some that had been passed down for generations.

Time went by and the day finally arrived. The woman gave birth to a baby girl, who was welcomed by the group with open arms. Things might have seemed fine at first, the baby crying, suckling, being passed around the group for love and comfort, but soon it would have been clear that the baby's health was declining. Less than two months after birth, the young girl was gone.

AN INFANT NAMED NEVE

Genevieve Pothier-Bouchard, Simon Paquin, and site co-director Julien Riel-Salvatore excavate the burial of the infant they named Neve.

DAVID STRAIT

The girl's mother and father, accompanied by their community, took her tiny body to a marble cave, just upslope from the river. Inside, the cave was beautiful. It ascended to a high point in the center, the walls draped by flowstone ribbons. A small pit was dug in the middle. The baby was wrapped in a garment decorated with over 60 pierced shell beads and three pendants. The pendants looked huge next to the tiny infant, but she was worth it. She had been a part of their group. The cave echoed with sounds of grief as the small body was returned to the earth. Along with her shells and pendants, she was removed from the life of the living and encapsulated in time.

The mother's hand slid along the cave wall as she steadied herself to leave, her fingerprints marking this place with her love and her grief. The father's tears dotted the ground. An aunt and uncle stayed back as other community members left, wanting one last moment. Their hands dug at the dirt covering the infant as they each made a small pit near the burial for their last gifts: the talon of an eagle owl, and another pendant.

This is what my scientific colleagues and I imagine unfolded at what is today known as the Arma Veirana Cave. We began excavating at Arma Veirana in 2015. Our goal was to uncover archaeological material from Neandertals, and we did just that—the first two excavation seasons exposed stratigraphic layers that contained not only tools often associated with

Neandertals in Europe (Mousterian tools) but also the remains of ancient meals that left behind cut-marked bones of wild boars, elk, and bits of charred fat.

We continued work at Arma Veirana in 2017, but that season was different. For one thing, I was pregnant, just beginning my second trimester, and having lost a prior pregnancy in a complicated miscarriage six months earlier.

Rather than starting the day on an arduous hike to the cave with the excavation team and hiking back to the lab in the village of Erli in the afternoon, as I had done in past seasons, I spent most days in the lab watching artifacts come out of the sieves, studying, and curating each found piece with students. Each night, as equipment was being put away, I was able to see what had been excavated and mapped in 3-D space, and members of the excavation team could see artifacts they had excavated, washed, and laid out in the lab. As we worked through July, 2017, everything was progressing as planned.

A main goal for the season was to better understand the stratigraphy of the cave as it related to the more than 50,000-year-old Mousterian artifacts we had recovered, and to expose potential Upper Paleolithic deposits that might be the source of artifacts we had found eroding down the cave floor, which slopes north toward the entrance. Our team expanded excavation units from the front toward the back of the cave. Sediments have eroded out of the front of the cave, so that older sediments are exposed nearer to the surface in the front, but younger sediments are still preserved in the back. As excavations expanded southward toward the back of the cave, we were moving forward in time.

I grieved over Neve's remains, especially as I sat recovering the tiny tubes of her hand bones.

In the lab, with one week left in the 2017 field season, I began to find pierced shell beads in the sieves. I called up to the cave with a warning, "We are getting close to something."

On a hot, humid late afternoon, as I sat analyzing bone fragments and my colleague Fabio Negrino, an archaeologist from the University of Genoa, analyzed stone tools, the cell phone rang. "We are uncovering a burial." Fabio and I rushed to the site. When we arrived, Geneviève Pothier-Bouchard, an anthropologist from the University of Montreal had exposed parts of an infant cranial vault and articulated lines of pierced shell beads.

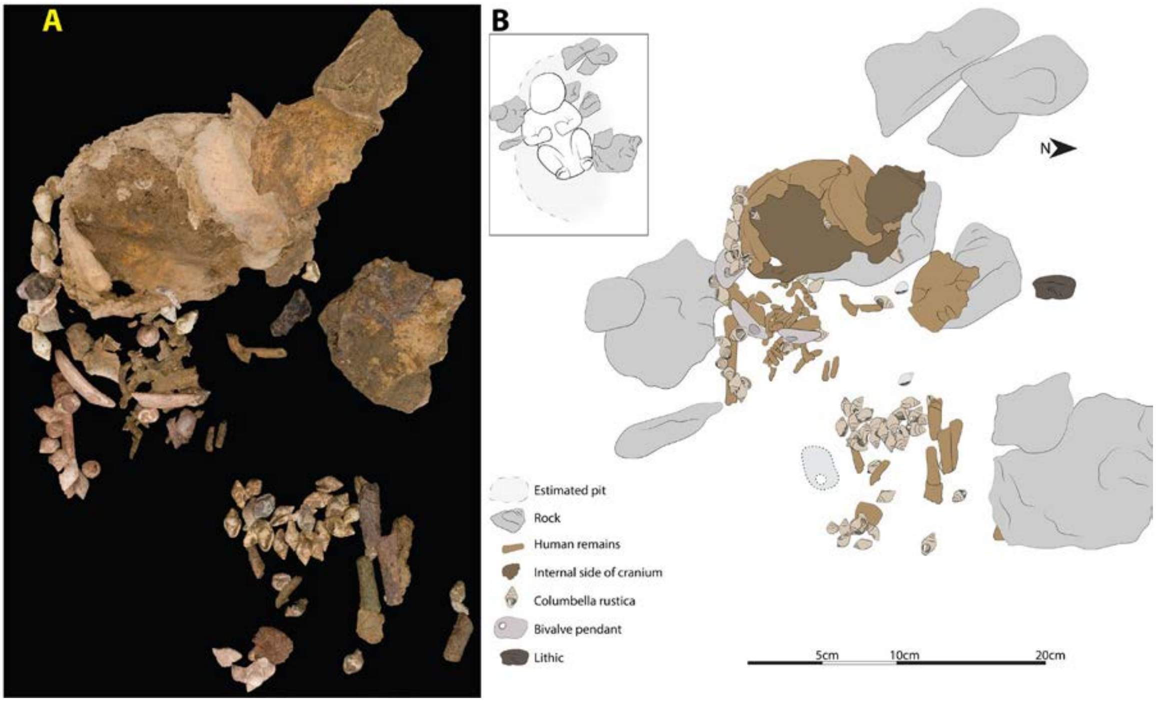
The cliché that you always make the biggest finds on the last day was true. We were out of time. This was scheduled to be the last day of the excavation. Students had flights home, grant money had run out, and the excavation leaders had classes to teach. There was no way to excavate the cranium quickly without breaking it. Work was going to take weeks longer. We made the decision to cover the remains in a protective layer of sand, netting, and plastic to protect everything underneath until we could come back the following season. We walked away worrying and hoping everything would be OK. As we left, we were comforted by the knowledge that people from the nearby villages of Cerisola and Erli would keep watch over the site throughout the year.

The cell phone rang. "We are uncovering a burial." We rushed to the site.

In 2018, we returned. This time, Caley Orr, a paleoanthropologist at the University of Colorado School of Medicine, and my husband, and I came as a family with our 6-month-old daughter, and her grandmother Deb Hulting. Over the course of five weeks, the remains of the buried baby were revealed by the steady hand of Pothier-Bouchard and Simon Paquin, also from the University of Montreal.

As we had done since the beginning of the excavation in 2015, photogrammetric images linked to 3-D coordinate data in the cave were taken by Dominique Meyer and Danylo Drohobytsky (then students at the University of California, San Diego), allowing for the team to recreate the excavation in a virtual environment. Sediment from the burial pit was placed in bags and carried in full to the lab, where I sieved the sediment through a 1 mm sieve. I recovered several of the infant's baby teeth, stained brown over time, along with the tiny remains of hand and finger bones. Though I assume my emotions over the death of Neve are not as strong as the grief her group must have felt, I cried and grieved over Neve's remains, especially as I sat recovering the tiny tubes of her hand bones.

By the end of the season, we had recovered all that remained of the infant of Arma Veirana. In a series of analyses, coordinated with multiple institutions and numerous experts, we learned details about this brief life.



NEVE'S CRADLE The burial of Neve is documented using 3-D photogrammetry. The insert shows the reconstructed position of the infant in her final resting place.

DOMINIQUE MEYER, DANYLO DROHOBYTSKY, FALKO KUESTER, THE CULTURAL HERITAGE ENGINEERING INITIATIVE (CHEI) TEAM, AND THE QUALCOMM INSTITUTE AND JACOBS SCHOOL OF ENGINEERING AT THE UNIVERSITY OF CALIFORNIA, SAN DIEGO.

Radiocarbon dating determined that the child lived 10,000 years ago. DNA and amelogenin protein analysis revealed that the infant was a female belonging to a lineage of European women known as the U5b2b haplogroup. Detailed virtual histology of the infant's teeth showed that she died 40 to 50 days after birth, and that she experienced stress while in the womb, likely due to stress her mother experienced, perhaps from starvation, sickness, or injury, that briefly halted the growth of her teeth 47 days and 28 days before she was born. Carbon and nitrogen analyses of the teeth helped us see that the baby's mother had been nourishing the infant in her womb on a diet composed of food from the land, not the sea. An analysis of the ornaments adorning the infant funded by the Social Science and Humanities Research Council demonstrated not only the time and care invested in each piece, but also that many of the ornaments exhibited would have taken longer to accumulate than she had lived and must have been passed down to her from group members only to be returned to the earth with her. Our team nicknamed the Arma Veirana baby "Neve," which (in a funny twist) comes from Caley's misspelling of the river valley where the site is located. But "neve" means "snow" in Italian, a beautiful word, and the name stuck.

As it turns out, Neve is the most ancient burial of a baby girl currently documented in the European archaeological record. In a paper published in *Scientific Reports*, we conclude that the burial of such a young female

BABY'S FIRST DIG Jamie Hodgkins stands holding her daughter with Julien Riel-Salvatore, the Arma Veirana Cave site co-director, excavating next to Simon Paquin.

FABIO NEGRINO

with abundant ornamentation reflects a degree of egalitarian treatment of individuals in life and death regardless of age or sex. The tremendous number of pierced shell beads and pendants found with Neve show very young females were afforded personhood in this Mesolithic society, despite the fact such young infants were unable to contribute materially to essential tasks. This is not always the case, especially in societies with high rates of infant mortality. Along with the burial of a similarly aged female from Upward Sun River in Alaska, the funerary treatment of Neve suggests that the recognition of infant females as full persons has deep origins in a common ancestral culture shared by peoples who migrated into Europe and those who migrated to North America. This recognition may have arisen in parallel in populations across the planet. Either way, the terminal Pleistocene and earliest Holocene shows definitive evidence for the recognition of young girls as members of human society.

In a strange way (a sort of ripple in time) it seems that Neve and my daughter were born together. The discovery of this infant at the time my child was developing in my womb, and the full excavation of Neve after the birth of my daughter are certainly intimately linked for me. The story of Neve offers many lessons.

There is pride and awe in the story of Neve's mom, apparently struggling, as indicated by the stress lines in Neve's teeth, and yet she carried on as generations of women have done, giving birth, and bearing loss. This is a connection that hits especially hard for me having experienced my own miscarriage mere months before Neve was found. The power and endurance of the mother should not be overlooked.

The story of Neve's group carefully burying an infant girl and investing handmade heirlooms with her body, removing those goods from the living is a profound human story. To me, the story took on added significance because Neve was discovered on the heels of the 2017 Global Women's March. It was a moment when equitable treatment for females seemed to have been illusory. It made me wonder: Are our modern attitudes toward women a continuation of long held ancestral behaviors? Or are the inequities we experience today a deviation from our ancient past? Is humanity defined by "othering" and demeaning some and elevating others, or is the creation of highly unequal societies a contradiction and betrayal of our humanity?

I hope the world into which Caley and I have brought our daughter will achieve higher standards of treatment and equality for women of all ages, cultures, and avocations around the world than it does now.

JAMIE HODGKINS is an associate professor of anthropology at the University of Colorado, Denver. Her research is focused on the origins, evolution, and ecology of modern humans and Neanderthals. Much of this work has focused on reconstructing ecology and behavior of these peoples by studying their patterns of hunting and butchery as well as analyzing the mobility of their prey species through isotopic analysis. She is a project director for excavations at the late Pleistocene and early Holocene site of Arma Veirana in northwestern Italy. Her fieldwork has also included projects in North America, France, Spain, Bulgaria, Morocco, and South Africa.

The excavation team: Caley Orr (Paleoanthropologist at the University of Colorado School of Medicine), Fabio Negrino (Paleolithic archaeologist at the University of Genova, Italy), Claudine Gravel Miguel (Paleolithic archaeologist at Arizona State University), Julien Riel-Salvatore (Paleolithic archaeologist at the University of Montreal), Marco Peresani (Paleolithic archaeologist at the University of Ferrara), Stefano Benazzi (Paleoanthropologist at the University of Bologna, Italy), David Strait (Paleoanthropologist at Washington University), Christopher Miller (Geoarchaeologist at University of Tübingen).

An earlier version of this article appeared in *Simple Beginnings: Exploring Human Origins*, a blog site hosted by the Evolutionary Morphology Lab at Washington University in St. Louis.

FUNNYANGEL / SHUTTERSTOCK

This Is Some Good Shit

How the sewage plant in our nation's capital spins human poop into fertilizer gold

BY LINA ZELDOVICH

I'M STANDING ON an observation platform atop 24 colossal pressure cookers that belong to DC Water, the sewage treatment plant of our country's capital. You may think that a sewage plant isn't much to look at, but there's a lot to take in from this observation platform. In front of me there are fields of silvery pipes stretching over massive sewage aeration tanks, where sludge percolates after it first arrives. To my left there's a building that holds a dewatering centrifuge that turns this sludge into a goo ready for the next processing step—the pressure cookers that hum steadily below me as they simmer. They are slowly cooking shit into something awesome.

DC Water processes the contributions of about 2.2 million people who live, work, or visit the capital and the area that surrounds it. There's input here from every residential house, every apartment building, every business and every historical landmark—Tyson's Corner, the Smithsonian Institution, the Lincoln Memorial, and Capitol Hill. And the White House, of course. There's some presidential poop percolating in those aerating tanks, along with the input from the Senate, the House of Representatives, the Pentagon, and the protestors chanting in front of the White House lawn. "That's where all of us come together," quips Bill Brower, a resource recovery engineer who is showing me around the plant. "And I'd like to thank all these people for their contributions."

When recycled properly, poop can power your home, cook your food, fuel your car, and even stave off algae blooms and floods.

Despite the joke, Brower is quite serious. Unlike many other wastewater treatment plants, DC Water doesn't identify as such. It describes itself in a different way: a resource recovery facility. There's a reason for that, says Christopher Peot, the plant's director of resource recovery, who is trying to change the mentality of the sanitation business. "There's no such thing as waste, only wasted resources," Peot says. "So we don't process waste here. We recover resources."

To an average toilet-flusher, resource recovery from poo may be a shocking concept. For one thing, sewage management is incredibly difficult, and happens on a large scale. An average adult produces about a pound of poop a day so the Washington area dishes out a pretty impressive pile. What do you do with all this crap? Especially when there's no vast amount of farmland nearby? Many wastewater plants destroy or landfill it. Meanwhile, farmlands are getting depleted after growing crops for years, so farmers use synthetic fertilizer to boost production. Mother Nature's link is clearly broken.

That's exactly what DC Water is trying to fix. One of the most ecologically savvy sewage treatment facilities in the country, DC Water uses the so-called thermal hydrolysis or THP process, which renders sludge harmless and converts it into a safe form of fertilizer. As Brower walks me down from the observation deck to the tanks labeled Heated Sludge, he explains the inner workings of the pressure coolers to me. Originally designed in Norway and called Cambi, the system consists of a pre-heating tank, called a pulper, and a series of upright cylinder tanks, in which pumped sewage is heated to 300 degrees Fahrenheit and pressurized to six atmospheres for half an hour. "That's six times more than what you are feeling now," Brower says. "That's how you kill all the pathogens."

The stewed sludge is loaded into the so-called biodigesters—four humongous concrete tanks where a microbial menagerie chews through it, slowly breaking it down. "Digesters work just like our stomachs," Brower explains. "They take big complex molecules like proteins, carbohydrates, and fats, and break them down into smaller and smaller bits. And just like bacteria in your stomach, bacteria in the digesters break down proteins into amino acids, which become food for the bacterial community further down the food chain, and so on."

As the microbes feast on the sewage stew, they dramatically reduce the amount of "dark matter" that DC Water needs dealt with. Without the digesters, the plant would generate 1,100 tons of biosolids daily, which even in their pathogen-free form still need to be trucked somewhere, with the use of fossil fuels. The microbes reduce this amount to nearly one third. "We went from producing 1,100 tons a day to 450 tons a day," Brower says. "The rest literally goes 'puff,' and not just puff but a puff that you can burn and create power," he points out. The microbes produce methane, which burns to spin the plant's electrical turbines, generating 10 megawatts of power. "Ten megawatts is enough to power about 8,000 homes in this area. And the remaining 450 tons becomes our premium product: Bloom. Let me show you how it happens."

He hands me a hardhat with a blue and green DC Water Logo, puts on his own, and heads into a concrete building filled with conveyor belts. Officially called

PRESSURE COOKERS At DC Water, a wastewater treatment plant, tanks "are slowly cooking shit into something awesome," writes Lina Zeldovich. That something awesome is plant soil rich in nutrients.

LINA ZELDOVICH

belt filter processors, they are designed to squeeze as much water out of the digested sludge as possible. They resemble giant moving cheesecloths stretched out flat, only instead of white squishy curds it's draining black soggy ones. And as the cheesecloth carries these glops along, the water drips down through it so the soupy substance becomes less and less watery. It starts like a muddy stream and drains to a consistency of wet forest soil.

At the conveyor's end, two roller presses flatten out this soil-like substance into shiny black sheets. The sheets quickly crumble into fragments resembling pieces of coal or graphite, only thinner and more uniform because they have been neatly pressed. The conveyor drops the fragments into a deep crater with an overhanging backhoe. It looks more like a coal-mining crater than a waste treatment plant and it makes me think of a quarry. And then it hits me. Of course it's a quarry. DC Water is quite literally mining black gold.

"I like that name, Black Gold," says Brower, chuckling at my description. But this isn't yet the last step, he adds. A third-party company named Homestead Gardens takes this black gold, ages it, dries it up, and packages it into 25-pound bags labeled Bloom. "We can make a more marketable material if we age it," Brower says, because the moist product sticks to your boots and shovels, but the dry one is powdery and light.

Brower finds an open bag and scoops up a handful of Bloom. He takes a sniff and offers me to do the same. I hold a little Bloom mound in my hands and examine

"We don't process waste here. We recover resources."

it closely. The dry, crumbly substance resembles your everyday garden dirt. It neither looks like shit nor reeks of it. It smells of forests, meadows, riverbanks, fertile earth, and the promise of the next harvest.

"I grow everything with it, squashes, tomatoes, eggplants," I hear Brower say. "Everything grows great and tastes great," he says. "And I'm not the only one who thinks so. We've heard from a lot of people that they've got the best response they've ever seen from the plants. Particularly with leafy greens because that nitrogen boost does well with leafy plants. And the plants seem to have fewer diseases and fewer pests around—probably because Bloom helps build healthy soils."

Besides gardeners, Bloom has proven popular with landscape architects and construction companies that buy good soil for horticultural use. As they clear sites for new developments, they often strip off the topsoil, which later needs to be replaced. Bloom helps restore the damage done—and it doesn't smell like manure, so tenants don't complain.

On my way back from DC Water I hold my hand to my face and realize it still smells of Bloom's pleasant springtime scent. I sit on the train sniffing my hands, oblivious to the curious glances of other passengers, wondering what else can we do with our dark matter, with that potent organic power within us? Can we turn it into other forms of black gold? And it turns out, we can. When recycled properly, poop can power your home, cook your food, fuel your car, and even stave off algae blooms and floods. We even have the technologies to do it, and some companies are doing it already. We just have to stop pretending that our shit doesn't stink—and use it for what it's worth.

LINA ZELDOVICH is an award-winning popular science writer and former *Nautilus* editor. She has written dozens of stories for major publications in the United States, Canada, and the United Kingdom, including the *Smithsonian*, *Popular Science*, and *Scientific American*, and won four awards for covering the science of poo. Her book, *The Other Dark Matter: The Science and Business of Turning Waste into Wealth and Health*, presents novel solutions to the world's oldest problem—keeping humans free from their own excrement. @LinaZeldovich

THEFTRASH / SHUTTERSTOCK

My 3 Greatest Revelations

The author on writing her new book, The Other Dark Matter

BY LINA ZELDOVICH

TOLD TO KEVIN BERGER

1

WE ARE SMOTHERING THE PLANET WITH OUR POOP

The next time you go grocery shopping, look at where your food comes from. Most of it isn't local. Strawberries come from California or Florida, asparagus from Mexico or Chile, bananas from Brazil or Ecuador. Most of the food gets shipped to us, trucked, flown, helicoptered, or whatever. We eat it and excrete it—in the same place, over and over. And that's a problem. Before humans settled and started farming, we were nomadic, just like other animals. We walked around. We left our dark matter wherever we went. Mother Nature then turned it back into soil. That's the circle of nutrients on the planet. After we settled and started farming, we couldn't walk away from our dark matter. It started piling up. So we were faced with a problem of what to do with it and how to get rid of it easily and efficiently. The answer to that was water because it conveniently flushes everything away. Our industrial wastewater treatment plants are marvels of modern engineering. They clean germs from the wastewater to the point it's safe to drink it! But nutrients such as nitrogen, phosphorus, potassium, which make potent fertilizers, often remain in that water. They flow into lakes and rivers and ultimately the ocean where they fertilize all the wrong things—like algae. So when we constantly extract nutrients from farmlands and deposit them in bodies of water, we deplete fields and over-fertilize lakes, rivers, and oceans. When we go into the bathroom and push that lever, we are causing algae blooms, which kill fish, destroy marshes, and contribute to climate change. Coastal marshes may not be sexy like a forest, but they're extremely important. They serve as fish nurseries and work as storm protectors. When they die, we get a lot more flooding. So you can legitimately say that humans are smothering the planet with their poop because we don't reuse it properly.

2

CRAP IS A COMMODITY

In 1737, a Chinese Emperor of the early Qing dynasty issued a decree that stated, "Treasure night soil as if it were gold." By night soil he was referring to excrement. The decree touted the achievement of the progressive residents of Jiangnan Province who diligently collected their night soil from the cities and brought it to the farmers in the countryside. That solved two problems at once: kept streets clean and gave farmers fertilizer. But the empire's northern residents apparently had not caught up with that wisdom, so their streets were dirty. The decree prescribed the northerners to implement the same measures.

In pre-industrial Japan, Osaka's city authorities discussed a complaint stating that ships coming to the city harbor to ferry out their night soil stunk too much. The complaint was taken seriously. It was debated and the ultimate verdict was that "it was unavoidable for the manure boats to come into the wharves used by the tea and other ships" because this is how we take the muck out of the city, and this is how we grow food. Culturally, societies that had poor, barren soils

THIEF TRASH / SHUTTERSTOCK

I knew the value of poop because I grew up differently than most people in the West.

learned not to have the negative reaction to excrement that we do today. It wasn't disgusting. It was a commodity. It was so much a part of life that you couldn't possibly exclude it. In Japan and China it had to be part of the circular economy just as fish, tea, vegetables, and other goods.

Excrement did become disgusting in societies that didn't see its value and didn't have established ways to ferret it from cities to the countryside. Medieval Berliners piled up their shit in front of St. Peter's Church until a 1671 law directed every visiting peasant to take home a load. And Paris was a mess because Parisians' emptied their chamber pots out the window in a method infamously dubbed as Tout-à-la-Rue—"all onto the street."

The germ theory solidified our "dark matter" disgust further. When biologists in the 18th and 19th centuries began to discover that poop contained microbes that could make us sick, excrement, already valued poorly, got devalued completely. Now we've been conditioned to look at excrement as both waste and an incredibly dangerous substance. If there was one thing your mother always yelled at you not to touch it was poop—dog poop, cat poop, and especially not human poop!

HUMANS, LOVE THY "HUMANURE"

I was never disgusted by poop. That's why I wrote the book. I knew the value of poop because I grew up differently than most people in the West. I grew up on a small family farm in Kazan, Russia, in the Soviet Union. Every fall my grandfather would set off to do two things: prepare our small family farm for the long Russian winters and empty our septic system. He had a system of how he did that. He would put on a hazard suit, special gloves, and special boots, and he would spend a day or two dipping buckets into that tank and transferring its contents into his compost piles. Then he would close the compost piles for the winter, sometimes for more than a year, and let all this stuff sit there and do whatever it does. When he opened it up, there was no sewage left. It was this incredibly rich, black garden dirt, which smelled so good. It smelled just like garden dirt's supposed to smell, with the promise of the next harvest. One of his favorite sayings was, "You have to feed the earth the way you feed people." And it all made a lot of sense.

3

MALLORY BETTE

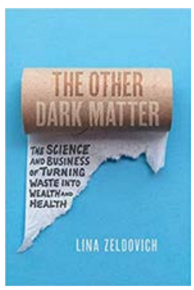
DEUCES WILD Author Lina Zeldovich grew up on a small farm in Russia, where her grandfather composted human poop into nutrient-rich soil. The compost pit, she says, “smelled of rich fertile soil, nature, spring, and the promise of the next harvest.”

MALLORY PETTEE

We knew that excrement was dangerous. My grandmother boiled my grandfather’s entire get-up in a big vat once he was done. And I knew that other people lived in big apartment buildings and they had flushing toilets and they didn’t have septic tanks. But I always thought their output also went to some kind of big septic system and was recycled. I was pretty shocked to learn that the rest of the world didn’t recycle their sewage. And when we came to New York I realized how difficult it is to make it work on a large scale. But the illogical aspect of wasting our waste stuck with me, because if we continue throwing away our shit, our farmfield would eventually turn to dust—and they already do! This book is an attempt to change humans’ perspective on their “humanure.” It implores us to reconsider the tremendous organic power we all carry within.

LINA ZELDOVICH is an award-winning popular science writer and former *Nautilus* editor. She has written dozens of stories for major publications in the United States, Canada, and the United Kingdom, including the *Smithsonian*, *Popular Science*, and *Scientific American*, and won four awards for covering the science of poo. Her book, *The Other Dark Matter: The Science and Business of Turning Waste into Wealth and Health*, presents novel solutions to the world’s oldest problem—keeping humans free from their own excrement. @LinaZeldovich

KEVIN BERGER is the editor of *Nautilus*.



NASA Is on the Cusp of a New Era

A planetary scientist explains why SpaceX's Starship will transform her field

BY BRIAN GALLAGHER

PAOPANO / SHUTTERSTOCK

JENNIFER HELDMANN LAUGHED when I pointed out that she used the word "unprecedented" five times in a recent paper. "I should have checked that," she said. But who could blame her? The NASA planetary scientist was describing a dream come true: The ability for humans to travel to the moon and Mars frequently—and not have to worry about packing lightly!

That's because of a new vehicle the rocket company SpaceX is developing and testing, called Starship. It shatters the size and constraints with which scientists and engineers have had to content themselves. With space-bound instruments no longer needing to be painstakingly and expensively miniaturized, and with launch costs down and launch frequency up, NASA can think big—really big.

PLANETARY SCIENTIST
"If you can use something like Starship, where you can refuel in Earth orbit, you basically reset the rocket equation," says Jennifer Heldmann. "You have greater abilities to get more payloads to the outer planets more rapidly and at a greater cadence than we currently can now."

NASA

No one is more excited about this than Heldmann. She works at NASA's Ames Research Center in the Space Science and Astrobiology Division and in the Planetary Systems Branch. She is an expert in the origin and evolution of water ice on the moon and Mars, and is intimately involved in planning, and campaigning for, human exploration missions on other worlds. Her paper, "Accelerating Martian and Lunar Science through SpaceX Starship Missions," co-authored with two dozen other researchers, including employees at SpaceX, preceded some promising news. SpaceX is preparing the ground for Starship operations at Launch Complex 39A, part of NASA's Kennedy Space Center near Cape Canaveral, the site that saw Apollo 11's astronauts land on the moon. "39A is hallowed spaceflight ground," Elon Musk, SpaceX's CEO and chief designer, tweeted. "[N]o place more deserving of a Starship launch pad!"

Part of Heldmann's mission is lighting a fire under the feet of her colleagues at NASA, to get them to start preparing missions aboard Starship as soon as possible, "potentially as soon as 2022, or failing that in the 2024 window," she writes. In conversation, Heldmann spoke with the enthusiasm of someone psyched to see her life's work reaching a pinnacle. "We're doing something that's never been done in human history before," she told me. "It forces us to think about questions that haven't been solved yet. That's one of the most exciting things about working for NASA. Every day my job is different, because there is no answer in the back of the textbook."

During our interview Heldmann explained, among other things, why water ice, the focus of her research, is the most valuable ingredient for expanding human civilization to the moon and Mars, and she outlined the unprecedented opportunities Starship offers for answering deep questions about life elsewhere in the solar system. Heldmann, who is no stranger to some of Earth's most extreme environments, also didn't rule out going to the Red Planet herself.

Water ice has the main constituents of rocket fuel.

How are you laying the groundwork for human settlements on the moon and Mars?
I do terrestrial fieldwork and go to places on Earth similar to the moon and Mars to try and understand how the systems work, the underlying physics, so we can apply those lessons to the moon and Mars. As we go to the moon for longer periods of time and need to stay there and use in situ resources, water ice is on top of the list of things we'd like to investigate. And the same goes for Mars. If we want humans to live and thrive on the Red Planet, we'll need to use in situ resources.

Where have you done terrestrial fieldwork?
I've been to the High Canadian Arctic—it's very cool up there—looking for water and ice. I've been to the Dry Valleys of Antarctica, which is one of the best Mars analogues because it's so cold and dry. There's subsurface ice underneath a dry layer of regolith, just like we see on Mars. I've gone to the islands of Spitsbergen, which is north of Norway, where there's very high latitude water springs coming through permafrost, which is very interesting—how you get liquid water at those cold temperatures. I've done work in the Atacama Desert looking at water flows under dry conditions. The Mojave Desert, Utah, Arizona—a whole bunch of places I never would have gotten to see if I weren't a research scientist trying to go to extreme environments to see places that are most like off-world locations on the moon and Mars.

What was your favorite trip?
Antarctica is amazing. It's unlike anywhere else I've ever been. And when we go to the Dry Valleys, we fly into the U.S. base at McMurdo, gather up all our gear, do all our prep work, and then the helicopters fly us out to our field site. They drop us off for a month or two. You bring all your gear, your food, your fuel, everything you're going to need, and then they come back and pick you up a couple months later. It's spectacular.

What's it like staying in Antarctica that long?
You realize that all these creature comforts that we have in our daily life really aren't necessary for our survival. Even something as simple as taking a shower seems luxurious, because think about the resources—just taking a shower takes all this water. Having heat inside of buildings, having buildings at all—all these small things that we don't think about in our daily life. But then when you become adjusted to living without them, you realize how well you can do and how much you can survive without having all these extra fancy things around you.

Tell us about Starship. What makes it special?
Starship is a large reusable vehicle that's capable of taking about 100 metric tons of payload to the moon and Mars. It allows us to send more payload, send it more often, and most likely, at a lower cost. The way

we do things now, we're always conscious of mass. We spend a lot of money on miniaturizing components to make them fit within the small mass box. But if that goes away, then you can start flying more things. You can take things off the shelf more easily. You can also fly more of them and lower your risk. If a couple of instruments don't work, then that's fine, you still have data from all the rest. It's really thinking in a different way. We can start asking, "What science could I do if I could have all of these flight opportunities, if I could fly this much mass?"

What can mission planners do to help prepare the way for humans to explore and live on Mars?

There's a laundry list of other activities you can do: What's your power infrastructure going to look like? What testing can you do for power systems, characterizing the local environment of where the humans will be? What are the variations in surface temperatures? Are there dust storms, atmospheric pressure changes? Humans will need long-term radiation shielding. You can test the effectiveness of different techniques. You can look at how you're going to grow food when you have a lot of humans there. You can start with some simple plant-growth experiments that have been designed already. You can preposition supplies. You can start bringing some of the hardware that you're going to need when the humans come and get it in place before they get there. You can start preparing landing pads. As you have multiple Starships coming and landing, instead of landing on native Martian terrain, you can do some experiments early with different landing components and techniques for creating landing pads, to see which ones work best.

Is there a sweet spot for where to land on Mars?

We've been doing some of this work, looking at optimal landing sites, because you want to find the sweet spot where you want to be close to the equator, because the temperatures are warmer, the thermal environment is more benign. We have a very nice day-night cycle. However, you want to be at a far-enough, sort of northern latitude, so that you have near-surface ice. We've seen impact craters that have excavated ice. We have multiple different datasets suggestive of ice. But we really need to get on the ground in those locations where we consider sending the humans and do the finer-scale, human-scale mapping to see what the distribution of that ice is, how pure it is, how deep it is.

Why is it crucial to be close to easily accessible water ice?

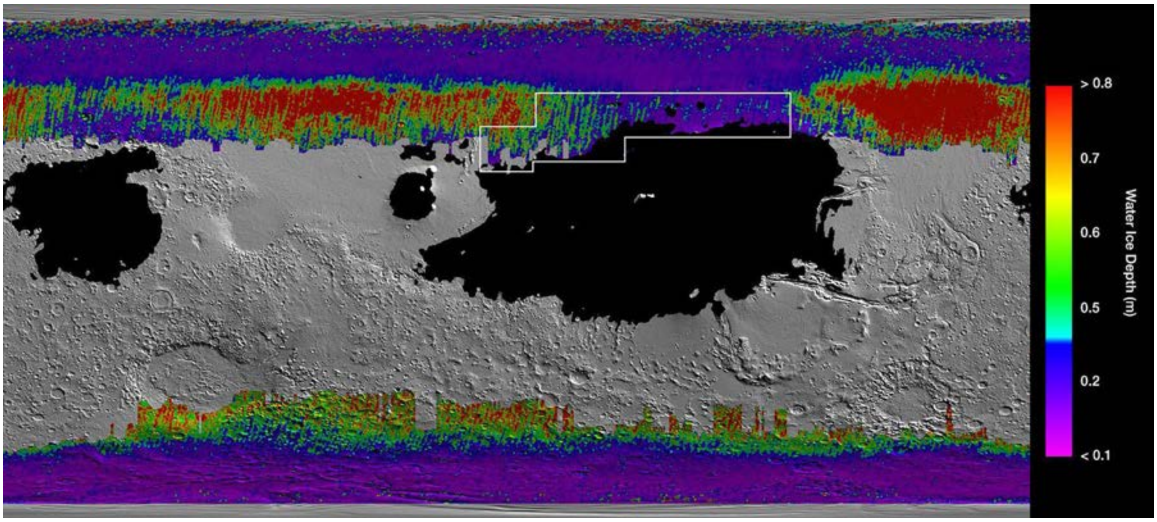
Water ice is important because that's going to be a fuel source. Water is made of hydrogen and oxygen, H_2O. Those are the main constituents of rocket fuel. So, in one of the leading contenders for the mission architecture, you're going to make your return-to-Earth Starship fuel from in situ resources on Mars from the water. You can also use some of that fuel in the base, to support the humans while they're there too, to brush your teeth and take a shower and grow your plants and all those things, too.

Do you know how much water ice Mars has? Is there a worry of running out?

There's a lot of ice sequestered, especially on Mars. We have all sorts of data. We have gamma-ray data and radar data and geomorphic data, modeling results that are consistent with this. If you want to go far north, there's polar caps that have water ice in them. There's small amounts of water in the atmosphere. So, there's a vast amount of water. It's an interesting science story, too, because billions of years ago, Mars had large volumes of flowing liquid water. We see giant canals and riverbeds that tell us that there was a lot of liquid water on Mars. That liquid water escaped and/or froze, and now Mars is a very dry place on the surface. It's just a matter of picking the optimal location for the human base.

How versatile is Starship as a human base—what can you do with it once it lands?

There's a lot of architectural versatility that's provided just with the structure itself. A lot of interior volume, for example, and you can repurpose that volume depending on your mission needs. You can have crew compartments. You can have large bulk spaces for sending large spacecraft. There are pods on the bottom, so you can have easy access to the surface. There can be an elevator, so you can lower payloads down to the ground, if you need to. On early flights, you can even use some of that material for building up your base.



HERE BE MARTIAN ICE Cool colors on this map of underground water ice on Mars indicate a depth of less than one foot; warmer colors over two feet deep. Spacecraft landing in the black zones would sink into fine dust. The boxed region is the ideal location for astronauts to prospect for ice.

NASA / JPL-CALTECH / ASU

Do you think you'll find fossils of past life, if life did evolve, on Mars?

I don't know. That's why it's so interesting to explore Mars, because we don't know. We don't know if there was life there. We don't know if there's still life there. Maybe there was never life there. That is the $1 billion question, right? But all the conditions seem to have been on Mars, especially around the time that we believe life started to evolve on Earth—warmer weather conditions, energy sources, and the organic elements. And if there was, is it similar to life on Earth? Is it different? Or did life evolve independently on both planets? The answer either way would be profound because that would help tell us about our own place in the universe. How common is it for life to emerge? Looking at our solar system, and then extrapolating that to other solar systems. That's one of the reasons why Mars is so interesting, because we can start to address some of these big-picture questions by going to the next planet over.

A single Starship heading to the moon, you write, could bring back more lunar samples than we have now.

Correct. I'm glad you pointed that out because that's the other end of the story. Because Starship's reusable, and because it has such a high-payload capacity, you can return more samples than we have ever dreamed that we could have. And samples are incredibly valuable for science, because we can get the samples in the labs on the Earth, where we have the state-of-the-art, the most highly capable instrumentation, to do that sample analysis. That's a game-changing proposition to be able to bring back so many samples. The diversity of samples will be higher because you can pick and choose what you leave.

It can also help us bring back unique samples. For example, the south pole of the moon is interesting because there are these permanently shadowed craters. And we've had multiple missions now telling us there's probably water ice and other frozen volatiles in these dark craters and around them. We'd really like samples of that very cold material. But to bring back samples of that cold material is hard, you have to keep them cold as they get back to Earth. You need refrigerators at very low temperatures. And that means mass. It's hard for us to fit a decent size refrigerator on a current vehicle. If you have something like Starship, you can fit some big freezers in there to keep your samples cold. You can get those ices back to the Earth for analysis.

Tell us about the epiphany you had while trying to understand how water flows on Mars.

There are features on Mars that look just like terrestrial gullies on Earth. There's V-shaped channels, they are meandering, they have debris when you hit the bottom, they have eroded alcoves up at the top—exactly the morphologies you would expect when you're looking at water flows on Earth. And they're usually on crater walls or the side of slopes. They're geologically young, probably the past few million years. That's interesting because how can you have recent water flows on Mars? We always thought Mars is too cold and too dry and the atmosphere is too thin to have liquid water.

It turns out that when you look at most of the gullies on Mars, they don't reach the bottom of the slope, which is interesting, because that means you're losing water along the way. Why does water behave this way on Mars? We know the atmosphere is so thin. We know that the temperatures are so cold. So when liquid water is exposed to the Martian surface, it boils and evaporates at the same time. You can model the rates of that. To match the length and the shapes of the channels, you had to be losing large volumes of water as it was flowing down the surface. We also know there were vast quantities of water early in Mars' history because we see these large valley networks and these large channels and riverbeds and shorelines and all this evidence telling us that there was a lot of liquid water in the past.

CAN CARRY FREEZERS "If you have something like Starship, you can fit some big freezers in there to keep your lunar samples cold," Jennifer Heldmann says. "You can get those ices back to the Earth for analysis."

NASA

Billions of years ago, Mars had large volumes of flowing liquid water.

You've said that you used to want to go to Mars yourself but changed your mind. You'll let others have the fame and glory. But you don't have to be the first, you can visit the Red Planet when SpaceX's habitat is more established. So, might you reconsider going?
I guess we'll have to see how it plays out. I think one of the things I learned through working at NASA is just how much work is required on the ground to enable even just a few astronauts to fly into space. And it's all incredibly important work. And it's all leading toward the same goal. So, I found that I'm very happy doing that hard work on the ground to enable others to go.

One of the fathers of rocketry, Konstantin Tsiolkovsky, said, "Earth is the cradle of humanity, but one cannot remain in the cradle forever." Do you see Earth as a place we must outgrow to mature as a species?
I love that quote. Studying planetary science, I realized that there are other worlds out there. I mean, our planet Earth is amazing. I have been very fortunate to have been able to go to places that most people don't get to go to just through the course of my research in my work, going to extreme environments, and places that are not tourist destinations and don't have hotels and whatnot. The more we can understand and appreciate our natural world, and how fortunate we are to have this planet, all the better.

In learning about our Earth, I can also appreciate that there are also other worlds out there that are also fascinating, from the spacecraft that we've sent and the data we've gotten back—we are always surprised. We think we know. We develop theories, and we think about what we think we're going to see. And then nature always surprises us. I expect it will be no different when we're exploring the moon even more, when we send humans to Mars and beyond. We will continue to learn, and I think that's our human nature—to explore. That's what we do.

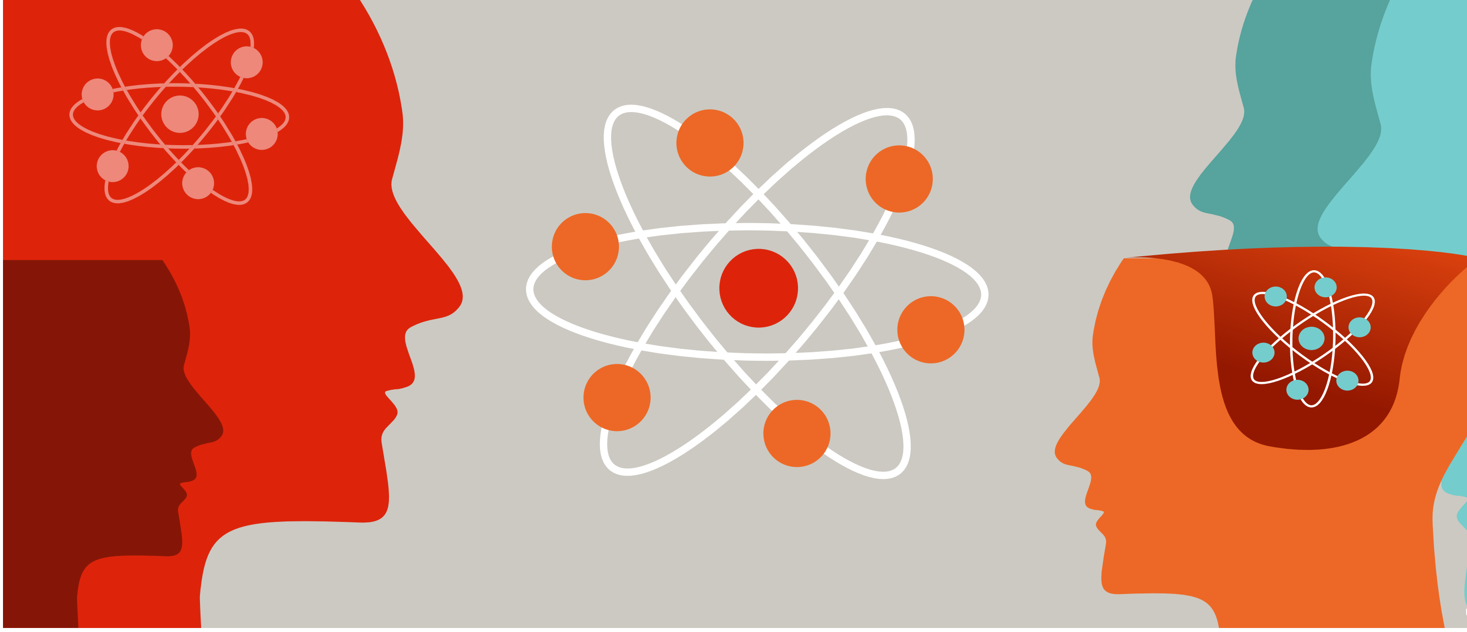
BRIAN GALLAGHER is an associate editor at *Nautilus*. Follow him on Twitter @bsgallagher.

The Enigma in Modern Living

For a theory nobody understands, quantum physics has remade human society in remarkable ways

BY SIDNEY PERKOWITZ

"NOBODY UNDERSTANDS QUANTUM MECHANICS," Richard Feynman famously said. Long after Max Planck's discovery in 1900 that energy comes in separate packets or quanta, quantum physics remains enigmatic. It is vastly different from how things work at bigger scales, where objects from baseballs to automobiles follow Newton's laws of mechanics and gravitation, consistent with our own bodily experiences. But at the quantum level, an electron is a particle and a wave, and light is a wave and a particle (wave-particle duality); an electron in an atom takes on only certain energies (energy quantization); electrons or photons can instantaneously affect each other over arbitrary distances (entanglement and teleportation); a quantum object exists in different states until it is measured (superposition, or popularly, Schrödinger's cat); and a real physical force emerges from the apparent nothingness of vacuum (the Casimir effect).



BAKHTIAR ZEIN / SHUTTERSTOCK

For a theory that nobody understands, quantum physics has changed human society in remarkable ways.[1] It lies behind the digital technology of integrated circuit chips, and the new technology of light-emitting diodes moving us toward a greener world. Scientists are now excited by one of the more elusive notions in quantum physics, the idea of ephemeral "virtual" photons, which could make possible non-invasive medical methods to diagnose the heart and brain. These connections illustrate the flow of ideas from scientific abstraction to useful application. But there is also a counter flow, where pragmatic requirements generate deep insight. The universal laws of thermodynamics have roots in efforts by 19th-century French engineer Sadi Carnot to make the leading technology of the time, the steam engine, more efficient. Similarly, the growth of quantum technology leads to deeper knowledge of the quantum. The interplay between pure theory, and its outcomes in the everyday world, is a continuing feature of science as it develops. In quantum physics, this interaction traces back to one of its founders, Danish physicist Niels Bohr.

In 1913, Bohr applied quantum ideas to the simplest atom, hydrogen. He found that the lone electron could occupy only certain orbits around the central proton, each with a specific energy, but not the spaces or energies in between. The electron jumps to other orbits by absorbing energy, or by emitting it as a photon at a wavelength set by the orbital energies involved. Bohr's model scored a huge success when it predicted the exact wavelengths of light emitted by energized hydrogen gas. Quantum jumps across the gaps between energy levels also produce the vividly colored light from advertising signs filled with neon and other gases, from lasers, and from LEDs.

Energy gaps are also at the heart of digital electronics and computing, which depend on the semiconducting transistor, invented in 1947. Semiconductors lie between metals, with many free electrons that carry electrical current, and insulators, whose electrons are held within its atoms and cannot form a current. The electrons in a semiconductor are also confined to its atoms, but once they jump across a so-called band gap, they can travel freely to form an electrical current. This current can be precisely manipulated to turn on and off as a switch, amplify signals, and perform other electronic functions when the semiconductor is formed into a transistor. Produced in millions within integrated circuit chips made of semiconducting silicon, transistors control the digital technology that defines our world. The band gap underlying all this is a pure quantum effect that arises because the electrons in a semiconductor occupy bands of energy separated by forbidden regions.

One promising idea is to use this technology to examine the human heart and brain without physical contact.

THE FACT THAT ENERGY is discontinuous at small scales is at odds with our view of the ordinary world, but now we take this aspect of nature for granted. However, superposition, entanglement, and teleportation raise deeper questions about quantum theory, yet also inspire new technology.

Superposition is tied to Erwin Schrödinger's famous equation, published in 1926. It is the quantum equivalent of Newton's equation $F = ma$ (that is, force = mass x acceleration, the basic equation of particle motion) but it describes a sub-atomic entity such as an electron as a wave, not a particle (although without telling us what this wave is). However, the equation's solution, called the wavefunction, can be used to calculate any property of the entity such as its position, but not definitively. The wavefunction only gives the probability that the electron can exist at a given position in an atom. In principle each location is possible according to its probability until an electron is measured, when the wavefunction is said to "collapse" to that value.

This view of quantum behavior is called the Copenhagen interpretation because of Bohr's role in developing it. It is like saying a deck of cards contains 52 different states that a selected card could take, in this case, with equal probabilities; but once you pick a card, that becomes the actual state, leaving the other 51 irrelevant. But the analogy is imperfect: We firmly believe that the suit and value printed on each card are real and fixed whether someone picks a card or not. In classical physics too we assume that objects have definite properties even if they are not being measured, a belief called realism. But the Copenhagen view makes it questionable whether an electron or photon has definite values independent of a measurement.

If, reading this, you are wondering how and why the act of measurement somehow deeply affects the nature of the thing measured, you are not alone. This is one of the enduring questions that Einstein, among other physicists, and philosophers too, have asked but not yet answered, leaving the full meaning of quantum theory unsettled. The Copenhagen view is widely used, but other interpretations attempt to resolve the issues it raises.

Regardless, superposition enables a novel approach to computation. For example: A photon has an electric field that can be polarized to point in a given direction. This can be arranged so that under superposition, the photon has a 50 percent probability of pointing either vertically or horizontally, representing binary "1" or "0" respectively. The result is a quantum computer bit (a "qubit") that is both 1 and 0 until it is measured. An ordinary computer bit is only either 1 or 0, so using qubits enhances computing capacity by a factor of 2^n where n is the number of qubits; for instance, four ordinary bits can hold only one of the 16 binary numbers 0000 to 1111 (decimal 0 to 15) but four qubits hold all 16 simultaneously. By handling many pieces of data in parallel, a quantum computer takes computational power to unprecedented levels.

Besides photons, qubits can be based on quantum objects and systems such as electrons,[2] ions, and superconductors. Researchers are now testing these approaches to find the best one for commercial quantum computation. IBM projects a 1,000-qubit superconducting chip in two years.[3] Even a smaller 11-qubit computer, one based on ion qubits, can in principle juggle 2,048 numbers at once.[4]

Entanglement provides other new ways to handle data; but when Schrödinger invented the term in 1935 he was thinking about entanglement as "not *one* but apparently *the* characteristic trait of quantum mechanics." This defining feature can be illustrated with a pair of electrons. Due to the property called spin, electrons are like tiny magnets with a north pole that points either up or down. It is possible to create a pair of electrons with total spin zero, with one north pole up and the other down, but we don't know which is which. Now separate the two electrons as far apart as you like and measure the spin direction of electron A; then whatever the result, a measurement of the spin direction of electron B always gives the opposite value.

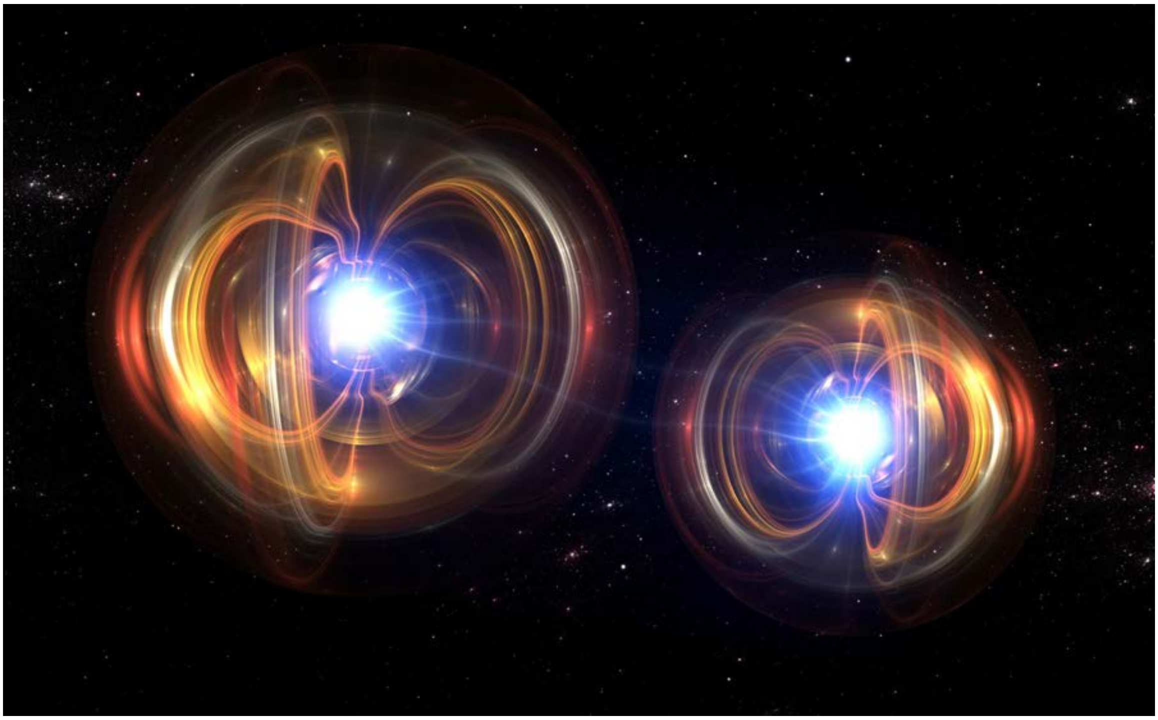
This is entanglement, where a measurement of a property of one of two linked quantum objects instantaneously sets the value of that property in the other, regardless of distance. Numerous experiments confirm that quantum objects are correlated in ways that ordinary objects are not, even if far apart. In 2017, a group under Jian-Wei Pan of the University of Science and Technology of China showed that a pair of photons remained entangled over a record distance of 1,200 kilometers. Experiments also show that any interaction between entangled objects occurs more quickly than the speed of light would allow. This violates the condition called locality that arises from special relativity,

It's like saying that once you pick a card, that becomes the actual state, leaving the other 51 irrelevant.

which is what troubled Einstein when he called entanglement "spooky action at a distance." With quantum realism already dubious, many physicists are tending to the view that both realism and locality do not apply in the quantum world.

Nevertheless, through its role in teleportation, entanglement enables quantum telecommunication, even at a global scale. In 1993, Charles Bennet of IBM and colleagues theorized about how to exactly copy and send the unknown state of a quantum system to a distant receiver, that is, teleport quantum information. This was revolutionary because in quantum theory, one cannot exactly clone, say, a photon with an unknown polarization, since making copies would provide a way to evade the uncertainty principle. But entanglement provides another workaround: If you measure the polarization of an entangled photon, you know the polarization of its partner without a direct measurement. The Bennett paper proposed using entangled photons A and B, located respectively with the sender and the recipient, to transmit the unknown state of a third photon X to photon B.

In 1997 Anton Zeilinger, then at the University of Innsbruck, and colleagues successfully teleported the unknown polarization state of a photon. Such experiments have opened the door to distributing data in the form of polarized photon qubits, with a huge bonus: The quantum nature of teleportation makes the transfer of confidential information secure against tampering or eavesdropping. This is not merely an issue in spy novels: Security is essential in a host of electronic transactions that support internet commerce and financial transfers and carry private information.



SPOOKY ACTION Entanglement, a key principle of quantum physics, enables quantum telecommunication, which makes the transfer of confidential information secure against tampering or eavesdropping.

JURIK PETER / SHUTTERSTOCK

For security, these transmissions are encrypted, then decoded by the recipient with a secret key sent via a separate secure channel, which is where the method is vulnerable. In a quantum system, however, the key is a random string of qubits, which is tamper-proof: If a third party reads or alters the key, that amounts to a quantum measurement, changing the key in a way that the sender and recipient can detect. With this feature, quantum teleportation raises the possibility of an utterly secure worldwide network implemented through space satellite transmissions over large distances. The 1,200 km transmission of entangled photons was carried out between a space satellite and ground stations.[5] It is a first step toward a global quantum internet.

THE QUANTUM EFFECTS that translate into technology are anti-intuitive and hard to visualize, but one recent development brings us back to the familiar world of Newtonian mechanics with an actual physical force—except that it arises from the quantum vacuum, which unlike the classical idea of vacuum, is not empty. Instead, in the extension of quantum mechanics called quantum field theory, the vacuum of space is the lowest energy state of the universe and supports "virtual" elementary particles that briefly pop into existence. These include virtual photons with varied wavelengths. In 1948, the Dutch theorist Hendrik Casimir predicted that two barely separated parallel metal plates placed in this quantum vacuum would be attracted to each other. This happens because only waves that fit exactly into

Apart from its usefulness, quantum technology shows that applied quantum physics can broaden fundamental understanding.

the gap between the plates survive there, producing a lower energy density than exists outside the plates and hence an inward force. This force is extremely small, and so is the necessary spacing between the plates, around 100 nanometers.

Finally in 1997 delicate measurements quantitatively confirmed Casimir's prediction, and other results show that the effect also occurs for non-metals in different geometries. Since then, researchers in micro- and nano-electromechanical systems—chip-size devices that combine electrical and mechanical functions—have begun exploiting the Casimir force. Its sensitivity to small distances allows ultra-precise measurements by tracking mechanical movements. One promising idea is to use this technology to examine the human heart and brain without physical contact, by measuring the extremely small magnetic fields they generate. At present this is done with bulky equipment that needs cryogenic cooling. An electromechanical chip would instead use the Casimir effect to analyze a heart or brain right in a physician's office at room temperature.

Apart from its usefulness, quantum technology shows that applied quantum physics can broaden fundamental understanding. Ingenious quantum scientists showed that teleportation can make an end run around the uncertainty principle and achieve a real-world result, secure telecommunications. In this case, researchers learned how to manipulate quantum effects to evade one basic principle; but also appreciate that the secure nature of teleported keys made up of qubits arises from other basic quantum properties, randomness, and sensitivity to measurement.

But will we ever fully understand why quantum theory works so well? Feynman's graduate adviser, the distinguished theorist John Archibald Wheeler, did not have the answer but clearly stated the goal when he wrote in 1984 that "the most revolutionary discovery in science is yet to come! … not by questioning the quantum, but by uncovering that utterly simple idea that demands the quantum."

SIDNEY PERKOWITZ is Candler Professor of Physics Emeritus, Emory University. His latest books are *Physics: A Very Short Introduction* and *Science Sketches* (forthcoming, 2022).

REFERENCES

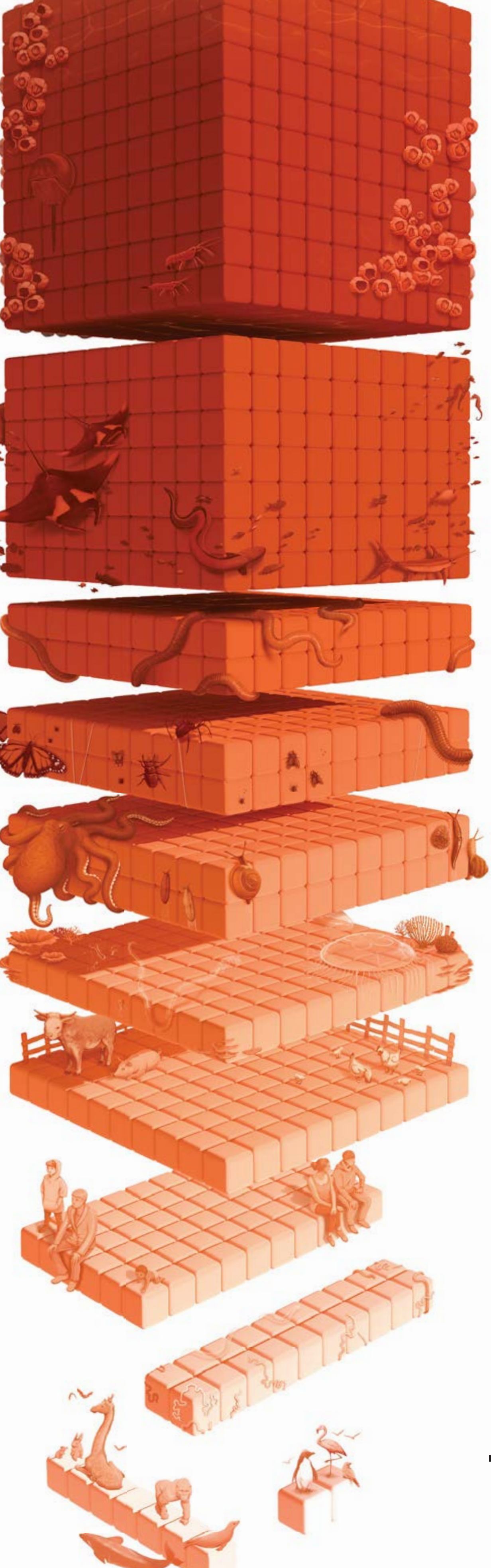
1. Adesso, G., Lo Franco, R., & Parigi, V. Foundations of quantum mechanics and their impact on contemporary society. *Philosophical Transactions of the Royal Society A* **376**, 20180112 (2018).

2. Valich, L. One small step for electrons, one giant leap for quantum computers. www.rochester.edu (2019).

3. Gambetta, J. IBM's roadmap for scaling quantum technology. www.research.ibm.com (2020).

4. Wright, K., *et al.* Benchmarking an 11-qubit computer. *Nature Communications* **10**, 5464 (2019).

5. Popkin, G. China's quantum satellite achieves "spooky action" at record distance. *Science* (2017).



All the Biomass on Earth

Our planet supports 8.7 million species. Here's how they break down.

BY IMAN GHOSH

ALL THE BIOMASS OF EARTH, IN ONE GRAPHIC

Our planet supports approximately 8.7 million species, of which over a quarter live in water.

But humans can have a hard time comprehending numbers this big, so it can be difficult to really appreciate the breadth of this incredible diversity of life on Earth.

To fully grasp this scale, we draw from research from "The biomass distribution on Earth," by Yinon M. Bar-On, Rob Phillips, and Ron Milo to break down the total composition of the living world, in terms of its biomass, and where we fit into this picture.

WHY CARBON?

A "carbon-based life form" might sound like something out of science fiction, but that's what we and all other living things are.

Carbon is used in complex molecules and compounds—making it an essential part of our biology. That's why biomass, or the mass of organisms, is typically measured in terms of carbon makeup.

In our visualization, one cube represents 1 million metric tons of carbon, and every thousand of these cubes is equal to 1 Gigaton (Gt C).

Here's how the numbers stack up in terms of biomass of life on Earth:

Taxon	Mass (Gt C)	% of total
Plants	450	82.4%
Bacteria	70	12.8%
Fungi	12	2.2%
Archaea	7	1.3%
Protists	4	0.70%
Animals	2.589	0.47%
Viruses	0.2	0.04%
Total	**545.8**	**100.0%**

Plants make up the overwhelming majority of biomass on Earth. There are 320,000 species of plants, and their vital photosynthetic processes keep entire ecosystems from falling apart.

Fungi is the third most abundant type of life—and although 148,000 species of fungi have been identified by scientists, it's estimated there may be millions more.

ANIMALS: A DROP IN THE BIOMASS OCEAN

Although animals make up only 0.47 percent of all biomass, there are many sub-categories within them that are worth exploring further.

Taxon	Mass (Gt C)	% of Animal Biomass
Arthropods (Marine)	1.0	38.6%
Fish	0.7	27.0%
Arthropods (Terrestrial)	0.2	7.7%
Annelids	0.2	7.7%
Mollusks	0.2	7.7%
Livestock	0.1	3.9%
Cnidarians	0.1	3.9%
Humans	0.06	2.3%
Nematodes	0.02	0.8%
Wild mammals	0.007	0.3%
Wild birds	0.002	0.1%
Animals (Total)	**2.589**	**100.0%**

Arthropods

Arthropods are the largest group of invertebrates, and include up to 10 million species across insects, arachnids, and crustaceans.

Chordates

The category of chordates includes wild mammals, wild birds, livestock, humans, and fish. Across 65,000 living species in total, nearly half are bony fish like piranhas, salmon, or seahorses.

Surprisingly, humans contribute a relatively small mass compared to the rest of the animal kingdom. People make up only 0.01 percent of all the biomass on the planet.

Annelids, Mollusks, Cnidarians, and Nematodes

Annelids are segmented worms like earthworms or leeches, with over 22,000 living species on this planet. After arthropods, mollusks are the second-largest group of invertebrates with over 85,000 living species. Of these, 80 percent are snails and slugs.

Cnidarians are a taxon of aquatic invertebrates covering 11,000 species across various marine environments. These include jellyfish, sea anemone, and even corals.

Nematodes are commonly referred to as roundworms. These sturdy critters have successfully adapted to virtually every kind of ecosystem, from polar regions to oceanic trenches. They've even survived traveling into space and back.

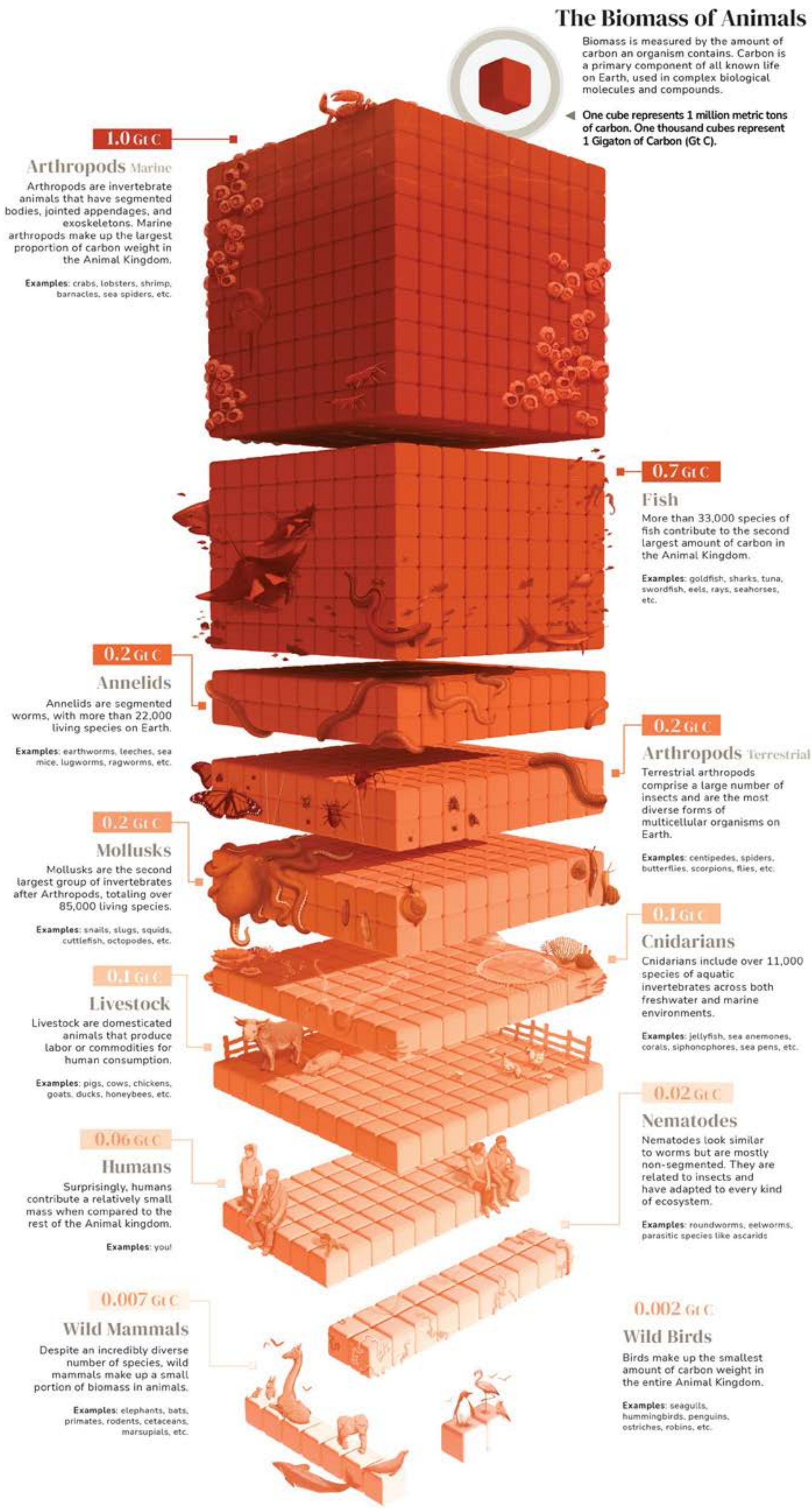
THE MICROSCOPIC REST

Beyond these animals, plants, and fungi, there are an estimated trillion species of microbes invisible to the naked eye—and we've probably only discovered 0.001 percent of them so far.

Bacteria

Bacteria were one of the first life forms to appear on Earth, and are classified as prokaryotes (nucleus-less). Today, they're the second-largest composition of biomass behind plants. Perhaps this is because these organisms can be found living literally everywhere—from your gut to deep in the Earth's crust.

Researchers at the University of Georgia estimate that there are 5 nonillion bacteria on the planet—that's a five with 30 zeros after it.



Humans make up approximately **0.01% of all biomass on Earth**.

SOURCE Bar-On, Y.M., Phillips, R., Milo, R., 2018. The biomass distribution on Earth. Proceedings of the National Academy of Sciences 115, 6506–6511.. doi:10.1073/pnas.1711842115

Protists and Archaea

Protists are mostly unicellular, but are more complex than bacteria, as they contain a nucleus. They're also essential components of the food chain.

Archaea are single-celled microorganisms that are similar to bacteria but differ in compositions. They thrive in extreme environments too, from high temperatures above 100 degrees Celsius (212 degrees Fahrenheit) in geysers to extremely saline, acidic, or alkaline conditions.

Viruses

Viruses are the most fascinating category of biomass. They have been described as "organisms at the edge of life," as they are not technically living things. They're much smaller than bacteria—however, as the COVID-19 pandemic has shown, their microscopic effects cannot be understated.

THE EARTH'S BIOMASS, UNDER THREAT

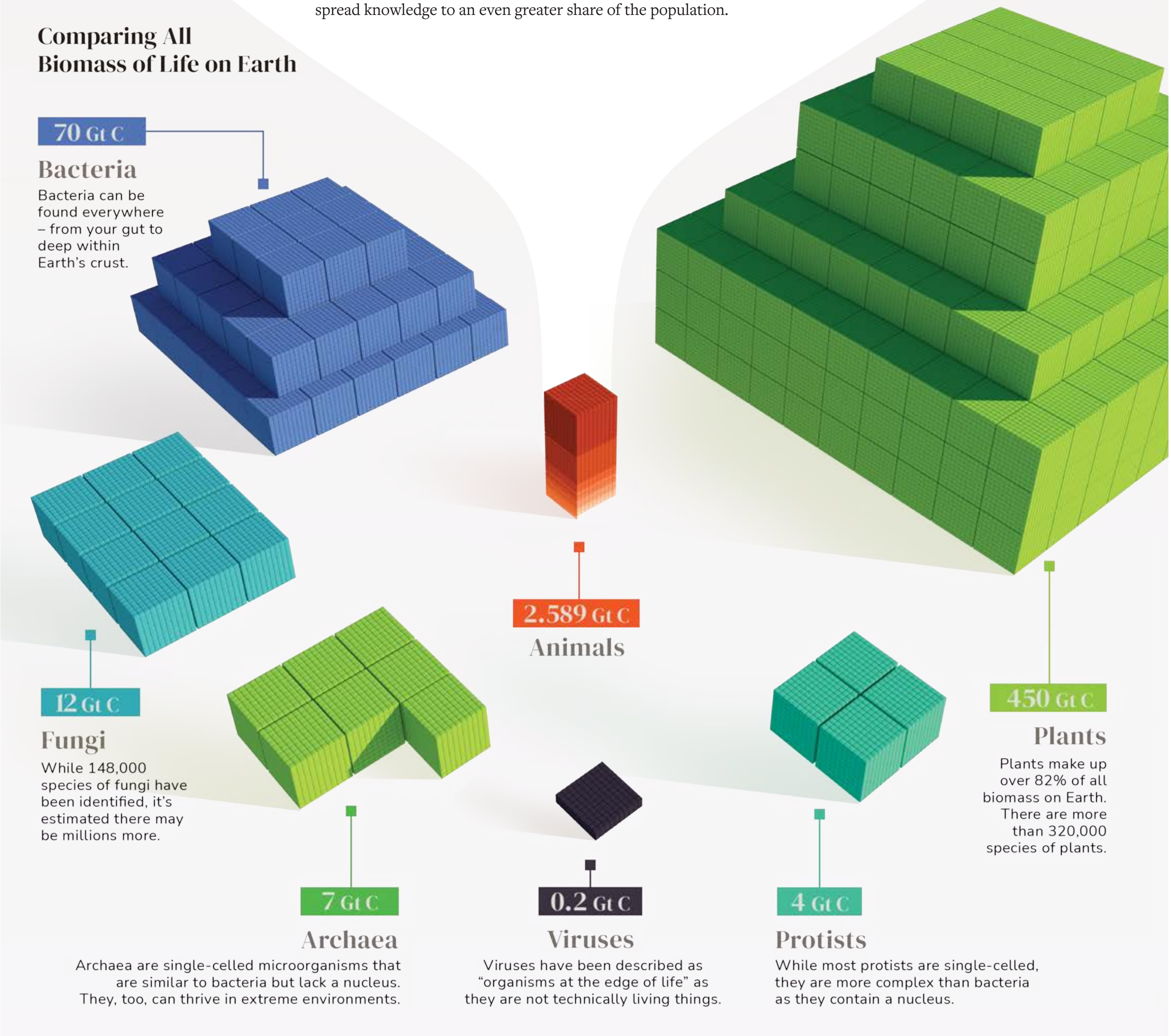
Human activities are having an ongoing impact on Earth's biomass.

For example, we've lost significant forest cover in the past decades to make room for agricultural land use and livestock production. One result of this is that biodiversity in virtually every region is on the decline.

Will we be able to reverse this trajectory and preserve the diversity of all the biomass on Earth, before it's too late?

ANUPA (IMAN) GHOSH is a senior writer and Publishing Operations Manager at Visual Capitalist, a data-driven media site focused on making the world's information more accessible.

This article was originally published on Visual Capitalist, with the following editor's note: This visualization was inspired by the work of Javier Zarracina for *Vox* from a few years ago. Our aim with this piece was to recognize that while great communication needs no reinvention, it can be enhanced and reimagined to increase editorial impact and help spread knowledge to an even greater share of the population.



The Power of the Waves

Understanding how oceans move is key to understanding life on Earth

BY RICHARD HAMBLYN

SEA WAVES ARE AMONG the world's most misunderstood phenomena. When an incoming wave breaks on the shoreline, it appears as though the water has come to the end of a long journey, but in fact the water itself has hardly moved. Most surface sea waves transmit energy, not water, and the turbulence at the surf zone is the result of that moving energy encountering a solid obstruction—usually the shelving sea floor—against which it noisily dissipates. It is at that point that the wave transforms, from an energy-transporting wave of oscillation to a water-moving wave of translation, more commonly known as "swash." So for most of its life a wave is not a thing so much as an event, a small part of a largescale transfer of energy from one part of the sea to another.

For most of its life a wave is not a thing so much as an event, a small part of a largescale transfer of energy from one part of the sea to another.

Waves are most commonly generated by the friction between wind and the surface of the water. As wind blows across the sea, the disturbance and perturbation cause a small wave crest to form, and the resulting up and down motion begins to transmit kinetic energy through the water in the form of a series of waves. As the waves grow, the energy (but not the water) passes from crest to crest, as is apparent when a piece of flotsam, say a tin can, can be seen bobbing up and down on the spot as waves pass beneath it.

Waves are classified according to their wave period or wavelength (the distance between two crests), from the smallest capillary waves to the greatest waves of all, the tides, and those who study them are known as kumatologists, from the Greek *kumas* (wave), a term coined by the wave-obsessed English geographer Vaughan Cornish in 1899. Capillary waves are the small, rippled disturbances that first appear on the surface of wind-blown water, which have been known to mariners for centuries as "cats' paws." William Henry Smyth, in his *Sailor's Word-Book* (1867), defined the cat's paw as "a light air perceived at a distance in a calm, by the impressions made on the surface of the sea, which it sweeps very gently," and noted the widespread superstition of rubbing a ship's backstay to invoke the lucky cat's paw, "the general forerunner of the steadier breeze." Samuel Taylor Coleridge, en route to Malta in April 1804, wrote a finely observed description of the various wave types seen from deck, starting with the hair's-breadth ripples of capillary waves:

> I particularly watched the beautiful Surface of the Sea in this gentle Breeze! – every form so transitory, so for the instant, & yet for that instant so substantial in all its sharp lines, steep surfaces, & hair-deep indentures, just as if it were cut glass, glass cut into ten thousand varieties / & then the network of the wavelets, & the rude circle hole network of the Foam.

As is evident from both Smyth's and Coleridge's accounts, the characteristically rippled structure of capillary waves is due to light breezes (blowing at

MAKING WAVES Utagawa Hiroshige, Naruto Whirlpool, Awa Province, from *Views of Famous Places in the Sixty-odd Provinces* (c. 1853).

THE METROPOLITAN MUSEUM OF ART

speeds of about 10–13 feet per second) that generate wavelengths typically less than 0.6 inch. Such gentle wind is not what sailors need to fill their sails, however, and neither is it enough to cause traveling waves to form. The threshold wavelength at which surface waves begin to travel is above 0.7 inch: Anything shorter than that will be suppressed by gravity. But if—as Smyth's sailors would have hoped—the wind strengthens to blow consistently over a substantial fetch of water, the second class of sea wave, gravity waves, will then begin to form.

Gravity waves occur when wavelength grows to around 5 feet, and gravity joins forces with wind as the main dispersing agent. A slight convexity in the wave shape is needed to give the wind something to work on, and as soon as a wavelet develops a leeward face and a windward back, the wave (as it now is) will begin to climb: The water's line of least resistance is to go upward as the energy in the wind is transferred to the sea. When longer gravity waves propagate over deep water, they move rapidly away from the generating wind, at which point they are known as swells, with a typical wavelength greater than 855 feet, up to a maximum of 2,950 feet. Swells lose so little energy as they cross open water that it's possible for one generated in the Antarctic Ocean to travel all the way to Alaska at full strength, taking several days to do so. Swells tend to flatten out as they move away from their source, and ripples and waves can form on top of underlying swells, causing a complex surface pattern which takes an experienced navigator to discern. But even the longest-lasting swell will eventually approach a shoreline, at which point contact with the shoaling sea floor will cause it to break and dissipate its energy remarkably quickly.

THE MOON'S COSMIC LEASH

The longest waves of all are the tides, the vertical movements of seawater dragged by the gravitational pull of the moon and sun. High tides and low tides occur on opposite sides of our planet at the same time, and, in the words of navigator Tristan Gooley, "can be thought of as a pair of very long waves that ride around the Earth," straddling half the globe between crests.

SAILOR'S WARNING The maelstrom off the coast of Norway, as illustrated in Olaus Magnus's Carta Marina, 1539.

Most coastal areas experience two high tides and two low tides every lunar day—the time taken for a specific spot to rotate from and return to an exact point under the moon: A lunar day is 50 minutes longer than a solar day because the moon revolves around Earth in the same direction that Earth rotates around its axis, so it takes Earth a little more time to "catch up" with the moon. The section of ocean nearest the moon is pulled by gravity into an upward bulge, while the Earth's rotation sends that bulge moving round the planet, giving us two high and two low tides every 24 hours and 50 minutes.

Tides are global forces, but they also feature local and regional improvisations—eddies, whirlpools, vortices, maelstroms—their cosmic regularity perturbed by wind and weather conditions, as well as by local topography. Gravitational lift alone can only raise a tide of some 18 inches: Anything higher than that is caused by the shape of the coastal land and its influence on the high-tide bulge, which can be funneled into heights as great as 50 feet, as seen in the steeply shoaling Severn Estuary. When a tide makes contact with the coast, its water rushes up inlets and estuaries, reflects off sea walls, swirls around rocks and islands. It can even bounce back and cancel itself out, as happens in parts of the Gulf of Mexico, where there is only one high tide per day, while the opposite effect can lead to so-called "double tides," where the topography and resulting flow leads to a double peak at high tide—an extra-long period of high water—which is the main reason why Southampton, shielded by the Isle of Wight on England's south coast, was developed as a major naval and commercial port.

But beneath their capriciousness, tides express an underlying order that is almost clock-like in its regularity, with a twelve-and-a-half-hour tidal cycle governing most of our planet's coastal waters: Tides typically run for around six hours in one direction, before reversing and running in the opposite direction for the following six hours. The writer Hugh Aldersey-Williams has described this as "one of the Earth's fundamental units of time," a temporal precondition that has made itself at home in our language, with its ancient interplays of time and tide.

Understanding tides was vital for seafarers, and the first predictive tide table appeared in 11th-century China in response to the powerful and deadly tidal bore that surges up the Qiantang River. Known locally as the Black Dragon, the world's largest tidal wave attracts thousands of spectators, but the tide tables outlining wave times and heights can be notoriously inaccurate. In August 2013, the bore was roughly twice its predicted height, sweeping hundreds of spectators into the water, while the following year the appearance of a supermoon generated another unexpectedly powerful 30-foot wave that injured dozens more.

Farther out at sea, tide-related perturbations such as whirlpools, vortexes, and tidal races are not always marked on charts. "They are places, but they are also theatrical events," as Aldersey-Williams observed in the course of an account of his journey into the maelstrom, a large whirlpool off Norway's Lofoten Islands, known locally as the Moskstraumen, after the nearby Moskenesøya Island. Rather than the wild vortex of literary legend, as invoked by Edgar Allan Poe in his celebrated story "A Descent into the Maelström" (1841), as well as by Jules Verne in the tragic finale of *Twenty Thousand Leagues Under the Seas*, the phenomenon is a system of tidal eddies and whirlpools that exude, in Aldersey-Williams's words, "a quiet venomous authority in contrast to the petulant rage of great waves."

Though whirlpools can be noisy and violent—they are caused when fast-moving tidal currents are sent into a spin by local topography, or by the meeting of a pair of opposing currents—the original, Norwegian, maelstrom is fairly pacific. It features a sequence of choppy waves and declivities fueled by strong diurnal tides rather than the hole in the sea—"the navel of the ocean"—implied by the popular legends.

But Earth will not experience such phenomena forever. A billion or so years ago, the moon was much nearer than it is today, with the correspondingly stronger gravitational attraction raising vast tides in Earth's young oceans that had condensed from atmospheric water vapor. The energy dissipated by those tides as friction helped slow Earth's rotational and orbital speeds, locking our moon into its present alignment, so it always shows the same face to Earth. Eventually our slowing planet will also become tidally locked, and so always show the same face to the moon. The tides will then cease, depriving any surviving intelligent life of one of Earth's great natural dramas, the spectacle of the oceans' rise and fall under the pull of the moon's cosmic leash.

THE GULF STREAM AND MODERN OCEANOGRAPHY

Among the many irritations suffered by the British during their administration of the American colonies was the fact that ships dispatched from Britain took two weeks longer to cross the Atlantic than ships dispatched from America. At a loss to account for this disparity, which could not be attributed to prevailing winds, the Admiralty eventually approached Benjamin Franklin, scientist and Postmaster General to the colonies, whose subsequent enquiries among his seafaring contacts revealed what Nantucket whalers had known for generations: the existence of a swift Atlantic current that plies its way along the eastern seaboard before heading across the open sea to Europe. Franklin, whose next two crossings were spent testing the waters, confirmed that a fast-flowing ocean river, known as the Gulf Stream, did indeed run across the North Atlantic, and that "a stranger may know when he is in it, by the warmth of the water, which is much greater than that of the water on each side of it." It was during an Atlantic crossing in April–May 1775 that he devoted most time to the subject, lowering his thermometer into the ocean several times a day, from 7 in the morning to 11 at night, while the ship kept along the eastern edge of the stream and then cut across it into colder water. He noticed that the water in the stream had a different color from the surrounding seawater, partly due to the increased quantity of gulf weed to be found in it, and that "it does not sparkle in the night." But it was his insight that the Gulf Stream "might be studied like a river" that transformed contemporary understanding of ocean currents, while pointing out the means by which vessels, armed only with a thermometer, could shorten their crossings in both directions by keeping variously in and out of this flowing Atlantic river.

Research into the movements of the Gulf Stream was continued by Alexander Dallas Bache, a superintendent of the United States Coast Survey, who also happened to be Franklin's great-grandson. In 1845 Bache issued a set of instructions for Gulf Stream studies that did much to establish the framework of the modern oceanographic survey:

> **First**: What are the limits of the Gulf Stream on this part of the coast of the United States, at the surface and below the surface?
>
> **Second**: Are they constant or variable, do they change with the season, with the prevalent and different winds; what is the effect of greater or less quantities of ice in the vicinity?
>
> **Third**: How may they best be recognized, by the temperature at the surface or below the surface, by soundings, by the character of the bottom, by peculiar forms of vegetable or animal life, by meteorology, by the saltness of the water?
>
> **Fourth**: What are the directions and velocities of the currents in this Stream and adjacent to it at the surface, below the surface, and to what variations are they subject?

The effect of the Gulf Stream's great circulation is to transfer significant amounts of heat across the North Atlantic.

By bringing together a range of physical, chemical, geological, biological, and meteorological questions, Bache extended oceanography toward an understanding of the ocean as a complex system of physical and biological interrelationships. Bache was proud to have continued the oceanographic work begun by his great-grandfather, although it would cost the life of his brother, George, a naval officer in command of the survey brig Washington, who was swept overboard along with 10 of his crew during a storm off Cape Hatteras while engaged in Gulf Stream research in September 1846.

In the centuries since, the course and pace of the Gulf Stream have been tracked and measured, as have the changes that it undergoes during its long Atlantic crossing: As the current heads north, its cargo of warm tropical water cools and evaporates, leaving saltier, heavier water behind. By the time it reaches the Norwegian Sea the Gulf Stream's payload is cold and dense enough to start sinking toward the ocean floor, turning to flow south toward the equator in a cold countercurrent that will eventually return it to the point where its journey began. The effect of this great circulation is to transfer significant amounts of heat across the North Atlantic—a thermal budget almost 100 times greater than world energy demand—preserving the inhabitants of western Europe from the harsh winters which besiege other places at similar latitudes, such as Canada or southern Alaska.

The process of thermohaline warming was first described in the 1850s by the American hydrographer Matthew Fontaine Maury, who characterized the oceans as a vast and efficient boiler house (the term derives from *thermo* (heat) and *haline* (salt), the two factors that influence the density of seawater). As Maury outlined in his landmark study *The Physical Geography of the Sea* (1855), "the furnace is the torrid zone, the Mexican Gulf and Caribbean Sea are the caldrons; the Gulf Stream is the conducting pipe" distributing tropical warmth toward Britain and western Europe. "It is the influence of this stream upon climate that makes Erin the "Emerald Isle of the Sea," and that clothes the shores of Albion in evergreen robes, while in the same latitude, on this side, the coasts of Labrador are fast bound in fetters of ice," he wrote. "There is a river in the ocean; in the severest droughts it never fails, and in the mightiest floods it never overflows. Its banks and bottoms are of cold water, while its current is of warm. The Gulf of Mexico is its fountain, and its mouth is in the Arctic Seas. It is the Gulf Stream. There is in the world no other such majestic flow of waters."

Maury's rhapsodic description captures the vastness of the Gulf Stream phenomenon, while hinting at its widespread influence on Earth's weather and climate. Such thermohaline currents are the engines of Earth's weather, due to seawater's efficiency at storing and transporting solar heat. Water covers 70 percent of the planet's total area, with around 97 percent of that water contained in the oceans; most of the remainder is locked up in ice sheets and glaciers, and less than 0.001 percent is ever present in the atmosphere: enough for only 10 days' rain. Thermohaline circulation transports a massive current of water around the globe, from northern oceans to southern oceans and back again. These currents—driven by differences in water density—slowly turn seawater over in the ocean, from top to bottom, like a vast conveyor belt, sending warm surface water downward and forcing cold, dense, nutrient-rich water upward. Cold seawater in the polar regions forms sea ice, as a consequence of which the surrounding water becomes saltier, since when sea ice forms, the salt is left behind. As the polar water grows saltier, its density increases, and it starts to sink. Surface water is then pulled in to replace the sinking water, which in turn grows cold and salty enough to sink, too. This movement is what initiates the deep-ocean currents that drive the global conveyer belt, with water always seeking an equilibrium; when cold, dense water sinks, sending warmer water welling up from below to balance out the loss at the surface.

This results in an intermixing of the solar energy collected by the top layer of ocean and the nutrient-filled sediment of decayed plant and animal matter found at the bottom. Without the great conveyor belt stirring them up, along with the wind-driven upwelling that occurs near coastal regions, most of these nutrients would remain sequestered at the sea floor, leaving the oceans unable to support its dazzling array of life forms.

RICHARD HAMBLYN is a senior lecturer in the department of English, Theatre and Creative Writing at Birkbeck, University of London. An award-winning environmental writer and historian, his previous books include *Terra: Tales of the Earth*, *The Art of Science*, *Extraordinary Weather*, *Tsunami: Nature and Culture*, and *Clouds: Nature and Culture* in Reaktion's Earth series.

It’s Not Irrational to Party Like It’s 1999

Contrary to what the philosopher said, passion can be a slave to reason

BY STEVEN PINKER

VCHAL / SHUTTERSTOCK

MUST WE ALWAYS follow reason? Do I need a rational argument for why I should fall in love, cherish my children, enjoy the pleasures of life? Isn't it sometimes OK to go crazy, to be silly, to stop making sense? If rationality is so great, why do we associate it with a dour joylessness? Was the philosophy professor in Tom Stoppard's play *Jumpers* right in his response to the claim that "the Church is a monument to irrationality?"

> "The National Gallery is a monument to irrationality! Every concert hall is a monument to irrationality! And so is a nicely kept garden, or a lover's favour, or a home for stray dogs! . . . If rationality were the criterion for things being allowed to exist, the world would be one gigantic field of soya beans!"

Here I'll take up the professor's challenge. We will see that while beauty and love and kindness are not literally rational, they're not exactly irrational, either. We can apply reason to our emotions and to our morals, and there is even a higher-order rationality that tells us when it can be rational to be irrational.

Stoppard's professor may have been misled by David Hume's famous argument that "reason is, and ought only to be the slave of the passions, and can never pretend to any other office than to serve and obey them." Hume, one of the hardest-headed philosophers in the history of Western thought, was not advising his readers to shoot from the hip, live for the moment, or fall head over heels for Mr. Wrong.[1] He was making the logical point that reason is the means to an end, and cannot tell you what the end should be, or even that you must pursue it. By "passions" he was referring to the source of those ends: the likes, wants, drives, emotions, and feelings wired into us, without which reason would have no goals to figure out how to attain. It's the distinction between thinking and wanting, between believing something you hold to be true and desiring something you wish to bring about. His point was closer to "There's no disputing tastes" than "If it feels good, do it."[2] It is neither rational nor irrational to prefer chocolate ripple to maple walnut. And it is in no way irrational to keep a garden, fall in love, care for stray dogs, party like it's 1999, or dance beneath the diamond sky with one hand waving free.[3]

Still, the impression that reason can oppose the emotions must come from somewhere—surely it is not just a logical error. We keep our distance from hotheads, implore people to be reasonable, and regret various flings, outbursts, and acts of thoughtlessness. If Hume was right, how can the opposite of what he wrote also be true: that the *passions* must often be slaves to *reason*?

In fact, it's not hard to reconcile them. One of our goals can be incompatible with the others. Our goal at one time can be incompatible with our goals at other times. And one person's goals can be incompatible with others.' With those conflicts, it won't do to say that we should serve and obey our passions. Something has to give, and that is when rationality must adjudicate.

PEOPLE DON'T WANT just one thing. They want comfort and pleasure, but they also want health, the flourishing of their children, the esteem of their fellows, and a satisfying narrative on how they have lived their lives. Since these goals may be incompatible—cheesecake is fattening, unattended kids get into trouble, and cutthroat ambition earns contempt—you can't always get what you want. Some goals are more important than others: the satisfaction deeper, the pleasure longer lasting, the narrative more compelling. We use our heads to prioritize our goals and pursue some at the expense of others.

Cheesecake is fattening, unattended kids get into trouble, and cutthroat ambition earns contempt—you can't always get what you want.

While Odysseus had himself tied to the mast and rationally relinquished his option to *act*, his sailors plugged their ears with wax and rationally relinquished their option to *know*. At first this seems puzzling. One might think that knowledge is power, and you can never know too much. Just as it's better to be rich than poor, because if you're rich you can always give away your money and be poor, you might think it's always better to know something, because you can always choose not to act on it. But in one of the paradoxes of rationality, that turns out not to be true. Sometimes it really is rational to plug your ears with wax.[4] Ignorance can be bliss, and sometimes what you don't know can't hurt you.

An obvious example is the spoiler alert. We take pleasure in watching a plot unfold, including the suspense, climax, and denouement, and may choose not to spoil it by knowing the ending in advance. Sports fans who cannot see a match in real time and plan to watch a recorded version later will sequester themselves from all media and even from fellow fans who might leak the outcome in a subtle tell. Many parents choose not to learn the sex of their unborn child to enhance the joy of the moment of birth. In these cases we rationally choose ignorance because we know how our own involuntary positive emotions work, and we arrange events to enhance the pleasure they give us.

By the same logic, we can understand our negative emotions and starve ourselves of information that we anticipate would give us pain. Many consumers of genetic testing know they would be better off remaining ignorant of whether the man who calls himself their father is biologically related to

We keep our distance from hotheads, implore people to be reasonable, and regret various flings, outbursts, and acts of thoughtlessness.

them. Many choose not to learn whether they have inherited a dominant gene for an incurable disease that killed a parent, like the musician Arlo Guthrie, whose father, Woody, died of Huntington's. There's nothing they can do about it, and knowledge of an early and awful death would put a pall over the rest of their lives. For that matter most of us would plug our ears if an oracle promised to tell us the day we will die.

We also preempt knowledge that would bias our cognitive faculties. Juries are forbidden to see inadmissible evidence from hearsay, forced confessions, or warrantless searches—"the tainted fruit of the poisoned tree"—because human minds are incapable of ignoring it. Good scientists think the worst of their own objectivity and conduct their studies double blind, choosing not to know which patients got the drug and which the placebo. They submit their papers to anonymous peer review, removing any temptation to retaliate after a bad one, and, with some journals, redact their names, so the reviewers can't indulge the temptation to repay favors or settle scores.

In these examples, rational agents choose to be ignorant to game their own less-than-rational biases. But sometimes we choose to be ignorant to prevent our rational faculties from being exploited by rational adversaries—to make sure they cannot make us an offer we can't refuse. You can arrange not to be home when the Mafia wiseguy calls with a threat or the deputy tries to serve you with a subpoena. The driver of a Brink's truck is happy to have his ignorance proclaimed on the sticker "Driver does not know combination to safe," because a robber cannot credibly threaten him to divulge it. A hostage is better off if he does not see the faces of his captors, because that leaves them an incentive to release him. Even misbehaving young children know they're better off not meeting their parents' glares.

Rational ignorance is an example of the mind-bending paradoxes of reason explained by the political scientist Thomas Schelling in his 1960 classic *The Strategy of Conflict*. In some circumstances it can be rational to be not just ignorant but powerless, and, most perversely of all, irrational.

In the game of Chicken, made famous in the James Dean classic *Rebel Without a Cause*, two teenage drivers approach each other at high speed on a narrow road and whoever swerves first loses face (he is the "chicken"). Since each one knows that the other does not want to die in a head-on crash, each may stay the course, knowing the other has to swerve first. Of course when both are "rational" in this way, it's a recipe for disaster (a paradox of game theory). So is there a strategy that wins at Chicken? Yes—relinquish your ability to swerve by conspicuously locking the steering wheel, or by putting a brick on the gas pedal and climbing into the back seat, leaving the other guy no choice but to swerve. The player who lacks control wins. More precisely, the *first* player to lack control wins: if both lock their wheels simultaneously …

Though the game of Chicken may seem like the epitome of teenage foolishness, it's a common dilemma in bargaining, both in the marketplace and in everyday life. Say you're willing to pay up to $30,000 for a car and know that it cost the dealer $20,000. Any price between $20,000 and $30,000 works to both of your advantages, but of course you want it to be as close as possible to the lower end of the range and the sales rep to the upper end. You could lowball him, knowing he's better off consummating the deal than walking away, but he could highball you, knowing the same thing. So he agrees that your offer is reasonable but needs the OK from his manager, but when he comes back he says regretfully that the manager is a hardass who nixed the deal. Alternatively, you agree that the price is reasonable but you need the OK from your bank, and the loan officer refuses to lend you that much. The winner is the one whose hands are tied. The same can happen in friendships and marriages in which both partners would rather do something together than stay home, but differ in what they most enjoy. The partner with the superstition or hang-up or maddeningly stubborn personality that categorically rules out the other's choice will get his or her own.

Threats are another arena in which a lack of control can afford a paradoxical advantage. The problem with threatening to attack, strike, or punish is that the threat may be costly to carry out, rendering it a bluff that the target of the threat could call. To make it credible, the threatener must be committed to carrying it out, forfeiting the control that would give his target the leverage to threaten him right back by refusing to comply. A hijacker who wears an explosive belt that goes off with the slightest jostle, or protesters who chain themselves to the tracks in front of a train carrying fuel to a nuclear plant, cannot be scared away from their mission.

The commitment to carry out a threat can be not just physical but emotional.[5] The narcissist, borderline, hothead, high-maintenance romantic partner, or "man of honor" who considers it an intolerable affront to be disrespected and lashes out regardless of the consequences is someone you don't want to mess with.

A lack of control can blend into a lack of rationality. Suicide terrorists who believe they will be rewarded in paradise cannot be deterred by the

Suicide terrorists who believe they will be rewarded in paradise cannot be deterred by the prospect of death on Earth.

prospect of death on Earth. According to the Madman Theory in international relations, a leader who is seen as impetuous, even unhinged, can coerce an adversary into concessions. In 1969 Richard Nixon reportedly ordered nuclear-armed bombers to fly recklessly close to the USSR to scare them into pressuring their North Vietnamese ally to negotiate an end to the Vietnam War. Donald Trump's bluster in 2017 about using his bigger nuclear button to rain fire and fury on North Korea could charitably be interpreted as a revival of the theory.

The problem with the madman strategy, of course, is that both sides can play it, setting up a catastrophic game of Chicken. Or the threatened side may feel it has no choice but to take out the madman by force rather than continue a fruitless negotiation. In everyday life, the saner party has an incentive to bail out of a relationship with a madman or madwoman and deal with someone more reasonable. These are reasons why we are not all madpeople all the time (though some of us get away with it some of the time).

Promises, like threats, have a credibility problem that can call for a surrender of control and of rational self-interest. How can a contractor convince a client that he will pay for any damage, or a borrower convince a lender that she will repay a loan, when they have every incentive to renege when the time comes? The solution is to post a bond that they would forfeit, or sign a note that empowers the creditor to repossess the house or car. By signing away their options, they become trustworthy partners. In our personal lives, how do we convince an object of desire that we will forsake all others till death do us part, when someone even more desirable may come along at any time? We can advertise that we are incapable of rationally choosing someone better because we never rationally chose that person in the first place—our love was involuntary, irrational, and elicited by the person's unique, idiosyncratic, irreplaceable qualities.[6] I can't help falling in love with you. I'm crazy for you. I like the way you walk, I like the way you talk.

The paradoxical rationality of irrational emotion is endlessly thought-provoking and has inspired the plots of tragedies, Westerns, war movies, mafia flicks, spy thrillers, and the Cold War classics *Fail Safe* and *Dr. Strangelove*. But nowhere was the logic of illogic more pithily stated than in the 1941 film noir *The Maltese Falcon*, when detective Sam Spade dares Kasper Gutman's henchmen to kill him, knowing they need him to find the jewel-encrusted falcon. Gutman replies:

> That's an attitude, sir, that calls for the most delicate judgment on both sides, because as you know, sir, in the heat of action men are likely to forget where their best interests lie, and let their emotions carry them away.

STEVEN PINKER is the author, most recently, of *Rationality: What It Is, Why It Seems Scarce, Why It Matters*. He is the Johnstone Family Professor in the Department of Psychology at Harvard University. His other books include *How the Mind Works* and *The Better Angels of Our Nature*.

REFERENCES

1. Cohon, R. The passions and intentional action. In Coventry, A.M. & Sager, A. (Eds.), *The Humean Mind* Taylor & Francis (2018).

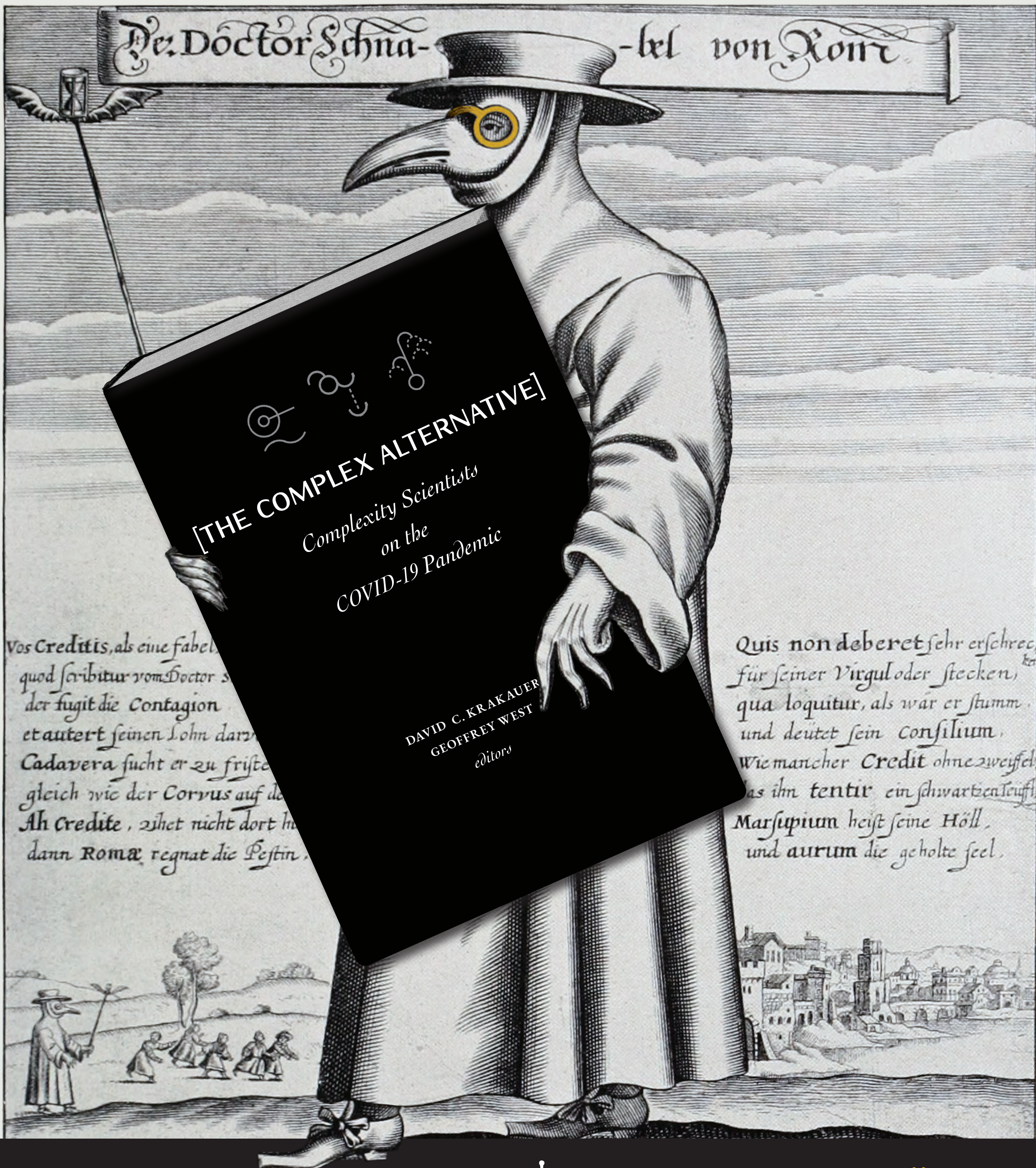
2. Though that's not what he literally believed about taste in art and wine, as expressed in "Of the standard of taste" (Gracyk 2020). His point here was only that goals are inherently subjective.

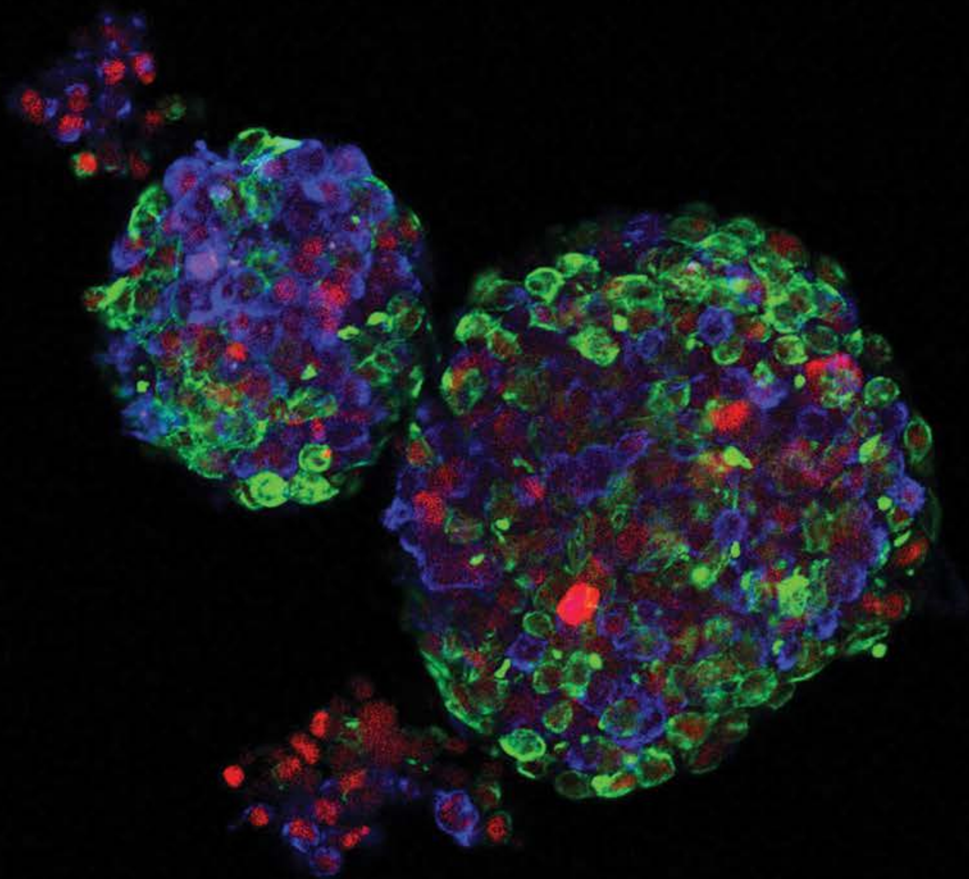
3. Bob Dylan, "Mr. Tambourine Man."

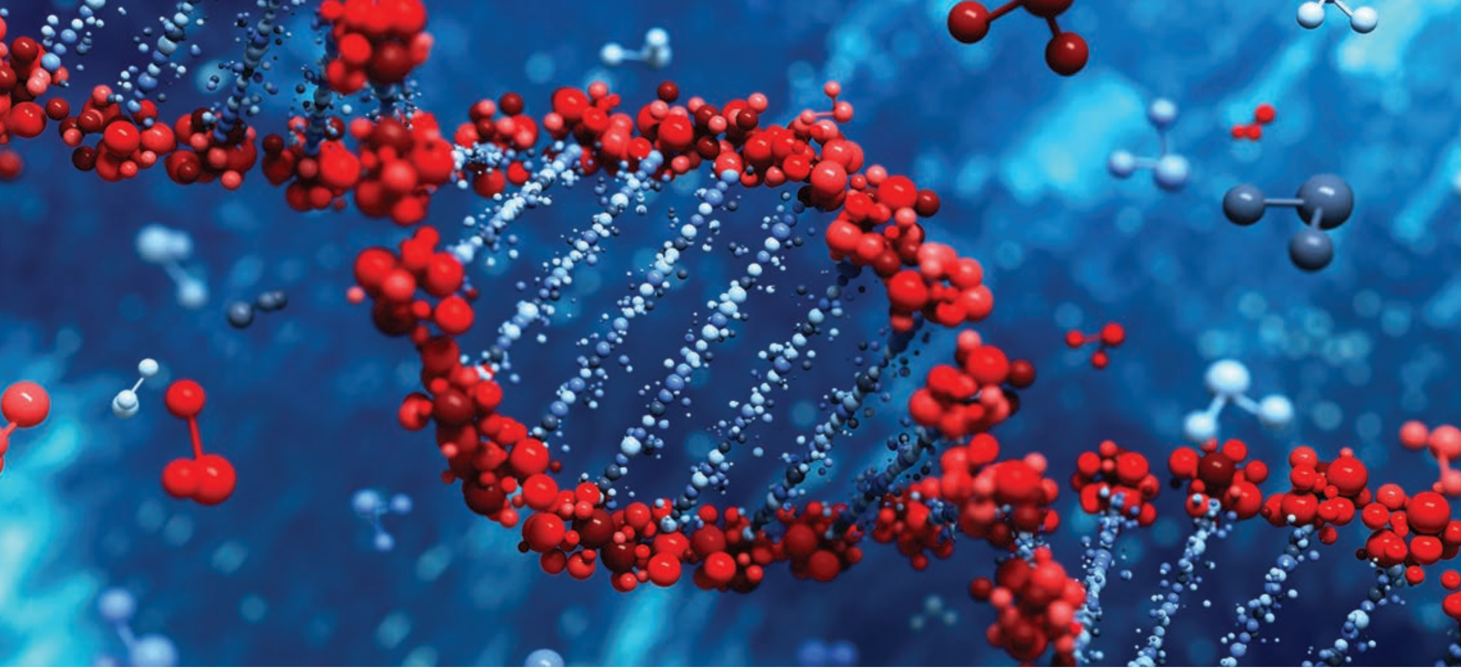
4. Gigerenzer, G. & Garcia-Retamero, R. Cassandra's regret: The psychology of not wanting to know. *Psychological Review* **124**, 179–196 (2017).

5. Frank, R.H. *Passions within reason: The strategic role of the emotions* W.W. Norton & Company, New York, NY (1988).

6. Pinker, S. *How the Mind Works* W.W. Norton & Company, New York, NY (1997/2009).


Der Doctor Schna- -bel von Rom
[THE COMPLEX ALTERNATIVE]
Complexity Scientists on the COVID-19 Pandemic
DAVID C. KRAKAUER
GEOFFREY WEST
editors
Quis non deberet sehr erschrec
für seiner Virgul oder stecken,
qua loquitur, als wär er stumm,
und deutet sein consilium.
Wie mancher Credit ohne zweiffel
das ihm tentir ein schwartzen Teuffl
Marsupium heist seine Höll,
und aurum die geholte seel.





SCIENCE
PHILANTHROPY ALLIANCE

Advancing basic science—The foundation of our future

sciphil.org

Pocket is where everything you save goes

Pocket scours the internet to bring you a curated mix of fascinating articles like these and a beautiful space to collect them in.

Sign up and save anything that sparks your curiosity in your Pocket to absorb when you're ready.

www.getpocket.com


LISTEN TO THE OCEAN
"We are inhabitants of an ocean world. Everything that happens down there is linked to us up here."
Dr Helen Czerski
Presenter, Ocean Matters
Take a deep dive into Ocean Matters - a new podcast series looking at aspects of life on, above and beneath the shimmering surface of our seas. With interviews and insights from specialists at the cutting edge of marine science, we explore the issues threatening the ocean and discover how we can protect the blue engine that's central to all life on earth.
Search for 'Ocean Matters' and subscribe wherever you get your podcasts.
Apple Podcasts
Google Podcasts
Spotify
fb fondation bertarelli
fondation-bertarelli.org

Issue Index

18

JAN/FEB 2017

44 LUCK
45 POWER

17

NOV/DEC 2016

42 FAKES
43 HEROES

16

SEP/OCT 2016

40 LEARNING
41 SELECTION

15

JULY/AUG 2016

38 NOISE
39 SPORT

14

MAY/JUNE 2016

36 AGING
37 CURRENTS

13

MAR/APR 2016

34 ADAPTATION
35 BOUNDARIES

12

JAN/FEB 2016

32 SPACE
33 ATTRACTION

11

NOV/DEC 2015

30 IDENTITY
31 STRESS

10

SEP/OCT 2015

28 2050
29 SCALING

09

JULY/AUG 2015

25 WATER
26 COLOR
27 DARK MATTER

08

MAY/JUNE 2015

22 SLOW
23 DOMINOES
24 ERROR

07

MAR/APR 2015

19 ILLUSIONS
20 CREATIVITY
21 INFORMATION

06

WINTER 2015

16 NOTHINGNESS
17 BIG BANGS
18 GENIUS

05

FALL 2014

13 SYMMETRY
14 MUTATION
15 TURBULENCE

04

SUMMER 2014

10 MERGERS & ACQUISITIONS
11 LIGHT
12 FEEDBACK

03

SPRING 2014

07 WASTE
08 HOME
09 TIME

02

WINTER 2014

04 THE UNLIKELY
05 FAME
06 SECRET CODES

01

FALL 2013

01 HUMAN UNIQUEN
02 UNCERTAINTY
03 IN TRANSIT

Science Connected.

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

SUBSCRIPTIONS
Address subscription and address changes to:
Nautilus
360 W 36th Street, 7S
New York, NY 10018;
email: order@nautil.us

Visit shop.nautil.us for more information.

POSTMASTER
Send address changes to:
Nautilus
360 W 36th Street, 7S
New York, NY 10018

THE LAST WORD

Steven Pinker

The psychologist unpacks rationality

INTERVIEW BY BRIAN GALLAGHER

CAPITALISM IS BEST

When people talk about capitalism, they often talk about something that doesn't exist. A kind of fantasy anarchical capitalism with no regulation or social safety net. Now, granted there are people on the right who might advocate for that—the Rand Paul-style of right-wing libertarians. But in practice, that's not what capitalism is anywhere, including the United States. When we talk about capitalism, we're talking about a system with a lot of social redistribution and a lot of regulation of environment, safety, workplace protections. That is capitalism. Compared to the alternatives, like communism, it is better. Not because I said so, but because that's what the evidence points to.

THE BILL GATES EFFECT

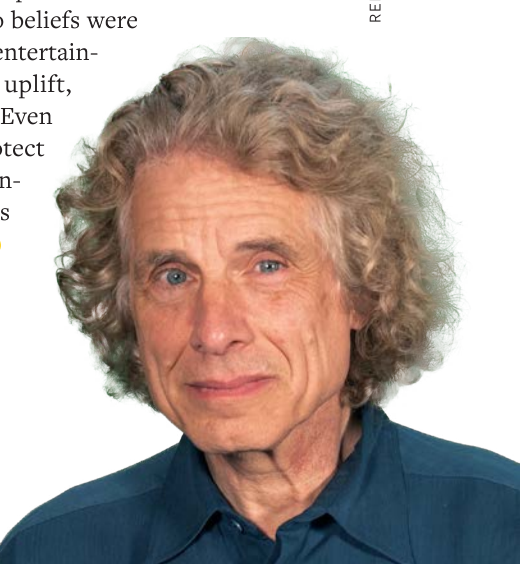
When it comes to some billionaire philanthropists, what is the alternative? Should we have a system that confiscates all the wealth of entrepreneurs? I'm not sure that that would be a better system, although I'd be open to arguments. Should someone like Bill Gates, who's credited with saving 100 million lives, have instead endowed some museums and opera houses? I think he deserves some credit for deploying the money to save lives instead, or to try and solve the very tough problems of climate change by investing in vulnerable startups that would have no chance otherwise, but might give us ways out of the climate crisis. I don't think we can depend on philanthropists, but on the other hand, I don't think that governments should have a monopoly on improving the world, because governments are hamstrung by numerous constraints—interest groups, democracy, and populist movements. If it was only governments that we had, I think we'd be worse off than if we had a mixture of governments and private actors.

RATIONAL IGNORANCE

A concrete example is the driver of the Brink's truck that has a sign plastered on the door saying, "Driver does not know combination to safe." That works in his interest because he can't be extorted into opening the safe if he doesn't know the combination. There are cases in which there can be an advantage to being ignorant or even irrational, to be the more stubborn, the more hotheaded member of a pair of negotiators to a degree, because of the peculiar game-theory logic of bargaining and negotiations. If you're too much of a loose cannon, others can either just take you out or decide never to enter negotiations with you in the first place. It's a calculated strategy of being irrational that may not pay off in the long run, but there can be those advantages.

ON WACKO CONSPIRACIES

Belief in them is not an assessment of the world that happens to be mistaken but an expression of moral condemnation of an enemy. "Hillary Clinton ran a child sex ring out of a pizzeria" is another way of saying, "Boo, Hillary!" Many of us are incredulous and outraged that people can turn a moralistic sentiment into a bogus factual claim. But that's because we have the historically unusual conviction that factual beliefs should be held only if one has good grounds for them. For most of our existence, there was no way to verify claims about the hidden processes or the machinations of the powerful, so beliefs were held for other reasons: entertainment, enchantment, uplift, solidarity, mobilization. Even today many people protect religious faith and nationalist founding myths from factual scrutiny.



REBECCA GOLDSTEIN


BALENCIAGA